

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

---

S. Sitaraman, S.S. Kim, and B.L. Anderson

Lawrence Livermore National Laboratory

Revision 1

Prepared by:



July 18, 2014

Dr. Shiva Sitaraman, Shielding Analyst  
Radioactive Material Packaging and Transportation  
E-Program, Global Security Principal Directorate

Reviewed by:



July 25, 2014

Dr. Soon S. Kim, Criticality/Shielding Analyst  
Nuclear Criticality Safety Division  
Nuclear Operations Principal Directorate

Approved:



August 1, 2014

Dr. Brian L. Anderson, Associate Program Leader  
Radioactive Material Packaging and Transportation  
E-Program, Global Security Principal Directorate

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

---

Shivakumar Sitaraman, Soon S. Kim, and Brian L. Anderson  
Lawrence Livermore National Laboratory  
Email: [sitaraman1@llnl.gov](mailto:sitaraman1@llnl.gov)

## 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 (e.g., dose rate and criticality) and package-specific limits (e.g., decay heat) 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]. In addition to the external radiation, Ref. 2 also accounted for design decay heat restrictions in prescribing the limiting masses. The method of ratioing from these calculations based on one-gram 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 other instances, for the combination of actinides and light elements, the prescribed mass limits were too conservative and would unnecessarily limit the shipper's ability to transport material. These cases mainly involved actinides with light element impurities that were weak ( $\alpha, n$ ) sources. In addition, many of the gamma emitting materials were also found to be either non-compliant or too restrictive. As a result, the mass limits prescribed in References 1 and 2 have been superseded by the limits presented in this report.

**The methodology set forth in Reference 1 (Packaging Certification Program Methodology for Determining Dose Rates for Small Gram Quantities in Shipping Packages,” PCP-2011-0001, DOE Packaging Certification Program, August 2011) and the resulting mass limits in References 1 and 2 should not be used for the purpose of determining the allowed quantities of radioactive material that would be compliant with the regulatory limits for external radiation due to the potential for erroneous results. The partially faulty content envelope limits presented in References 1, and extended in Reference 2, will be hereafter referred to as the “TF-limits (i.e., transfer function limits).”**

The content material in the Model 9977 Packaging can be placed in one of four inner containers, which are then placed in the containment vessel. The first container is an engineered stainless steel container, which provides negligible radiation shielding. The unshielded mass limits presented in this study are applicable when this particular container is used for shipping. For gamma sources, the Model 9977 Packaging has two shielded inner containers available—lead and tungsten. A polyethylene shielded inner container has been approved for use with neutron emitting materials.

In this study, the unshielded 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. For the cases with shielded containers, the source sphere was placed at the bottom of the shielded container and against the side wall to present the shortest source-to-detector distance. For some of the actinide contents with weak neutron sources, a sphere was too large to fit inside. In these instances, the source was modeled as a cylinder with the cavity radius and height that depended on the mass present. There were cases where the source material filled the entire cavity. Starting with previously estimated masses, some amount of iteration was required in some instances to adjust them for regulatory compliance of external radiation levels. Design decay heat limits were also taken into account in determining the isotopic mass limits. For the engineered container and the tungsten shielded container, the design decay heat limit is 19 W. For the lead and polyethylene shielded containers, the decay heat limits are 6 W and 3 W, respectively. The isotopic mass limits presented 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 package external surface 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 for both the unshielded and polyethylene shielded conditions. In addition, revised limits for gamma sources for the unshielded, lead shielded, and tungsten shielded conditions are also presented. Several tables are presented in the following sections with the mass limits as well as changes from previously presented TF limits.

This revised content envelope, covering a wide range of materials present in the DOE complex, was developed for the Model 9977 Packaging. In addition, this content envelope provides conservative mass limits for other commonly-used Type B Packagings, such as the Models 9975 and 9978. Note that criticality safety concerns are not factored into these limits and should be evaluated on a case by case basis.

### **Radiation Transport Model**

The source spectra for the neutrons were based on a 47-group structure while the gamma source spectrum had 77 groups. This is consistent with the spectral structure used in deriving the mass limits in References 1 and 2. Sources were derived using either the ORIGEN-S code [4] or the RASTA code [5]. The choice of code used depended on which of these two produced a more conservative source spectrum for a given isotope. Reference 1 has descriptions of these sources including any conservatisms that result from buildup of daughter isotopes for the gamma emitters. The sources for the gamma emitters were taken directly from Reference 1. In the case of actinides, the spectra were reevaluated for this study for several light elements at varying levels of concentration. The actinides studied were:  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{242}\text{Pu}$ ,  $^{241}\text{Pu}+^{241}\text{Am}$ ,  $^{243}\text{Am}$ ,  $^{237}\text{Np}$ ,  $^{244}\text{Cm}$ ,  $^{248}\text{Cm}$ , and  $^{252}\text{Cf}$ . The light elements, Be, B, F, Li, C, Al, Mg, Na, Si, O, and Cl, were mixed with actinides such that they constituted 1000 ppm, 5000 ppm, 1%, 5%, 10%, 30% , 50% 70%, and 90% by weight of the mixture. Pure actinide mass limits, without any light elements included, were also established. Since  $^{248}\text{Cm}$  and  $^{252}\text{Cf}$  are mainly spontaneous fission neutron sources, only pure forms of these two actinides were considered.

The radiation transport was performed using the Monte Carlo radiation transport code, MCNP6 [6] (some analyses were done using MCNP5 [7]) using cross section data from the ENDF/B-VII set [8]. Ring or point detector type of tallies were used to estimate the fluxes on the bottom and side surfaces of the package and the ANSI/ANS 6.1.1/1977 [9] dose conversion factors were used for both gammas and neutrons. Figures 1, 2, 3, and 4 show the layout of the unshielded, polyethylene shielded, lead shielded and tungsten shielded models used for all the calculations. Figures 1 and 2 show the detector locations (detector locations in Figure 2 are also valid for Figures 3 and 4). For the unshielded cases, only the bottom dose rate was calculated since it was bounding. For the shielded cases, both the side and bottom dose rates were calculated.

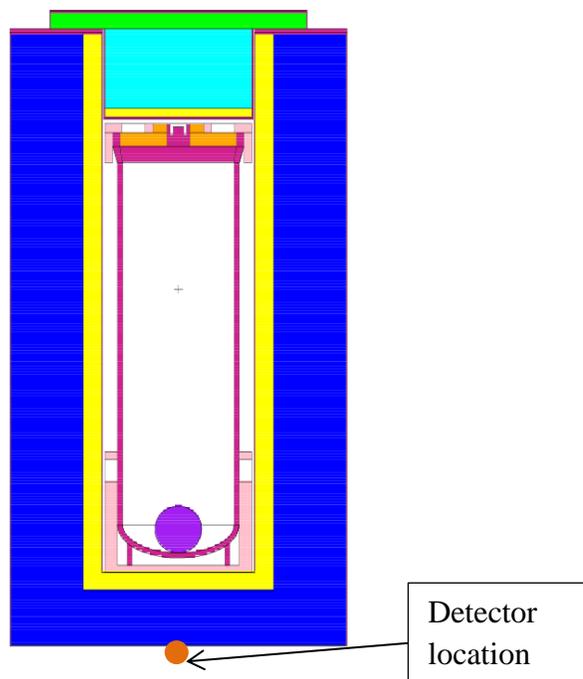


Figure 1. MCNP Model: Unshielded with source

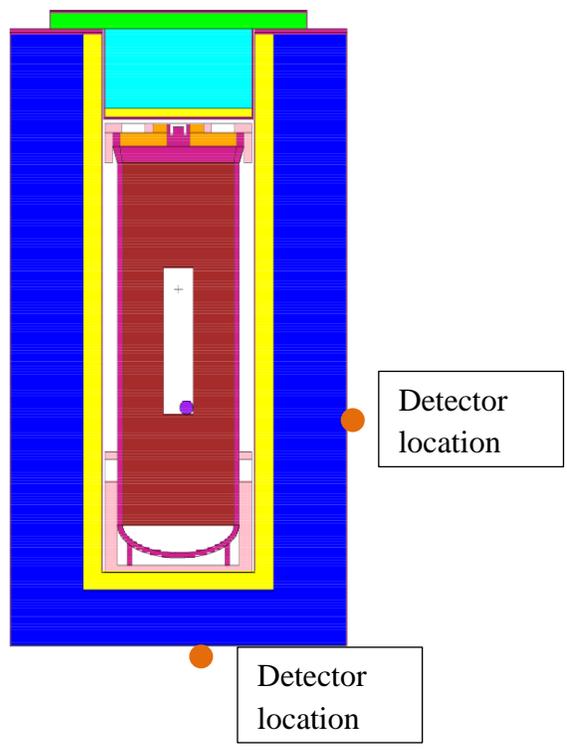


Figure 2. MCNP Model: Polyethylene Shielded Container with source

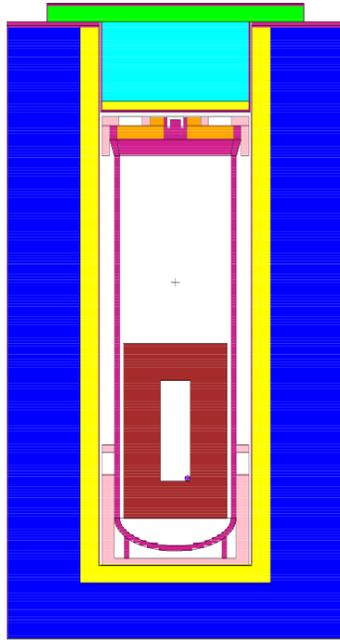


Figure 3. MCNP Model: Lead Shielded Container with source

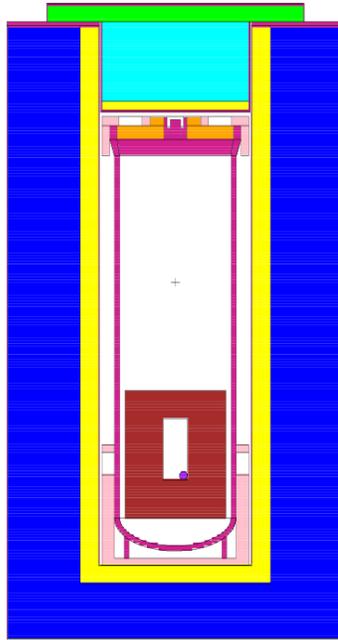


Figure 4. MCNP Model: Tungsten Shielded Container with source

### Discussion of the Results

The Tables 1a, 2a–9a, and 10a contain the updated mass limits for the various isotopes and sources in an unshielded form inside the containment vessel. The **orange** highlighted data represent limits further restricted by decay heat. The changes shown (Table 1a, Tables 2b–9b, and Table 10a) are the ratio of current mass limit to the corresponding TF limit. 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 30 pc 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. Similarly, Tables 1b and 2c–9c, present the mass limits for the pure actinides and actinides with impurities. Table 1b also shows the ratio of the mass limits inside the polyethylene shielded container to the unshielded mass. Tables 2d–6d and 9d, show the ratios of the masses for each actinide with the various impurities in the polyethylene shielded container to the corresponding TF limit. Ratios equal to one are again highlighted in **green**. It is noted that Reference 2 did not contain data for two of the isotopes,  $^{243}\text{Am}$  and  $^{237}\text{Np}$ , and consequently, there are no Tables numbered 7d and 8d to compare the mass limits from these analyses to their TF limits. Table 10b presents the mass limits for the gamma emitters in both the

lead and tungsten shielded containers as well as the ratio of the updated mass limit to the corresponding TF limit for each shielded container.

### *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 × 4cm cylinder) as modeled in Ref. 2. While  $^{248}\text{Cm}$  and  $^{252}\text{Cf}$  are unaffected by light element impurities,  $^{244}\text{Cm}$  has a reasonable ( $\alpha, n$ ) source when mixed with light elements. The impact of this for  $^{244}\text{Cm}$  will be discussed later in this report.  $^{242}\text{Pu}$ , which has a shorter half-life for spontaneous fission than  $^{240}\text{Pu}$ , 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 when deriving the TF limits. At the lower end of increase are  $^{238}\text{Pu}$  and  $^{240}\text{Pu}$  both of which have reasonable spontaneous fission source terms. At the high end of increase are isotopes like  $^{243}\text{Am}$  and  $^{237}\text{Np}$  with dominant gamma sources. The  $^{239}\text{Pu}$  mass limit has been set at 5000 g and could be further reduced because of criticality concerns.  $^{238}\text{Pu}$ ,  $^{240}\text{Pu}$ , and  $^{241}\text{Pu}+^{241}\text{Am}$  are limited by the design decay heat limit of 19W for unshielded contents in the Model 9977 Packaging. Results are presented in Table 1.

When these actinides are placed in their pure form inside the polyethylene shielded container, five of the actinides are limited by the design decay heat of the polyethylene container (see Table 1b). Three of these,  $^{238}\text{Pu}$ ,  $^{240}\text{Pu}$ , and  $^{241}\text{Am}+^{241}\text{Pu}$ , were also decay heat limited in the unshielded condition. For these cases, the shielded masses are approximately 16% of the unshielded limits, which simply is the ratio of 3 W decay heat limit, with the use of the polyethylene shielded container, to the 19 W limit. In addition, both  $^{239}\text{Pu}$  and  $^{244}\text{Cm}$  are limited by decay heat considerations, though the latter limit is about 4 times the corresponding limit in the unshielded condition.  $^{242}\text{Pu}$  and  $^{237}\text{Np}$  both have large limits when placed in the polyethylene shield but are limited by the volume of the cavity. The two spontaneous fission actinides,  $^{248}\text{Cm}$  and  $^{252}\text{Cf}$ , have larger limits when compared to the unshielded condition as would be expected with the presence of the shielding provided by the polyethylene.  $^{243}\text{Am}$ , a strong gamma emitter, also has a larger limit principally because of the larger source to package surface distance.

### *Pu Isotopes*

The mass limits for  $^{238}\text{Pu}$  were restricted by the design decay heat limits for several of the light elements that have low ( $\alpha, n$ ) 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 ( $\alpha, n$ ) producing isotopes B, F, and Li, decay heat limits

dictated the allowable plutonium mass at very low concentrations of these impurities. Table 2a presents these results.

In the case of  $^{239}\text{Pu}$  combined with beryllium, all combinations of the two except 1000 ppm 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 ( $\alpha, n$ ) 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 3a presents these results.

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

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

$^{242}\text{Pu}$  generally has a weaker dependence on light element ( $\alpha, n$ ) source of neutrons than  $^{240}\text{Pu}$ . However, it has a stronger spontaneous fission source than  $^{240}\text{Pu}$  since its half-life for this process is shorter than that of  $^{240}\text{Pu}$ . Examining the content envelope for  $^{242}\text{Pu}$  and beryllium in Table 5a with that for  $^{240}\text{Pu}$  (see Table 4a), 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  $^{240}\text{Pu}$  has a higher source from ( $\alpha, n$ ) reactions in beryllium than  $^{242}\text{Pu}$ . On the other hand, for weaker ( $\alpha, n$ ) 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,  $^{240}\text{Pu}$  has higher mass limits than  $^{242}\text{Pu}$ . Both these isotopes, as well as  $^{239}\text{Pu}$ , have mass limits at the kilogram levels for combinations with most light elements barring beryllium, boron, fluorine, and, to a lesser extent, lithium.

The mass limits for the plutonium isotopes  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ , and  $^{240}\text{Pu}$  in the polyethylene shielded container were for the most part restricted by the design decay heat. Except for the higher concentrations of Be, B, and to much lesser extent, F, the mass limits were set by decay heat considerations. In such cases, the mass limits were higher, as expected, when compared to the unshielded condition. For  $^{242}\text{Pu}$ , apart from higher concentrations of Be and B, the limits were determined by the volume of the payload cavity in the polyethylene shielded container. When compared to the corresponding TF limit for  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ , and  $^{240}\text{Pu}$ , except for higher concentrations of Be, B, and F where the TF limit was non-conservative, all other limits were the same since decay heat considerations were the determining factor. In the case of  $^{242}\text{Pu}$ , all TF limits were non-conservative since the mass limits with the polyethylene shield were mostly limited by the cavity volume.

## *Am Isotopes*

Since  $^{241}\text{Pu}$  beta decays with a half-life of 14.35 years to its daughter  $^{241}\text{Am}$ , 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  $^{241}\text{Pu}$  occurs in little over 73 years at which time 89% of the original  $^{241}\text{Pu}$  has been converted to  $^{241}\text{Am}$ .  $^{241}\text{Am}$  combined with light elements is a good source of neutrons produced via the  $(\alpha, n)$  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.

$^{243}\text{Am}$  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  $^{239}\text{Np}$  (half-life of 2.36 days) with which it is in secular equilibrium. Table 7a presents the mass limits for this actinide.

Just like the Pu isotopes,  $^{241}\text{Am}$  together with its parent isotope,  $^{241}\text{Pu}$ , was limited by decay heat for all but higher concentrations of Be and B. The set of mass limits for  $^{243}\text{Am}$ , predominantly a gamma emitter, were the same as the pure form for most of light elements except again for some higher concentrations of Be and B. This trend was very similar to that seen for the unshielded case for this actinide. Comparison of the polyethylene shielded limits to the TF limits, the behavior was very similar to that of the Pu isotopes with identical limits in most cases except for the higher concentrations of Be and B where the old limits were non-conservative. In the case of high concentrations of F, the old limits were overly conservative.

### $^{237}\text{Np}$

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. This isotope, like  $^{242}\text{Pu}$ , was limited by the volume of the payload cavity of the polyethylene shielded container. A few exceptions to this were seen with 30% and higher concentrations of Be present in the mixture.

### $^{244}\text{Cm}$

This isotope of curium has strong neutron sources from both spontaneous fission and  $(\alpha, n)$  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 9a presents the mass limits. The mass limits for the weaker  $(\alpha, n)$  light elements at lower concentrations are identical to that of the pure isotope.

This actinide was also limited by its decay heat limit of 1.06 g with the exception of Be at most concentrations, and B and F at levels above 5–10%. In these cases the mass limits were higher

because of the presence of the polyethylene shielding. This isotope too was limited by decay heat considerations for most of the mixtures, leading to identical mass limits for the polyethylene shielded cases when compared to the TF limits. Once more the TF limits were non-conservative for higher concentrations of Be, B, and F.

### *Gamma Sources*

Gamma emitters are mostly lower for isotopes with harder gamma spectra compared to the previous set (provided in References 1 and 2) 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 × 4cm cylinder) in the old set of calculations (References 1 and 2). For the sources 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 of masses was conservative. The entire set of limits is presented in Table 10a.

The two shielded containers that have been approved for use with the Model 9977 Packaging are made of lead or tungsten. The mass limits of several gamma emitters were restricted by decay heat considerations rather than external radiation levels. <sup>210</sup>Po was the only isotope to be decay heat limited for the unshielded condition as well as the two shielded conditions. In almost all these cases since the TF limits were already constrained by decay heat considerations, there was no change in the limiting masses as determined by the current set of analyses. Similar to the unshielded cases, the gamma emitters with harder spectra tended to have lower limits when compared to the TF limits. For those with softer spectra, the self-shielding effect resulted in larger mass limits. The limits for both shielded containers and their difference from the TF limits are presented in Table 10b.

### *Observations*

Overall, for the pure actinides in the unshielded form, the three with the spontaneous fission sources (<sup>244</sup>Cm, <sup>248</sup>Cm and <sup>252</sup>Cf) were all non-conservative when compared to the TF limits. <sup>242</sup>Pu, very long lived and with a spontaneous fission source of 1720 n/s-g, also was non-conservative. The other six mass limits were underestimated using the TF method. Three actinides (<sup>238</sup>Pu, <sup>240</sup>Pu and <sup>241</sup>Am+<sup>241</sup>Pu) were limited by design decay heat considerations, though both <sup>238</sup>Pu and <sup>240</sup>Pu have spontaneous fission sources comparable to <sup>242</sup>Pu but have shorter half-lives.

In the case of pure actinides in the polyethylene shielded container, in addition to the three actinides, <sup>238</sup>Pu, <sup>240</sup>Pu and <sup>241</sup>Am+<sup>241</sup>Pu, the <sup>239</sup>Pu mass limit was also constrained by the now lower decay heat limit of 3 W. These four also had lower mass limits than in their unshielded form mainly because of the lower decay heat limit. Two actinides (<sup>242</sup>Pu and <sup>237</sup>Np) were constrained by the volume of the cavity in the shielded container. The other actinides all had limits higher than in their unshielded form.

For the eight unshielded actinides with various light element impurities, 45% of the limits were non-conservative compared to the TF limits with another 45% non-conservative. In 10% of the cases there was no change in large part due to decay heat limitations.

In the case of six actinides with impurities in the polyethylene shielded container, 70.7% of the mass limits were unchanged mainly due to the lower decay heat limits. On the non-conservative side, 28.6% of the limits were in this category with a negligible 0.7% being too conservative. There was no TF mass limit data for two of the isotopes,  $^{243}\text{Am}$  and  $^{237}\text{Np}$ , with the latter being limited mainly by volume constraints of the shielded container cavity.

In the case of the gamma sources, two thirds of the unshielded mass limits were non-conservative compared to the TF limits, with a quarter too conservative. With the lead shield in place, 46% were non-conservative with 12.5% too conservative. For the tungsten shielded isotopes, 33% were non-conservative with 25% too conservative. In both the shielded cases a little over 41% of the mass limits were unchanged, all of them limited by decay heat. Only two of the 24 isotopes in the unshielded condition were unchanged.

### 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  $i^{\text{th}}$  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 isotopic 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, which is based on the Model 9977 Package, 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. It is clear from these analyses that the effects of self-shielding from the source itself are in many instances overcome by the subcritical multiplication in the case of actinides. In the case of the gamma sources, the previous TF model

used volume source where as in most case the actual source is more of a point making these less self-shielded than the model used in the TF analyses.

## References

1. S.J. Nathan, J.M. Risner, and S. Sitaraman, "Packaging Certification Program Methodology for Determining Dose Rates for Small Gram Quantities in Shipping Packages," PCP-2011-0001, DOE Packaging Certification Program, August 2011.
2. S. Sitaraman, S. Kim, and B. Anderson, "Functional Bounding Content Envelope for Type B Radioactive Material Transportation Packages," 53rd Annual Meeting of the INMM, Orlando, Florida, July 2012.
3. S. Sitaraman, S. Kim, and B. Anderson, "Functional Bounding Content Envelope for Actinides—Impact of Subcritical Multiplication," PATRAM 2013, San Francisco, CA, August 2013.
4. ORNL/TM-2005/39, Version 5, Volume II, Section F7, ORIGEN-S: Scale System Module to Calculate Fuel Depletion, Actinide Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Terms, Hermann, O. W. and Westfall, R. M., Oak Ridge National Laboratory, Oak Ridge, TN, April 2005.
5. Nathan, S. J., Radiation Source Term Analysis Code RASTA User Guide (U), SRNS-RP-2009-00275, Revision 0, Savannah River Nuclear Solutions, Aiken, S. C., March 2009.
6. T. Goorley et. al., "Initial MCNP 6 Release Overview", LA-UR-11-07082, Los Alamos National Laboratory, Dec 2012.
7. X-5 MONTE CARLO TEAM, "MCNP – A General Monte Carlo N-Particle Transport Code, Version 5, Volume I: Overview and Theory," LA-UR-03-1987, Los Alamos National Laboratory (April 2003).
8. M.B. Chadwick et. al., "ENDF/B-VII.1 Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data," LA-UR 11-05121, Los Alamos National Laboratory, Dec 2011.
9. American Nuclear Society, "Flux to Dose Rate Conversion Factors", ANSI/ANS-6.1.1-1977, LaGrange Park, IL (1977).

## Acknowledgements

The authors wish to thank Dr. J. M. Shuler, Manager, DOE Packaging Certification Program, EM-33, for his support of this work. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Table 1a. Mass Limits in grams for Pure Actinides

Isotope	Unshielded Mass Limit (g)	Change from TF Limit
<sup>238</sup> Pu	33.46	1.05
<sup>239</sup> Pu	5000.0	1.50
<sup>240</sup> Pu	2687.03	1.05
<sup>242</sup> Pu	2003.19	0.84
<sup>241</sup> Am+ <sup>241</sup> Pu	165.94	7.94
<sup>243</sup> Am	1.32	4.34
<sup>237</sup> Np	2982.00	56.05
<sup>244</sup> Cm	0.26	0.69
<sup>248</sup> Cm	0.07	0.68
<sup>252</sup> Cf	1.20E-06	0.66

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

Table 1b. Mass Limits in grams for Actinides in the Polyethylene Shielded Container

Isotope	Mass Limit (g)	Ratio of shielded/unshielded
$^{238}\text{Pu}$	5.28	0.158
$^{239}\text{Pu}$	1555.21	0.311
$^{240}\text{Pu}$	424.27	0.158
$^{242}\text{Pu}$	5394.00	2.693
$^{241}\text{Am} + ^{241}\text{Pu}$	26.20	0.158
$^{243}\text{Am}$	8.60	6.515
$^{237}\text{Np}$	5546.40	1.86
$^{244}\text{Cm}$	1.06	4.077
$^{248}\text{Cm}$	0.44	6.286
$^{252}\text{Cf}$	6.83E-06	5.689

Note: Blue shaded values are limited by payload cavity volume

Table 2a. <sup>238</sup>Pu Mass Limits in grams

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

Table 2b. <sup>238</sup>Pu Mass Limits— Change from TF Limit

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

Table 2c. <sup>238</sup>Pu Mass Limits in grams — Polyethylene Shielded Container

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28
5000 ppm	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28
10000 ppm	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28
50000 ppm	1.32	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28
10 pc	0.73	3.66	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28
30 pc	0.34	1.65	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28
50 pc	0.26	1.27	5.28	4.55	5.28	5.28	5.28	5.28	5.28	5.28	5.28
70 pc	0.23	1.11	5.28	4.11	5.28	5.28	5.28	5.28	5.28	5.28	5.28
90 pc	0.21	1.02	5.28	3.71	5.28	5.28	5.28	5.28	5.28	5.28	5.28

Table 2d. <sup>238</sup>Pu Mass Limits— Change from TF Limit

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50000 ppm	0.82	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10 pc	0.82	0.84	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
30 pc	0.83	0.81	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50 pc	0.83	0.81	1.00	0.86	1.00	1.00	1.00	1.00	1.00	1.00	1.00
70 pc	0.84	0.81	1.00	0.82	1.00	1.00	1.00	1.00	1.00	1.00	1.00
90 pc	0.84	0.82	1.00	0.81	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 3a. <sup>239</sup>Pu Mass Limits in grams

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

Table 3b. <sup>239</sup>Pu Mass Limits— Change from TF Limit

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

Table 3c. <sup>239</sup>Pu Mass Limits in grams—Polyethylene Shielded Container

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21
5000 ppm	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21
10000 ppm	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21
50000 ppm	453.00	1415.47	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21
10 pc	253.25	964.48	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21
30 pc	118.00	495.00	1555.21	1232.55	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21
50 pc	89.80	409.00	1555.21	1026.59	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21
70 pc	78.29	350.45	1555.21	925.33	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21
90 pc	70.76	325.00	1555.21	867.60	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21	1555.21

Table 3d. <sup>239</sup>Pu Mass Limits— Change from TF Limit

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50000 ppm	0.84	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10 pc	0.83	0.74	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
30 pc	0.83	0.77	1.00	0.79	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50 pc	0.81	0.82	1.00	0.66	1.00	1.00	1.00	1.00	1.00	1.00	1.00
70 pc	0.81	0.80	1.00	0.59	1.00	1.00	1.00	1.00	1.00	1.00	1.00
90 pc	0.80	0.80	1.00	0.56	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 4a. <sup>240</sup>Pu Mass Limits in grams

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

Table 4b. <sup>240</sup>Pu Mass Limits— Change from TF Limit

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

Table 4c. <sup>240</sup>Pu Mass Limits in grams—Polyethylene Shielded Container

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27
5000 ppm	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27
10000 ppm	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27
50000 ppm	128.01	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27
10 pc	71.29	318.92	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27
30 pc	33.24	159.95	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27
50 pc	25.55	120.05	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27
70 pc	22.26	100.39	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27	424.27
90 pc	20.44	78.82	424.27	394.41	424.27	424.27	424.27	424.27	424.27	424.27	424.27

Table 4d. <sup>240</sup>Pu Mass Limits— Change from TF Limit

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50000 ppm	0.85	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10 pc	0.85	0.83	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
30 pc	0.85	0.88	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50 pc	0.85	0.86	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
70 pc	0.85	0.82	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
90 pc	0.85	0.70	1.00	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5a. <sup>242</sup>Pu Mass Limits in grams

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

Table 5b. <sup>242</sup>Pu Mass Limits– Change from TF Limit

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

Table 5c. <sup>242</sup>Pu Mass Limits in grams—Polyethylene Shielded Container

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00
5000 ppm	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00
10000 ppm	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00
50000 ppm	5263.98	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00
10 pc	3597.56	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00
30 pc	2051.56	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00
50 pc	1653.52	5086.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00
70 pc	1472.74	4734.42	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00
90 pc	1370.00	4330.62	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00	5394.00

Table 5d. <sup>242</sup>Pu Mass Limits— Change from TF Limit

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	0.48	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
5000 ppm	0.52	0.48	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
10000 ppm	0.58	0.49	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
50000 ppm	0.95	0.58	0.47	0.48	0.47	0.47	0.47	0.47	0.47	0.47	0.47
10 pc	0.92	0.66	0.47	0.50	0.47	0.47	0.47	0.47	0.47	0.47	0.47
30 pc	0.92	0.89	0.47	0.54	0.47	0.47	0.48	0.47	0.47	0.47	0.47
50 pc	0.92	0.95	0.47	0.56	0.47	0.47	0.49	0.47	0.47	0.47	0.47
70 pc	0.92	0.95	0.47	0.58	0.47	0.47	0.49	0.47	0.47	0.47	0.47
90 pc	0.92	0.92	0.47	0.59	0.47	0.47	0.49	0.47	0.47	0.47	0.47

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

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

Table 6b.  $^{241}\text{Am} + ^{241}\text{Pu}$  Mass Limits— Change from TF Limit

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

Table 6c. <sup>241</sup>Am+ <sup>241</sup>Pu Mass Limits in grams—Polyethylene Shielded Container

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20
5000 ppm	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20
10000 ppm	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20
50000 ppm	6.75	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20
10 pc	3.75	18.79	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20
30 pc	1.68	8.70	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20
50 pc	1.30	6.83	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20	26.20
70 pc	1.14	5.85	26.20	22.00	26.20	26.20	26.20	26.20	26.20	26.20	26.20
90 pc	1.04	5.39	26.20	20.16	26.20	26.20	26.20	26.20	26.20	26.20	26.20

Table 6d.  $^{241}\text{Am} + ^{241}\text{Pu}$  Mass Limits— Change from TF Limit

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50000 ppm	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10 pc	0.88	1.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
30 pc	0.83	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50 pc	0.84	0.93	1.00	1.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00
70 pc	0.84	0.91	1.00	1.06	1.00	1.00	1.00	1.00	1.00	1.00	1.00
90 pc	0.83	0.91	1.00	1.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 7a. <sup>243</sup>Am Mass Limits in grams

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

Table 7b. <sup>243</sup>Am Mass Limits— Change from TF Limit

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

Table 7c. <sup>243</sup>Am Mass Limits in grams—Polyethylene Shielded Container

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60
5000 ppm	8.50	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60
10000 ppm	8.07	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60
50000 ppm	8.07	8.50	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60
10 pc	7.21	8.30	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60
30 pc	6.50	8.17	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60
50 pc	6.00	8.05	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60
70 pc	5.68	7.95	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60
90 pc	5.14	7.48	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60	8.60

Table 8a. <sup>237</sup>Np Mass Limits in grams

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

Table 8b. <sup>237</sup>Np Mass Limits— Change from TF Limit

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

Table 8c. <sup>237</sup>Np Mass Limits in grams—Polyethylene Shielded Container

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40
5000 ppm	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40
10000 ppm	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40
50000 ppm	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40
10 pc	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40
30 pc	4264.29	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40
50 pc	3828.81	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40
70 pc	3586.69	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40
90 pc	3586.69	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40	5546.40

Table 9a. <sup>244</sup>Cm Mass Limits in grams

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

Table 9b. <sup>244</sup>Cm Mass Limits— Change from TF Limit

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

Table 9c. <sup>244</sup>Cm Mass Limits in grams—Polyethylene Shielded Container

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
5000 ppm	0.89	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
10000 ppm	0.60	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
50000 ppm	0.20	0.65	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
10 pc	0.11	0.45	1.06	1.00	1.06	1.06	1.06	1.06	1.06	1.06	1.06
30 pc	0.06	0.25	1.06	0.65	1.06	1.06	1.06	1.06	1.06	1.06	1.06
50 pc	0.04	0.20	1.06	0.52	1.06	1.06	1.06	1.06	1.06	1.06	1.06
70 pc	0.04	0.18	1.06	0.48	1.06	1.06	1.06	1.06	1.06	1.06	1.06
90 pc	0.03	0.17	1.06	0.45	1.06	1.06	1.06	1.06	1.06	1.06	1.06

Table 9d. <sup>244</sup>Cm Mass Limits— Change from TF Limit

Impurity Content	Be	B	Li	F	C	Al	Mg	Na	Si	O	Cl
1000 ppm	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000 ppm	0.87	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10000 ppm	0.83	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50000 ppm	0.83	0.83	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10 pc	0.83	0.83	1.00	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00
30 pc	0.83	0.83	1.00	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50 pc	0.83	0.83	1.00	0.86	1.00	1.00	1.00	1.00	1.00	1.00	1.00
70 pc	0.83	0.83	1.00	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00
90 pc	0.83	0.83	1.00	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 10a. Gamma Source Mass Limits –Unshielded

Isotope	Mass Limit (g)	Change from TF Limit
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

Isotope	Mass Limit (g)	Change from TF Limit
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

Table 10b. Gamma Source Mass Limits – Lead and Tungsten Shield

Isotope	Mass Limit (g) - Lead	Change from TF Limit – Lead	Mass Limit (g) - Tungsten	Change from TF Limit – Tungsten
Ac-227	4.178E-01	1.00E+00	1.323E+00	1.00E+00
Cd-109	3.748E+00	1.00E+00	1.187E+01	1.00E+00
Co-60	1.119E-04	9.33E-01	4.161E-04	9.25E-01
Cs-137	1.018E-01	9.25E-01	8.713E-01	1.32E+00
Eu-152	2.362E-03	8.75E-01	9.868E-03	9.87E-01
Fe-59	5.736E-06	9.56E-01	2.059E-05	9.36E-01
Gd-153	1.931E+00	1.00E+00	6.115E+00	1.00E+00
Hf-181	2.150E-02	1.43E+00	2.571E-01	6.95E+00
Ho-166m	8.135E-01	4.11E+02	4.821E+00	7.69E+02
Ir-192	7.402E-03	1.09E+00	6.285E-02	1.53E+00
Mn-54	1.948E-04	9.74E-01	1.133E-03	1.03E+00
Pb-210	2.474E+00	1.00E+00	7.835E+00	1.00E+00
Pm-147	1.765E+01	1.00E+00	5.588E+01	1.00E+00
Po-210	4.167E-02	1.00E+00	1.319E-01	1.00E+00
Ra-226	2.204E-01	9.58E-01	7.121E-01	9.76E-01

Isotope	Mass Limit (g) - Lead	Change from TF Limit – Lead	Mass Limit (g) - Tungsten	Change from TF Limit – Tungsten
Ru-106	1.526E-03	6.63E-01	6.213E-03	7.31E-01
Sc-46	8.432E-06	9.69E-01	3.338E-05	9.02E-01
Se-75	1.712E-01	1.00E+00	5.422E-01	1.00E+00
Sm-145	4.127E+00	1.00E+00	1.307E+01	1.00E+00
Sr-90	5.396E-01	3.85E-01	2.297E+00	3.96E-01
Tm-170	5.098E-01	1.00E+00	1.614E+00	1.00E+00
Yb-169	9.770E-02	1.00E+00	3.094E-01	1.00E+00
Zn-65	8.565E-05	9.02E-01	3.715E-04	9.52E-01
Zr-95	1.220E-04	9.38E-01	8.276E-04	1.07E+00