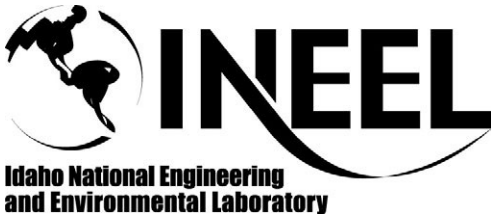


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# Direct Dose Consequences Due To DOE-STD-1027 Threshold Values

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# DIRECT DOSE CONSEQUENCES DUE TO DOE-STD-1027 THRESHOLD VALUES

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ABSTRACT

The purpose of this paper is to discuss the potential direct dose consequences to facility workers and/or co-located workers from a Hazard Category 2 or 3 nuclear facility or a less than Hazard Category 3 radiological inventory. At the Idaho National Engineering and Environmental Laboratory (INEEL), the safety analysis for several Hazard Category 3 nuclear facilities had to be revisited and the direct dose consequences associated with the facility radiological inventory had to be analyzed and incorporated into the safety analysis. This additional safety analysis was required because it was assumed that for a nuclear facility operating with radiological inventories between the Hazard Category 3 threshold quantities as a lower bounds and less the Hazard Category 2 threshold quantities as an upper bounds, the risk to the facility worker and/or co-located worker was within the INEEL Evaluation Guidelines for radiological exposures.

Hazard categorization for facilities operated under nuclear safety analysis in compliance with Department of Energy Order 5480.23, "Nuclear Safety Analysis Reports," must be performed in accordance with DOE-STD-1027-92, "Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports." The hazard categorization process is based upon defined dose consequences to the receptor from an unmitigated airborne release via the inhalation pathway. When performing the hazard categorization, the radiological inventory present in the facility is addressed either as a total cumulative inventory or it can be partitioned into isolated units. This inventory distribution is defined as the material-at-risk (MAR) inventory. The MAR is then compared to the threshold values for each hazard category provided in DOE-STD-1027-92. The nuclear facility categorization is based on whether the MAR inventory exceeds the threshold values for a particular nuclear facility hazard category. For example, the Hazard Category 3 classification allows facilities to have a radiological inventory greater than the Hazard Category 3 threshold quantities given that than the MAR inventory does not meet or exceed the Hazard Category 2 threshold quantities. Further restrictions are provided for this classification in that ratios of each individual radionuclide MAR to the corresponding threshold quantity, summed over all of the radionuclides (sum of the ratios), does not exceed 1.0.

DOE-STD-1027-92 threshold values could allow significant curie quantities of radionuclides within a nuclear facility. Some of those radionuclides are gamma emitters. This situation would not necessarily cause a safety analyst to consider the impacts of the direct dose consequences resulting from such large radionuclide quantities; if the safety analyst is assuming the facility has an acceptable level of risk using the DOE-STD-1027 unmitigated airborne release dose consequence assumptions. For example, the Hazard Category 3 threshold quantity for Cobalt 60 is 280 curies and the Hazard Category 2 threshold quantity is 190,000 curies. A Hazard Category 3, nuclear facility could contain up to 190,000 curies of Co-60, provided the sum of the ratios does not exceed 1.0. Both of these threshold quantities have a significant direct dose hazard associated with them. Therefore, Hazard Category 2/3, nuclear facility and less than Hazard Category 3 radiological facility safety analysis must consider and analyze the direct gamma dose consequences to the facility worker and the co-located workers from the facility radiological inventory.

## INTRODUCTION

Safety Analysis for Hazard Category 3, nuclear facilities according to DOE Order 5480.23[1] and DOE-STD-3009-94[2] (Chapter 3, "Application of Graded Approach) does not specifically require dose consequence analysis based on the Hazard Category 3 threshold quantities presented in DOE-STD-1027-92.[3] It is stated that hazard identification and evaluation is sufficient for Hazard Category 3, nuclear facilities. This assumption is based upon the release of the radionuclide inventory listed for the Hazard Category 3, nuclear facility. However, this assumption is only based on a release scenario and does not take into account the direct dose contribution to a facility or co-located worker from the allowed Hazard Category 3 radiological inventory. Therefore, the safety analysis for a Hazard Category 3, nuclear facility must analyze the direct gamma dose consequences to the facility worker and the co-located workers in order to provide a complete safety analysis. This same safety analysis issue would apply to both Hazard Category 2, nuclear facilities and less than Hazard Category 3 radiological facilities.

## DISCUSSION

The current safety analysis process at the INEEL had prepared upgraded safety analysis reports (SARs) for Hazard Category 3, nuclear facilities without radiological dose consequence analysis (direct doses or releases) based upon the discussions in DOE Order 5480.23 and DOE-STD-3009. During the Independent Safety Review Committee (ISRC) reviews of several Hazard Category 3, nuclear facility SARs, the ISRC review team identified the potential for direct gamma doses from the facility radiological inventory exceeding the INEEL Evaluation Guidelines.[4] The facility-specific SARs had identified a technical safety requirement (TSR) level control to limit the facility radionuclide inventory within a Hazard Category 3, nuclear facility categorization. A review of the DOE-STD-1027 threshold values for a Hazard Category 2, nuclear facility indicates that

the radiological inventory could approach millions of curies of mixed fission products and actinides provided the sum of the ratios does not exceed a value of 1.0.

In order to better understand the overall safety analysis impacts associated with this issue, a large number of direct dose consequence calculations were performed.[5] The direct dose consequences for selected single radionuclides (e.g., Cs-137, Co-60, etc.) using the assumptions listed in Table 1 and for the entire list of radionuclides listed in Tables 2 and 3 were calculated using the computer code MicroShield 5.03B.[6]

The threshold quantity activities for this direct gamma dose consequence analysis was based on the DOE-STD-1027-92 Hazard Category 2 and Hazard Category 3 threshold quantities.

**Table 1. Direct Dose Consequence Analysis Assumptions for Single Radionuclides.**

| **Hazard Category 2 Parameters** | **Units** | **Cs-137** | **Co-60** |
|---|---|---|---|
| Threshold Quality Activity | Curies | 8.9E+04 | 1.9E+05 |
| Threshold Quantity Mass | Grams | 1.0E+03 | 1.7E+02 |

| Hazard Category 3 Parameters | Units | Cs-137 | Co-60 |
|---|---|---|---|
| Threshold Quantity Activity | Curies | 6.0E+01 | 2.8E+02 |
| Threshold Quantity Mass | Grams | 6.9E-01 | 2.5E-01 |

For the entire list of DOE-STD-1027 radionuclides it has to be understood that the total threshold quantity for each radionuclide would not be allowed, since the sum of the ratios would exceed a value of 1.0. Therefore, the Hazard Category 2 and 3 threshold quantity distributions were normalized to unity. The Hazard Category 2 and 3 threshold quantities were divided by the total number of radionuclide in the threshold list so that the sum of the ratios of each individual radionuclide activity to that of the total activity was normalized to a value of 1.0. The normalized radionuclide inventory for both the Hazard Category 2 and 3 threshold quantities is listed in Tables 2 and 3, respectively. The only exception to this list of radionuclide was Cd-113, since it composed the bulk of the hazard category distribution (5.3E+13 grams) and would dramatically attenuate the photons from the volume source; Cd-113 was removed from the inventory. Cd-113 is not a significant gamma emitter. The normalized inventories in Tables 2 and 3 were used as the basis for the maximum radionuclide inventory used in the various source geometries, along with two individual radionuclides (Co-60 and Cs-137).

Seven source geometries were selected for dose consequence analysis based upon potential types of samples or materials that could be available across the INEEL. The seven geometry models used were:

1. point source
2. spherical volume source
3. annular cylindrical volume source
4. 40 ml sample bottle volume source
5. 250 ml sample bottle volume source

6. 500 ml sample bottle volume source
7. 1000 ml sample bottle volume source

The point source model (item 1 above) was analyzed for two single radionuclides (i.e., Cs-137 or Co-60) with the full threshold curie values and both Hazard Category 2 and 3 normalized radionuclide inventories. The point source model for a single radionuclide and/or the Hazard Category 2 or 3 normalized inventory would provide a conservative bounding gamma dose consequence analysis for comparison to the volumetric source models and the Hazard Category 2 and 3 inventories presented in Tables 2 and 3, respectively. The volumetric models (items 2-7) accounted for the source volume, the bulk density of the solution or solid being analyzed, the overall dimensions of the each container type, and the radionuclide inventories in Tables 2 and 3.

Only the results of the point source model are presented in this paper. The point source model neglects self-shielding and attenuation caused by the larger volume sources. Therefore, the point source model provides an extremely conservative bounding direct dose consequence analysis for all the geometries analyzed.

**Table 2. Hazard Category 2 Normalized Inventory.**

| Parameter | Nuclide | HC2 Activity TQ | HC2 Mass TQ | Adjusted Sum of the Ratios HC2 Activity TQ | Adjusted Sum of the Ratios HC2 Mass TQ | Sum of the Ratios |
|---|---|---|---|---|---|---|
| Source | *DOE-STD-1027* | *DOE-STD-1027* | *DOE-STD-1027* | Calculated | Calculated | *DOE-STD-1027* |
| **Units** | **(Name)** | **(Ci)** | **(g)** | **(Ci)** | **(g)** | **(fraction)** |
| | Ac-225 | 2.90E+03 | 4.90E-02 | 3.05E+01 | 5.16E-04 | 7.06E-06 |
| | Ac-227 | 4.30E+00 | 5.90E-02 | 4.53E-02 | 6.21E-04 | 1.05E-08 |
| | Ag-110m | 5.30E+05 | 1.10E+02 | 5.58E+03 | 1.16E+00 | 1.29E-03 |
| | Am-241 | 5.50E+01 | 1.60E+01 | 5.79E-01 | 1.68E-01 | 1.34E-07 |
| | Am-242m | 5.60E+01 | 5.80E+00 | 5.89E-01 | 6.11E-02 | 1.36E-07 |
| | Am-243 | 5.50E+01 | 2.80E+02 | 5.79E-01 | 2.95E+00 | 1.34E-07 |
| | Au-198 | 9.30E+06 | 3.80E+01 | 9.79E+04 | 4.00E-01 | 2.26E-02 |
| | Ba-133 | 4.00E+06 | 1.60E+04 | 4.21E+04 | 1.68E+02 | 9.74E-03 |
| | Ba-137m | 8.42E+04 | 1.57E-04 | 8.86E+02 | 1.65E-06 | 2.05E-04 |
| | Ba-140 | 7.80E+06 | 1.10E+02 | 8.21E+04 | 1.16E+00 | 1.90E-02 |
| | Bi-207 | 2.20E+06 | 4.30E+04 | 2.32E+04 | 4.53E+02 | 5.35E-03 |
| | Bi-210 | 1.50E+05 | 1.20E+00 | 1.58E+03 | 1.26E-02 | 3.65E-04 |
| | C-14 | 1.40E+06 | 3.10E+05 | 1.47E+04 | 3.26E+03 | 3.41E-03 |
| | Ca-45 | 4.70E+06 | 2.60E+02 | 4.95E+04 | 2.74E+00 | 1.14E-02 |
| | Ca-47 | 4.80E+06 | 7.80E+00 | 5.05E+04 | 8.21E-02 | 1.17E-02 |
| | Cd-109 | 2.90E+05 | 1.10E+02 | 3.05E+03 | 1.16E+00 | 7.06E-04 |
| | Cd-113 | 1.80E+04 | 5.30E+16 | 1.89E+02 | 5.58E+14 | 4.38E-05 |
| | Ce-141 | 3.30E+06 | 1.20E+02 | 3.47E+04 | 1.26E+00 | 8.03E-03 |
| | Ce-144 | 8.20E+04 | 2.60E+01 | 8.63E+02 | 2.74E-01 | 2.00E-04 |
| | Cf-252 | 2.20E+02 | 4.10E-01 | 2.32E+00 | 4.32E-03 | 5.35E-07 |
| | Cl-36 | 1.40E+03 | 4.30E+04 | 1.47E+01 | 4.53E+02 | 3.41E-06 |
| | Cm-242* | 1.70E+03 | 5.10E-01 | 1.79E+01 | 5.37E-03 | 4.14E-06 |
| | Cm-245 | 5.30E+01 | 3.10E+02 | 5.58E-01 | 3.26E+00 | 1.29E-07 |
| | Co-60 | 1.90E+05 | 1.70E+02 | 2.00E+03 | 1.79E+00 | 4.62E-04 |
| | Cr-51 | 1.00E+08 | 1.10E+03 | 1.05E+06 | 1.16E+01 | 2.43E-01 |
| | Cs-134 | 6.00E+04 | 4.60E+01 | 6.32E+02 | 4.84E-01 | 1.46E-04 |
| | Cs-137 | 8.90E+04 | 1.00E+03 | 9.37E+02 | 1.05E+01 | 2.17E-04 |
| | Eu-152 | 1.30E+05 | 7.50E+02 | 1.37E+03 | 7.89E+00 | 3.16E-04 |
| | Eu-154 | 1.10E+05 | 4.20E+02 | 1.16E+03 | 4.42E+00 | 2.68E-04 |
| | Eu-155 | 7.30E+05 | 1.60E+03 | 7.68E+03 | 1.68E+01 | 1.78E-03 |
| | Fe-55 | 1.10E+07 | 4.60E+03 | 1.16E+05 | 4.84E+01 | 2.68E-02 |
| | Fe-59 | 1.80E+06 | 3.70E+01 | 1.89E+04 | 3.89E-01 | 4.38E-03 |
| | Gd-153 | 1.40E+06 | 3.90E+02 | 1.47E+04 | 4.11E+00 | 3.41E-03 |
| | Ge-68 | 5.80E+05 | 8.80E+01 | 6.11E+03 | 9.26E-01 | 1.41E-03 |
| | H-3 | 3.00E+05 | 3.00E+01 | 3.16E+03 | 3.16E-01 | 7.30E-04 |
| | Hf-181 | 2.20E+06 | 1.30E+02 | 2.32E+04 | 1.37E+00 | 5.35E-03 |
| | Hg-203 | 4.30E+05 | 3.10E+01 | 4.53E+03 | 3.26E-01 | 1.05E-03 |
| | Ho-166m | 4.00E+04 | 2.20E+04 | 4.21E+02 | 2.32E+02 | 9.74E-05 |
| | I-125 | 2.40E+03 | 1.40E-01 | 2.53E+01 | 1.47E-03 | 5.84E-06 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | I-131 | 1.80E+03 | 1.40E-02 | 1.89E+01 | 1.47E-04 | 4.38E-06 |
| | In-114m | 3.70E+05 | 1.60E+01 | 3.89E+03 | 1.68E-01 | 9.01E-04 |
| | Ir-192 | 1.20E+06 | 1.30E+02 | 1.26E+04 | 1.37E+00 | 2.92E-03 |
| | K-40 | 4.70E+03 | 6.80E+08 | 4.95E+01 | 7.16E+06 | 1.14E-05 |
| | Kr-85 | 2.80E+07 | 7.20E+04 | 2.95E+05 | 7.58E+02 | 6.81E-02 |
| | Mn-52 | 4.00E+06 | 8.80E+00 | 4.21E+04 | 9.26E-02 | 9.74E-03 |
| | Mo-99 | 7.80E+06 | 1.60E+01 | 8.21E+04 | 1.68E-01 | 1.90E-02 |
| | Na-22 | 6.30E+03 | 1.00E+00 | 6.63E+01 | 1.05E-02 | 1.53E-05 |
| | Nb-94 | 8.60E+04 | 4.60E+05 | 9.05E+02 | 4.84E+03 | 2.09E-04 |
| | Ni-63 | 4.50E+06 | 8.00E+04 | 4.74E+04 | 8.42E+02 | 1.10E-02 |
| | Np-237 | 5.80E+01 | 8.30E+04 | 6.11E-01 | 8.74E+02 | 1.41E-07 |
| | Np-238 | 9.10E+05 | 3.50E+00 | 9.58E+03 | 3.68E-02 | 2.21E-03 |
| | P-32 (acid)** | 2.20E+06 | 7.70E-02 | 2.32E+04 | 8.11E-04 | 5.35E-03 |
| | P-33 (acid)** | 1.50E+07 | 9.60E+01 | 1.58E+05 | 1.01E+00 | 3.65E-02 |
| | Pb-210 | 2.20E+03 | 2.90E+01 | 2.32E+01 | 3.05E-01 | 5.35E-06 |
| | Pm-145 | 1.10E+06 | 7.60E+03 | 1.16E+04 | 8.00E+01 | 2.68E-03 |
| | Pm-147 | 8.40E+05 | 9.00E+02 | 8.84E+03 | 9.47E+00 | 2.04E-03 |
| | Po-210 | 3.50E+02 | 7.80E-02 | 3.68E+00 | 8.21E-04 | 8.52E-07 |
| | Pu-238 | 6.20E+01 | 3.60E+00 | 6.53E-01 | 3.79E-02 | 1.51E-07 |
| | Pu-239 | 5.60E+01 | 9.00E+02 | 5.89E-01 | 9.47E+00 | 1.36E-07 |
| | Pu-241 | 2.90E+03 | 2.80E+01 | 3.05E+01 | 2.95E-01 | 7.06E-06 |
| | Ra-223 | 3.80E+03 | 7.40E-02 | 4.00E+01 | 7.79E-04 | 9.25E-06 |
| | Ra-224 | 9.90E+03 | 6.10E-02 | 1.04E+02 | 6.42E-04 | 2.41E-05 |
| | Ra-225 | 3.80E+03 | 9.60E-02 | 4.00E+01 | 1.01E-03 | 9.25E-06 |
| | Rn-222 | 1.60E+08 | 1.10E+03 | 1.68E+06 | 1.16E+01 | 3.89E-01 |
| | Ru-106 | 6.50E+03 | 1.90E+00 | 6.84E+01 | 2.00E-02 | 1.58E-05 |
| | S-35 | 2.50E+04 | 5.80E-01 | 2.63E+02 | 6.11E-03 | 6.08E-05 |
| | Sb-124 | 1.30E+06 | 7.50E+01 | 1.37E+04 | 7.89E-01 | 3.16E-03 |
| | Sb-126 | 2.50E+06 | 3.00E+01 | 2.63E+04 | 3.16E-01 | 6.08E-03 |
| | Sc-46 | 1.40E+06 | 4.00E+01 | 1.47E+04 | 4.21E-01 | 3.41E-03 |
| | Se-75 | 3.40E+05 | 2.40E+01 | 3.58E+03 | 2.53E-01 | 8.28E-04 |
| | Sm-151 | 9.90E+05 | 3.70E+04 | 1.04E+04 | 3.89E+02 | 2.41E-03 |
| | Sn-113 | 3.20E+06 | 3.20E+02 | 3.37E+04 | 3.37E+00 | 7.79E-03 |
| | Sn-123 | 9.50E+05 | 1.20E+02 | 1.00E+04 | 1.26E+00 | 2.31E-03 |
| | Sn-126 | 3.30E+05 | 1.20E+07 | 3.47E+03 | 1.26E+05 | 8.03E-04 |
| | Sr-89 | 7.70E+05 | 2.70E+01 | 8.11E+03 | 2.84E-01 | 1.87E-03 |
| | Sr-90 | 2.20E+04 | 1.60E+02 | 2.32E+02 | 1.68E+00 | 5.35E-05 |
| | Tb-160 | 1.30E+06 | 1.10E+02 | 1.37E+04 | 1.16E+00 | 3.16E-03 |
| | Tc-99 | 3.80E+06 | 2.30E+08 | 4.00E+04 | 2.42E+06 | 9.25E-03 |
| | Te-127m | 1.50E+05 | 1.60E+01 | 1.58E+03 | 1.68E-01 | 3.65E-04 |
| | Te-129m | 1.40E+05 | 4.70E+00 | 1.47E+03 | 4.95E-02 | 3.41E-04 |
| | Th-228 | 9.20E+01 | 1.10E-01 | 9.68E-01 | 1.16E-03 | 2.24E-07 |
| | Th-230 | 8.90E+01 | 4.40E+03 | 9.37E-01 | 4.63E+01 | 2.17E-07 |
| | Th-232 | 1.80E+01 | 1.60E+08 | 1.89E-01 | 1.68E+06 | 4.38E-08 |
| | Ti-44 | 3.20E+04 | 1.90E+02 | 3.37E+02 | 2.00E+00 | 7.79E-05 |
| | Tm-170 | 1.20E+06 | 2.10E+02 | 1.26E+04 | 2.21E+00 | 2.92E-03 |
| | U-233 | 2.20E+02 | 2.30E+04 | 2.32E+00 | 2.42E+02 | 5.35E-07 |
| | U-234 | 2.20E+02 | 3.50E+04 | 2.32E+00 | 3.68E+02 | 5.35E-07 |
| | U-235 | 2.40E+02 | 1.10E+08 | 2.53E+00 | 1.16E+06 | 5.84E-07 |
| | U-238 | 2.40E+02 | 7.10E+08 | 2.53E+00 | 7.47E+06 | 5.84E-07 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | V-48 | 3.00E+06 | 1.80E+01 | 3.16E+04 | 1.89E-01 | 7.30E-03 |
| | Xe-133 | 1.80E+06 | 9.60E+00 | 1.89E+04 | 1.01E-01 | 4.38E-03 |
| | Y-91 | 6.50E+05 | 2.70E+01 | 6.84E+03 | 2.84E-01 | 1.58E-03 |
| | Zn-65 | 1.60E+06 | 1.90E+02 | 1.68E+04 | 2.00E+00 | 3.89E-03 |
| | Zr-93 | 8.90E+04 | 3.60E+07 | 9.37E+02 | 3.79E+05 | 2.17E-04 |
| | Zr-95 | 1.50E+06 | 6.90E+01 | 1.58E+04 | 7.26E-01 | 3.65E-03 |
| TOTAL | 9.50E+01 | 4.11E+08 | 5.30E+16 | 4.32E+06 | 5.58E+14 | 1.00E+00 |

**Table 3. Hazard Category 3 Normalized Inventory.**

| Parameter | Nuclide | HC3 Activity TQ | HC3 Mass TQ | Adjusted Sum of the Ratios HC3 Activity TQ | Adjusted Sum of the Ratios HC3 Mass TQ | Sum of the Ratios |
|---|---|---|---|---|---|---|
| Source | *DOE-STD-1027* | *DOE-STD-1027* | *DOE-STD-1027* | Calculated | Calculated | *DOE-STD-1027* |
| **Units** | **(Name)** | **(Ci)** | **(g)** | **(Ci)** | **(g)** | **(fraction)** |
| | Ac-225 | 3.20E+01 | 5.50E-04 | 3.37E-01 | 5.79E-06 | 2.59E-04 |
| | Ac-227 | 4.20E-02 | 5.80E-04 | 4.42E-04 | 6.11E-06 | 3.40E-07 |
| | Ag-110m | 2.60E+02 | 5.50E-02 | 2.74E+00 | 5.79E-04 | 2.10E-03 |
| | Am-241 | 5.20E-01 | 1.50E-01 | 5.47E-03 | 1.58E-03 | 4.20E-06 |
| | Am-242m | 5.20E-01 | 5.30E-02 | 5.47E-03 | 5.58E-04 | 4.20E-06 |
| | Am-243 | 5.20E-01 | 2.60E+00 | 5.47E-03 | 2.74E-02 | 4.20E-06 |
| | Au-198 | 2.00E+03 | 8.20E-03 | 2.11E+01 | 8.63E-05 | 1.62E-02 |
| | Ba-133 | 1.10E+03 | 4.30E+00 | 1.16E+01 | 4.53E-02 | 8.89E-03 |
| | Ba-137m | 5.68E+01 | 1.06E-07 | 5.97E-01 | 1.11E-09 | 4.59E-04 |
| | Ba-140 | 6.00E+02 | 8.20E-03 | 6.32E+00 | 8.63E-05 | 4.85E-03 |
| | Bi-207 | 5.00E+02 | 1.10E+01 | 5.26E+00 | 1.16E-01 | 4.04E-03 |
| | Bi-210 | 3.20E+02 | 2.60E-03 | 3.37E+00 | 2.74E-05 | 2.59E-03 |
| | C-14 | 4.20E+02 | 9.40E+01 | 4.42E+00 | 9.89E-01 | 3.40E-03 |
| | Ca-45 | 1.10E+03 | 6.20E-02 | 1.16E+01 | 6.53E-04 | 8.89E-03 |
| | Ca-47 | 7.00E+02 | 1.10E-03 | 7.37E+00 | 1.16E-05 | 5.66E-03 |
| | Cd-109 | 1.80E+02 | 7.00E-02 | 1.89E+00 | 7.37E-04 | 1.46E-03 |
| | Cd-113 | 1.10E+01 | 3.20E+13 | 1.16E-01 | 3.37E+11 | 8.89E-05 |
| | Ce-141 | 1.00E+03 | 3.50E-02 | 1.05E+01 | 3.68E-04 | 8.09E-03 |
| | Ce-144 | 1.00E+02 | 3.10E-02 | 1.05E+00 | 3.26E-04 | 8.09E-04 |
| | Cf-252 | 3.20E+00 | 5.90E-03 | 3.37E-02 | 6.21E-05 | 2.59E-05 |
| | Cl-36 | 3.40E+02 | 1.00E+04 | 3.58E+00 | 1.05E+02 | 2.75E-03 |
| | Cm-242 | 3.20E+01 | 9.70E-03 | 3.37E-01 | 1.02E-04 | 2.59E-04 |
| | Cm-245 | 5.20E-01 | 3.00E+00 | 5.47E-03 | 3.16E-02 | 4.20E-06 |
| | Co-60 | 2.80E+02 | 2.50E-01 | 2.95E+00 | 2.63E-03 | 2.26E-03 |
| | Cr-51 | 2.20E+04 | 2.40E-01 | 2.32E+02 | 2.53E-03 | 1.78E-01 |
| | Cs-134 | 4.20E+01 | 3.30E-02 | 4.42E-01 | 3.47E-04 | 3.40E-04 |
| | Cs-137 | 6.00E+01 | 6.90E-01 | 6.32E-01 | 7.26E-03 | 4.85E-04 |
| | Eu-152 | 2.00E+02 | 1.20E+00 | 2.11E+00 | 1.26E-02 | 1.62E-03 |
| | Eu-154 | 2.00E+02 | 7.60E-01 | 2.11E+00 | 8.00E-03 | 1.62E-03 |
| | Eu-155 | 9.40E+02 | 2.00E+00 | 9.89E+00 | 2.11E-02 | 7.60E-03 |
| | Fe-55 | 5.40E+03 | 2.20E+00 | 5.68E+01 | 2.32E-02 | 4.37E-02 |
| | Fe-59 | 6.00E+02 | 1.20E+02 | 6.32E+00 | 1.26E+00 | 4.85E-03 |
| | Gd-153 | 1.00E+03 | 2.80E-01 | 1.05E+01 | 2.95E-03 | 8.09E-03 |
| | Ge-68 | 1.00E+03 | 1.50E-01 | 1.05E+01 | 1.58E-03 | 8.09E-03 |
| | H-3 | 1.60E+04 | 1.60E+00 | 1.68E+02 | 1.68E-02 | 1.29E-01 |
| | Hf-181 | 7.60E+02 | 4.50E-02 | 8.00E+00 | 4.74E-04 | 6.15E-03 |
| | Hg-203 | 3.60E+02 | 2.60E-02 | 3.79E+00 | 2.74E-04 | 2.91E-03 |
| | Ho-166m | 7.20E+01 | 4.00E+01 | 7.58E-01 | 4.21E-01 | 5.82E-04 |
| | I-125 | 5.60E-01 | 3.20E-05 | 5.89E-03 | 3.37E-07 | 4.53E-06 |
| | I-131 | 9.20E-01 | 7.40E-06 | 9.68E-03 | 7.79E-08 | 7.44E-06 |
| | In-114m | 2.20E+02 | 9.50E-03 | 2.32E+00 | 1.00E-04 | 1.78E-03 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Ir-192 | 9.40E+02 | 1.00E-01 | 9.89E+00 | 1.05E-03 | 7.60E-03 |
| | K-40 | 1.70E+02 | 2.40E+07 | 1.79E+00 | 2.53E+05 | 1.37E-03 |
| | Kr-85 | 2.00E+04 | 5.10E+01 | 2.11E+02 | 5.37E-01 | 1.62E-01 |
| | Mn-52 | 3.40E+02 | 7.60E-04 | 3.58E+00 | 8.00E-06 | 2.75E-03 |
| | Mo-99 | 3.40E+03 | 7.10E-03 | 3.58E+01 | 7.47E-05 | 2.75E-02 |
| | Na-22 | 2.40E+02 | 3.80E-02 | 2.53E+00 | 4.00E-04 | 1.94E-03 |
| | Nb-94 | 2.00E+02 | 1.10E+03 | 2.11E+00 | 1.16E+01 | 1.62E-03 |
| | Ni-63 | 5.40E+03 | 9.50E+01 | 5.68E+01 | 1.00E+00 | 4.37E-02 |
| | Np-237 | 4.20E-01 | 6.00E+02 | 4.42E-03 | 6.32E+00 | 3.40E-06 |
| | Np-238 | 1.30E+03 | 5.00E-03 | 1.37E+01 | 5.26E-05 | 1.05E-02 |
| | P-32 (acid)** | 1.20E+01 | 4.20E-05 | 1.26E-01 | 4.42E-07 | 9.70E-05 |
| | P-33 (acid)** | 9.40E+01 | 6.00E-04 | 9.89E-01 | 6.32E-06 | 7.60E-04 |
| | Pb-210 | 3.60E-01 | 4.70E-03 | 3.79E-03 | 4.95E-05 | 2.91E-06 |
| | Pm-145 | 2.00E+03 | 1.40E+01 | 2.11E+01 | 1.47E-01 | 1.62E-02 |
| | Pm-147 | 1.00E+03 | 9.50E-01 | 1.05E+01 | 1.00E-02 | 8.09E-03 |
| | Po-210 | 1.90E+00 | 4.20E-04 | 2.00E-02 | 4.42E-06 | 1.54E-05 |
| | Pu-238 | 6.20E-01 | 3.60E-02 | 6.53E-03 | 3.79E-04 | 5.01E-06 |
| | Pu-239 | 5.20E-01 | 8.40E+00 | 5.47E-03 | 8.84E-02 | 4.20E-06 |
| | Pu-241 | 3.20E+01 | 3.10E-01 | 3.37E-01 | 3.26E-03 | 2.59E-04 |
| | Ra-223 | 6.20E+01 | 1.20E-03 | 6.53E-01 | 1.26E-05 | 5.01E-04 |
| | Ra-224 | 2.00E+02 | 1.20E-03 | 2.11E+00 | 1.26E-05 | 1.62E-03 |
| | Ra-225 | 7.20E+01 | 1.80E-03 | 7.58E-01 | 1.89E-05 | 5.82E-04 |
| | Rn-222 | 1.00E+01 | 6.50E-05 | 1.05E-01 | 6.84E-07 | 8.09E-05 |
| | Ru-106 | 1.00E+02 | 3.00E-02 | 1.05E+00 | 3.16E-04 | 8.09E-04 |
| | S-35 | 7.80E+01 | 1.80E-03 | 8.21E-01 | 1.89E-05 | 6.31E-04 |
| | Sb-124 | 3.60E+02 | 2.10E-02 | 3.79E+00 | 2.21E-04 | 2.91E-03 |
| | Sb-126 | 2.80E+02 | 3.40E-03 | 2.95E+00 | 3.58E-05 | 2.26E-03 |
| | Sc-46 | 3.60E+02 | 1.10E-02 | 3.79E+00 | 1.16E-04 | 2.91E-03 |
| | Se-75 | 3.20E+02 | 2.20E-02 | 3.37E+00 | 2.32E-04 | 2.59E-03 |
| | Sm-151 | 1.00E+03 | 3.80E+01 | 1.05E+01 | 4.00E-01 | 8.09E-03 |
| | Sn-113 | 1.30E+03 | 1.30E-01 | 1.37E+01 | 1.37E-03 | 1.05E-02 |
| | Sn-123 | 3.20E+02 | 3.90E-02 | 3.37E+00 | 4.11E-04 | 2.59E-03 |
| | Sn-126 | 1.70E+02 | 6.00E+03 | 1.79E+00 | 6.32E+01 | 1.37E-03 |
| | Sr-89 | 3.40E+02 | 1.20E-02 | 3.58E+00 | 1.26E-04 | 2.75E-03 |
| | Sr-90 | 1.60E+01 | 1.20E-01 | 1.68E-01 | 1.26E-03 | 1.29E-04 |
| | Tb-160 | 5.60E+02 | 5.00E-02 | 5.89E+00 | 5.26E-04 | 4.53E-03 |
| | Tc-99 | 1.70E+03 | 1.00E+05 | 1.79E+01 | 1.05E+03 | 1.37E-02 |
| | Te-127m | 4.00E+02 | 4.20E-02 | 4.21E+00 | 4.42E-04 | 3.23E-03 |
| | Te-129m | 4.00E+02 | 1.30E-02 | 4.21E+00 | 1.37E-04 | 3.23E-03 |
| | Th-228 | 1.00E+00 | 1.20E-03 | 1.05E-02 | 1.26E-05 | 8.09E-06 |
| | Th-230 | 6.20E-01 | 3.10E+01 | 6.53E-03 | 3.26E-01 | 5.01E-06 |
| | Th-232 | 1.00E-01 | 9.10E+05 | 1.05E-03 | 9.58E+03 | 8.09E-07 |
| | Ti-44 | 6.20E+01 | 3.60E-01 | 6.53E-01 | 3.79E-03 | 5.01E-04 |
| | Tm-170 | 5.20E+02 | 8.70E-02 | 5.47E+00 | 9.16E-04 | 4.20E-03 |
| | U-233 | 4.20E+00 | 4.40E+02 | 4.42E-02 | 4.63E+00 | 3.40E-05 |
| | U-234 | 4.20E+00 | 6.70E+02 | 4.42E-02 | 7.05E+00 | 3.40E-05 |
| | U-235 | 4.20E+00 | 1.90E+06 | 4.42E-02 | 2.00E+04 | 3.40E-05 |
| | U-238 | 4.20E+00 | 1.30E+07 | 4.42E-02 | 1.37E+05 | 3.40E-05 |
| | V-48 | 6.40E+02 | 3.80E-03 | 6.74E+00 | 4.00E-05 | 5.17E-03 |
| | Xe-133 | 2.00E+04 | 1.10E-01 | 2.11E+02 | 1.16E-03 | 1.62E-01 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Y-91 | 3.60E+02 | 1.50E-02 | 3.79E+00 | 1.58E-04 | 2.91E-03 |
| | Zn-65 | 2.40E+02 | 2.90E-02 | 2.53E+00 | 3.05E-04 | 1.94E-03 |
| | Zr-93 | 6.20E+01 | 2.50E+04 | 6.53E-01 | 2.63E+02 | 5.01E-04 |
| | Zr-95 | 7.00E+02 | 3.30E-02 | 7.37E+00 | 3.47E-04 | 5.66E-03 |
| TOTAL | 9.50E+01 | 1.24E+05 | 3.20E+13 | 1.30E+03 | 3.37E+11 | 1.00E+00 |

## DOSE CONSEQUENCE RESULTS

The results of the direct dose consequence analysis for the point source model are summarized in Table 4 for the Co-60, Cs-137 and HC2/HC3 radionuclide inventories. The remaining volume models are not summarized in this paper, but provide comparable results. A review of Table 4 indicates that calculated direct gamma exposure rates from a single radionuclide such as Co-60 or Cs-137 at the Hazard Category 3 and 2 threshold quantities could exceed the DOE-ID Order 420.D Dose Consequence Evaluation Guidelines shown in Table 5 for a one hour exposure time interval.

**Table 4. Direct Dose Consequence Results.**

| Description | 1 m Exposure Rate (mR/hr) | 10 m Exposure Rate (mR/hr) | Hazard Category 3 Threshold Quantity (Curies) | Hazard Category 2 Threshold Quantity (Curies) |
|---|---|---|---|---|
| Co-60 Point Source | 3.6E+05 | 3.6E+03 | 2.8E+02 | -- |
| Co-60 Point Source | 2.5E+08 | 2.4E+06 | -- | 1.9E+05 |
| Cs-137 Point Source | 2.0E+04 | 1.9E+02 | 6.0E+01 | -- |
| Cs-137 Point Source | 2.9E+07 | 2.9E+05 | -- | 8.9E+04 |
| HC3 Point Source | 1.2E+05 | 1.2E+03 | See Table 3 | -- |
| HC2 Point Source | 4.9E+08 | 4.9E+06 | -- | See Table 2 |

**Table 5. DOE-ID Risk Evaluation Guidelines.**

| Frequency | Radiological Dose Guidelines |
|---|---|
| Anticipated (1E-01 to 1E-02 per year) | 5.0 Rem TEDE[a] |
| Unlikely (1E-01 to 1E-04 per year) | 25 Rem TEDE |
| Extremely Unlikely (1E-04 to 1E-06 per year) | 100 Rem TEDE |

a. TEDE – Total Effective Dose Equivalent

The threshold quantities for Co-60 (Table 4) are 280 Ci for Hazard Category 3 and 190,000 Ci for Hazard Category 2. The direct gamma exposure rates for a Co-60 point source model were calculated to be 3.6E+05 mR/hr and 2.5E+08 mR/hr at 1 m, respectively. The threshold quantities for Cs-137 (Table 4) are 60 Ci for Hazard Category 3 and 89,000 Ci for Hazard Category 2. The direct gamma exposure rates for a Cs-137 point source model were calculated to be 2.4E+04 mR/hr and 1.2E+07 mR/hr at 1 m, respectively. The direct gamma exposure rates from the Hazard Category 3 and 2 normalized threshold quantities (Tables 2 and 3) were calculated to be 1.2E+05 mR/hr and 4.9E+08 mR/hr, respectively.

## CONCLUSIONS

The direct dose from a single gamma emitting radionuclide at the Hazard Category 2 or 3 threshold quantities or from a mixed normalized distribution of radionuclides at a Hazard Category 2 or 3 threshold quantities present a significant radiological exposure hazard. These sources could deliver an unmitigated dose consequence to the facility worker that could significantly exceed the DOE-ID Evaluation Guidelines, depending on the accident scenario and the frequency of the event being analyzed. It is important for less than Hazard Category 3, nuclear facilities, Hazard Category 3, nuclear facilities and even Hazard Category 2 nuclear facilities that direct gamma dose consequence analysis be considered for facility worker protection when preparing the facility safety analysis. This may include the addition of TSR-level controls to limit gamma emitting radionuclide inventories within a facility, as well as the selection of safety structures, systems, or components (SSCs) such as shielding for worker protection.

Two hazard category 3 nuclear facilities at the INEEL currently have upgraded SARs and TSRs at DOE-ID for review and approval. Both sets of safety documents have identified a TSR-level control and a safety significant SSC for worker protection from direct dose consequences. In the same set of safety documents, TSR-level controls or safety-significant SSCs were not identified for radiological release scenarios based on the DOE-STD-1027-92 threshold values listed in Appendix A.

## REFERENCES


1. DOE Order 5480.23, Nuclear Safety Analysis Reports, Change 1, dated March 10, 1994.

2. DOE-STD-3009-94, *Preparation Guide U. S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports,* Change 1, dated January 2000.

3. Department of Energy, DOE-STD-1027-92, Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Report," Change 1,dated September 1997.

4. DOE-ID Order 420.D, Requirements and Guidance for Safety Analysis," dated July 17, 2000.

5. Engineering Design File (EDF-1714), "Hazard Category 2 and 3 Nuclear Facilities External Gamma Radiation Level Determination," by J. B. Walker, R. P. Durante, and E. E. Hochhalter, dated May 15, 2001.

6. MicroShield, Version 5.03B, Rockville, Maryland: Grove Engineering Inc., 1996.