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Functional Bounding Content Envelope for Type B Radioactive Material Transportation Packages

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DOE Packaging Certification Program

Bounding Content Envelope for Type B Radioactive Material Transportation Packages

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Functional Bounding Content Envelope for Type B Radioactive Material Transportation Packages

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ABSTRACT

There is an increasing need within DOE/NNSA to transport radioactive material items that contain relatively unique mixtures of isotopes and/or impurities that are not currently approved for transportation in a Type B radioactive material transportation package. To reduce the need to develop new addenda to the Safety Basis [i.e., Safety Analysis Report for Packaging (SARP)] to include each additional new contents for a Type B packaging, it would be extremely useful and overall much more cost efficient, to identify and develop a broad bounding content envelope in the safety basis (i.e., SARP) that includes a large variety of isotopes, chemical forms, and impurities (including, light-element impurities). A recent report issued by the DOE presented a comprehensive set of shippable masses of various gamma emitters as well as neutron emitters with varying amounts of beryllium impurities to account for the neutron emissions from the (α, n) reaction in the Model 9977 packaging. This paper extends this set by presenting mass limits for the various actinides combined with varying amounts of light element impurities in the range of 0.1% through 90% by mass of the mixture. The light elements included are: beryllium, boron, lithium, fluorine, carbon, aluminum, magnesium, sodium, silicon, oxygen, and chlorine. In addition to complying with external radiation limits as prescribed by 10 CFR Part 71, the isotopic mass limits in this paper also account for design decay heat limits for bare sources as well as those in a polyethylene shielded container that has been approved for use in the Model 9977 packaging. A new set of mass limits for the gamma emitters that accounts for decay heat limits in an unshielded form or in the approved tungsten and lead shielded containers is also presented. These data will also serve as conservative limits of shippable masses in the Models 9975 and 9978 packagings.

INTRODUCTION

The specific contents approved for shipment in a Type B radioactive material transportation package has historically been descriptions of discrete items, or groupings of well-defined similar items, in the package safety basis documentation [i.e., Safety Analysis Report for Packaging (SARP)]. As new radioactive items were identified that needed to be shipped, an addendum to the safety basis was needed to be made to add these new items. To develop, review and approve numerous addenda over time as more contents need to be added to the safety basis is both expensive and time consuming. Of late, there has been an increasing need at the DOE/NNSA complex to transport radioactive materials, including sources and special nuclear materials and other actinides with light element impurities. A recent DOE report [1] jointly developed by three national laboratories provides a set of allowable small masses of both gamma and neutron emitting radioactive isotopes in the Model 9977 packaging that are compliant with the external radiation limits set forth in 10 CFR Part 71 [2]. This set of limiting masses also included mixtures of alpha-emitting actinides with beryllium impurities up to approximately 50% by mass of the mixture.

The Model 9977 packaging has three shielded containers, lead and tungsten for gamma emitters and polyethylene for neutron emitters, which have been approved for use inside the containment vessel. The design decay heat limit for each of these is different and limiting masses should account for these limits

in addition to external radiation limits prescribed by 10 CFR Part 71. This paper presents an updated set of mass limits that account for decay heat limits for each shielded container as well as shipments that do not use these containers. In addition, the paper presents mass limits for an extended set of light element impurities that may be present in mixtures of common alpha emitting actinides. The light-element impurity content considered ranges from 1000 ppm to 90% by mass of the mixture. The light-element impurities included are beryllium, boron, lithium, fluorine, carbon, aluminum, magnesium, sodium, silicon, oxygen, and chlorine.

The isotopic mass limits presented in this paper were calculated for the Model 9977 radioactive material transportation package by way of example. A similar methodology could be employed to determine a functional bounding content envelope for other radioactive material transportation packages that includes allowable isotopic mass limits for numerous isotopes, and also includes light-element impurities and constraints related to design decay heat limits.

METHODOLOGY

The DOE report [1] presents details of the methodology used to develop the bounding masses for both gamma and neutron emitters. The set of isotopes selected for the study were from an earlier study [3] which presented a set of gamma sources and actinides that was developed based on input from several DOE sources. Source spectra were established based on a 47-group structure for the neutron emitters and a 77-group structure for the gamma emitters. The source terms were generated using the source generating codes RASTA [4] or ORIGEN [5], depending on which one of these codes was suitable and bounding for a specific isotope. All source spectra were based on 1g of the isotope.

The radiation transport calculations were performed using the Monte Carlo code, MCNP [6]. A detailed MCNP model of the Model 9977 packaging was created and dose rates were calculated on the surfaces of the package as well as at 1m from the surfaces as prescribed in 10 CFR Part 71 for non-exclusive use shipments. The dose rates were calculated as transfer functions starting with a single particle in each group for each source. The final dose rate at each point of interest was then estimated by folding in the appropriate source spectrum with the transfer functions. The sources were modeled as small cylinders placed at the bottom center of the containment vessel for the unshielded cases and at the bottom of the shielded container cavity. The sources were modeled as voids and with a representative nominal density material to examine self-shielding effects of the source.

The limiting dose rate for compliance with the non-exclusive use shipments was at the bottom surface and the limiting mass of each isotope was derived using this bounding set of dose rates. Since the radiation transport calculations were based on a very conservative model, all masses were calculated based on the limiting surface dose rate of 200 mrem/h, which occurred at the bottom surface of the package. As mentioned earlier, the set presented in Reference 1 did not account for the design decay heat limit for the three shielded containers or that for an unshielded shipment. The design decay heat limit for the Model 9977 package with an unshielded source or tungsten shielded gamma source is 19W. The decay heat limits for the lead shielded gamma source and the polyethylene shielded neutron source are 6W and 3W, respectively.

This paper will incorporate the appropriate decay heat limits and present a modified set of bounding masses for the gamma sources and neutron sources that are not impacted by light element impurities. For the alpha emitting actinides, where the (α, n) source is important, a new set of source spectra was developed for each light element mixed in proportions ranging from 1000 ppm to 90% of the mixture

mass. The bounding masses were calculated based on the 200 mrem/h limit as well as applicable design decay heat limits.

Since the limiting masses for some isotopes were quite large, there was a concern that the assumption that the sources were point sources may not result in the most limiting mass. Additional analyses for Pu-239 (which have kilogram level limits) were performed [3], whereby the sources were not assumed to be point sources but volume sources, consistent with their densities and the point source mass limits, and subcritical multiplication was taken into account. However, the self-shielding that occurs in the volume sources and the geometry effect of a volume source, more than compensated for the additional neutrons produced by subcritical multiplication, resulting in the point source models producing the most conservative values (i.e., lowest) for the limiting masses. It should be noted that these results are for homogeneous mixtures of light elements and actinides and thus yield conservative mass limits. For actinides and light elements combined in a different physical form, the mass limits could be higher.

MASS LIMITS FOR GAMMA SOURCES

Table 1 presents the mass limits for the gamma emitting isotopes that are compliant with the limiting 200 mrem/h package surface dose rate for non-exclusive use transport as well as the design decay heat limits for the various types of shielded containers.

Table 1. Mass Limits in grams for the Gamma Emitting Isotopes

	Allowed Mass of Isotope (g)			
	No Shielded	SC1 Lead Shielded	SC2 Polyethylene Shielded	SC3 Tungsten Shielded
Isotope	Container	Container	Container	Container
Ac-227	4.10E-04	4.18E-01	1.40E-03	1.32E+00
Cd-109	5.70E-03	3.75E+00	2.80E-02	1.19E+01
Co-60	3.30E-06	1.20E-04	9.60E-06	4.50E-04
Cs-137	1.60E-04	1.10E-01	5.00E-04	6.60E-01
Eu-152	4.40E-05	2.70E-03	1.30E-04	1.00E-02
Fe-59	1.60E-07	6.00E-06	4.60E-07	2.20E-05
Gd-153	1.40E-04	1.93E+00	6.40E-04	6.12E+00
Hf-181	9.10E-07	1.50E-02	3.00E-06	3.70E-02
Ho-166m	2.60E-03	1.98E-03	9.90E-04	6.27E-03
Ir-192	1.00E-06	6.80E-03	3.40E-06	4.10E-02
Mn-54	1.30E-06	2.00E-04	3.90E-06	1.10E-03
Pb-210	2.80E-02	2.47E+00	1.00E-01	7.84E+00
Pm-147	2.70E-01	1.76E+01	1.20E+00	5.59E+01
Po-210	1.32E-01	4.17E-02	2.08E-02	1.32E-01
Ra-226	5.30E-03	2.30E-01	1.60E-02	7.30E-01
Ru-106	9.30E-06	2.30E-03	2.90E-05	8.50E-03
Sc-46	1.30E-07	8.70E-06	3.80E-07	3.70E-05
Se-75	1.50E-06	1.71E-01	5.60E-06	5.42E-01
Sm-145	1.40E-02	4.13E+00	7.60E-02	1.31E+01
Sr-90	2.90E-03	1.40E+00	1.00E-02	5.80E+00
Tm-170	2.70E-04	5.10E-01	1.00E-03	1.61E+00
Yb-169	2.10E-06	9.77E-02	8.10E-06	3.09E-01
Zn-65	1.90E-06	9.50E-05	5.50E-06	3.90E-04
Zr-95	4.60E-07	1.30E-04	1.40E-06	7.70E-04

MASS LIMITS FOR NEUTRON EMITTING ISOTOPES

The actinide isotopes emit neutrons via two mechanisms. Most of them decay emitting alpha particles which can interact with light elements that could be present to produce neutrons via the (α, n) reaction. The other mechanism by which neutrons are produced is spontaneous fission. As mentioned earlier, this study covers several of the commonly occurring actinides combined with varying amounts of several light elements that may need to be transported in the Department of Energy (DOE) or National Nuclear Security Administration (NNSA) complexes. The data presented will cover the allowed masses for both the unshielded source as well as that placed in the polyethylene shielded container (SC2). The neutron induced gamma and source gamma contributions were also accounted for in determining the limiting masses.

Table 2 presents limiting mass data for all the actinides with no impurities in both unshielded as well as in the SC2 shielded conditions. External radiation limits and decay heat limits have been accounted for in determining these bounding masses.

Table 2. Actinides with no Impurities

Isotope	Unshielded	SC2 Polyethylene Shielded Container
Am-241	2.20E+01	2.62E+01
Am-243	3.20E-01	1.20E+00
Cf-252	1.90E-06	8.60E-06
Cm-244	3.90E-01	1.06E+00
Cm-248	1.10E-01	5.30E-01
Np-237	5.60E+01	2.00E+02
Pu-238	3.35E+01	5.28E+00
Pu-239	3.50E+03	1.55E+03
Pu-240	2.69E+03	4.24E+02
Pu-241	2.30E+01	2.94E+01
Pu-242	2.50E+03	1.20E+04

The set of six actinides that were studied with varying amounts of impurities are: ^{241}Am, ^{244}Cm, ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{242}Pu. Tables 3 through 8 present the bounding masses for these isotopes for each impurity in the set studied. These limits account for both external radiation and decay heat limits. Linear interpolation can be applied to determine mass limits at impurity contents that fall between those listed in the tables.

Some results in these tables may seem counter intuitive where the mass limit for the unshielded actinide is larger than that for it in the shielded SC2 container. As an example, the data in Tables 5a and 5b containing the data for ^{238}Pu exhibit this behavior. This occurs because of the design decay heat limit of 3W for the SC2 shielded container. The mass limits for ^{239}Pu and ^{240}Pu also exhibit this behavior.

Table 3a. ^{241}Am Mass Limits in grams - Unshielded

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	1.76E+01	1.99E+01	2.08E+01	2.05E+01	2.09E+01	2.08E+01	2.08E+01	2.08E+01	2.09E+01	2.09E+01	2.09E+01
5000ppm	1.08E+01	1.70E+01	2.05E+01	1.92E+01	2.09E+01	2.08E+01	2.06E+01	2.06E+01	2.08E+01	2.08E+01	2.08E+01
10000ppm	7.35E+00	1.44E+01	2.01E+01	1.78E+01	2.09E+01	2.07E+01	2.04E+01	2.03E+01	2.08E+01	2.08E+01	2.08E+01
50000ppm	2.22E+00	6.83E+00	1.78E+01	1.17E+01	2.08E+01	2.00E+01	1.88E+01	1.84E+01	2.06E+01	2.07E+01	2.06E+01
10pc	1.29E+00	4.44E+00	1.59E+01	8.52E+00	2.08E+01	1.92E+01	1.74E+01	1.67E+01	2.05E+01	2.06E+01	2.05E+01
30pc	6.17E-01	2.33E+00	1.24E+01	4.87E+00	2.08E+01	1.75E+01	1.43E+01	1.33E+01	2.00E+01	2.03E+01	1.99E+01
50pc	4.77E-01	1.84E+00	1.11E+01	3.87E+00	2.08E+01	1.65E+01	1.30E+01	1.18E+01	1.97E+01	2.01E+01	1.96E+01
70pc	4.16E-01	1.62E+00	1.04E+01	3.39E+00	2.08E+01	1.59E+01	1.22E+01	1.10E+01	1.95E+01	2.00E+01	1.94E+01
90pc	3.83E-01	1.50E+00	9.93E+00	3.12E+00	2.07E+01	1.55E+01	1.16E+01	1.05E+01	1.94E+01	2.00E+01	1.92E+01

Table 3b. ^{241}Am Mass Limits in grams – in SC2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01
5000ppm	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01
10000ppm	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01
50000ppm	7.49E+00	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01
10pc	4.27E+00	1.83E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01
30pc	2.02E+00	9.32E+00	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01
50pc	1.56E+00	7.32E+00	2.62E+01	2.36E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01
70pc	1.36E+00	6.43E+00	2.62E+01	2.08E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01
90pc	1.25E+00	5.94E+00	2.62E+01	1.91E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01	2.62E+01

Table 4a. ^{244}Cm Mass limits in grams- Unshielded

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	3.46E-01	3.72E-01	3.79E-01	3.77E-01	3.80E-01	3.80E-01	3.80E-01	3.80E-01	3.80E-01	3.80E-01	3.80E-01
5000ppm	2.55E-01	3.42E-01	3.75E-01	3.62E-01	3.80E-01	3.79E-01	3.78E-01	3.77E-01	3.80E-01	3.80E-01	3.80E-01
10000ppm	1.93E-01	3.11E-01	3.70E-01	3.46E-01	3.80E-01	3.78E-01	3.75E-01	3.73E-01	3.80E-01	3.80E-01	3.80E-01
50000ppm	6.99E-02	1.88E-01	3.36E-01	2.61E-01	3.80E-01	3.69E-01	3.57E-01	3.48E-01	3.78E-01	3.79E-01	3.77E-01
10pc	4.21E-02	1.34E-01	3.08E-01	2.06E-01	3.80E-01	3.59E-01	3.39E-01	3.25E-01	3.75E-01	3.78E-01	3.74E-01
30pc	2.08E-02	7.71E-02	2.52E-01	1.31E-01	3.80E-01	3.35E-01	2.98E-01	2.74E-01	3.69E-01	3.75E-01	3.65E-01
50pc	1.61E-02	6.22E-02	2.30E-01	1.07E-01	3.79E-01	3.21E-01	2.77E-01	2.50E-01	3.65E-01	3.73E-01	3.59E-01
70pc	1.41E-02	5.55E-02	2.17E-01	9.52E-02	3.79E-01	3.13E-01	2.65E-01	2.36E-01	3.63E-01	3.72E-01	3.55E-01
90pc	1.30E-02	5.16E-02	2.09E-01	8.84E-02	3.79E-01	3.07E-01	2.57E-01	2.26E-01	3.61E-01	3.72E-01	3.52E-01

Table 4b. ^{244}Cm Mass limits in grams- in SC2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00
5000ppm	1.03E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00
10000ppm	7.30E-01	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00
50000ppm	2.36E-01	7.93E-01	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00
10pc	1.39E-01	5.50E-01	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00
30pc	6.73E-02	3.07E-01	1.06E+00	7.22E-01	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00
50pc	5.20E-02	2.46E-01	1.06E+00	6.02E-01	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00
70pc	4.55E-02	2.19E-01	1.06E+00	5.41E-01	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00
90pc	4.18E-02	2.03E-01	1.06E+00	5.05E-01	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00	1.06E+00

Table 5a. ^{238}Pu Mass limits in grams- Unshielded

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	1.84E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01
5000ppm	4.33E+00	1.57E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01
10000ppm	2.23E+00	8.53E+00	3.35E+01	2.00E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01	3.35E+01
50000ppm	4.95E-01	2.00E+00	1.94E+01	5.03E+00	3.35E+01	3.35E+01	2.82E+01	2.38E+01	3.35E+01	3.35E+01	3.35E+01
10pc	2.74E-01	1.12E+00	1.17E+01	2.80E+00	3.35E+01	3.35E+01	1.74E+01	1.44E+01	3.35E+01	3.35E+01	3.35E+01
30pc	1.27E-01	5.22E-01	5.76E+00	1.25E+00	3.35E+01	1.77E+01	8.42E+00	6.81E+00	3.35E+01	3.35E+01	3.35E+01
50pc	9.73E-02	4.03E-01	4.49E+00	9.36E-01	3.35E+01	1.36E+01	6.40E+00	5.15E+00	3.35E+01	3.35E+01	3.35E+01
70pc	8.47E-02	3.51E-01	3.94E+00	8.00E-01	3.35E+01	1.18E+01	5.50E+00	4.41E+00	3.35E+01	3.35E+01	3.35E+01
90pc	7.77E-02	3.23E-01	3.62E+00	7.24E-01	3.35E+01	1.07E+01	5.00E+00	4.00E+00	3.35E+01	3.35E+01	3.33E+01

Table 5b. ^{238}Pu Mass limits in grams- in SC2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00
5000ppm	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00
10000ppm	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00
50000ppm	1.60E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00
10pc	8.88E-01	4.34E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00
30pc	4.10E-01	2.03E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00
50pc	3.15E-01	1.56E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00
70pc	2.74E-01	1.36E+00	5.28E+00	5.04E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00
90pc	2.51E-01	1.25E+00	5.28E+00	4.56E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00	5.28E+00

Table 6a. ^{239}Pu Mass limits in grams- Unshielded

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	2.32E+03	2.99E+03	3.31E+03	3.22E+03	3.33E+03	3.32E+03	3.31E+03	3.31E+03	3.33E+03	3.33E+03	3.33E+03
5000ppm	1.06E+03	2.14E+03	3.25E+03	2.84E+03	3.33E+03	3.30E+03	3.26E+03	3.25E+03	3.32E+03	3.32E+03	3.32E+03
10000ppm	6.34E+02	1.59E+03	3.17E+03	2.48E+03	3.33E+03	3.28E+03	3.19E+03	3.18E+03	3.31E+03	3.32E+03	3.32E+03
50000ppm	1.64E+02	5.55E+02	2.71E+03	1.28E+03	3.32E+03	3.10E+03	2.76E+03	2.75E+03	3.26E+03	3.28E+03	3.30E+03
10pc	9.26E+01	3.33E+02	2.36E+03	8.47E+02	3.32E+03	2.93E+03	2.41E+03	2.40E+03	3.21E+03	3.24E+03	3.27E+03
30pc	4.35E+01	1.64E+02	1.77E+03	4.36E+02	3.30E+03	2.53E+03	1.79E+03	1.77E+03	3.07E+03	3.14E+03	3.19E+03
50pc	3.36E+01	1.28E+02	1.55E+03	3.37E+02	3.30E+03	2.34E+03	1.55E+03	1.52E+03	2.99E+03	3.08E+03	3.14E+03
70pc	2.93E+01	1.12E+02	1.44E+03	2.92E+02	3.29E+03	2.22E+03	1.42E+03	1.39E+03	2.94E+03	3.05E+03	3.11E+03
90pc	2.69E+01	1.04E+02	1.37E+03	2.67E+02	3.29E+03	2.14E+03	1.34E+03	1.31E+03	2.91E+03	3.03E+03	3.08E+03

Table 6b. ^{239}Pu Mass limits in grams- in SC2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03
5000ppm	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03
10000ppm	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03
50000ppm	5.39E+02	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03
10pc	3.05E+02	1.29E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03
30pc	1.43E+02	6.42E+02	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03
50pc	1.10E+02	5.01E+02	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03
70pc	9.62E+01	4.40E+02	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03
90pc	8.84E+01	4.05E+02	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03

Table 7a. ^{240}Pu Mass limits in grams- Unshielded

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	1.20E+03	2.10E+03	2.69E+03	2.57E+03	2.69E+03	2.69E+03	2.69E+03	2.69E+03	2.69E+03	2.69E+03	2.69E+03
5000ppm	3.66E+02	1.04E+03	2.64E+03	1.84E+03	2.69E+03	2.69E+03	2.66E+03	2.66E+03	2.69E+03	2.69E+03	2.69E+03
10000ppm	1.97E+02	6.37E+02	2.45E+03	1.36E+03	2.69E+03	2.69E+03	2.50E+03	2.49E+03	2.69E+03	2.69E+03	2.69E+03
50000ppm	4.57E+01	1.69E+02	1.64E+03	4.70E+02	2.69E+03	2.31E+03	1.72E+03	1.71E+03	2.69E+03	2.69E+03	2.69E+03
10pc	2.55E+01	9.67E+01	1.22E+03	2.76E+02	2.69E+03	1.99E+03	1.29E+03	1.27E+03	2.56E+03	2.62E+03	2.69E+03
30pc	1.19E+01	4.61E+01	7.38E+02	1.29E+02	2.69E+03	1.42E+03	7.63E+02	7.46E+02	2.26E+03	2.39E+03	2.50E+03
50pc	9.16E+00	3.57E+01	6.05E+02	9.77E+01	2.69E+03	1.21E+03	6.11E+02	5.96E+02	2.11E+03	2.28E+03	2.39E+03
70pc	7.98E+00	3.12E+01	5.43E+02	8.40E+01	2.69E+03	1.10E+03	5.39E+02	5.23E+02	2.01E+03	2.21E+03	2.32E+03
90pc	7.33E+00	2.87E+01	5.07E+02	7.62E+01	2.69E+03	1.03E+03	4.96E+02	4.82E+02	1.95E+03	2.17E+03	2.27E+03

Table 7b. ^{240}Pu Mass limits in grams- in SC2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02
5000ppm	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02
10000ppm	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02
50000ppm	1.51E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02
10pc	8.39E+01	3.82E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02
30pc	3.91E+01	1.81E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02
50pc	3.01E+01	1.40E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02
70pc	2.62E+01	1.23E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02
90pc	2.40E+01	1.13E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02	4.24E+02

Table 8a. ^{242}Pu Mass limits in grams- Unshielded

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	2.38E+03	2.41E+03	2.43E+03	2.42E+03	2.43E+03	2.43E+03	2.43E+03	2.43E+03	2.43E+03	2.43E+03	2.43E+03
5000ppm	2.24E+03	2.37E+03	2.42E+03	2.41E+03	2.43E+03	2.43E+03	2.42E+03	2.42E+03	2.43E+03	2.43E+03	2.43E+03
10000ppm	2.08E+03	2.33E+03	2.42E+03	2.40E+03	2.43E+03	2.42E+03	2.42E+03	2.42E+03	2.43E+03	2.42E+03	2.43E+03
50000ppm	1.39E+03	2.03E+03	2.42E+03	2.30E+03	2.42E+03	2.42E+03	2.41E+03	2.41E+03	2.42E+03	2.42E+03	2.43E+03
10pc	1.03E+03	1.79E+03	2.41E+03	2.20E+03	2.43E+03	2.42E+03	2.40E+03	2.40E+03	2.42E+03	2.42E+03	2.42E+03
30pc	6.25E+02	1.38E+03	2.39E+03	1.97E+03	2.42E+03	2.40E+03	2.36E+03	2.37E+03	2.42E+03	2.42E+03	2.42E+03
50pc	5.11E+02	1.23E+03	2.38E+03	1.85E+03	2.42E+03	2.40E+03	2.34E+03	2.35E+03	2.42E+03	2.42E+03	2.42E+03
70pc	4.59E+02	1.15E+03	2.38E+03	1.79E+03	2.42E+03	2.39E+03	2.33E+03	2.34E+03	2.41E+03	2.42E+03	2.42E+03
90pc	4.28E+02	1.10E+03	2.37E+03	1.74E+03	2.42E+03	2.39E+03	2.32E+03	2.33E+03	2.42E+03	2.42E+03	2.42E+03

Table 8b. ^{242}Pu Mass limits in grams- in SC2

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000ppm	1.13E+04	1.15E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04
5000ppm	1.03E+04	1.13E+04	1.16E+04	1.15E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04
10000ppm	9.36E+03	1.10E+04	1.16E+04	1.15E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04	1.16E+04
50000ppm	5.57E+03	9.37E+03	1.16E+04	1.12E+04	1.16E+04	1.16E+04	1.15E+04	1.15E+04	1.16E+04	1.16E+04	1.16E+04
10pc	3.93E+03	8.13E+03	1.15E+04	1.08E+04	1.16E+04	1.15E+04	1.14E+04	1.15E+04	1.16E+04	1.16E+04	1.16E+04
30pc	2.24E+03	6.08E+03	1.15E+04	1.00E+04	1.16E+04	1.15E+04	1.12E+04	1.15E+04	1.15E+04	1.15E+04	1.16E+04
50pc	1.81E+03	5.35E+03	1.15E+04	9.56E+03	1.16E+04	1.15E+04	1.11E+04	1.14E+04	1.15E+04	1.15E+04	1.16E+04
70pc	1.61E+03	4.97E+03	1.15E+04	9.30E+03	1.16E+04	1.15E+04	1.10E+04	1.14E+04	1.15E+04	1.15E+04	1.16E+04
90pc	1.50E+03	4.73E+03	1.15E+04	9.11E+03	1.16E+04	1.15E+04	1.10E+04	1.14E+04	1.15E+04	1.15E+04	1.16E+04

In the case of ^{237}Np, ^{241}Pu, and ^{243}Am, bounding mass limits were estimated in Reference 1 with beryllium impurity contents ranging from 9.1 to 47.4% by mass of the mixture. The odd percentage figures are a result of the way the mixture content was defined in Reference 1, where, for example, 90% Be content was defined as a ratio of 0.9g of Be for every gram of the actinide resulting in a 47.4 weight percent beryllium in the mixture. These mass limits were also adjusted to account for the design decay heat limits and are presented in Tables 9a and 9b.

Table 9a. Mass Limits for ^{243}Am, ^{237}Np, and ^{241}Pu with Be- Unshielded

Be Content	Am-243	Np-237	Pu-241
9.1pc	2.60E-01	5.60E+01	1.60E+00
16.7pc	2.40E-01	5.60E+01	1.10E+00
23.1pc	2.30E-01	5.60E+01	8.50E-01
28.6pc	2.20E-01	5.60E+01	7.50E-01
33.3pc	2.10E-01	5.50E+01	6.90E-01
37.5pc	2.10E-01	5.50E+01	6.50E-01
41.2pc	2.00E-01	5.50E+01	6.20E-01
44.4pc	2.00E-01	5.50E+01	6.00E-01
47.4pc	2.00E-01	5.50E+01	5.80E-01

Table 9b. Mass Limits for ^{243}Am, ^{237}Np, and ^{241}Pu with Be- in SC2

Be Content	Am-243	Np-237	Pu-241
9.1pc	1.20E+00	2.00E+02	5.40E+00
16.7pc	1.20E+00	2.00E+02	3.50E+00
23.1pc	1.20E+00	2.00E+02	2.80E+00
28.6pc	1.20E+00	2.00E+02	2.50E+00
33.3pc	1.20E+00	1.90E+02	2.20E+00
37.5pc	1.20E+00	1.90E+02	2.10E+00
41.2pc	1.20E+00	1.90E+02	2.00E+00
44.4pc	1.20E+00	1.90E+02	1.90E+00
47.4pc	1.20E+00	1.90E+02	1.90E+00

CONCLUSIONS

The content envelope presented in this paper could also be conservatively applied to packages with similar structural material and equal or larger dimensions, i.e., distance from the inner wall of the containment vessel to the outside of the package. Thus, the content envelope presented here would qualify as conservative limits for the Models 9975 and 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” containment vessel compared to a 6” containment vessel for the Model 9977 packaging, making the source to dose measurement point distance larger. For mixtures of isotopes, the sum of the fraction of each isotope to its individual limit should be less than or equal to 1, i.e.,

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

where,
M_i is the mass of the ith isotope in the mixture containing n isotopes, and
M_{LP} is the maximum allowed mass for that isotope.

Further work is underway to extend the content envelope to include all the light element impurities to ^{243}Am, ^{237}Np, and ^{241}Pu as well as a few rare actinides that are present in the complex.

The purpose of this study is to provide guidance on shippable quantities in the current set of packagings that are in use in the DOE/NNSA complexes where a broad functional content envelope, that includes a wide range of isotopes and light-element impurities, can be defined for a particular packaging that is compliant with the shielding requirements of 10 CFR 71 and with the packaging-specific design decay heat limits. The comprehensive set of mass limits presented here covers to a very large extent the material that is present in these complexes and when adopted as certified content limits, should minimize the need for the submission of new addenda to the existing safety basis.

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