EXPANSION OF DOSE RATE COMPLIANCE METHODOLOGIES FOR RH-TRU WASTE SHIPMENTS IN THE RH-72B CASK

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ABSTRACT

Compliance with 10 CFR §71 dose rate limits for shipments of Remote-Handled Transuranic (RH-TRU) waste in the RH-TRU 72-B package is accomplished through preshipment radiological surveys and limiting radionuclide activity to that bounded by conservative point-source analyses. The advantage of the preshipment survey/point-source analysis approach is that knowledge of the source response to accident conditions is not required because the source is assumed to redistribute and reconfigure to a point location that maximizes dose. Expansion of the compliance method is required to maximize the shippable source activity, minimize or reduce the source assay requirements, and to allow the shipment of radionuclides for which an activity limit has not previously been determined.

The expansion of dose rate compliance methodologies, developed for Revision 3 of the RH-TRU 72-B package Safety Analysis Report (SAR), consists of three primary initiatives: 1) Refinement of the conservative point source analysis for neutron radionuclides, 2) Evaluation of the effect of redistribution, reconfiguration, and loss of self-shielding from Normal Conditions of Transport (NCT) to Hypothetical Accident Condition (HAC) on gamma and neutron dose rates, and 3) Development of a screening methodology for gamma and neutron radionuclides.

The Monte Carlo N-Particle (MCNP) analysis of NCT and HAC geometries, for waste forms that meet specific self-shielding criteria, show that the preshipment radiological survey is sufficient to ensure compliance with 10 CFR §71 dose rate requirements. The allowable activity of neutron radionuclides that are defined by the point source analysis is significantly increased through the use of a subcritical neutron multiplication factor that is derived from a MCNP analysis. To ensure the ability to ship waste that does not meet specific self-shielding criteria and that contains radionuclides for which a conservative point source analysis does not exist, the screening methodology provides an option to bound the radionuclide activity limit based on limited assay data.

Overall, the compliance methodology expansion will allow many waste forms for which self-shielding properties are known to be shipped with a simple pre-shipment radiological survey. For waste forms that do not meet the self-shielding criteria, use of the MCNP analysis will increase the shippable neutron HAC activity limit by an average factor of 22.5 and use of the screening methodology will allow shipment of radionuclides for which a HAC activity value has not been established a priori.

INTRODUCTION

The RH-TRU 72-B package (Figure 1) transports payload canisters that contain gamma and neutron sources. The gamma sources are primarily fission products or bi-product material mixed in various waste forms that are of sufficient strength to require shielding. The neutron source material is of lower source strength, and specific neutron shielding is not required. The current number of radionuclides identified in the RH-TRU waste inventory is 204.

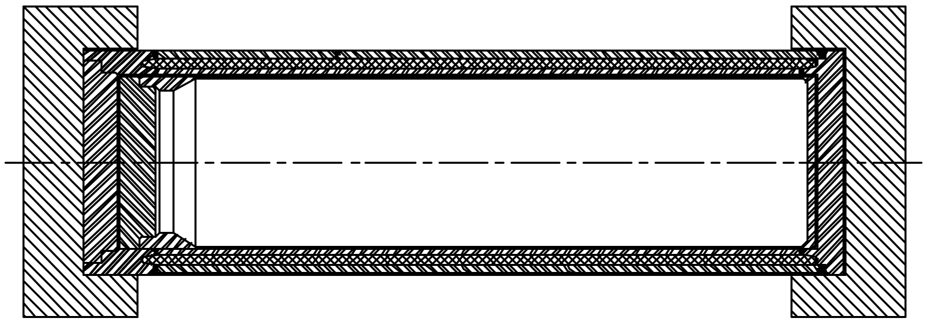

Figure 1 - RH-TRU 72-B package (with reduced impact limiters)

The RH-TRU 72-B package steel canister, steel inner vessel, and the steel and lead outer cask provide the required gamma shielding in the radial direction for the authorized contents. Impact limiters provide modest neutron shielding and spacing that reduces the magnitude of the surface dose rate near the ends of the package. Thick steel end plates and lids, along with impact limiters provide shielding and spacing to reduce the dose rates to acceptable levels out the ends of the package. The shielding evaluation is based on the radial direction because it represents the worst case: the relative spacing between the source and the detector location is least, and the effective shielding, including puncture damage, is lowest.

The RH-TRU 72-B package is transported by exclusive use shipment where the Normal Conditions of Transport (NCT) radiation dose rate limits are given in 10 CFR §71.47 (b). Compliance with the NCT limits is verified by preshipment radiological survey of the loaded package and transporter. The maximum dose rate under Hypothetical Accident Conditions (HAC) is given in 10 CFR §71.51 (a)(2). Compliance with the HAC limits is achieved by limiting the sum of partial fractions of all radionuclides in the waste to less than unity. The partial fraction values are obtained by dividing the actual activity of each radionuclide in the waste by the maximum allowable activity value calculated using a conservative point-source analysis. Alternatively, compliance with both the NCT and HAC dose rate limits can be accomplished through the preshipment radiological surveys if it can be shown, for waste forms that meet a specific self-shielding criteria, that the HAC limits could not be exceeded when compliance with the NCT limits are met.

POINT-SOURCE SHIELDING EVALUATION

Each authorized radionuclide was evaluated to determine its gamma and/or neutron source spectrum. The maximum activity of each isotope was then found by calculating the activity that would lead to the dose rate limit for the HAC model. The gamma evaluation involved discrete point source calculations, in one dimension, and ignores any self-shielding. The neutron evaluation included a three dimensional MCNP dose rate calculation for each isotope, adjusted with a derived conservative subcritical multiplication factor. The neutron source strength is based on a uranium oxide matrix to account for alpha-n production, but conservatively neglects self-shielding effects. Mixtures of isotopes are limited by the sum of the fractions method.

In order to develop a reasonably correct but bounding neutron source, the point source assumption is maintained for the source geometry. However, alpha-n production is assumed to occur as though there is a homogeneous media of the source isotope and UO_2, and a subcritical multiplication factor is developed and applied to the source. In this manner, the activity limits bound the authorized payloads. The neutron source for each isotope is developed using the computer code Sources-4A. The code generates neutron production rates for spontaneous fission and alpha-n reactions (based on the assumed source matrix, UO_2). In addition, the code outputs the average neutron energy and spectra, by isotope. The actual neutron source spectra for each isotope was input into the computer code MCNP normalized as a unit source strength. The resulting dose rate was then multiplied by the respective source strength for each isotope and the derived subcritical neutron multiplication factor. This product was then divided into 1000 to establish the HAC allowable activity for each isotope.

The subcritical neutron multiplication factor was developed by assuming a point neutron source imbedded in a theoretical sphere of homogenized Pu-239 and a 30% polyethylene and 70% water mixture. It was assumed that 325 g of Pu-239 are in the "target" matrix. Calculations were done for varying point sources and source spheres using MCNP with the effect of subcritical multiplication enabled. These calculations were then compared to the equivalent point source calculation to determine the effective increase, or multiplication, in dose rate (See Figure 2). The resulting neutron subcritical multiplication factor, 2.70, was applied to the point source calculations to conservatively include neutron multiplication. This approach results in an approximately 22.5 times increase in the allowable activity of neutron radionuclides when compared to the previous approach of using $1/1\text{-}k_{eff}$ as the subcritical neutron multiplication factor.

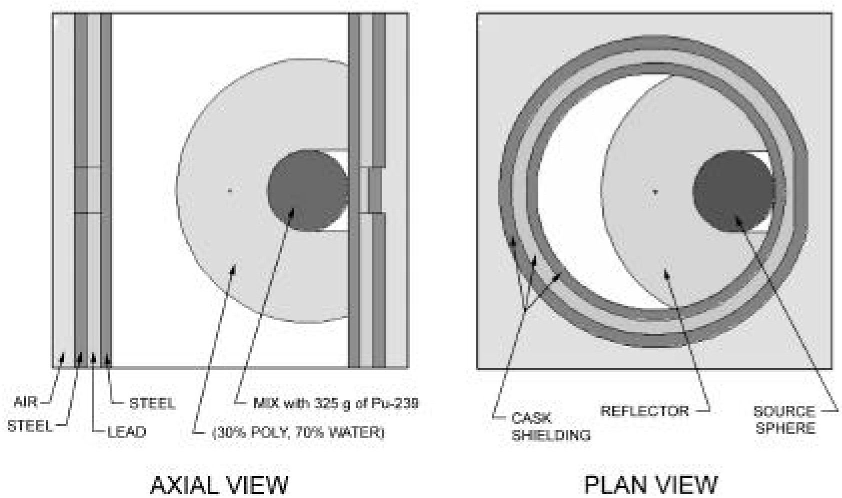

Figure 2 - MCNP Geometry Model for Neutron Subcritical Multiplication Factor

EVALUATION OF NCT TO HAC CHANGES ON DOSE RATES

The normal conditions of transport (NCT) dose rates are measured at the time of shipment. Movement of the source isotopes or displacement of internal self shielding under HAC may cause the external dose rates to increase. The purpose of this evaluation was to determine whether the

HAC dose rate acceptance criteria could be exceeded due to source or self shielding displacement in the RH-TRU 72-B Package for candidate waste forms, if the NCT measured dose rates (at time of shipment) meet the acceptance criteria. The candidate waste forms shall be such that self-shielding properties and the physical response to accident conditions are constrained through one of the following payload requirements:

- Payload configurations that naturally preclude the loss of greater than 8 inches of water/polyethylene or 1 inch of steel equivalent self-shielding material in response to accident conditions (e.g. homogeneous solids/sludges).
- Payload configurations that fill greater than 90% of the canister volume and are configured to preclude the loss of greater than 8 inches of water/polyethylene or 1 inch of steel equivalent self-shielding material in response to accident conditions (e.g. compacted waste).
- Payload configurations that do not initially provide more than 8 inches of water/polyethylene or 1 inch of steel equivalent self-shielding materials (e.g., loosely packed materials with the preclusion of shielded payload containers, etc.).

SOURCE DISPLACEMENT EFFECTS

Two source distributions were selected to represent the NCT conditions that maximizes allowable source activity: a point source at the cask center, and a uniformly distributed source. One source distribution was selected to represent the HAC condition that minimizes allowable source activity: a point source just inside the puncture location. The ratio of the 1 meter dose rates under the NCT and HAC distributions represents a reasonable approximation of the maximum increase in HAC dose rate due to source displacement. Calculations were performed using MCNP to assess the effect of source displacement. A point source of unit strength was placed in the center of the package, and calculations were performed for the radial surface, 1 meter, and 2 meter dose rates. The source strength was then scaled to normalize to the applicable NCT acceptance criteria limit. Additional calculations were then performed for the point source in the center of the package with puncture damage and with the same source uniformly distributed inside the cask. Calculations were then performed for the case where the point source is moved to the radial side of the package, just inside the puncture damage. The resulting maximum HAC dose rate increase due to point source displacement was found to be 2x for neutrons and 3.2x for gammas.

SELF-SHIELDING REDUCTION EFFECTS

Calculations were performed with the unit neutron source in the center of the cask and two self-shielding cases, using 30% polyethylene and 70% water mixture spheres. Removal of 8 inches of self shielding would lead to an increase in the HAC dose rate of 18.4x. Calculations were performed with the unit gamma source in the center of the cask for four shielding cases, two using 30% polyethylene and 70% water mixture spheres and two using steel spheres. Removal of 8 inches of 30% polyethylene and 70% water mixture self shielding would lead to an increase in the HAC dose rate of 4.7x. Removal of 1” of steel shielding would lead to HAC dose rate increases of 3.7x.

COMBINED EFFECTS

Maximum point source displacement under HAC would increase the 1 meter dose rate by no more than 3.2x. The 1 meter dose rate could increase by a greater factor if a uniform source was able to reconfigure into a point source at the puncture bar location . However, if the cask experienced a side drop, the contents would tend to displace horizontally, and the axial orientation of the source would not change. Consequently, the point source displacement case would bound. If the cask experienced an end drop, the contents would tend to displace axially. The radial puncture location could correspond to a location that would effectively see an increase in source strength. This is like a case where the distributed source is compressed to a disk. However, because the authorized contents are constrained, the compression would be much less than 50%, and the corresponding increase in HAC dose rate would be no more than a factor of two. Conservatively, the total displacement of the neutron source combined with the effective loss of 8 inches of self shielding would increase the HAC dose rate by no more than 37x. This is below the 43x calculated to reach the limit. Correspondingly, the total displacement of the gamma source and the effective loss of 8 inches of 30% polyethylene and 70% water mixture self shielding or 1 inch of steel would increase the HAC dose rate by no more than = 48x. This is below the 55x calculated to reach the limit.

Therefore, for contents that meet the specified criteria, source movements and self-shielding displacements would not be sufficient to cause the HAC limit to be exceeded, if the NCT measured dose rates meet the acceptance criteria.

RADIONUCLIDE SCREENING METHODOLOGIES

Screening methodologies were developed to allow the shipment of gamma and neutron radionuclides that are either newly identified by the shipper or require additional consideration (e.g. a waste form matrix that produces more neutrons than the uranium oxide assumed in the development of the alpha – n component of the total neutron source strengths). All radionuclides that do not have gamma energies and do not undergo spontaneous fission or whose maximum allowable activity is calculated to be greater than 1×10^8 Curies are classified as "unlimited" and can be shipped without restriction. Therefore, the objective was to determine characteristic neutron source strengths and gamma energy/intensity values which could be classified as "unlimited" or to define a methodology for calculating a conservative activity which could be used in the sum of partial fractions point-source compliance methodology.

NEUTRON

An analysis of the Sources-4A output and the MCNP point-source dose rate calculations revealed the following:

- The total source strength for each isotope is the sum of the alpha – n and spontaneous fission contributions. This source strength is a characteristic of the specific isotope and the assumed target matrix (UO_2).
- The neutron source strength for each isotope has a unique neutron energy spectrum, and a corresponding average energy.
- The average energies for the isotopes fall between 1.5 and 2.6 MeV.
- The dose rate calculations show no functional relationship between average energy and dose rate. In fact, the calculated dose rates for unit neutron sources generated with the unique neutron energy spectra, are all within about 5% of the mean.

Figure 3 shows that the total neutrons per second per Curie (for each radionuclide) as a function of the maximum allowable activity inventory as predicted by MCNP. A curve fit of the data and rearrangement yields

$$y = \frac{4.60 \times 10^{8}}{x^{1.0025}},$$

where y is the total number of total neutrons per second per Curie and x is the Inventory in Curies.

This relationship may be used for screening additional radionuclides based on their characteristic total "neutrons per second per Curie." Setting x equal to 10^8 Ci and solving for y in the above equation, yields a screening value for total neutrons per second per Curie of 4.40 n/s-Ci. Thus, a radionuclide having a neutron source strength per curie of less than 4.40 n/s-Ci is may be shipped without restriction.

Alternately, the formula may be used to predict the maximum allowable activity based on the neutron source strength per curie. This should only be used for source spectra that have an average neutron source energy between 1.5 and 2.6 MeV. The code Sources-4A can be used to develop the source strength per curie based on the isotopic characteristics and the target matrix assumption. The equation can be solved for x, by inputting the neutron source strength per curie as y. The solution is the maximum activity allowed for the radionuclide in Curies.

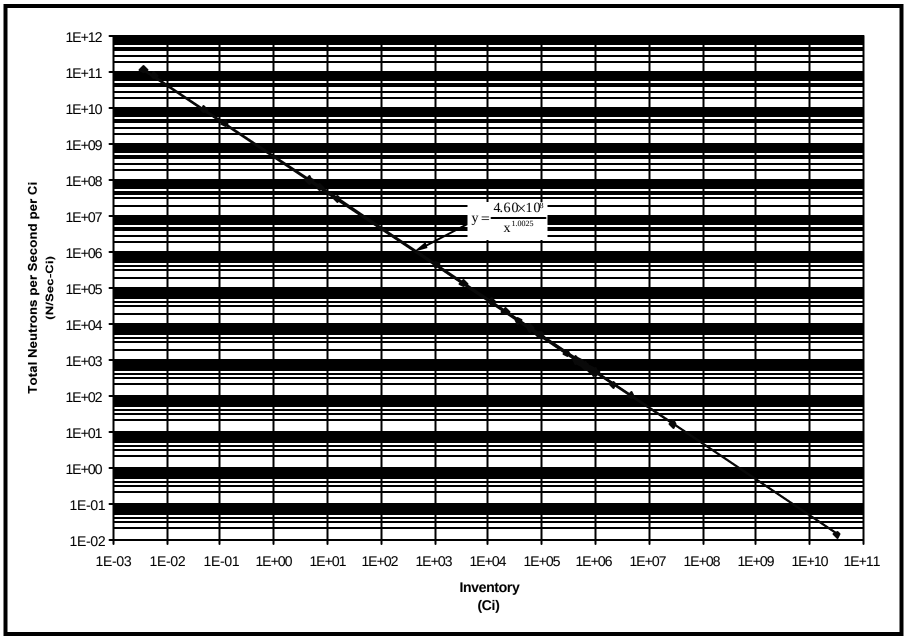

Figure 3 - Total Neutron Source Strength vs Inventory Activity

GAMMA

Calculations were performed to evaluate the relationship of gamma energy vs. gamma intensity to reach the 1000 mrem/h dose rate limit for a given activity of $1x10^8$ Ci . Evaluation of the results reveals the following:

- The maximum allowable gamma source effective activity is related to the gamma energy (See Figure 4).
- Gamma energies less than 0.3 MeV are acceptable, and require no additional screening or evaluation.

A curve fit of the data and rearrangement yields

$$I = 10^{\left(1.256\gamma^{-1.6281} - 7.1\right)},$$

where I is the intensity factor (as a fraction where 1 = 100%), and ã is the Gamma Energy (MeV). Because this curve fit slightly over predicts allowable gamma intensity at lower energies, its use would not be conservative. Consequently, to ensure conservative results for gamma energies below

~1.0 MeV, and the entire energy range, the following bounding equation which slightly under predicts the allowable gamma was derived:

$$I_{critical} = 10^{\left(0.952\gamma^{-1.6281} - 7.1\right)}$$

This relationship may be used for screening additional radionuclides based on their characteristic gamma energy intensities. For an isotope wit
energy in MeV and solving for $I_{critical}$ in the above equation, yields the maximum allowable intensity. Thus, a radionuclide having a lower gamma intensity may be shipped without restriction.

In addition to screening radionuclides that may be shipped without restriction, the relationship derived above can be extended to determine conservative activity limits for any gamma radionuclide based on the gamma spectrum. Given a gamma energy in MeV, the effective activity may be determined by using the following equation:

$$A_{allowable} = 10^{8}\left(\frac{I_{critical}}{I_{gamma}}\right) = 10^{8}\left(\frac{10^{\left(0.952g^{-1.6281} - 7.1\right)}}{I_{gamma}}\right) = \frac{10^{\left(0.952g^{-1.6281} + 0.9\right)}}{I_{gamma}}$$

Note that I_{gamma} represents the gamma intensity for the specific gamma energy, and is represented as a fraction (e.g.- use 0.5 for 50%).

For radionuclides that have multiple gamma energies, the above process is followed for each gamma energy. The sum of the fractions method is then used to determine the maximum allowable activity for that isotope. Note that this method under predicts the allowable activity, intentionally, to allow its use for any gamma energy.

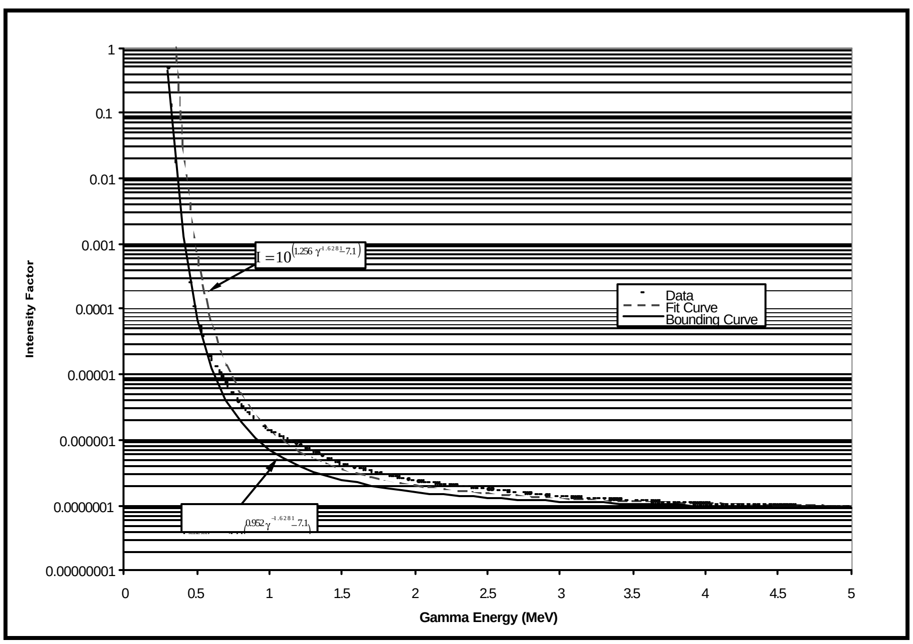

Figure 4 - Intensity Factor Vs. Gamma Energy for a Dose at 1 Meter of 1000 mrem/hr

SUMMARY

The expansion of the allowable activity limits through the use of an accurate subcritical neutron multiplication factor, the ability to use preshipment radiological surveys in lieu of extensive assay of controlled payload forms, and the ability to ship newly discovered radionuclides for which a point-source activity limit does not exist are all benefits of the RH-TRU 72-B dose rate compliance methodology initiatives. Nuclear Regulatory Commission approval of Revision 3 of the Safety Analysis Report for the RH-TRU 72-B Waste Shipping Package, which details dose rate compliance expansion methodologies, is pending.

REFERENCES

[1] U.S. Department of Energy (DOE), "Safety Analysis Report for the RH-TRU 72-B Waste Shipping Package", USNRC Certificate of Compliance 71-9212, U.S Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

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