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Supplemental Release Limits for the Directed Reuse of Steel in Road Barriers and Lead in Shielding Products by the Department of Energy

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PREFACE

This report presents a modification to ORNL-TM2001-36, "Supplemental Release Limits for the Directed Reuse of Lead in Shielding Products by the Department of Energy". The previous report focused solely on the directed reuse of radiologically contaminated lead (Pb) as shielding—with a primary anticipated product being the use of Pb to construct liners within radioactive waste containers. The analysis is now being extended to address the reuse of recycled steel for the fabrication of road barriers that can be used at nuclear facilities. This report does not replace the original but provides some modified limits for radionuclides in Pb while extending the recommendations to include limits for steel.

A number of detection issues were noted during implementation of the originally recommended limits for radionuclides in Pb. As an example, it was found that the isotope Pb-210 could not easily be measured at the previously recommended level of 3 pCi/g using conventional laboratory methods. The original analysis alluded to this possibility but a detailed evaluation was not performed— thereby creating difficulties during implementation of the recommended limits. A more complete assessment of measurement sensitivity issues was performed while developing this update for hard-to-detect radionuclides. The additional analysis, coupled with equivalently scaled dose modeling, resulted in recommended limits for both Pb and steel, but with Pb limits that are slightly different from those that were originally published.

The previous report, ORNL/TM2001-36 included a life cycle analysis for various disposition alternatives for lead. The information did not affect the dose modeling involved nor did it contribute to the selection of specific release criteria. The analysis included in the original report, as well as the conclusions that were drawn, are still considered valid for the purpose that they were originally performed—*i.e.* to demonstrate that directed-reuse strategies are a beneficial alternative to disposal and storage options. A life cycle analysis has not been performed for the reuse of steel.

ACKNOWLEDGMENTS

1. SUMMARY

The DOE National Center of Excellence for Metals Recycle (NMR) proposes to define and implement a complex-wide directed reuse strategy for surplus radiologically impacted lead (Pb) and steel as part of the U.S. Department of Energy's commitment to the safe and cost-effective recycle or reuse of excess materials and equipment across the DOE complex. NMR will, under this proposal, act on behalf of the DOE Office of Environmental Management, Office of Technical Program Integration (specifically EM-22), as the Department's clearinghouse for DOE surplus lead, steel and products created from these materials by developing and maintaining a cost-effective commercially-based contaminated lead and steel recycle program. It is NMR's intention, through this directed reuse strategy, to mitigate the adverse environmental and economic consequences of managing surplus lead and steel as a waste within the complex. This approach promotes the safe and cost-effective reuse of scrap metals in support of the Department's goals of resource utilization, energy conservation, pollution prevention and waste minimization.

This report discusses recommendations for supplemental radiological release limits for the directed reuse of contaminated lead and steel by the DOE within the nuclear industry. The limits were originally selected from the American National Standards Institute and Health Physics Society standard N13.12 titled *Surface and Volume Radioactivity Standards for Clearance* (Health Physics Society, 1999) but were subsequently modified as a result of application-specific issues. Both the health and measurement implications from the adoption and use of the limits for directed reuse scenarios are discussed within this report.

2. INTRODUCTION

Directed reuse and recycling strategies are continuing to be developed by the Facilities and Materials Reuse Division at Oak Ridge Operations (ORO) to address a January, 2000, Secretarial moratorium on the release of volume-contaminated metal. The moratorium was issued by former Secretary of Energy Richardson's and was followed by a memorandum dated July 13, 2000 requiring the suspension of the unrestricted release for recycling of metal from radiological areas at DOE facilities. The memorandum required action to

- improve the DOE's release criteria and monitoring program,
- expand efforts to promote reuse and recycling within the DOE complex,
- improve DOE management information about material inventories and the release of property from radiological control, and
- accelerate the recovery of sealed radioactive sources.

The DOE National Center of Excellence for Metals Recycle (NMR) subsequently proposed to define and implement a complex-wide internally-controlled directed reuse strategy for surplus radiologically impacted lead and steel. NMR would, under this proposal, act on behalf of the DOE Office of Environmental Management, Office of Technical Program Integration (specifically EM-22), as the Department's clearinghouse for DOE surplus lead and steel developing and maintaining a cost-effective commercially-based contaminated lead and steel recycle program. It would be NMR's intention, through this directed reuse strategy, to mitigate the adverse environmental and economic consequences of managing surplus metals as waste within the complex. This approach would promote the safe and cost-effective reuse of the greatest portion of DOE's scrap and surplus metal in support of the Department's goals of resource utilization, energy conservation, pollution prevention and waste minimization.

Incorporating radioactively contaminated lead as shielding for storage and disposal containers is envisioned as a principal means of reusing this material within DOE with a high degree of safety and control, as discussed in ORNL/TM-2001/36 (Coleman and Bogard, 2001). The principal means of re-use for steel is foreseen to be the construction of vehicle barriers for use at facility entrances and other traffic control points. The use of such barriers has increased in response to new security requirements since destruction of the World Trade Center by terrorists on September 11, 2001 and subsequent related events. The most likely alternative to the proposed recycling of radiologically impacted steel is disposal as low-level radioactive waste. The disposal alternative is less attractive in both environmental and economic terms and is considered by most to be a poor example of natural resource husbandry.

The term *directed reuse* is used throughout this report to describe the controlled deployment of lead and steel products solely within the nuclear industry following initial production. As such, the DOE may direct the products for use either within its own complex or at commercial licensee sites. The supplemental release limits recommended within this report were determined to meet DOE requirements for protection of the public consistent with DOE's As Low As Reasonably Achievable (ALARA) requirements. The limits are generally consistent with the recommended screening levels for unconditional clearance of materials to the general public provided in the ANSI N13.12-1999 Standard—which were developed to provide a reasonable expectation that public dose from uncontrolled releases would not exceed 1 mrem in a year. Under this DOE Authorized release for direct reuse, public exposures would be even lower or, considering the expected uses, almost non-existent.

The following sections describe radiological limits recommended for the *directed reuse* of radiologically contaminated lead and steel within DOE. The limits are based on existing regulatory limits and national standards for releasing materials with surface and volumetric radiological contamination. Public health implications from the adoption and use of the recommended limits for the directed reuse scenario are discussed.

3. DISCUSSION

This report presents a modification to ORNL/TM-2001/36, "Supplemental Release Limits for the Directed Reuse of Lead in Shielding Products by the Department of Energy". ORNL/TM-2001focused solely on the directed reuse of radiologically contaminated lead (Pb) as shielding—with a primary anticipated product being the use of Pb to construct liners within radioactive waste containers. The discussion contained in that report is still considered valid and is not repeated here. The analysis is being extended to address the reuse of recycled steel for the fabrication of road barriers and to also reconsider the detection sensitivity for some difficult-to-detect radionuclides.

The final product for recycled steel will be solid road barriers. There are many shapes and sizes of such barriers but one particularly prominent profile is the New Jersey Concrete Safety Shape Barrier—commonly referred to as a "Jersey barrier". A photograph depicting devices of this type is shown in **Figure 1** and a cross-sectional diagram is shown in **Figure 2**. This particular shape is

Figure 1. The New Jersey Concrete Safety Shape Barrier ("*Jersey Barrier*").

used to minimize vehicle damage by causing vehicle tires to ride up onto the lower sloped face before the side body has made contact. While there are other, similar profiles in use these dimensions are believed to be generally representative of the most common types that are presently in use and was selected as the basis for modeling external exposure scenarios.

The purpose of the following analyses is to support the development of DOE-approved limits for the directed reuse and recycling of both lead and steel that may contain slight concentrations of residual radioactive material. The basis for these limits is found in ANSI/HPS N13.12-1999 (Health Physics Society, 1999). This standard was developed under the direction of the Health Physics Society by the ANSI-accredited HPS N13 Committee and provides recommended screening levels for the release of potentially contaminated materials and equipment for unconditional use. Although the standard recommends *de-minimis* release criteria for unconditional reuse for materials that could be contaminated volumetrically or on their surfaces, its application in these recommendations is for directed reuse.

The Department has not approved guidelines set forth in ANSI/HPS N13.12-1999 for DOE's radiologically contaminated metals. Their use therefore requires case-by-case approval by the DOE. The application of limits for unrestricted (public) use would simplify the release process but this is not being considered because it is inconsistent with the present DOE suspension on the recycling of metal from radiological areas.
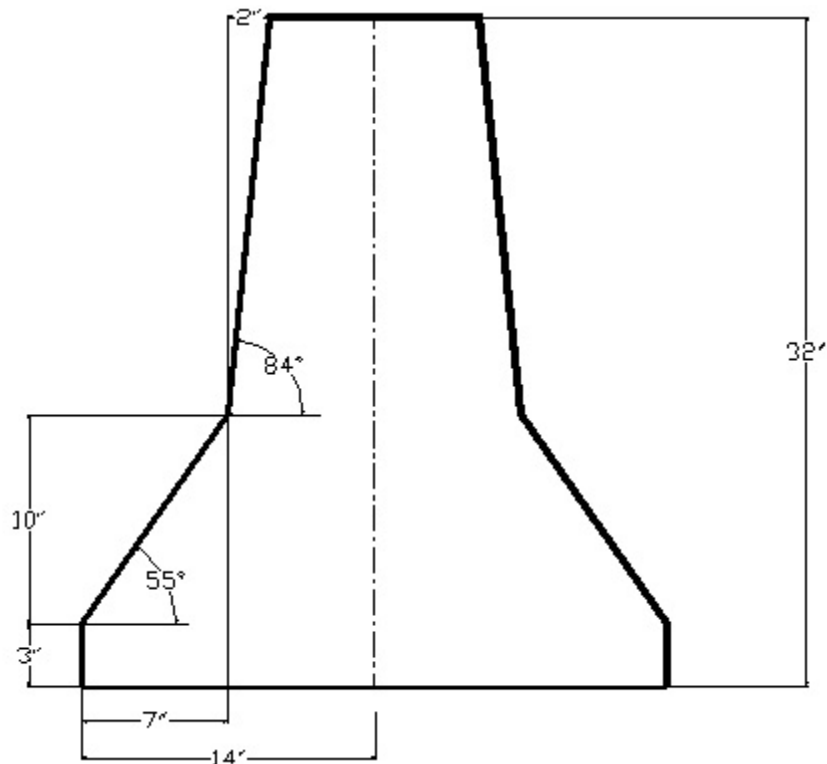
Figure 2. Cross section of a *Jersey Barrier*.

3.1 Consideration of Alternatives

Supplemental limits are being proposed because DOE surface activity guidelines[1] are not adequate to address lead or steel reuse. The development of specific authorized or supplemental limits are required by DOE for release of contaminated materials under this circumstance. The clearance standards in ANSI N13.12 are proposed here for adoption, with some exceptions because of detectibility, because they contain both surface and volumetric standards and because they are risk based. The following alternative approaches were considered and rejected.

> *Alternative I—Higher Limits*: Limits that allow higher concentrations of residual radioactive material in the lead and steel than would be allowed by ANSI N13.12[2] could be established by DOE, since the proposed supplemental limit is for directed recycle. DOE considered this possibility and concluded that increasing the limits would not produce a commensurate benefit, except in the case of specific radionuclides that cannot be easily detected at the ANSI N13.12 limit. Raising the limits for all radioactive contaminants does

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[1]DOE 5400.5 permits the use of the DOE surface activity guidelines as authorized limits for the unrestricted release of property. Although the recent DOE policy to suspend unrestricted recycling of metal prohibits releases into commerce of metal from radiological areas, the surface guidelines may still be used for restricted release.

[2] N13.12 presumes unrestricted use of the released material and its limits provide reasonable assurance that dose releases will be less than 1 mrem/y. Therefore, it is reasonable to conclude that less restrictive limits may be possible if analysis was performed specifically for controlled reuse scenarios.

not significantly affect the potential public radiological hazard, but it also is not likely to increase significantly the quantity of lead or steel available for reuse. Additionally, the use of alternative criteria that are different from ANSI N13.12 criteria requires additional resource commitments to conduct the assessments. Measurement and associated survey requirements can only be met with higher limits for some radionuclides, however, without the need for resorting to exotic and costly analytical techniques. Based on a qualitative review of this option, it was determined that increasing the release limits for directed reuse above those of ANSI N13.12 provides a commensurate benefit for health, the environment or for program implementation only in the case of specific radionuclides that cannot otherwise be reliably detected in any cost-effective way.

Alternative II—Lower Limits: DOE considered criteria that would be more stringent than the ANSI N13.12 standard. As noted, ANSI N13.12 clearance screening levels are for unrestricted clearance and provide reasonable confidence that the incremental dose to an individual member of the public will be very small (*i.e.* less than 1 mrem/y). As such, there is no significant public health or environmental benefit to be gained by adopting limits below the ANSI N13.12 screening levels. From a program implementation perspective, if the limits were lowered substantially there could be a significant reduction in the amount of lead or steel available for reuse, while measurement difficulties could substantially increase costs and adversely impact resources of the program.

3.2 Review of ANSI/HPS Standard

The ANSI/HPS N13.12 standard is *"intended to provide guidance for protecting the public and the environment from radiation exposure by recommending a primary radiation dose criterion and derived screening levels for the clearance of items that could contain radioactive material"*. The intent is purely for application to items or materials that may contain residual radioactive materials *above* those naturally found in such materials and does not apply to naturally-occurring background radionuclides— other than those that have been concentrated by human technology.

The primary bounding condition used within the standard is a dose criterion of 1 mrem/y (0.01 mSv/y) to the average member of a critical group. Scenarios for direct-reuse, disposal and public recycle are considered. The analysis incorporates the as-low-as-reasonably-achievable (ALARA) philosophy with the intent of balancing the primary dose criterion with detection issues as well as background exposure to natural sources. The result is a table of recommended free-release screening levels for a broad range of common radionuclides. Levels are given for materials contaminated either volumetrically or on their surfaces—with surface criteria given as a constant ratio to those given for volumetric contamination. When more than one radioisotope is present, a *unity rule* applies.

Important issues arise when considering ANSI/HPS N13.12 as a technical basis for recommending limits for the directed reuse of Pb in shielding containers. Previous studies referenced within N13.12 primarily consider the unconditional release of steel and have usually found that maximally exposed individuals are those employed during initial processing tasks—such as steel workers at processing facilities. The proposed shielding containers will be processed and built by a contractor regulated by the Nuclear Regulatory Commission (NRC), the DOE or an Agreement State and will require radiological controls during initial processing and fabrication. Following manufacture, shield

products are intended for use at nuclear facilities, whereas ANSI/HPS N13.12 criteria were established assuming unconditional release and uncontrolled use.

Another distinct issue is that Pb is a chemical toxin and has exposure risks separate from those that may be added by the presence of residual radioactive materials. This fact must be considered parallel to evaluations of incremental hazard due to the presence of radioactive materials. Finally, Pb is used in a more narrow range of public products than steel or other commodity metals thereby limiting the number of potential exposure scenarios if Pb products were unintentionally released for public recycle or reuse.

Implementation guidance is also provided within ANSI/HPS N13.12 and discusses topics such as process knowledge, instrumentation selection and measurement considerations. Process knowledge generally refers to all historical information that can be documented about a material and is very useful when considering disposition alternatives prior to reuse or release. Unfortunately, historical information usually lacks the detail required for confirming radiological criteria, and pre-release measurements are typically required. Detection sensitivity for surface and volumetric measurements was an important consideration when the recommended derived screening levels were selected, and discussions for each are provided.

As a final note related to the selection of volumetric limits, the standard states that "*items known to be contaminated at activity levels that are in excess of the clearance screening levels should not be: a) intentionally blended with lower specific activity material, or b) intentionally coated, plated or covered to reduce apparent surface contamination*". This statement was included to emphasize that the mixing of contaminated and "clean" materials is not justified by monetary interest. Although doing so may be perfectly safe, it is considered to be a poor use of natural resources and is therefore not viewed to be acceptable.

3.3 Radiation Exposure Scenarios

The screening values given in HPS/ANSI N13.12 were selected based on public exposure scenarios and were primarily concerned with contaminated steel. Discussions for plausible exposure scenarios that could be associated with internally recycled Pb products, scripts for internal worker usage, a review of unintentional release to the public, and a review of some potential consequences (exposures) that might result should restrictions fail have been provided by Coleman and Bogard (2001).

The processing and reuse of radiologically contaminated steel through commercial processing facilities is considered quite extensively within references from which ANSI/HPS N13.12 recommended screening levels were selected. A variety of public dose scenarios were considered within these documents but none focused specifically on the use of solid steel road barriers. It is not expected that these barriers will ever be used as-is in the public sector so it is accepted that the dose models and final-use scenarios considered within the standard are valid for an uncontrolled release.

It was not clear, however, what the potential for occupational exposure may be for a steel barrier used on DOE property. This application is somewhat special and poses the potential for exposure to workers under conditions that may not be obvious to them. It was therefore decided to evaluate the possible impact on workers within the Department or their contractors so that special labeling needs, if any, could be considered.

Occupational Exposure—External

External exposure for occupational use was modeled using the Microshield™ code for a geometry closely mimicking that of a Jersey barrier. 7 displays the overall dimensions of a typical barrier and shows an overlay of the shape used for input to the model. The closest dose point was placed midway along the length of a single barrier at a height of 3.3 ft (1 m) and at a lateral offset from the centerline of 2.5 ft (0.76 m) and is labeled *DP1* in **Figure 3**. The dose point was then varied out laterally to a maximum distance of about 10 meters to demonstrate the manner with which exposure rates would vary with distance.

External dose rates were calculated for ^{60}Co, ^{134}Cs, ^{137}Cs and ^{152}Eu since these represent common isotopes having high gamma exposure coefficients. A summary of the exposure rate for each of these radionuclides at 0.8 meters from the side of a barrier (location DP1 in **Figure 3**) is summarized in **Table 1**. The rate at which exposure rates will decrease with lateral displacement is shown graphically in **Figure 4**. For the radionuclides modeled, the highest dose equivalent rate is produced by ^{60}Co with a maximum value of 0.02 mrem/h at a radial distance of 0.8 m from the center of a barrier. The value drops to about 0.005 mrem/h at 3 meters and to less than 0.003 mrem/h at a distance of 5 meters from the side of a barrier.

There are many exposure scenarios that can be imagined for a road barrier in use. These devices are used as barricades to parking areas, office buildings, entry portals and roadway medians just to name a few. Considering that these will be directed for reuse within the DOE complex it is imagined that the highest external dose scenario will occur at portal entryways and that the greatest individual exposures will be received by security personnel.

Table 1. Dose equivalent rates for selected radionuclides at 0.8 m (2.5 ft) offset from the center of a barrier (see point DP1 in **Figure 3**).

Isotope	Concentration (pCi/g)	Dose Equivalent Rate at 0.8 m (2.5 ft) (mrem/h)
^{60}Co	30	0.02
^{134}Cs	30	0.01
^{137}Cs	30	0.004
^{152}Eu	30	0.009

Assume that a portal guard is stationed within a distance of about 3 meters (10 feet) of a row of steel barriers containing ^{60}Co at a concentration of 30 pCi/g and that the person is positioned at this distance for 25% of their work year. This would mean that the guard would be exposed to external radiation originating from the barrier at a rate of approximately 5 μrem/h for a total duration of around 500 hours each year. Accepting this as a plausible scenario it is estimated that an upper-bound dose equivalent for such a person would be on the order of about 3 mrem in a year—or less than 0.1% of the maximum occupational exposure limit at DOE sites.
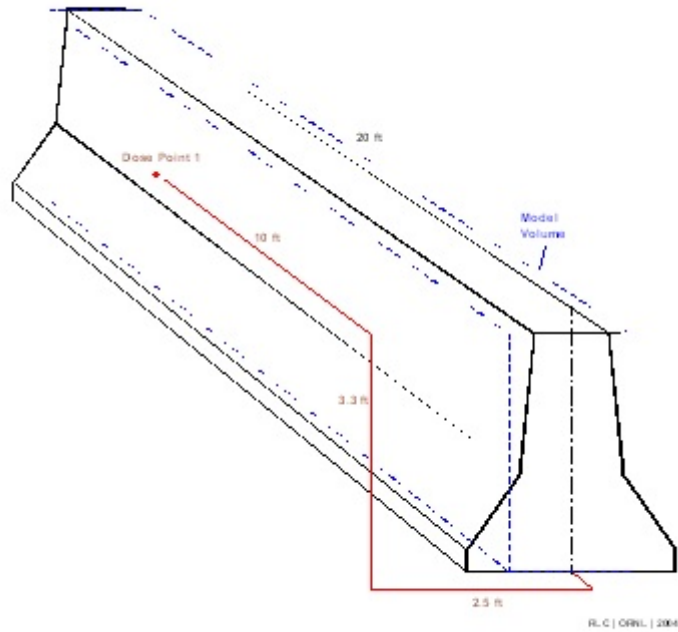
Figure 4. Overall dimensions and closest dose point, DP1, used to model external gamma dose rates from volumetric contamination in the Jersey Barrier.
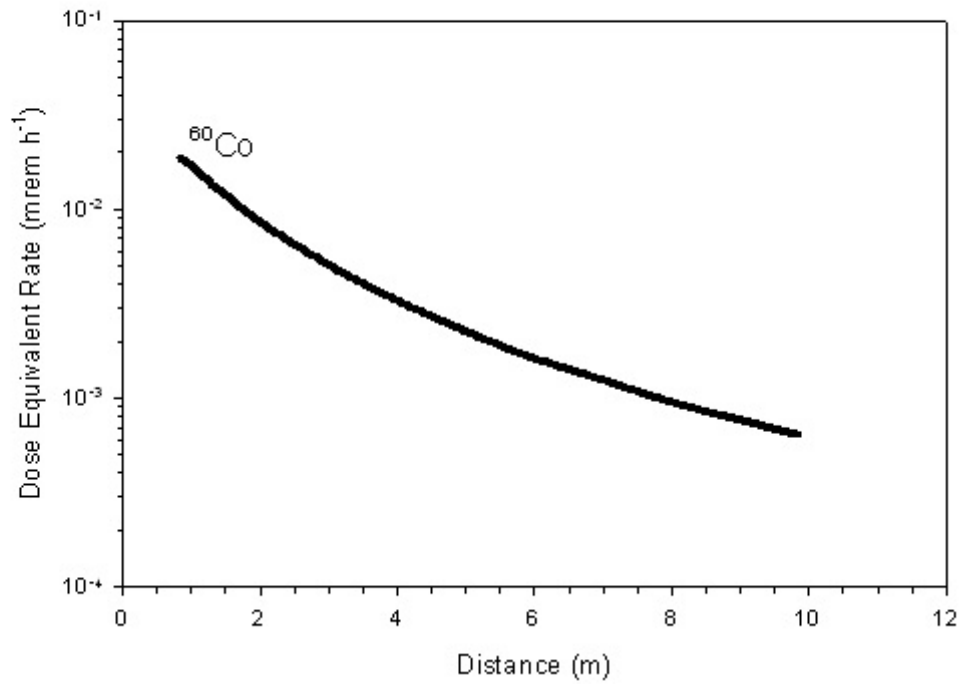
Figure 3. Dose equivalent rate versus radial distance from a Jersey Barrier with volumetric contamination of 30 pCi/g ^{60}Co (see **Figure 3**).

Occupational Exposure—Internal

A substantial amount of work has previously been performed for modeling internal exposures related to the recycle of contaminated steel. These studies have evaluated worker exposures during the handling, reprocessing and final use in both commercial and consumer markets. The ANSI N13.12 report drew heavily on these reports and selected its screening levels appropriately. Once specific area that did not appear to be considered, however, was the welding of steel assemblies where the parts may be contaminated with radioactive materials. Since it seems likely that road barriers made of solid steel may indeed be joined into longer sections it was decided that occupational welding exposures should be evaluated.

Analyses for internal exposure focused on ^{90}Sr, ^{210}Pb, ^{239}Pu, ^{241}Pu, and ^{241}Am since these represent common isotopes having relatively high internal dose factors. A critical component for modeling inhalation into the lungs is the form of the source material itself. Very large particles tend to be stopped in the upper respiratory system rather than passing into the lower passages whereas very small particles—*i.e.* those with an aerodynamic mean activity diameter (AMAD) less than 10 μm—will tend to be pass into deeper regions where they may impact tissue and remain (ICRP 66, 1994).

According to the **Effects of Welding on Health** (AWS 1979) the availability of base metal welding fumes in the vicinity of a welder would be expected to vary due to a number of parameters. The most notable of these are the method and materials employed—*e.g.*, the type, pH and size of filler material—and the dilution characteristics of the work environs. Particulate iron concentrations in the breathing zone of welders appear to range from a weight percent of about 20% to over 60% with total fume generation rates ranging from 0.4 up to 1.6 g/min. Most of the volatilized metal will be present as a fume and will have sizes of less than 10 μm AMAD. A more complete summary of the characteristics associated with welding fumes is provided in **Appendix B**.

Referencing **Appendix B** it is found that a typical welding event will produce a breathing zone fume concentration in the neighborhood of about 20 mg/m^3 (2×10^{-5} g/L). Considering the relatively small sizes of the particles within the fume, it can be conservatively assumed that all material inhaled will be deposited within the respiratory tract of a worker when performing this task. According to ICRP 23 (1975), *reference man* has a typical breathing rate while performing light work of about 1200 liters per hour. Coupling this value with dose coefficient parameters for insoluble 1μm AMAD particles found in ICRP 68 (1994) yields the effective dose coefficients per unit air concentration shown in **Table 2**. These values are approximately an order of magnitude lower than derived air concentration guides published in ICRP 30 (1979) and come as a result of using the more complete lung model found in ICRP 68. To simplify dose calculations it is assumed that metals taken into a persons body are dissolved and that each radionuclide travels independent of the host material.

Assuming that a worker will spend no more than 100 hours during a work year performing welding on such items allows the direct calculation of committed effective dose equivalent for each isotope. **Table 3** shows the effective dose equivalent for a 100 hour exposure to an air mixture containing 20 mg/m^3 of base metal carrying an isotope burden equal to the recommended screening level. The maximum dose expected will be about 1×10^{-5} Sv (1×10^{-3} rem).

Table 2. Effective dose coefficients for inhalation and ingestion. The most insoluble class for each nuclide was selected. (ICRP 68)

Isotope	Inhalation (1 μm)	Ingestion
	Effective Dose Coefficient (Sv/Bq)	
^{90}Sr	1.5×10^{-7} S	2.7×10^{-9} S
^{210}Pb	8.9×10^{-7} F	6.8×10^{-7} F
^{239}Pu	1.5×10^{-5} S	9×10^{-9} S
^{241}Pu	1.6×10^{-7} S	1.1×10^{-10} S
^{241}Am	4.0×10^{-5} M	2.0×10^{-7} M

Clearance classifications: F = Fast, M = moderate and S = slow.

A similar analysis can be performed for ingestion, although the likelihood of exposure *via* this pathway will be very small for steel road barriers. Nonetheless, a simple analysis can provide insight into the magnitude of dose that may be expected from such an event. Assume that a person were to directly ingest (not inhale) 100 mg of contaminated metal during a year and also that the base metal is dissolved so that each nuclide travels independent of its host. Such an intake could come as a result of various actions but would most likely occur *via* bare handling of the material with subsequent transfer to food. It should be stressed that this route of exposure has a very low chance of occurring since most people wear gloves when handling these types of products and that people will most likely wash their hands before eating. The committed effective dose for each nuclide can be readily calculated for a 1-mg ingestion of metal when contaminated at the ANSI recommended screening levels by referring to **Table 2**. The results of these calculations, displayed in **Table 4**, show that the magnitude of exposure will be less than 0.01 μSv (1 μrem) for all cases considered.

Table 3. Effective dose equivalent (EDE) for a 100 hour welding exposure of contaminated base metal at the ANSI recommended screening concentration shown

Isotope	ANSI Screening Level (pCi/g)	Parent Concentration (pCi/g)	EDE (Sv)	EDE (rem)
^{90}Sr	30	15	2×10^{-7}	2×10^{-5}
^{210}Pb	3	1	8×10^{-8}	8×10^{-6}
^{239}Pu	3	3	4×10^{-6}	4×10^{-4}
^{241}Pu	300	300	5×10^{-6}	5×10^{-4}
^{241}Am	3	3	1×10^{-5}	1×10^{-3}

Table 4. Effective dose equivalent (EDE) for ingestion of 100 mg of contaminated base metal at the ANSI recommended screening concentration shown.

Isotope	ANSI Screening Level (pCi/g)	Parent Concentration (pCi/g)	EDE (Sv)	EDE (rem)
^{90}Sr	30	15	2×10^{-10}	2×10^{-8}
^{210}Pb	3	1	3×10^{-9}	3×10^{-7}
^{239}Pu	3	3	1×10^{-10}	1×10^{-8}
^{241}Pu	300	300	1×10^{-10}	1×10^{-8}
^{241}Am	3	3	2×10^{-9}	2×10^{-7}

Internal dose calculations reveal an important observation—that the classification of ^{210}Pb within the same screening group as ^{239}Pu and ^{241}Am is overly conservative when viewed from the inhalation pathway. The low predicted dose consequence for inhalation, coupled with the very small dose consequence expected *via* ingestion, takes on special significance when viewed in light of the detection difficulties for ^{210}Pb and its progeny and together justify the use of higher screening value for these radionuclides.

3.4 Auxiliary Concerns

Measurement Sensitivity

As discussed within HPS/ANSI N13.12, measurement sensitivity is a key consideration when selecting release criteria. Recommended surface contamination screening levels within the guidance are detectable using commercially available detection systems. Detection levels of radionuclides in water matrix were provided, but an evaluation of *in-situ* measurements of volumetrically contaminated metals was not considered.

Three broad radionuclide categories can be considered when evaluating techniques for volumetric analysis. These categories are defined by the mode of radioactive decay, *i.e.* whether the nucleus decays primarily by emission of gamma photons, beta particles, or alpha particles. Gamma-emitting radionuclides are typically the easiest to quantify—even when the host medium is Pb or steel. Other modes of decay are usually also accompanied by the emission of energetic photons that can used for detection (the usefulness of which is related to both photon energy and abundance), with the exception of a few radionuclides like ^{90}Sr/^{90}Y that emit only beta particles.

Numerous analytical methods exist for determining the concentration of radionuclides in host matrices. Direct spectrometry is generally the preferred method for measuring gamma-emitting

radionuclides in bulk materials since it allows the measurement of all material present. The dissolution of small aliquots with subsequent chemical separation and beta or alpha counting can provide highly accurate results, but the degree to which they represent the bulk radionuclide concentration depends on the degree to which contaminants are homogeneously distributed within the host material. This presumption is not necessarily valid for metals that have been cast from high-temperature melts. To complicate the matter further, radionuclides of the same element as the host—such as ^{210}Pb in a lead matrix—cannot be separated chemically to any significant degree. Although mass spectrometry may be capable of resolving these components the accuracy of the method is very reliant upon homogeneity since very small samples are used. Additionally, the separation of a few atoms of one isotope from billions of another isn't easy. Since it is unlikely that metal samples will have contaminants distributed in a homogenous form it makes sense to consider high resolution gamma spectrometry as the first analytical option when gamma-emitting radionuclides are present.

Models were constructed for bulk lead and steel samples using ISOCS™ to determine reasonable detection efficiencies for the more common gamma-emitting radionuclides. Although real standards
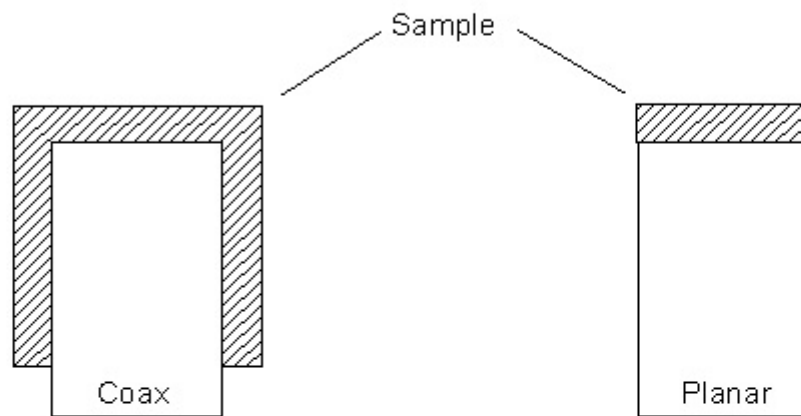
Figure 5. Measurement geometries for coaxial and low-energy planar high-purity germanium (HPGe) detectors.

planar detector. A counting time of 15 hours is assumed, and sample sizes used in the models were 80 grams of Fe or 50 grams of Pb for the coaxial geometry, and 90 grams of Fe or 80 grams of Pb for the planar geometry. The MDAs were calculated for paired-blank measurements with a 5% probability of Type I and Type II errors and are based on one or more progeny detection limits where applicable. Secular equilibrium of progeny has been assumed when calculating these levels using a daughter radionuclide. These and related 'targeted concentration levels' are compared in the tables with the HPS/ANSI N13.12 screening levels, which reflect the "total activity" of the isotope with all of its progeny.

Targeted concentration levels (TCL) presented in the tables represent concentrations that, if present, should be measurable with a moderate level of uncertainty. The TCL is taken in the tables to be three times the MDA, since measurements of radionuclide concentrations at this level will typically have associated relative uncertainties of less than 20% (Appendix A).

Detection and quantitative measurement of all the selected radionuclides is possible under the conditions given, with the exception of Pb-210, a radionuclide that decays by beta particle emission with a low abundance of low-energy X-ray emissions from its daughter Bi-210. Quantitative detection of Pb-210 is possible in steel using a 70-mm planar HPGe detector, but not using the $50\%_{[3\times3 \text{ NaI}]}$ coaxial HPGe detector, and not in Pb with either detector.[3]

Department of Transportation Considerations

The U. S. Department of Transportation (DOT) regulates the commercial transport of materials and promulgates requirements for the packaging, labeling, placarding and movement of radioactive materials on public road systems. The DOT establishes *exempt material activity concentrations and exempt consignment activity limits for radionuclides* in §173.436 of 49 CFR. These values are reproduced for all radionuclides in Appendix C. Comparisons to HPS/ANSI N13.12 recommended screening levels (RSLs) for selected radionuclides are shown in **Table 7**. Examination of the table shows that, for steel or lead contaminated at the RSL for the most restrictive isotopes, masses exceeding 9 kg are not exempt from DOT regulations for transportation as radioactive material.

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[3]Quantitative detection may be possible with much longer counting times or different analytical techniques.

Table 5. Estimated minimum detection limits and target concentration levels for the gamma spectrometry analysis of lead (Pb)

| Isotope | 50% Coaxial HPGe[a] | | 70-mm Planar HPGe[a] | | ANSI N13.12 | |
	MDA[b] (pCi/g)	TCL[c] (pCi/g)	MDA[b] (pCi/g)	TCL[c] (pCi/g)	Recommended Screening Level (pCi/g)[d]	Detectable at the ANSI level?
I-131	0.02	0.06	0.02	0.06	300	Yes
Cs-137	0.02	0.06	0.03	0.09	30	Yes
Pb-210	10.0	30	4	12	3	**No**
Th-228	0.05	0.15	0.07	0.21	3	Yes
Ra-226	0.05	0.15	0.06	0.18	3	Yes
U-235	0.04	0.12	0.06	0.18	30	Yes
Np-237	0.2	0.6	0.6	1.8	3	Yes
U-238[e]	0.5	1.5	1.4	4.2	30	Yes
Am-241	0.4	1.2	0.5	1.5	3	Yes

[a]These estimates were calculated using models of a Marinelli-like arrangement on a 50% relative efficiency coaxial HPGe detector and a petri dish arrangement on a 70-mm planar HPGe detector inside heavy shielding. Sample sizes assumed in the model were 80 grams of Pb for the planar geometry and 50 grams for the coaxial geometry, and the counting times for both the sample and the paired blank is 15 hours.

[b]The minimum detectable activity (MDA) was calculated for a paired blank measurement with a 5% probability of Type I and Type II errors (Currie, 1984). MDA values are based on one or more progeny detection limits where applicable. Secular equilibrium of progeny has been assumed when calculating these levels using a daughter radionuclide.

[c]Targeted concentration levels (TCL) represent concentrations that, if present, should be measurable with a moderate level of uncertainty. It has been assumed that measurements of concentrations equal to three times the MDA will typically have associated relative error rates of less than 20%.

[d]The screening levels reflect the "total activity" of the isotope with all of its progeny.

[e]The assumption has been made that U-238 is present in equilibrium with all of its progeny. If non-depleted, non-enriched separated uranium were assumed without the progeny following U-234, then the recommended screening level for each radionuclide in the series would be approximately 8 pCi/g. The MDA for U-238 is based on the 92.5-keV multiplet from Th-234.

Table 6. Estimated minimum detection limits and target concentration levels for the gamma spectrometry analysis of iron (Fe)

| Isotope | 50% Coaxial HPGe[a] | | 70-mm Planar HPGe[a] | | ANSI N13.12 | |
	MDA[b] (pCi/g)	TCL[c] (pCi/g)	MDA[b] (pCi/g)	TCL[c] (pCi/g)	Recommended Screening Level (pCi/g)[d]	Detectable at the ANSI level?
I-131	0.02	0.06	0.01	0.03	300	Yes
Cs-137	0.02	0.06	0.02	0.06	30	Yes
Pb-210	6	18	1	3	3	Yes
Th-228	0.05	0.15	0.03	0.09	3	Yes
Ra-226	0.05	0.15	0.04	0.12	3	Yes
U-235	0.03	0.09	0.02	0.06	30	Yes
Np-237	0.1	0.3	0.06	0.18	3	Yes
U-238[e]	0.3	0.9	0.2	0.6	30	Yes
Am-241	0.2	0.6	0.06	0.18	3	Yes

[a]These estimates were calculated using models of an arrangement similar to that of a Marinelli beaker on a 50% relative efficiency coaxial HPGe detector and a petri dish arrangement on a 70-mm planar HPGe detector. Both were assumed to be well shielded. Sample sizes used in the models were of 90 grams of Fe for the planar geometry and 80 grams for the coaxial geometry, and the counting times for both the sample and the paired blank is 15 hours.

[b]The minimum detectable activity (MDA) was calculated for a paired blank measurement with a 5% probability of Type I and Type II errors (Currie, 1984). MDA values are based on one or more progeny detection limits where applicable. Secular equilibrium of progeny has been assumed when calculating these levels using a daughter radionuclide.

[c]Targeted concentration levels (TCL) represent concentrations that, if present, should be measurable with a moderate level of uncertainty. It has been assumed that measurements of concentrations equal to three times the MDA will typically have associated relative error rates of less than 20%.

[d]The screening levels reflect the "total activity" of the isotope with all of its progeny.

[e]The assumption has been made that U-238 is present in equilibrium with all of its progeny. If non-depleted, non-enriched separated uranium were assumed without the progeny following U-234, then the recommended screening level for each radionuclide in the series would be approximately 8 pCi/g. The MDA for U-238 is based on the 92.5 keV multiplet from Th-234.

Table 7. Comparison of DOT Exempt Limits with HPS/ANSI Recommended Screening Levels (RSL).

Isotope	HPS/ANSI 13.12 RSL[a] (pCi/g)	DOT Exempt Limits Activity Concentration (pCi/g)	Total Activity (pCi)	Mass Limit at RSL (kg)
I-131	300	2700	2.7×10^7	90
Cs-137	30	270	2.7×10^5	9
Pb-210	3	270	2.7×10^5	90
Th-228	3	27	2.7×10^5	90
Ra-226	3	270	2.7×10^5	90
U-235	30	270	2.7×10^5	9
Np-237	3	27	2.7×10^4	9
U-238[e]	30	270	2.7×10^5	9
Am-241	3	27	2.7×10^5	90

[a]Recommended Screening Levels reflect the "total activity" of the isotope with all of its progeny.

4. RECOMMENDATIONS

Recommend supplemental release limits for directed reuse of lead and iron by the Department of Energy are summarized in **Table 8**. Radionuclides are divided into four groups with recommended supplemental release volumetric limits of 3, 30, 300 and 3000 pCi/g as

<u>Group 1</u>   Radium, Thorium and transuranics and associated decay chains,
<u>Group 2</u>   Uranium and selected high specific-dose-factor beta-gamma emitters,
<u>Group 3</u>   Moderate specific-dose-factor beta-gamma emitters and
<u>Group 4</u>   Low specific dose factor beta-gamma emitters.

The gamma-emitting radionuclides listed, with the exception of ^{210}Pb/^{210}Bi, can be assayed in both lead and steel using gamma spectrometry methods at concentrations equal to the ANSI N13.12 recommended screening levels. Dosimetric considerations for ^{210}Pb/^{210}Bi support their reclassification to a grouping with screening levels for directed reuse that are higher than the corresponding HPS/ANSI N13.12 recommended screening levels for unrestricted release. A screening level of 30 pCi/g for these radionuclides permits the use of typical gamma spectrometry methods for the analysis of bulk aliquots for both matrices. If a plausible exposure were to occur at these higher concentrations (10 times the ANSI recommended values) the resulting dose would be less than 0.01 Sv (1 mrem)—or less than 1% of the recommended dose limit for members of the public.

The recommended limits provide a realistic expectation that the radionuclides in each group can be quantitatively measured while, at the same time, providing assurance that doses to workers, if any, will be well below those allowable for the general public. It appears very unlikely that doses to workers involved with the handling and use of shielding containers and road-barriers constructed from such materials would ever exceed 1 mrem in a year.

Table 8. Recommended Supplemental Release Limits for the Directed (Controlled) Reuse of Lead in Shielding Products and Steel in Road Barriers by the Department of Energy[a]

Radionuclide Group	Recommended Volume Limit [b] (pCi/g)	Estimated Surface Equivalent [b] (dpm/100 cm^2)
Group 1 Radium, Thorium and Transuranics and *associated decay chains*[c], ^{226}Ra, ^{228}Ra, ^{228}Th, ^{230}Th, ^{232}Th, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{241}Am, ^{244}Cm	3	5×10^3
Group 2 Uranium and Selected High *Specific Dose Factor*[d] Beta-Gamma Emitters: ^{24}Na, ^{54}Mn, ^{58}Co, ^{60}Co, ^{65}Zn, ^{90}Sr, ^{94}Nb, ^{106}Ru, ^{110m}Ag, ^{124}Sb, ^{134}Cs, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{192}Ir, ^{210}Pb, ^{210}Po, ^{234}U, ^{235}U, ^{238}U, Natural Uranium	30	5×10^4
Group 3 Moderate *Specific Dose Factor*[d] Beta-gamma Emitters: ^{24}Na, ^{36}Cl, ^{59}Fe, ^{109}Cd, ^{129}I, ^{131}I, ^{144}Ce, ^{198}Au, ^{241}Pu	300	5×10^5
Group 4 Low *Specific Dose Factor*[d] Beta-gamma Emitters: ^{3}H, ^{14}C, ^{32}P, ^{35}S, ^{45}Ca, ^{51}Cr, ^{55}Fe, ^{63}Ni, ^{89}Sr, ^{99}Tc, ^{111}In, ^{125}I, ^{147}Pm	3000	3×10^6

[a] Adapted from Table 1 of ANSI/HPS N13.12 with minor rewording. The limit for ^{210}Pb has been increased to 30 pCi/g and moved to a new *Group 1a* based on detection issues associated with lead and steel matrices.

[b] Volume screening levels were selected as the basis for release limits. Surface limits (dpm/100 cm^2) are for reference purposes only and were estimated by calculating how much contamination could be present on the surface of ½-inch-thick sheets of metal prior to melting by assuming that all input material will remain in the final product. Actual allowable surface contamination levels will vary depending on the form of the metal being processed.

[c] For decay chains, the limits represent total activity present—i.e., the activity of the parent plus the activity of all progeny.

[d] *Specific Dose Factor*— Used here to mean committed dose equivalent per unit intake

5. REFERENCES

AWS, 1973. **The Welding Environment**, *A Research Report on Fumes and Gases Generated During Welding Operations,* edited by the American Welding Society Technical Department, Jay Bland, Technical Director, published by the American Welding Society, Miami, Florida.

AWS, 1979. **Effects of Welding on Health**, prepared for the Safety and Health Committee, American Welding Society, Miami, Florida.

EPA, 1988. Eckerman K. F., Wolbarst A. B., Richardson A. C. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion and Ingestion* Federal Guidance Report No. 11, EPA-520/1-88-020.

HPS, 1999. *Surface and Volume Radioactivity Standards for Clearance*, **ANSI/HPS N13.12-1999**.

Coleman, 2001. R. L. Coleman and J. S. Bogard, *Supplemental Release Limits for the Directed Reuse of Lead in Shielding Products by the Department of Energy*, Oak Ridge National Laboratory, **ORNL/TM-2001/136**.

Currie, 1984. L. A. Currie, *Lower Limit of Detection: Definition and Elaboration of a Proposed Position for Radiological Effluent and Environmental Measurements*, U. S. Nuclear Regulatory Commission, **NUREG/CR-4007**.

ICRP 23, 1975. *Report of the Task Group on Reference Man*, International Commission on Radiological Protection.

ICRP 66, 1994. International Commission on Radiological Protection, *Human Respiratory Tract Model for Radiological Protection*, Volume 24 Nos. 1-3.

ICRP 68, 1994. International Commission on Radiological Protection, *Dose Coefficients for Intakes of Radionuclides by Workers*, Volume 24 No. 4.

Appendix A: Relative Errors in Measurement Results

Relative error E is defined as the ratio of the standard deviation of the net result σ_N to the net result N itself,

$$E = \frac{\sigma_N}{N} \quad . \tag{A.1}$$

Since the net result is the difference between the gross result G (sample plus background) and background B,

$$N = G - B \quad , \tag{A.2}$$

then σ_N for Poisson-distributed random variables such as measurements of radioactive decay is given by

$$\sigma_N = \sqrt{\sigma_B{}^2 + \sigma_G{}^2} = \sqrt{G + B} = \sqrt{(N + B) + B} = \sqrt{N + 2B} \quad . \tag{A.3}$$

The MDA is estimated (Currie, 1984) by

$$\text{MDA} \propto 3 + 4.65\sqrt{B} \quad , \tag{A.4}$$

so, for a net result expressed as some multiple of the MDA,

$$N = m \times \text{MDA} \quad , \tag{A.5}$$

the relative error is

$$E = \frac{\sigma_N}{N} = \frac{\sqrt{N + 2B}}{N} = \frac{\sqrt{m \times \text{MDA} + 2B}}{m \times \text{MDA}} = \frac{\sqrt{m\left(3 + 4.7\sqrt{B}\right) + 2B}}{m\left(3 + 4.7\sqrt{B}\right)} \quad . \tag{A.6}$$

Plots of the relative error as a function of m are provided for different values of background in Figure A.1.
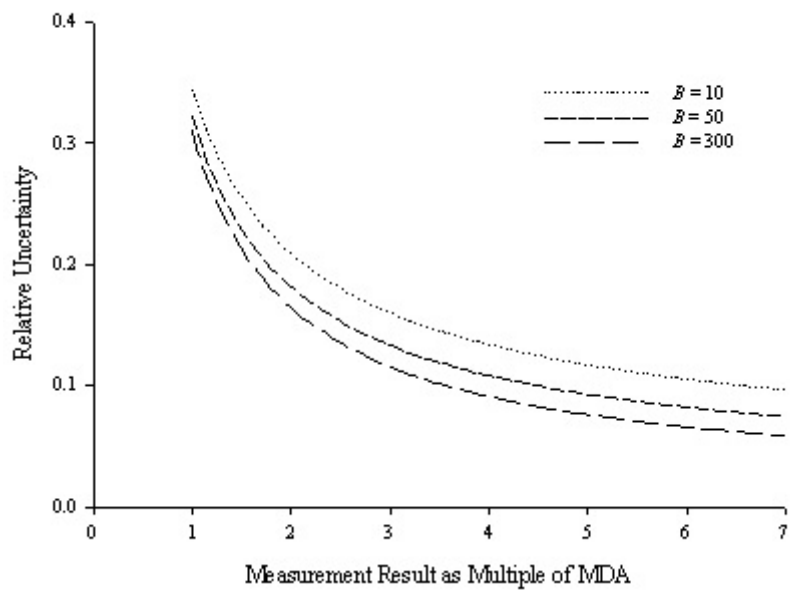
Figure A1. **Relative uncertainty in a measurement as a function of the measurement result for several values of background**

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Appendix B: Parameters of the Welding Environment

Most common welding processes generate fumes and gases as byproducts. Fumes are chemically very complex, their composition arising primarily from filler metals of consumable electrodes and any electrode coatings or fluxing materials (AWS, 1979). The fractional amount of iron compounds in welding fumes varies with the type of electrode. Data from a 1978 study show that the mass fraction of elemental iron in fumes from welding carbon and low-alloy steel, using 6 different shielded metal arc electrodes[4], ranged from 21.9% to 61.4%, with an average and standard deviation of 38.7% ± 15.2%. Earlier studies demonstrated that 'acid' and 'basic' electrodes had the lowest fractional amount of iron (about 18%) in fumes, and reutile electrodes, the greatest (about 50%). These compare with 92% iron oxide (as Fe_3O_4) (corresponding to 67% elemental iron) of fume mass with a bare wire electrode. The fume generation rate (for electrode currents in the middle to upper portion of the recommended range for each electrode) measured in the 1978 study was 0.21 - 0.83 g/min (average and sample standard deviation, 0.54 ± 0.16 g/min), or 19.5 ± 9.0 g of fume per kg of deposited metal. Table B1 presents summary data from similar studies with electrodes used in other types of welding. Fume concentration in the welder's working area was measured during submerged arc welding[5] in a shipyard production area at 12.4 mg/m³, of which 3.30 mg/m³ was iron oxide (as FeO).

Fumes are formed by vaporization, some oxidation, and rapid condensation. The base metal remains much cooler than the electrode tip and becomes a significant contributor to fume composition only when it contains a volatile coating or volatile alloying elements. The potential for worker exposure depends on the process and welding conditions. Electrode current is an important parameter on which fume production depends, as illustrated in **Figure B1**.
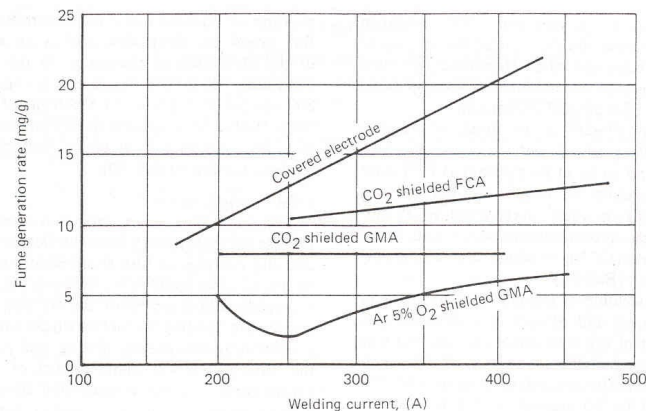
Figure B1. Rate of fume generation for various arc welding processes as a function of current

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[4] Shielded metal arc electrodes may be referred to as 'acid' (containing high percentages of cellulose), 'rutile' (containing significant quantities of TiO_2), 'basic' (with substantial amounts of inorganic carbonates and fluorspar) or 'neutral' (containing low levels of titanium, carbonate, cellulose and fluorspar).

[5] Submerged arc welding generate fewer fumes than other types of welding, because the arc is completely submerged in flux and is not exposed to the atmosphere.

Particle sizes in welding fumes are predominantly less than 1 μm. **Figure B2** shows the distribution of particle sizes determined by optical and electron microscopy in one study of fumes generated by shielded-metal arc welding using rutile electrodes conducted in a shipyard hall and in a ship's double bottom. Particles exceeding 1 μm diameter were less than 15% of the total in all cases. Summary results of some other studies are presented in **Table B2**. Studies of the gas-metal arc and flux-cored arc welding in **Table B2** also led the authors to conclude that particle sizes are log-normally distributed and that agglomeration, beginning about 2 minutes after welding activities stop, significantly reduces the number of sub-micrometer particles and generates particles with diameters exceeding 1 μm.
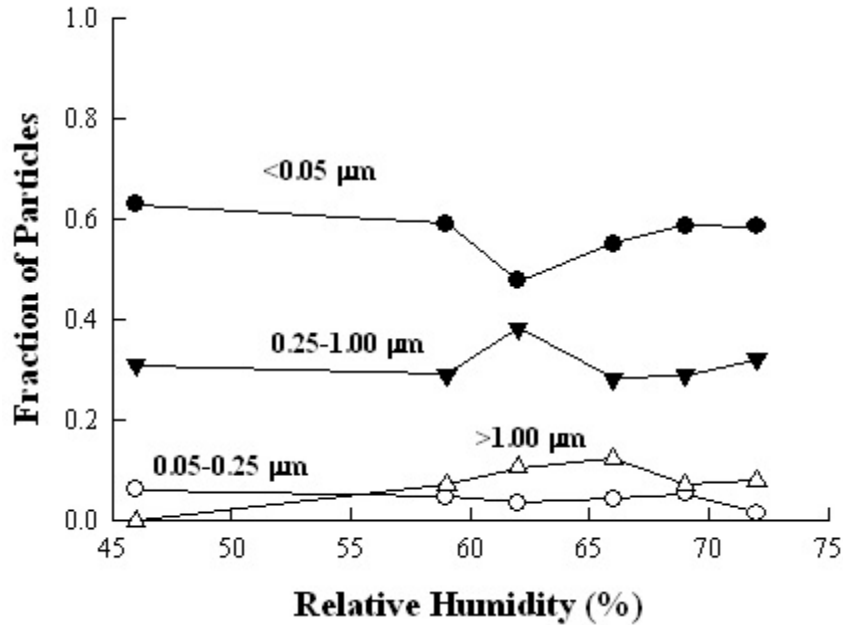
Figure B2. Particle size distributions in welding fumes produced in a shipyard hall and ship's double bottom. Ambient temperatures are from 2.1 °C - 37.2 °C

Table B1. Fume generation[a] from welding carbon and low-alloy steels

Type of Electrode	Fe Concentration (%, w/w)	Generation Rate (g/min)	Fumes-to-Metal Ratio (g/kg)
Shielded Metal Arc	38.7 ± 15.2	0.54 ± 0.16	19.47 ± 9.04
Flux Cored[b]	21.7 ± 10.5	1.59 ± 0.60	17.08 ± 4.27
Gas Metal Arc	60.7 ± 3.6	0.44 ± 0.03	4.63 ± 2.17

[a]Average and sample standard deviation of reported values.
[b]Also includes data from welding stainless steel.

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Table B2. Particle size data from some studies of fumes generated in welding stainless steel

	Particle Fraction <1 μm	Mass Median Diameter (μm)
Shielded-Metal Arc	~ 0.90	0.3 - 0.5
Gas-Metal Arc	~ 0.90	0.25

		Mean Diameter (μm)
Gas-Metal Arc (CO_2, Ar)	'Most'	0.03
Flux-Cored Arc	'Most'	0.12

A prior study (AWS, 1973) reported that fumes generated by welding in an open, unventilated[6] room with an approximate volume of 2200 ft^3 (62.4 m^3) were collected on a cellulose membrane filter at a position directly in front of the welder's mouth and nose both inside and outside the welder's helmet[7]. The welder's position was chosen to correspond with the location of maximum fume concentrations during measurements. Shielded metal-arc, gas metal-arc and flux cored arc welding techniques were used in separate measurements. Elemental iron concentrations inside the helmet ranged from 7.70 - 11.85 mg/m^3 (9.89 ± 2.09 mg/m^3)[8]. The ratio of fume concentrations inside the helmet to those outside varied from 0.066 - 0.303 mg/m^3 (0.171 ± 0.121 mg/m^3). Concentrations of fumes inside and outside of the helmet are presented for each electrode type in **Table B3**.

Particle sizes, measured using a cascade impactor, were all ≤ 1 μm.

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[6]Welding was performed in the open without forced ventilation.

[7]A standard wide shell, curved front helmet was used. The lower section of the helmet was curved under the chin to provide protection against heat, radiation, spatter and fumes.

[8]Total and elemental fume concentrations were determined using duplicate fume samples collected during welding with a single lot of electrodes representing each selected electrode classification. Concentrations outside the helmet at the location of the sampler were highly dependent on the welder's position.

Table B3. Fume concentrations (mg/m^3) in the helmet region during welding operations[a]

Electrode (AWS Classification)	Average Total Fume Concentration		Inside/ Out- side Ratio	Iron Concentration[b]	
	Inside Helmet	Outside Helmet		Inside Helmet	Outside Helmet
E70S-3 Gas Metal-Arc	31.0	217	0.143	11.85 (16.9)	83.00 (119)
E70T-1 Flux Cored Arc	25.7	84.6	0.303	7.70 (11)	25.30 (36.2)
E11018 Shielded Metal-Arc	47.2	713.0[c]	0.066	10.130 (14.5)	153.20 (218)

[a]Welding was performed in an open, unventilated room with an approximate volume of 2200 ft^3 (62.4 m^3). The welder's position was selected to maximize exposure to fumes.

[b]The primary entry is for elemental iron. Values in parentheses are the concentrations of iron as oxide that can be compared with published Threshold Limit Values.

[c]Actual fume concentration was higher because the filter overloaded during testing, decreasing flow rate.

Appendix C: Exempt Material Activity Concentrations and Exempt Consignment Activity Limits for Radionuclides (from 49 CFR §173.436)

Symbol of radionuclide	Element and atomic number	Activity concentration for exempt material (Bq/g)	Activity concentration for exempt material (Ci/g)	limit for exempt consignment (Bq)	limit for exempt consignment (Ci)
Ac-225.........................	Actinium (89)....	1.0×10^1	2.7×10^{-10}	1.0×10^4	2.7×10^{-7}
Ac-227.........................	....	1.0×10^{-1}	2.7×10^{-12}	1.0×10^3	2.7×10^{-8}
Ac-228.........................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Ag-105.........................	Silver (47)......	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Ag-108m (b).....................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Ag-110m........................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Ag-111.........................	....	1.0×10^3	2.7×10^{-8}	1.0×10^6	2.7×10^{-5}
Al-26..........................	Aluminum (13)....	1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Am-241.........................	Americium (95)...	1.0	2.7×10^{-11}	1.0×10^4	2.7×10^{-7}
Am-242m (b).....................	....	1.0	2.7×10^{-11}	1.0×10^4	2.7×10^{-7}
Am-243 (b)......................	....	1.0	2.7×10^{-11}	1.0×10^3	2.7×10^{-8}
Ar-37..........................	Argon (18).......	1.0×10^6	2.7×10^{-5}	1.0×10^8	2.7×10^{-3}
Ar-39..........................	....	1.0×10^7	2.7×10^{-4}	1.0×10^4	2.7×10^{-7}
Ar-41..........................	....	1.0×10^2	2.7×10^{-9}	1.0×10^9	2.7×10^{-2}
As-72..........................	Arsenic (33).....	1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
As-73..........................	....	1.0×10^3	2.7×10^{-8}	1.0×10^7	2.7×10^{-4}
As-74..........................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
As-76..........................	....	1.0×10^2	2.7×10^{-9}	1.0×10^5	2.7×10^{-6}
As-77..........................	....	1.0×10^3	2.7×10^{-8}	1.0×10^6	2.7×10^{-5}
At-211.........................	Astatine (85)....	1.0×10^3	2.7×10^{-8}	1.0×10^7	2.7×10^{-4}
Au-193.........................	Gold (79)........	1.0×10^2	2.7×10^{-9}	1.0×10^7	2.7×10^{-4}
Au-194.........................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Au-195.........................	....	1.0×10^2	2.7×10^{-9}	1.0×10^7	2.7×10^{-4}
Au-198.........................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Au-199.........................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Ba-131.........................	Barium (56)......	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Ba-133.........................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Ba-133m........................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}

Ba-140 (b)......................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Be-7.......................	Beryllium (4)....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Be-10......................	....	1.0x104	2.7x10-7	1.0x106	2.7x10-5
Bi-205.....................	Bismuth (83).....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Bi-206.....................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Bi-207.....................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Bi-210.....................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Bi-210m....................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Bi-212 (b)..................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Bk-247.....................	Berkelium (97)...	1.0	2.7x10-11	1.0x104	2.7x10-7
Bk-249.....................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Br-76......................	Bromine (35).....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Br-77......................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Br-82......................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
C-11.......................	Carbon (6).......	1.0x101	2.7x10-10	1.0x106	2.7x10-5
C-14.......................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Ca-41......................	Calcium (20).....	1.0x105	2.7x10-6	1.0x107	2.7x10-4
Ca-45......................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Ca-47......................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Cd-109.....................	Cadmium (48).....	1.0x104	2.7x10-7	1.0x106	2.7x10-5
Cd-113m....................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Cd-115.....................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Cd-115m....................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Ce-139.....................	Cerium (58)......	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Ce-141.....................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Ce-143.....................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Ce-144 (b).................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Cf-248.....................	Californium (98).	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Cf-249.....................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
Cf-250.....................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Cf-251.....................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
Cf-252.....................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Cf-253.....................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Cf-254.....................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
Cl-36......................	Chlorine (17)....	1.0x104	2.7x10-7	1.0x106	2.7x10-5
Cl-38......................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Cm-240.....................	Curium (96)......	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Cm-241.....................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Cm-242.....................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Cm-243.....................	....	1.0	2.7x10-11	1.0x104	2.7x10-7

Cm-244.........................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Cm-245.........................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
Cm-246.........................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
Cm-247.........................	....	1.0	2.7x10-11	1.0x104	2.7x10-7
Cm-248.........................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
Co-55..........................	Cobalt (27)......	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Co-56..........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Co-57..........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Co-58..........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Co-58m.........................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Co-60..........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Cr-51..........................	Chromium (24)....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Cs-129.........................	Cesium (55)......	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Cs-131.........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Cs-132.........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Cs-134.........................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Cs-134m........................	....	1.0x103	2.7x10-8	1.0x105	2.7x10-6
Cs-135.........................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Cs-136.........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Cs-137 (b).....................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Cu-64..........................	Copper (29)......	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Cu-67..........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Dy-159.........................	Dysprosium (66)..	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Dy-165.........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Dy-166.........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Er-169.........................	Erbium (68)......	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Er-171.........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Eu-147.........................	Europium (63)....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Eu-148.........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Eu-149.........................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Eu-150 (short lived)...........	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Eu-150 (long lived)...........	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Eu-152.........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Eu-152m........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Eu-154.........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Eu-155.........................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Eu-156.........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
F-18...........................	Fluorine (9).....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Fe-52..........................	Iron (26).......	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Fe-55..........................	....	1.0x104	2.7x10-7	1.0x106	2.7x10-5

Fe-59...........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Fe-60...........................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Ga-67...........................	Gallium (31).....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Ga-68...........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Ga-72...........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Gd-146..........................	Gadolinium (64)..	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Gd-148..........................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Gd-153..........................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Gd-159..........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Ge-68...........................	Germanium (32)...	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Ge-71...........................	....	1.0x104	2.7x10-7	1.0x108	2.7x10-3
Ge-77...........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Hf-172..........................	Hafnium (72).....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Hf-175..........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Hf-181..........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Hf-182..........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Hg-194..........................	Mercury (80).....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Hg-195m.........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Hg-197..........................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Hg-197m.........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Hg-203..........................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Ho-166..........................	Holmium (67).....	1.0x103	2.7x10-8	1.0x105	2.7x10-6
Ho-166m.........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
I-123...........................	Iodine (53)......	1.0x102	2.7x10-9	1.0x107	2.7x10-4
I-124...........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
I-125...........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
I-126...........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
I-129...........................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
I-131...........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
I-132...........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
I-133...........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
I-134...........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
I-135...........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
In-111..........................	Indium (49)......	1.0x102	2.7x10-9	1.0x106	2.7x10-5
In-113m.........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
In-114m.........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
In-115m.........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Ir-189..........................	Iridium (77).....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Ir-190..........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Ir-192..........................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7

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Radionuclide	Element (Z)				
Ir-194		1.0×10^2	2.7×10^{-9}	1.0×10^5	2.7×10^{-6}
K-40	Potassium (19)	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
K-42		1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
K-43		1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Kr-81	Krypton (36)	1.0×10^4	2.7×10^{-7}	1.0×10^7	2.7×10^{-4}
Kr-85		1.0×10^5	2.7×10^{-6}	1.0×10^4	2.7×10^{-7}
Kr-85m		1.0×10^3	2.7×10^{-8}	1.0×10^{10}	2.7×10^{-1}
Kr-87		1.0×10^2	2.7×10^{-9}	1.0×10^9	2.7×10^{-2}
La-137	Lanthanum (57)	1.0×10^3	2.7×10^{-8}	1.0×10^7	2.7×10^{-4}
La-140		1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Lu-172	Lutetium (71)	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Lu-173		1.0×10^2	2.7×10^{-9}	1.0×10^7	2.7×10^{-4}
Lu-174		1.0×10^2	2.7×10^{-9}	1.0×10^7	2.7×10^{-4}
Lu-174m		1.0×10^2	2.7×10^{-9}	1.0×10^7	2.7×10^{-4}
Lu-177		1.0×10^3	2.7×10^{-8}	1.0×10^7	2.7×10^{-4}
Mg-28	Magnesium (12)	1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Mn-52	Manganese (25)	1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Mn-53		1.0×10^4	2.7×10^{-7}	1.0×10^9	2.7×10^{-2}
Mn-54		1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Mn-56		1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Mo-93	Molybdenum (42)	1.0×10^3	2.7×10^{-8}	1.0×10^8	2.7×10^{-3}
Mo-99		1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
N-13	Nitrogen (7)	1.0×10^2	2.7×10^{-9}	1.0×10^9	2.7×10^{-2}
Na-22	Sodium (11)	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Na-24		1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Nb-93m	Niobium (41)	1.0×10^4	2.7×10^{-7}	1.0×10^7	2.7×10^{-4}
Nb-94		1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Nb-95		1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Nb-97		1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Nd-147	Neodymium (60)	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Nd-149		1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Ni-59	Nickel (28)	1.0×10^4	2.7×10^{-7}	1.0×10^8	2.7×10^{-3}
Ni-63		1.0×10^5	2.7×10^{-6}	1.0×10^8	2.7×10^{-3}
Ni-65		1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Np-235	Neptunium (93)	1.0×10^3	2.7×10^{-8}	1.0×10^7	2.7×10^{-4}
Np-236 (short-lived)		1.0×10^3	2.7×10^{-8}	1.0×10^7	2.7×10^{-4}
Np-236 (long-lived)		1.0×10^2	2.7×10^{-9}	1.0×10^5	2.7×10^{-6}
Np-237 (b)		1.0	2.7×10^{-11}	1.0×10^3	2.7×10^{-8}
Np-239		1.0×10^2	2.7×10^{-9}	1.0×10^7	2.7×10^{-4}
Os-185	Osmium (76)	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}

Nuclide	Element				
Os-191........................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Os-191m.......................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Os-193........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Os-194........................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
P-32..........................	Phosphorus (15)..	1.0x103	2.7x10-8	1.0x105	2.7x10-6
P-33..........................	....	1.0x105	2.7x10-6	1.0x108	2.7x10-3
Pa-230........................	Protactinium (91)	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Pa-231........................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
Pa-233........................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Pb-201........................	Lead (82)........	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Pb-202........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Pb-203........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Pb-205........................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Pb-210 (b)....................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Pb-212 (b)....................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Pd-103........................	Palladium (46)...	1.0x103	2.7x10-8	1.0x108	2.7x10-3
Pd-107........................	....	1.0x105	2.7x10-6	1.0x108	2.7x10-3
Pd-109........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Pm-143........................	Promethium (61)..	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Pm-144........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Pm-145........................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Pm-147........................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Pm-148m.......................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Pm-149........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Pm-151........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Po-210........................	Polonium (84)....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Pr-142........................	Praseodymium (59)	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Pr-143........................	....	1.0x104	2.7x10-7	1.0x106	2.7x10-5
Pt-188........................	Platinum (78)....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Pt-191........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Pt-193........................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Pt-193m.......................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Pt-195m.......................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Pt-197........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Pt-197m.......................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Pu-236........................	Plutonium (94)...	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Pu-237........................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Pu-238........................	....	1.0	2.7x10-11	1.0x104	2.7x10-7
Pu-239........................	....	1.0	2.7x10-11	1.0x104	2.7x10-7
Pu-240........................	....	1.0	2.7x10-11	1.0x103	2.7x10-8

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Radionuclide	Element (Z)				
Pu-241............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^5	2.7×10^{-6}
Pu-242............................	....	1.0	2.7×10^{-11}	1.0×10^4	2.7×10^{-7}
Pu-244............................	....	1.0	2.7×10^{-11}	1.0×10^4	2.7×10^{-7}
Ra-223 (b)......................	Radium (88)......	1.0×10^2	2.7×10^{-9}	1.0×10^5	2.7×10^{-6}
Ra-224 (b)......................	....	1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Ra-225............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^5	2.7×10^{-6}
Ra-226 (b)......................	....	1.0×10^1	2.7×10^{-10}	1.0×10^4	2.7×10^{-7}
Ra-228 (b)......................	....	1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Rb-81............................	Rubidium (37)....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Rb-83............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Rb-84............................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Rb-86............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^5	2.7×10^{-6}
Rb-87............................	....	1.0×10^4	2.7×10^{-7}	1.0×10^7	2.7×10^{-4}
Rb(nat)...........................	....	1.0×10^4	2.7×10^{-7}	1.0×10^7	2.7×10^{-4}
Re-184............................	Rhenium (75).....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Re-184m...........................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Re-186............................	....	1.0×10^3	2.7×10^{-8}	1.0×10^6	2.7×10^{-5}
Re-187............................	....	1.0×10^6	2.7×10^{-5}	1.0×10^9	2.7×10^{-2}
Re-188............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^5	2.7×10^{-6}
Re-189............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Re(nat)...........................	....	1.0×10^6	2.7×10^{-5}	1.0×10^9	2.7×10^{-2}
Rh-99............................	Rhodium (45).....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Rh-101............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^7	2.7×10^{-4}
Rh-102............................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Rh-102m...........................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Rh-103m...........................	....	1.0×10^4	2.7×10^{-7}	1.0×10^8	2.7×10^{-3}
Rh-105............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^7	2.7×10^{-4}
Rn-222 (b)......................	Radon (86).......	1.0×10^1	2.7×10^{-10}	1.0×10^8	2.7×10^{-3}
Ru-97............................	Ruthenium (44)...	1.0×10^2	2.7×10^{-9}	1.0×10^7	2.7×10^{-4}
Ru-103............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Ru-105............................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Ru-106 (b)......................	....	1.0×10^2	2.7×10^{-9}	1.0×10^5	2.7×10^{-6}
S-35............................	Sulphur (16).....	1.0×10^5	2.7×10^{-6}	1.0×10^8	2.7×10^{-3}
Sb-122............................	Antimony (51)....	1.0×10^2	2.7×10^{-9}	1.0×10^4	2.7×10^{-7}
Sb-124............................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Sb-125............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}
Sb-126............................	....	1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Sc-44............................	Scandium (21)....	1.0×10^1	2.7×10^{-10}	1.0×10^5	2.7×10^{-6}
Sc-46............................	....	1.0×10^1	2.7×10^{-10}	1.0×10^6	2.7×10^{-5}
Sc-47............................	....	1.0×10^2	2.7×10^{-9}	1.0×10^6	2.7×10^{-5}

Radionuclide	Element (atomic number)	Col 1	Col 2	Col 3	Col 4
Sc-48............................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Se-75............................	Selenium (34)....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Se-79............................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Si-31............................	Silicon (14).....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Si-32............................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Sm-145...........................	Samarium (62)....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Sm-147...........................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Sm-151...........................	....	1.0x104	2.7x10-7	1.0x108	2.7x10-3
Sm-153...........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Sn-113...........................	Tin (50)........	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Sn-117m..........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Sn-119m..........................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Sn-121m..........................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Sn-123...........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Sn-125...........................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Sn-126...........................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Sr-82............................	Strontium (38)...	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Sr-85............................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Sr-85m...........................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Sr-87m...........................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Sr-89............................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Sr-90 (b)........................	....	1.0x102	2.7x10-9	1.0x104	2.7x10-7
Sr-91............................	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Sr-92............................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
T(H-3)...........................	Tritium (1)......	1.0x106	2.7x10-5	1.0x109	2.7x10-2
Ta-178 (long-lived)..............	Tantalum (73)....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Ta-179...........................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Ta-182...........................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Tb-157...........................	Terbium (65).....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Tb-158...........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Tb-160...........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Tc-95m...........................	Technetium (43)..	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Tc-96............................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Tc-96m...........................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Tc-97............................	....	1.0x103	2.7x10-8	1.0x108	2.7x10-3
Tc-97m...........................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Tc-98............................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Tc-99............................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
Tc-99m...........................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Te-121...........................	Tellurium (52)...	1.0x101	2.7x10-10	1.0x106	2.7x10-5

Te-121m............................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Te-123m............................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Te-125m............................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Te-127.............................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Te-127m............................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Te-129.............................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Te-129m............................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Te-131m............................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Te-132.............................	....	1.0x102	2.7x10-9	1.0x107	2.7x10-4
Th-227.....................	Thorium (90).....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Th-228 (b).................	....	1.0	2.7x10-11	1.0x104	2.7x10-7
Th-229 (b).................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
Th-230.....................	....	1.0	2.7x10-11	1.0x104	2.7x10-7
Th-231.....................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
Th-232.....................	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
Th-234 (b).................	....	1.0x103	2.7x10-8	1.0x105	2.7x10-6
Th (nat) (b)...............	....	1.0	2.7x10-11	1.0x103	2.7x10-8
Ti-44......................	Titanium (22)....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
Tl-200.....................	Thallium (81)....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Tl-201.....................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Tl-202.....................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Tl-204.....................	....	1.0x104	2.7x10-7	1.0x104	2.7x10-7
Tm-167.....................	Thulium (69).....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
Tm-170.....................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Tm-171.....................	....	1.0x104	2.7x10-7	1.0x108	2.7x10-3
U-230 (fast lung absorption) (b),(d).	Uranium (92).....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
U-230 (medium lung absorption) (e).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U-230 (slow lung absorption) (f).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U-232 (fast lung absorption) (b),(d).	....	1.0	2.7x10-11	1.0x103	2.7x10-8
U-232 (medium lung absorption) (e).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U-232 (slow lung absorption) (f).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U-233 (fast lung absorption) (d).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U-233 (medium lung absorption) (d)	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6

U-233 (slow lung absorption) (f).	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
U-234 (fast lung absorption) (d).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U-234 (medium lung absorption) (e).	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
U-234 (slow lung absorption) (f).	....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
U-235 (all lung absorption types) (b),(d),(e),(f).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U-236 (fast lung absorption) (d).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U-236 (medium lung absorption) (e).	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
U-236 (slow lung absorption) (f).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U-238 (all lung absorption types) (b),(d),(e),(f).	....	1.0x101	2.7x10-10	1.0x104	2.7x10-7
U (nat) (b)...................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
U (enriched to 20% or less)(g)	....	1.0	2.7x10-11	1.0x103	2.7x10-8
U (dep).......................	....	1.0	2.7x10-11	1.0x103	2.7x10-8
V-48........................	Vanadium (23)....	1.0x101	2.7x10-10	1.0x105	2.7x10-6
V-49........................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
W-178.......................	Tungsten (74)....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
W-181.......................	....	1.0x103	2.7x10-8	1.0x107	2.7x10-4
W-185.......................	....	1.0x104	2.7x10-7	1.0x107	2.7x10-4
W-187.......................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5
W-188.......................	....	1.0x102	2.7x10-9	1.0x105	2.7x10-6
Xe-122......................	Xenon (54).......	1.0x102	2.7x10-9	1.0x109	2.7x10-2
Xe-123......................	....	1.0x102	2.7x10-9	1.0x109	2.7x10-2
Xe-127......................	....	1.0x103	2.7x10-8	1.0x105	2.7x10-6
Xe-131m.....................	....	1.0x104	2.7x10-7	1.0x104	2.7x10-7
Xe-133......................	....	1.0x103	2.7x10-8	1.0x104	2.7x10-7
Xe-135......................	....	1.0x103	2.7x10-8	1.0x1010	2.7x10-1
Y-87........................	Yttrium (39).....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Y-88........................	....	1.0x101	2.7x10-10	1.0x106	2.7x10-5
Y-90........................	....	1.0x103	2.7x10-8	1.0x105	2.7x10-6
Y-91........................	....	1.0x103	2.7x10-8	1.0x106	2.7x10-5
Y-91m.......................	....	1.0x102	2.7x10-9	1.0x106	2.7x10-5

Nuclide	Element (atomic number)	Col3	Col4	Col5	Col6
Y-92......................	....	1.0x10^2	2.7x10^-9	1.0x10^5	2.7x10^-6
Y-93......................	....	1.0x10^2	2.7x10^-9	1.0x10^5	2.7x10^-6
Yb-169....................	Ytterbium (70)...	1.0x10^2	2.7x10^-9	1.0x10^7	2.7x10^-4
Yb-175....................	....	1.0x10^3	2.7x10^-8	1.0x10^7	2.7x10^-4
Zn-65.....................	Zinc (30).......	1.0x10^1	2.7x10^-10	1.0x10^6	2.7x10^-5
Zn-69.....................	....	1.0x10^4	2.7x10^-7	1.0x10^6	2.7x10^-5
Zn-69m....................	....	1.0x10^2	2.7x10^-9	1.0x10^6	2.7x10^-5
Zr-88.....................	Zirconium (40)...	1.0x10^2	2.7x10^-9	1.0x10^6	2.7x10^-5
Zr-93 (b).................	....	1.0x10^3	2.7x10^-8	1.0x10^7	2.7x10^-4
Zr-95.....................	....	1.0x10^1	2.7x10^-10	1.0x10^6	2.7x10^-5
Zr-97 (b).................	....	1.0x10^1	2.7x10^-10	1.0x10^5	2.7x10^-6

\a\ [Reserved]

\b\ Parent nuclides and their progeny included in secular equilibrium are listed in the following:

Sr-90 Y-90

Zr-93 Nb-93m

Zr-97 Nb-97

Ru-106 Rh-106

Cs-137 Ba-137m

Ce-134 La-134

Ce-144 Pr-144

Ba-140 La-140

Bi-212 Tl-208 (0.36), Po-212 (0.64)

Pb-210 Bi-210, Po-210

Pb-212 Bi-212, Tl-208 (0.36), Po-212 (0.64)

Rn-220 Po-216

Rn-222 Po-218, Pb-214, Bi-214, Po-214

Ra-223 Rn-219, Po-215, Pb-211, Bi-211, Tl-207

Ra-224 Rn-220, Po-216, Pb-212, Bi-212, Tl-208(0.36), Po-212 (0.64)

Ra-226 Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210

Ra-228 Ac-228

Th-226 Ra-222, Rn-218, Po-214

Th-228 Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208 (0.36), Po-212 (0.64)

Th-229 Ra-225, Ac-225, Fr-221, At-217, Bi-213, Po-213, Pb-209

Th-nat Ra-228, Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208 (0.36), Po-212 (0.64)

Th-234 Pa-234m

U-230 Th-226, Ra-222, Rn-218, Po-214

U-232 Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208 (0.36), Po-212 (0.64)

U-235 Th-231

U-238 Th-234, Pa-234m

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U-nat Th-234, Pa-234m, U-234, Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210
U-240 Np-240m
Np-237 Pa-233
Am-242 mAm-242
Am-243 Np-239
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\c\ [Reserved]

\d\ These values apply only to compounds of uranium that take the chemical form of UF6, UO2F2 and UO2(NO3)2 in both normal and accident conditions of transport.

\e\ These values apply only to compounds of uranium that take the chemical form of UO3, UF4, UCl4 and hexavalent compounds in both normal and accident conditions of transport.

\f\ These values apply to all compounds of uranium other than those specified in notes (d) and (e) of this table.

\g\ These values apply to unirradiated uranium only.

[69 FR 3685, Jan. 26, 2004]

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