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RADIOLOGICAL CONTROL CRITERIA FOR MATERIALS CONSIDERED FOR RECYCLE AND REUSE

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DISCLAIMER

RADIOLOGICAL CONTROL CRITERIA FOR MATERIALS CONSIDERED FOR RECYCLE AND REUSE

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ABSTRACT

Pacific Northwest Laboratory (PNL) is conducting technical analyses to support the U.S. Department of Energy (DOE), Office of Environmental Guidance, Air, Water, and Radiation Division (DOE/EH-232) in developing radiological control criteria for recycling or reuse of metals or equipment containing residual radioactive contamination from DOE operations. The criteria, framed as acceptable concentrations for release of materials for recycling or reuse, are risk-based and were developed through analysis of generic radiation exposure scenarios and pathways. The analysis includes evaluation of relevant radionuclides, potential mechanisms of exposure, and non-health-related impacts of residual radioactivity on electronics and film. The analysis considers 42 key radionuclides that DOE operations are known to generate and that may be contained in recycled or reused metals or equipment. The preliminary results are compared with similar results reported by the International Atomic Energy Agency, by radionuclide grouping.

1.0 INTRODUCTION

Pacific Northwest Laboratory (PNL) is collecting data and conducting technical analyses to support efforts by the U.S. Department of Energy (DOE) to develop radiological control criteria for the recycling and reuse of scrap materials and equipment that contain residual radioactive contamination. The initial radiological control criteria are the concentrations in or on materials considered for recycling or reuse that meet the individual or industrial (electronics/film) dose criteria. The analyses include determining relevant radionuclides, potential mechanisms of exposure, and methods to determine possible non-health-related impacts from residual radioactive contamination in materials considered for recycling or reuse. The data and models described in this paper may be considered by DOE (in coordination with other U.S. Federal agencies) with other information to set radiological control criteria for recycling that are as low as reasonably achievable (ALARA) and to support environmental regulations.

To determine if recycling is the "preferred" action or approach for management of material, DOE has identified two criteria. The action must be 1) environmentally acceptable and cost effective or 2) environmentally preferred. Under this approach it is recognized that some situations exist under which the direct costs may be higher for recycling than for burial, but environmental costs avoided by recycling (e.g., the recycling option reduces environmental insults associated with certain secondary impacts and reduces the overall need for disposal space) balance the short-term costs associated with the recycling activity (i.e., the costs recovered from the recycled materials may not compensate for overall program expenses).

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The preliminary results described in this paper are based on generic exposure scenarios and pathway analyses using 42 radionuclides determined to be potentially present as residual contamination in metals or equipment from DOE operations. These radionuclides were identified from input provided across the DOE complex that considered all aspects of the defense nuclear fuel cycle and research activities including the operation of accelerators. The scenarios and information developed by the International Atomic Energy Agency (IAEA) in Safety Series No. 111-P-1.1 (1992), Application of Exemption Principles to the Recycle and Reuse of Materials from Nuclear Facilities [1], were considered as a primary reference in developing the initial radiation exposure pathway and scenario analysis. Additional analyses were conducted to determine the potential non-health-related impacts industry may experience from residual contamination in recycled metals, such as those used in industries producing and using electronics and X-ray film.

Although alternative public dose limits were considered, the initial control criteria in this report are based on 1) a dose of 10 μSv y^{-1} (1 mrem y^{-1}) to a worker in a smelter or an individual who uses consumer products made from recycled materials, 2) a dose of 1 μSv y^{-1} (0.1 mrem y^{-1}) to an individual downwind from a smelter used to process recycled metals, and 3) minimizing non-health impacts associated with potential radiation effects on electronics or film.

2.0 DOSE ASSESSMENT METHODS

To determine if radioactively contaminated materials can be released from regulatory controls, it is necessary to first determine the potential future uses for the materials and then the potential radiation doses resulting from those future uses. Generic radiation exposure scenarios were used to conceptually model likely future uses for materials released for recycle or reuse. While these scenarios may not exactly match existing or projected future conditions, they are designed to serve as the basis for conducting a dose analysis for the average member of a critical population group. These scenarios are a combination of radiation exposure pathways that contain specific exposure conditions. This section contains a summary of the basic radiation exposure pathways, scenarios, and methods used to estimate the preliminary control criteria for recycle or reuse of materials.

2.1 General Assumptions

For the preliminary calculations that follow, it is necessary to assume that 100 t of contaminated steel, aluminum, and concrete and 10 t of copper with a normalized unit of initial activity per unit mass are recycled during a year. This assumption allowed a normalized calculation that leads to the development of bulk contamination control criteria. For the development of surface contamination control criteria, individual tools or pieces of equipment for reuse are considered. A unit concentration of each radionuclide is assumed and control criteria in terms of Bq g^{-1} for volume and Bq cm^{-2} for surface contamination are derived. For the scenario calculations that follow, 42 reference radionuclides (plus two additional concrete activation products) were selected. The radionuclides considered and their physical half-lives are listed in Table 1.

TABLE 1. Radionuclides Considered in the Recycle and Reuse Analysis

Nuclide	Half-Life (y)	Nuclide	Half-Life (y)
^{3}H	12.3	^{144}Ce	0.78
^{14}C	$5.7x10^{3}$	^{147}Pm	2.62
^{36}Cl	$3x10^{5}$	^{151}Sm	87
^{41}Ca	$1.3x10^{5}$	^{152}Eu	13.6
^{54}Mn	0.86	^{154}Eu	8.8
^{55}Fe	2.7	^{226}Ra	$1.6x10^{3}$
^{57}Co	0.74	^{228}Th	1.91
^{60}Co	5.3	^{229}Th	$7.34x10^{3}$
^{63}Ni	99.9	^{230}Th	$7.7x10^{4}$
^{65}Zn	0.67	^{232}Th	$1.4x10^{10}$
^{79}Se	$6.5x10^{4}$	^{232}U	72
$^{90}Sr + Y$	28.5	^{233}U	$1.5x10^{5}$
^{93}Zr	$1.5x10^{6}$	^{234}U	$2.47x10^{5}$
^{94}Nb	$2.0x10^{4}$	^{235}U	$7.1x10^{8}$
^{99}Tc	$2.13x10^{5}$	^{238}U	$4.51x10^{9}$
^{106}Ru	1.01	^{237}Np	$2.14x10^{6}$
^{110m}Ag	0.68	^{238}Pu	87.6
^{125}Sb	2.8	^{239}Pu	$2.4x10^{4}$
^{129}I	$1.6x10^{7}$	^{240}Pu	$6.57x10^{3}$
^{134}Cs	2.06	^{241}Pu	14.4
^{137}Cs	30.1	^{241}Am	$4.34x10^{2}$

The choice of the 42 radionuclides also takes into account other considerations including

- the origin of the radionuclides; whether natural uranium (^{238}U), uranium activation products (^{239}Pu, ^{241}Pu, and ^{241}Am), fission products (^{90}Sr, ^{99}Tc, and ^{137}Cs), or activation products (^{36}Cl, ^{41}Ca, ^{54}Mn, ^{55}Fe, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{94}Nb, ^{99}Tc, and ^{152}Eu)

- the half-life of the radionuclides; whether relatively short (^{65}Zn) or very long (^{94}Nb or ^{239}Pu)

- the importance of the radionuclides in the context of bulk activation or surface contamination; that is, over the short term (^{55}Fe, ^{65}Zn, and ^{60}Co), long term (^{63}Ni, ^{137}Cs, and ^{152}Eu), or very long term (^{238}U, ^{239}Pu, ^{94}Nb, and ^{99}Tc)

- the mode of decay and internal dose conversion factors (DCF) including alpha emitters with large DCFs (^{228}Th, ^{230}Th, ^{232}Th, ^{232}U, ^{233}U, ^{234}U, ^{235}U, ^{238}U, ^{226}Ra, ^{237}Np, ^{238}Pu, ^{240}Pu, ^{241}Pu, and ^{241}Am); beta/gamma emitters with large DCFs (^{60}Co, ^{65}Zn, ^{94}Nb, ^{90}Sr, ^{110m}Ag, ^{129}I, ^{134}Cs, ^{137}Cs, ^{144}Ce, ^{147}Pm, ^{151}Sm, ^{152}Eu, and ^{154}Eu), non-photon emitters with moderate DCFs (^{90}Sr, ^{106}Ru, and ^{241}Pu), beta/gamma emitters with low DCFs (^{36}Cl, ^{54}Mn, ^{55}Fe, ^{57}Co, ^{99}Tc, and ^{125}Sb), or non-photon emitters with low DCFs (^{3}H, ^{14}C, ^{41}Ca, ^{63}Ni, and ^{79}Se)

- the behavior of the radionuclides during recycle operations; that is, whether they are volatilized and escape, are concentrated in the metal product, or partitioned in slag or ingots (products).

Early daughter products in equilibrium with parent radionuclides are assumed in all cases. For smelting, it is probable that the majority of some radionuclides, such as ^{60}Co, remain in the ingot. However, a fraction of material will remain in the slag, and another portion will likely volatilize and be released with fumes and gases. The behavior of a specific radionuclide will depend on the chemistry of the radionuclide in question and the type of smelting process considered. Because the partitioning is not known for most radionuclides during smelting, the dose calculations that follow are based on the conservative assumption that, for each radionuclide, all of the activity is retained in each of the three phases of smelting: the metal (steel, aluminum, or copper), the slag, and gases released out of the stack. The slag is assumed to equal about 10% of initial mass of the steel, or about 10 t in the steel and aluminum analyses and 1 t in the copper analysis. This triple accounting approach will overestimate the true doses; however, it will maximize the potential importance of the scenarios and should serve as an adequate basis for the initial development of radiological control criteria for recycling and reuse.

2.2 Radiation Exposure Pathways

Humans may be exposed to radiation in three main ways:

- exposure to external radiation
- inhalation of radioactive gases or small particles
- ingestion of radioactive material.

The following paragraphs describe the specific ways in which these pathways have been used as part of the assessment methods in this study.

2.2.1 External Radiation Exposure

The radioactive sources considered in this study are generally represented by a self-absorbing, homogeneous, cylindrical volume or surface contaminated source with the dose point on the central, longitudinal axis of the cylinder [1, 2]. Except for exposure conditions that represent exposure to molten metals contained in a furnace, external absorbers and shields are ignored. This procedure tends to maximize the estimated dose equivalents from exposure to external radiation. In some situations, a source can be represented better by a half cylinder than by a full cylinder. For these

situations, a full cylinder is defined such that the area of its flat surface is twice that actually needed; the effective dose equivalent is then calculated by using the full cylinder and dividing the resulting dose by two. The external dose calculations are performed using the EXTDF module of the GENII Software System [3].

2.2.2 Inhalation Exposure

Committed effective dose equivalent factors are taken from International Commission on Radiological Protection (ICRP 1977-1982) Publication No. 30, and its supplements [4]. The concentration of respirable dust in the air will vary depending upon a variety of factors including the physical condition of the material being handled, the quantity of the material present, and the building ventilation. Thus, it is difficult to predict the concentrations that may be present during any recycle step. However, so that a complete analysis may be performed, air concentrations have been assumed based on the information in IAEA Safety Series No. 111-P-1.1 [1] for those recycle steps where the potential for inhalation is most likely. In general, the air concentrations were assumed to vary between about 10^{-3} and 10^{-5} g m^{-3}.

2.2.3 Ingestion Exposure

For this study, ingestion is assumed to occur by one of three separate routes:

- ingestion of removable radioactive materials on surfaces
- ingestion of corroded material from using frying pans or water pipes
- ingestion of food products contaminated by airborne plumes released from a smelter.

Ingestion of removable radioactive contamination found on recycled metals or reused equipment can occur when workers inadvertently transfer contamination from a surface to hands, foodstuffs, cigarettes, or other items that enter the mouth. Since very little information exists on the estimated radiation doses associated with this pathway, the methods outlined by the IAEA for recycle and reuse [1] are used for this study. A quantity of 10 mg of contamination per hour of direct contact exposure is assumed for ingestion by adult workers at a smelter. Ingestion of contaminated metal corroded from frying pans during cooking or from copper water pipes are considered as separate ingestion pathways. O'Donnel et al. [5] studied the potential impact of recycle considered cast iron pans using an assumed corrosion rate of 0.127 cm y^{-1} [5]. Since the use of stainless steel and aluminum pans with a much lower corrosion rate is perhaps more consistent with current domestic practice, a lower value of 0.13 mm y^{-1} is used for this study.

2.2.4 Downwind Exposures

A potential source of public exposure from metal recycling materials that may volatilize and released through the stack during smelting. The potential radiation doses to the downwind public are estimated using the CAP88-PC [6] computer code. This software was developed by the U.S. Environmental Protection Agency to perform dose and risk assessments for demonstrating compliance with the National Emission Standards for Hazardous Air Pollutants (NESHAPS) rules in 40 CFR 61.93a [7]. The exposure pathways considered in the analysis included inhalation of airborne material, external exposure to penetrating radiation, and ingestion of contaminated foods. The default meteorological data files for Chicago contained in the CAP88-PC code are used in this

study. Meteorological data for Chicago are selected because they were felt to be representative of many midwestern U.S. industrial settings with a large population in the nearby vicinity.

3.0 RADIATION EXPOSURE SCENARIOS AND ASSUMPTIONS

For this analysis, six separate categories of contaminated (or activated) materials and future conditions were considered:

- recycle of steel
- recycle of aluminum
- recycle of copper
- recycle of concrete (as aggregate)
- reuse of a contaminated room within a facility
- reuse of tools or equipment (with surface contamination).

These six categories are further subdivided into various exposure scenarios, describing the activities of specific individuals or groups of individuals. The range of scenarios evaluated is based on previous dose estimates for recycling and reuse [1, 5, 8, 9] to adequately represent those scenarios likely to be of generic importance and relevance to all DOE nuclear facilities. The scenarios presented here yield the highest potential doses for each category of recycled material and radionuclide grouping, as determined from the IAEA [1] study. Details of the scenarios considered, the relevant assumptions, and the values assigned to the important parameters are discussed in the following sections.

3.1 Scenarios for Steel Recycle

Recycled steel may contain both activation products and surface contamination from reactor coolant or other sources. The three most limiting scenarios identified by the IAEA [1] are for 1) a slag worker at the smelter, 2) consumers who drive an automobile, and 3) consumers who work with a piece of large equipment made of recycled steel.

3.2 Scenarios for Aluminum Recycle

Although the long-lived activation of aluminum is negligible, surfaces may become contaminated through contact with reactor coolant or other sources. The scenarios described by the IAEA [1] for recycle of aluminum were evaluated and the three most limiting ones are used in this study. The limiting scenarios are 1) an operator at a furnace, 2) consumers using automobiles, and 3) consumers using frying pans.

3.3 Scenarios for Copper Recycle

The IAEA [1] study did not consider copper recycle. However, within the DOE complex, copper recycle may be quite significant; thus, it is included in this analysis. By analogy with steel and aluminum, three scenarios for recycle of copper are identified for this study. They are doses to 1) a furnace operator, 2) individuals who use copper pans, and 3) individuals who live in houses with pipes made from recycled copper.

3.3 Scenarios for Concrete Recycle

Large quantities of activated or contaminated concrete will be encountered during decommissioning of DOE facilities. Because there is an economic incentive to avoid the costs of transport and disposal of radioactive concrete as radioactive waste, recycling of concrete as feedstock for further concrete manufacture has been considered by European countries [1]. Before such reuse could be authorized, it is clear that any existing building candidate for release would have to pass an extensive radiation survey to assure compliance with existing national regulations. For the IAEA [1] study, the recycled concrete is assumed to be used to build a new structure in which individuals live or work for 6000 h y^{-1}. For calculational purposes, the initial concrete is assumed to be contaminated to an undiluted, unit concentration. Although a very large dilution could occur during the manufacture of new concrete structures, for this analysis a 1:10 dilution is assumed. The limiting scenarios used are a concrete worker and a resident in a room made from recycled concrete. The concrete activation products ^{36}Cl and ^{41}Ca are included in the analysis to account for the potential activation of concrete.

3.4 Scenario for Reuse of Contaminated Rooms

Concrete buildings may be decontaminated and reused for other purposes after decommissioning. The scenario considered for building reuse is intended to account for normal occupancy, as described in an evaluation of residual radioactive contamination conducted for the U.S. Nuclear REgulatory Commission by Kennedy and Strenge [10]. For the building occupancy scenario, individuals are assumed to work in a building after unrestricted release. Although the residence time could vary, a normal work year of 2000 h y^{-1} is assumed. Because decontamination efforts before release focus on the removal of surface sources, the air concentration was assumed to be 10^{-5} g m^{-3} and the ingestion rate was assumed to be 1.0 mg h^{-1} of exposure. These values are 10% of the values assumed for workers at a smelter.

3.5 Scenarios for Reuse of Equipment or Tools

During decommissioning, discrete pieces of contaminated equipment (including hand tools, pumps, small motors, furniture, and storage tanks) may be salvaged and released for unrestricted use if they can meet radiological control criteria. For the IAEA [1] study, it is assumed that the fixed contamination present on the surfaces of the tools or equipment is ten times higher than the removable fraction as measured by swabbing. For this study, the radiation exposure scenarios that may be most limiting are used. These involve the use of hand tools that incorporate a small motor (i.e., an electric hand drill or saw) because of the potential presence of contamination on the inner surfaces of the motor which is difficult to monitor. A high exposure duration of 600 h y^{-1} is assumed because of the relative proximity of power tools to workers under construction conditions. The exposure pathways considered by the IAEA included exposure to external radiation, ingestion of contamination transferred from the surfaces of the tool to hands and then to the mouth, and inhalation of localized airborne material from the hand tool. In addition to reuse of small items, the IAEA considered that larger items could also be candidates for reuse. These items are likely to contain surface contamination; thus, the same exposure considerations as for hand tools apply, with modifications accounting for the size of the item.

4.0 POTENTIAL EFFECTS ON ELECTRONICS

In addition to human radiation doses, another concern is the potential effects of unrestricted use of radioactively contaminated recycled metals on electronic components. The threshold range for damage to electronic components from radiation varies with the type of component. In addition, selected electronic components can be "hardened" against radiation effects when it is anticipated that they may be used in high radiation fields (such as space applications). In general, for non-hardened components, the damage thresholds for electronic components range from about 5 Gy (500 rad) to about 500 Gy (50,000 rad) [11]. Assuming a 10-y lifetime for electronic components, this translates to a dose-rate range of about 5×10^{-5} Gy h^{-1} (5×10^{-3} rad h^{-1}) to 5×10^{-3} Gy h^{-1} (0.5 rad h^{-1}) [11]. For comparison, natural background radiation is about 1×10^{-3} Gy y^{-1} (0.1 rad y^{-1}, or about 1×10^{-7} Gy h^{-1} (1×10^{-5} rad h^{-1}). Since the dose limits considered for the development of control criteria are a fraction of annual background, the development of a special control criteria for electronic components is deemed unnecessary.

5.0 POTENTIAL EFFECTS ON FILM

One potential concern related to recycling of metals and concrete containing residual radioactive contamination is that these recycled materials may be used as material for making film-storage boxes. It is well known that film is sensitive to exposure to radiation and that two of the major uses of film are in the fields of medical and industrial radiography. To help prevent undesirable darkening or fogging of films prior to use, the National Council on Radiation Protection and Measurements (NCRP) recommended that radiographic film stored in darkrooms or storage areas should not be exposed to more than 2 μGy (0.2 mrad) of radiation prior to developing [12]. For design specifications for film-storage areas, the NCRP recommends assuming a one-month storage time as an average, if the exact time is not known. In this analysis, an estimate of the potential doses to film resulting from storage was made for storage in four different types of containers constructed from recycled materials.

6.0 RESULTS AND DISCUSSION

The results of this preliminary study are based on generic exposure scenarios and pathway analyses using 42 radionuclides determined to be potentially present as residual contamination in metals or on equipment from DOE operations that may be considered for recycling or reuse. Although alternative public dose limits were considered, the initial control criteria in this report are based on 1) a dose of 10 μSv y^{-1} (1 mrem y^{-1}) to a worker in a smelter or to an individual who uses consumer products made from recycled materials, 2) a dose of 1 μSv y^{-1} (0.1 mrem y^{-1}) to an individual downwind from a smelter used to process recycled metals, or 3) non-health impacts associated with potential radiation effects on electronics or film.

Table 2 summarizes the limiting concentrations based on individual radiation dose for residual contamination in (or on) recycled materials. For the radionuclides in Table 2, doses to smelter workers or to users of consumer products provided the most restrictive (i.e., the smallest) derived residual concentrations. This table shows the initial radiological control criteria for bulk materials, in units of Bq g^{-1}, for steel, aluminum, copper, and concrete, and the initial control criteria for surface contamination in units of Bq cm^{-2}.

TABLE 2. Draft Radiological Control Levels Based on an Individual Dose of 10 μSv y^{-1} for Recycling and Reuse of DOE Metals or Equipment Containing Residual Radioactive Contamination[a]

	Bulk Contamination (Bq g^{-1})				Surface Contamination (Bq cm^{-1})
Radionuclide	Steel	Aluminum	Copper	Concrete	Tools and Equipment
^{3}H	2.1E+05	3.3E+05	3.3E+05	6.3E+06	9.6E+04
^{14}C	7.0E+03	9.6E+03	9.6E+03	2.1E+04	2.9E+03
^{36}Cl	NA[b]	NA	NA	6.3E+02	NA
^{41}Ca	NA	NA	NA	3.1E+02	NA
^{54}Mn	4.8E-01	1.3E+00	7.0E+00	2.2E-01	1.2E+02
^{55}Fe	5.6E+02	9.3E+02	7.8E+03	1.4E+02	5.6E+03
^{57}Co	3.3E+00	8.9E+00	5.2E+01	2.9E+00	6.7E+02
^{60}Co	1.6E-01	4.8E-01	2.5E+00	6.3E-02	4.1E+01
^{63}Ni	1.9E+04	3.7E+04	3.7E+04	2.0E+05	1.1E+04
^{65}Zn	6.3E-01	1.8E+00	9.6E+00	2.5E-01	1.2E+02
^{79}Se	1.6E+03	2.5E+03	2.5E+03	2.7E+04	7.4E+02
^{90}Sr	9.3E+01	1.6E+02	1.6E+02	1.2E+03	4.8E+01
^{93}Zr	1.4E+03	7.0E+03	7.0E+03	5.2E+03	2.5E+03
^{94}Nb	2.6E-01	7.4E-01	4.1E+00	1.3E-01	6.3E+01
^{99}Tc	4.8E+03	1.1E+04	1.6E+04	5.2E+03	4.4E+03
^{106}Ru	1.6E+00	4.8E+00	2.5E+01	8.9E-01	1.6E+02
^{110m}Ag	1.4E-01	4.1E-01	2.1E+00	6.3E-02	3.6E+01
^{125}Sb	8.9E-01	2.4E+00	1.3E+01	4.8E-01	2.1E+02
^{129}I	4.8E+01	4.4E+01	7.4E+01	2.0E+01	2.2E+01
^{134}Cs	2.3E-01	6.7E-01	3.6E+00	1.1E-01	3.6E+01
^{137}Cs	7.0E-01	2.0E+00	1.0E+01	3.6E-01	7.4E+01
^{144}Ce	2.7E+01	5.9E+01	4.4E+02	2.2E+01	2.4E+02
^{147}Pm	2.9E+03	1.5E+04	1.5E+04	9.3E+03	4.4E+03
^{151}Sm	3.7E+03	1.9E+04	1.9E+04	1.3E+04	8.9E+03
^{152}Eu	3.4E-01	9.6E-01	5.2E+00	1.4E-01	8.1E+01
^{154}Eu	3.3E-01	9.2E-01	4.8E+00	1.4E-01	7.4E+01
^{226}Ra	7.4E+00	1.9E+01	1.9E+01	4.8E+01	5.2E+00
^{228}Th	4.1E-01	2.0E+00	2.0E+00	1.3E+00	1.5E+00
^{229}Th	7.0E-02	3.6E-01	3.6E-01	2.3E-01	2.6E-01
^{230}Th	4.8E-01	2.3E+00	2.3E+00	1.5E+00	1.7E+00

TABLE 2. (Cont'd)

	Bulk Contamination ($Bq\ g^{-1}$)				Surface Contamination ($Bq\ cm^{-1}$)
Radionuclide	Steel	Aluminum	Copper	Concrete	Tools and Equipment
^{232}Th	1.1E-01	5.5E-01	5.5E-01	3.5E-01	3.7E-01
^{232}U	1.8E-01	9.2E-01	9.2E-01	5.9E-01	7.8E-01
^{233}U	9.6E-01	4.8E+00	4.8E+00	3.0E+00	4.1E+00
^{234}U	9.6E-01	4.8E+00	4.8E+00	3.0E+00	4.1E+00
^{235}U	1.0E+00	5.2E+00	5.2E+00	3.2E+00	4.1E+00
^{238}U	1.0E+00	5.2E+00	5.2E+00	3.2E+00	4.1E+00
^{237}Np	2.4E-01	1.2E+00	1.2E+00	7.8E-01	6.3E-01
^{238}Pu	4.1E-01	2.0E+00	2.0E+00	1.3E+00	1.7E+00
^{239}Pu	3.7E-01	1.8E+00	1.8E+00	1.2E+00	1.5E+00
^{240}Pu	3.7E-01	1.8E+00	1.8E+00	1.2E+00	1.5E+00
^{241}Pu	2.1E+01	1.1E+02	1.1E+02	6.7E+01	8.9E+01
^{241}Am	2.2E-01	1.1E+00	1.1E+00	7.4E-01	5.9E-01

(a) Calculations were made using the EXTDF module from the GENII Software System [3] and selected scenarios based on the methods in IAEA Safety Series No. III-P-1.1 [1].

(b) "NA" indicates that this concrete activation product was Not Applicable to this scenario and was considered only for concrete recycle scenarios.

Doses to the public downwind of a smelter are estimated using the generic data on atmospheric dispersion and medium-high population density in the U.S. Environmental Protection Agency's CAP88-PC software. Doses were calculated to the maximally exposed individual (MEI) downwind of a smelter, assuming a unit release. For all radionuclides considered (except ^{238}U), the individual doses were more restrictive than the collective doses to the downwind public.

Also evaluated were non-health-related impacts industry may experience from residual contamination in recycled metals, such as those used in the electronics and film industries. Upon investigation, we found that most electronic components can withstand doses well in excess of the DOE individual dose limit. Thus, recycling the materials considered in this report at or below the contamination levels indicated Table 2 would have little impact on the electronics industry. On the other hand, use of recycled metals were found to have potential impacts on the film industry. Table 3 summarizes the limiting concentrations in recycled materials based on a 2 μGy (0.2 mrad) exposure to film stored for one month [12] in a box constructed of either undiluted steel or concrete for each of the 42 radionuclides considered. This table shows the initial radiological control criteria

TABLE 3. Draft Radiological Control Levels Based on 2 μGy Exposure to Film Stored for One Month[a]

Radionuclide	Initial Radiological Control Levels for Bulk Contamination (Bq g^{-1})			
	Steel	Lead-lined Steel	Concrete	Lead-lined Concrete
^{3}H	1.3E+08	---[b]	6.3E+07	---[b]
^{14}C	7.8E+03	8.5E+10	4.4E+03	3.0E+11
^{36}Cl	NA[c]	NA[c]	2.0E+02	1.7E+04
^{41}Ca	NA[c]	NA[c]	4.4E+01	---[b]
^{54}Mn	1.3E-01	2.5E-01	1.0E-01	1.9E-01
^{55}Fe	1.3E+02	---[b]	2.0E+01	---[b]
^{57}Co	9.6E-01	2.4E+02	1.1E+00	2.0E+02
^{60}Co	4.4E-02	7.4E-02	3.1E-02	4.8E-02
^{63}Ni	1.0E+05	SpA[d]	4.8E+04	SpA[d]
^{65}Zn	1.8E-01	2.8E-01	1.2E-01	1.8E-01
^{79}Se	1.0E+04	SpA[d]	5.6E+03	SpA[d]
^{90}Sr	2.8E+02	5.6E+04	3.6E+02	1.2E+05
^{93}Zr	1.3E+05	SpA[d]	5.6E+04	SpA[d]
^{94}Nb	7.4E-02	1.6E-01	5.9E-02	1.3E-01
^{99}Tc	1.5E+03	2.5E+07	1.2E+03	6.7E+07
^{106}Ru	4.4E-01	1.3E+00	4.1E-01	1.1E+00
^{110m}Ag	4.1E-02	7.8E-02	3.0E-02	5.5E-02
^{125}Sb	2.5E-01	7.8E-01	2.1E-01	6.3E-01
^{129}I	3.2E+01	SpA[d]	5.5E+00	SpA[d]
^{134}Cs	6.7E-02	1.4E-01	5.2E-02	1.1E-01
^{137}Cs	1.9E-01	4.8E-01	1.6E-01	4.1E-01
^{144}Ce	8.1E+00	8.9E+04	8.1E+00	1.2E+05
^{147}Pm	3.0E+03	2.0E+08	2.2E+03	3.7E+08
^{151}Sm	1.9E+04	SpA[d]	3.5E+03	SpA[d]
^{152}Eu	9.6E-02	1.8E-01	6.7E-02	1.2E-01
^{154}Eu	9.2E-02	1.7E-01	6.7E-02	1.2E-01
^{226}Ra	2.7E+01	3.7E+04	3.2E+01	3.6E+04
^{228}Th	6.7E+01	1.0E+04	3.6E+01	1.1E+04
^{229}Th	1.8E+00	7.0E+02	1.6E+00	7.8E+02
^{230}Th	2.6E+02	1.4E+07	5.9E+01	1.9E+07
^{232}Th	3.3E+02	SpA[d]	6.3E+01	SpA[d]
^{232}U	2.3E+02	1.3E+07	4.4E+01	1.8E+07
^{233}U	3.4E+02	5.2E+06	1.2E+02	7.0E+06

TABLE 3. (Cont'd)

Radionuclide	Initial Radiological Control Levels for Bulk Contamination ($Bq\ g^{-1}$)			
	Steel	Lead-lined Steel	Concrete	Lead-lined Concrete
^{234}U	2.8E+02	2.4E+07	5.2E+01	3.2E+07
^{235}U	1.1E+00	4.1E+02	1.2E+00	4.4E+02
^{238}U	3.7E+02	SpA[(d)]	6.3E+01	SpA[(d)]
^{237}Np	7.4E+00	1.5E+04	4.1E+00	1.6E+04
^{238}Pu	3.0E+02	SpA[(d)]	4.8E+01	SpA[(d)]
^{239}Pu	5.9E+02	2.0E+07	1.2E+02	2.7E+07
^{240}Pu	3.2E+02	SpA[(d)]	5.2E+01	SpA[(d)]
^{241}Pu	4.1E+07	---[(b)]	1.9E+07	---[(b)]
^{241}Am	1.5E+01	SpA[(d)]	5.9E+00	SpA[(d)]

(a) Calculations were made assuming that the film was stored for one month in a rectangular container made from either steel or concrete, with or without lead shielding lining (0.5 cm thickness) the box. The radiological control levels were determined based on the 2 μ Gy (0.2 mrad) limit recommended by the NCRP [12] for diagnostic x-ray film.

(b) For radionuclides having no gamma emissions, the lead lining reduced the dose to zero resulting in initial control levels that approached infinity. This is represented by (---) in the table.

(c) "NA" indicates that this concrete activation product was Not Applicable to this scenario and was considered only for concrete recycle scenarios.

(d) "SpA" indicates calculated control level exceeds the specific activity possible for the radionuclide shown.

smelter workers or to consumers for the photon-emitting radionuclides. This result is considered to be preliminary because of the highly conservative assumptions used in the analysis and because it is unlikely that storage areas for film would be constructed exclusively of undiluted (i.e., 100%), recycled steel or concrete. Further evaluation of the assumptions and data associated with the film scenario are underway.

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