4 RECYCLING AND DISPOSAL OF COPPER SCRAP

Assessments have been performed of the potential radiation doses to individuals from the recycling or disposal of copper scrap that could be cleared from nuclear facilities. The assessment addresses 20 scenarios that depict exposures resulting from the handling and processing of cleared scrap and the products of melting and refining this scrap at secondary copper producers, emission of airborne effluents from these facilities, transportation of scrap and furnace products, the use of copper products, the landfill disposal of cleared scrap and reverberatory furnace slag, and the infiltration of well water by leachate from landfills containing cleared scrap or slag. The analysis utilizes data on secondary copper production, as currently practiced in the United States, and on contemporary U.S. work practices and living habits.

The critical group for the largest number of radionuclides, accounting for over three-fourths of the 115 radionuclides in the analysis, consists of workers handling copper slag at a secondary fire refinery. The critical group accounting for the second largest number of nuclides comprises workers processing copper scrap at a scrap yard.

Mean values of mass-based normalized EDEs to critical groups range from a high of 36 :Sv/y per Bq/g (0.13 mrem/y per pCi/g) from Th-229 to a low of 1.4e-5 :Sv/y per Bq/g (5.0e-8 mrem/y per pCi/g) from Mn-53. The corresponding surficial EDEs are 69 and 2.6e-5 :Sv/y per Bq/cm^2, respectively. Mean values of mass-based normalized effective doses range from a high of 8.7 :Sv/y per Bq/g (0.032 mrem/y per pCi/g) from Cf-254 to a low of 6.3e-6 :Sv/y per Bq/g (2.3e-8 mrem/y per pCi/g) from Mn-53. The corresponding surficial effective doses are 17 and 1.2e-5 :Sv/y per Bq/cm^2, respectively. The critical group in all four cases comprises the workers handling copper slag.

This chapter describes the radiological assessment of the recycling and/or disposal of copper scrap that could be cleared from NRC-licensed facilities. This assessment is based on a realistic appraisal of current U.S. industrial practices involving the recycling of copper scrap into various copper products, or of disposing of the scrap in an industrial or municipal landfill.

4.1 Introduction to Analysis

As was the case with steel, the evaluation of the potential doses from cleared copper scrap consists of two main parts. The first step is characterizing the flow of cleared scrap through the normal recycling process, beginning with the generation of scrap, through refining, manufacturing, and product use, as well as disposal as an alternative to recycling. This enables the calculation of concentrations of the various radionuclides in products and by-products of the refining of copper scrap, normalized to an initial concentration of unit specific activity (Bq/g) or unit areal activity concentration (Bq/cm^2).

The second step is the development and analysis of exposure scenarios. Most of the 20 scenarios in the copper analysis were modeled on corresponding scenarios for iron and steel scrap. Essential differences between the two sets of scenarios are discussed in Section 4.6.

4.2 Flow of Copper Scrap

This section presents an overview of the recycling of copper scrap in the United States. Its purpose is: (1) to serve as an information source for the radiological assessment, and (2) to present a context for those aspects of the recycling and disposal of copper scrap that are addressed by this assessment. It thus includes some data which are not directly utilized in our study.

Figure 4.1 presents a schematic diagram of the flow of copper scrap, as characterized in our analysis. As is the case for other cleared materials, this is a simplified idealization of the actual process. The diagram depicts the sequence of steps which are represented by the exposure scenarios. Intermediate steps, not represented by exposure scenarios, are indicated by dashed lines or boxes. Other steps and processes are discussed in the following sections of this chapter.

The process begins with the release of cleared scrap from an NRC-licensed facility. It is assumed that the scrap is shipped by truck[1] to a scrap yard operated by a scrap metal dealer. The processing performed by this dealer, which can vary with the grade (i.e., type or composition) of scrap, includes shearing the metal into size, briquetting or crushing thin and lightweight materials (e.g., turnings and borings), magnetically separating ferrous metals, and cleaning and degreasing. Insulation removal is required for the recycling of most copper wire. The scrap dealer then ships the processed scrap to a secondary producer that employs a reverberatory (fire-refining) furnace[2] to make finished copper products (e.g., copper tubing).

Alternatively, the licensee or demolition contractor may elect to dispose of the scrap in an industrial or municipal solid waste (MSW) landfill.[3] Jolly (1997) has suggested that about one-half of discarded copper products is sent to landfills or other disposal facilities.

By-products of the reverberatory furnace include slag and offgas. The slag is transported by truck[1] for disposal in a landfill. (Slag may also be sold to a processor for recovery of copper, who would ship the residue to a landfill). The offgas consists of the fumes and particulates evolved during melting which are captured by the facility's emission control system. After cooling, most of the offgas is collected in the baghouse (or some other air pollution control device [APCD]) in the form of dust. The dust, like the slag, is transported by truck for disposal in a landfill. Gases, vapors, and some of the particulates escape the filtration system and are released to the atmosphere. These airborne effluents may be transported by air currents to a nearby residence.

Copper produced by secondary refiners is used to make a variety of finished products. The present analysis examines three such products. Two are generic shapes that can represent a

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[1] Scrap and refinery products can also be shipped by rail or waterway.

[2] "Reverberatory" refers to the design of the furnace (see Glossary for full explanation of this term). "Fire refining" refers to the process which typically utilizes this type of furnace. These two descriptive terms are sometimes used interchangeably in the present chapter.

[3] Another alternative, the processing of scrap at the nuclear facility, is outside the scope the analysis. Such processing would in most cases be performed by radiation workers whose occupational exposures are controlled under current regulations.

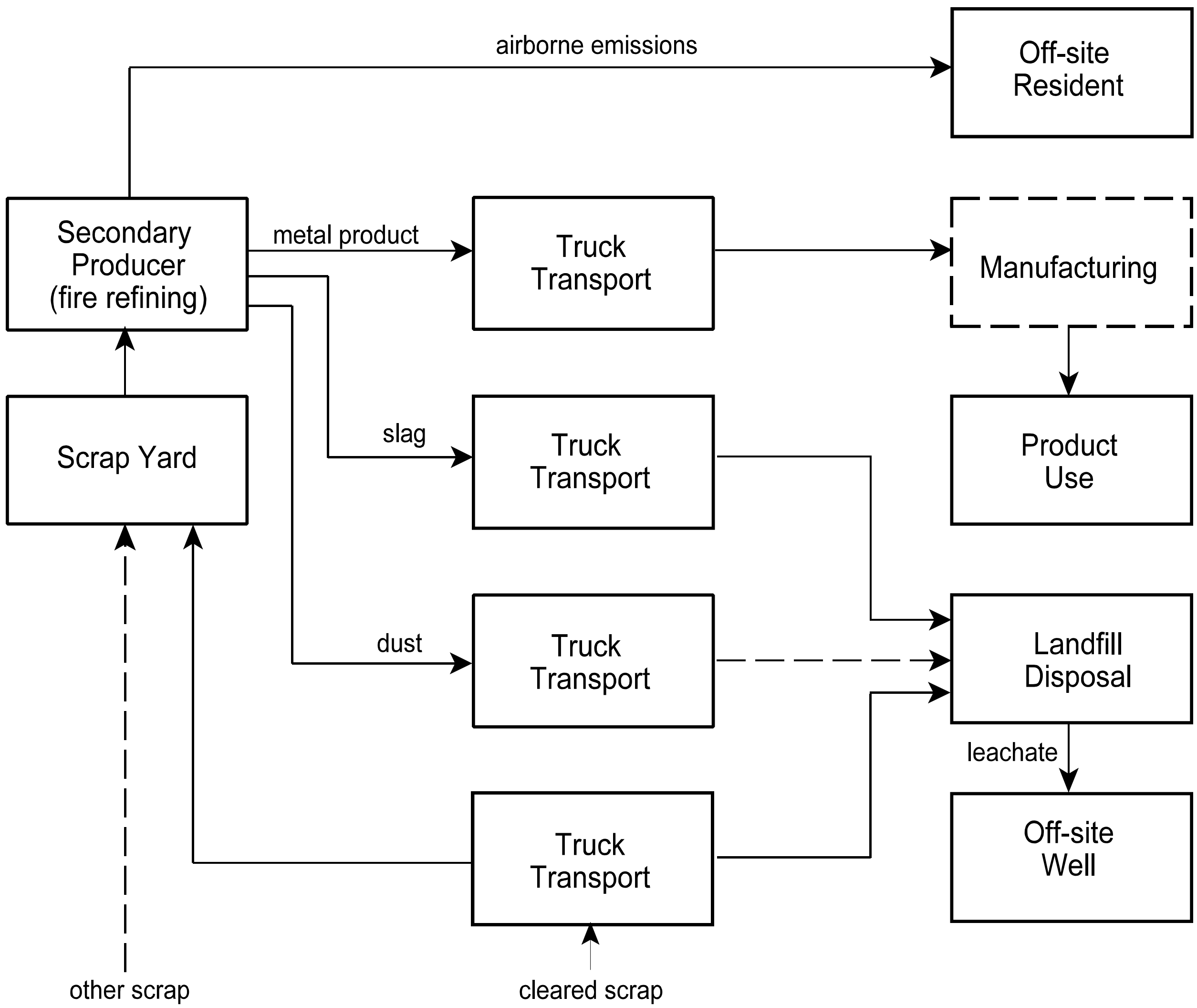

Figure 4.1 Flow of copper scrap

number of individual products. In addition, one specific product—copper pipes used in a domestic water supply system—is included in the assessment.

4.2.1 Sources of Material

As is the case for steel scrap, the main generator of copper scrap addressed in this study is the nuclear industry, which consists primarily of commercial power plants, test and research reactors, and industrial nuclear facilities. It has been estimated that a 1,000 Mw(e) PWR power plant contains about 694 t of copper (plus 25 t of bronze and 10 t of brass) (Bryan and Dudley 1974). As shown in Table A.10 (Appendix A of the present report), a total of 51.5 t of copper is associated with equipment—reactor plant equipment, fuel storage, and reactor auxiliaries— that is assumed to be significantly contaminated and not a likely candidate for clearance. Table A.10 further indicates that a total of 580.3 t of copper is associated with non-impacted systems—electrical plant equipment, miscellaneous equipment, site improvements, intake/discharge, and miscellaneous buildings. Subtracting the contaminated and the non-impacted metal from the total copper inventory yields a balance of 62 t of material that would be a potential candidate for clearance. Much of this scrap would be high quality unalloyed copper from copper wire, cable, and bus bar. It is assumed that this relatively small quantity of scrap would be cleared during a single year.[4]

A discussion of the mass-to-surface ratios of the copper components of a nuclear power plant is presented in Section A.6.3. The data in that section describe all of the copper components, while the parameter required for the present analysis is the average of the components likely to be cleared. A probability distribution of mass-to-surface ratios of the cleared scrap was determined as follows. As stated in Section A.6.3, most of the copper is assumed to be in the form of single- or multi-stranded wire, the remainder being in the form of busbars. The individual strands are assumed to range from 8 to 14 AWG.[5] The probability distribution was generated by a Monte Carlo sampling of the gauge of the copper wire, assuming that all even-number gauges from 8 to 14 were equally probable. The total mass of copper was divided by the sum of the surface areas of the individual strands of wire plus the surface areas of the busbars to yield a mass-to-surface ratio of copper scrap. The results of 10,000 Monte Carlo simulations have a mean value of 0.52 g/cm^2 and a coefficient of variation of 8.3%.

4.2.2 Recycling of Copper Scrap

Copper scrap typically accounts for about one-half of the total amount of copper consumed in the United States. From 1975 through 1995, scrap has accounted for 44% to 54.7% of total copper consumption ("Trends in U.S. Copper . . . " 1997). As cited in the same source, copper products have long lives, ranging from 10 to 100 years or more. The average product life, and hence the average age of old or post-consumer scrap, has been estimated to be about 20 years (Jolly 1997). In contrast, new scrap may have a 30-day turnaround. Unalloyed copper scrap is commonly smelted, or smelted and refined, while brass and bronze scrap (the largest source of copper-containing scrap) is remelted for use in mill products with little refining.[6] As stated in Section 4.2.1, copper scrap from a nuclear power plant will primarily be in the form of unalloyed copper.

In its annual survey of copper, the U.S. Geological Survey provides data on the sources of copper-bearing scrap. Table 4.1 presents data on the quantities of copper recovered from copper-base alloys in 2000. As shown in this table, about 73% of recycled copper was recovered from new scrap, the balance from old scrap. About 81% of recycled copper was recovered in

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[4] The much smaller quantities of bronze and brass are not addressed by the main analysis; however, they are included in the scoping analysis of a large brass musical instrument cited in Section 4.6.9.

[5] American Wire Gauge, also known as Brown & Sharpe gauge.

[6] The terms "smelting," "melting," and "refining" are used loosely and often interchangeably by the nonferrous metals industry. Strictly speaking, smelting refers to the reduction of ores or scrap with a significant nonmetallic content, melting (also "casting" or "founding") is changing the shape but not the chemical form of the material, and refining refers to chemical purification. Brass production can involve all three processes and is often generically referred to as "smelting." Technical terms specific to the metals industry are defined in the Glossary.

brass and bronze, most of the balance being in the form of unalloyed copper. A breakdown of copper recovery by type of processing operation is shown in Table 4.2.

Since the copper scrap from nuclear power reactors would be *old, unalloyed* scrap, the rest of this discussion will focus on scrap of that form. Edelstein (2002, Table 10) provides the following *gross* weights for consumption of unalloyed copper scrap in 2000:

- Smelters, refiners, and ingot makers .... 219,000 t
- Brass and wire rod mills .... 452,000 t
- Foundries and miscellaneous manufacturers .. 48,800 t

Table 4.1 Copper recovered from copper-base scrap in 2000

Recovery	Amount (t)	Fraction
From new scrap	906,000	73.1%
From old scrap	334,000	26.9%
Total recovery by type of scrap	1,240,000	100.0%
As unalloyed copper		
at electrolytic plants	128,000	10.3%
at other plants	88,400	7.1%
Subtotal	217,000	17.5%
In brass and bronze	1,010,000	81.5%
In chemical compounds	11,700	0.9%
Total recovery by form	1,240,000	100.0%

Source: Edelstein 2002, Table 6.

Note: Data are rounded to no more than three significant figures; may not add to totals shown.

Table 4.2 Copper recovered from copper-base scrap by type of operation in 2000

Type of operation	From new scrap		From old scrap		Total	
	Amount (t)	Fraction[a]	Amount (t)	Fraction[a]	Amount (t)	Fraction[a]
Ingot makers	29,900	3.3%	90,700	27.2%	121,000	9.8%
Refineries[b]	39,000	4.3%	169,000	50.6%	208,000	16.8%
Brass & wire rod mills	822,000	90.7%	22,200	6.6%	844,000	68.1%
Foundries & manufacturers	10,800	1.2%	44,500	13.3%	55,400	4.5%
Chemical plants[c]	3,880	0.4%	7,840	2.3%	11,700	0.9%
Total	906,000	73.1%[d]	334,000	26.9%[d]	1,240,000	100.0%

Source: Edelstein 2002, Table 7.

Note: Data are rounded to three significant figures, may not add to totals shown.

[a] Fraction of total of each column

[b] Amounts of electrolytically refined and fire-refined scrap based on source of material at smelter level.

[c] Includes copper sulfate and other copper compounds.

[d] Total new scrap and total old scrap as fraction of total scrap

Our estimates of the recovery from unalloyed copper scrap in 2000, listed in Table 4.3, are based on the following assumptions: (1) the consumption of unalloyed scrap cited by Edelstein (2002, Table 10) is equated to the *net* recovery of copper from copper-base scrap; (2) "miscellaneous manufacturers" in the cited data includes chemical plants; (3) the ratio of new-to-old *unalloyed* scrap for each type of operation is equal to the ratio of *all* new-to-old copper-based scrap for the same type of operation, as listed in Table 4.2. Since refiners use only unalloyed scrap, the total amount of unalloyed scrap recovered by ingot makers is estimated by subtracting the amount of copper recovered from copper-base scrap by refiners (208 kt) from the total amount of unalloyed scrap consumed by "smelters, refiners, and ingot makers" (219 kt).

The data in Table 4.3 show that about 74% of old, unalloyed scrap—the principal form of copper scrap that would be generated by the dismantlement of nuclear power plants—was consumed by refiners in 2000 (169 kt ÷ 227 kt = 0.744). Table 4.4 lists the amounts of unalloyed copper products made from scrap in 2000. Of the total of 208 kt of such products made by electrolytic and fire refineries, the fire refineries accounted for 80 kt or 38.5%. Thus, fire refiners are estimated to have consumed 28.6% of old, unalloyed scrap in 2000, the base year for the present analysis (0.744 × 0.385 = 0.286).

Table 4.3 Unalloyed copper and total copper recovered from copper-base alloys in 2000 (t)

Type of operation	All copper-base scrap[a]	Unalloyed scrap			
		New	Old		Total
			Amount	Fraction	
Ingot makers	121,000	2,700	8,300	3.7%	11,000
Refineries (including smelters)	208,000	39,000	169,000	74.4%	208,000
Brass and wire rod mills	844,000	440,000	12,000	5.3%	452,000
Foundries, manufacturers, chemical plants	67,100	10,700	38,100	16.8%	48,800
Total	1,240,000	492,000	227,000	100.0%	720,000

[a] From Table 4.2

Note: Data are rounded to three significant figures; totals may differ due to rounding.

Table 4.4 Unalloyed copper products made from scrap in 2000

Item produced from scrap	Amount (t)	Fraction
Electrolytically refined copper	128,000	59.2%
Fire-refined copper	80,000	37.0%
Copper powder	7,510	3.5%
Copper castings	839	0.4%
Total	216,349	100.0%

Source: Edelstein (2002, Table 8)

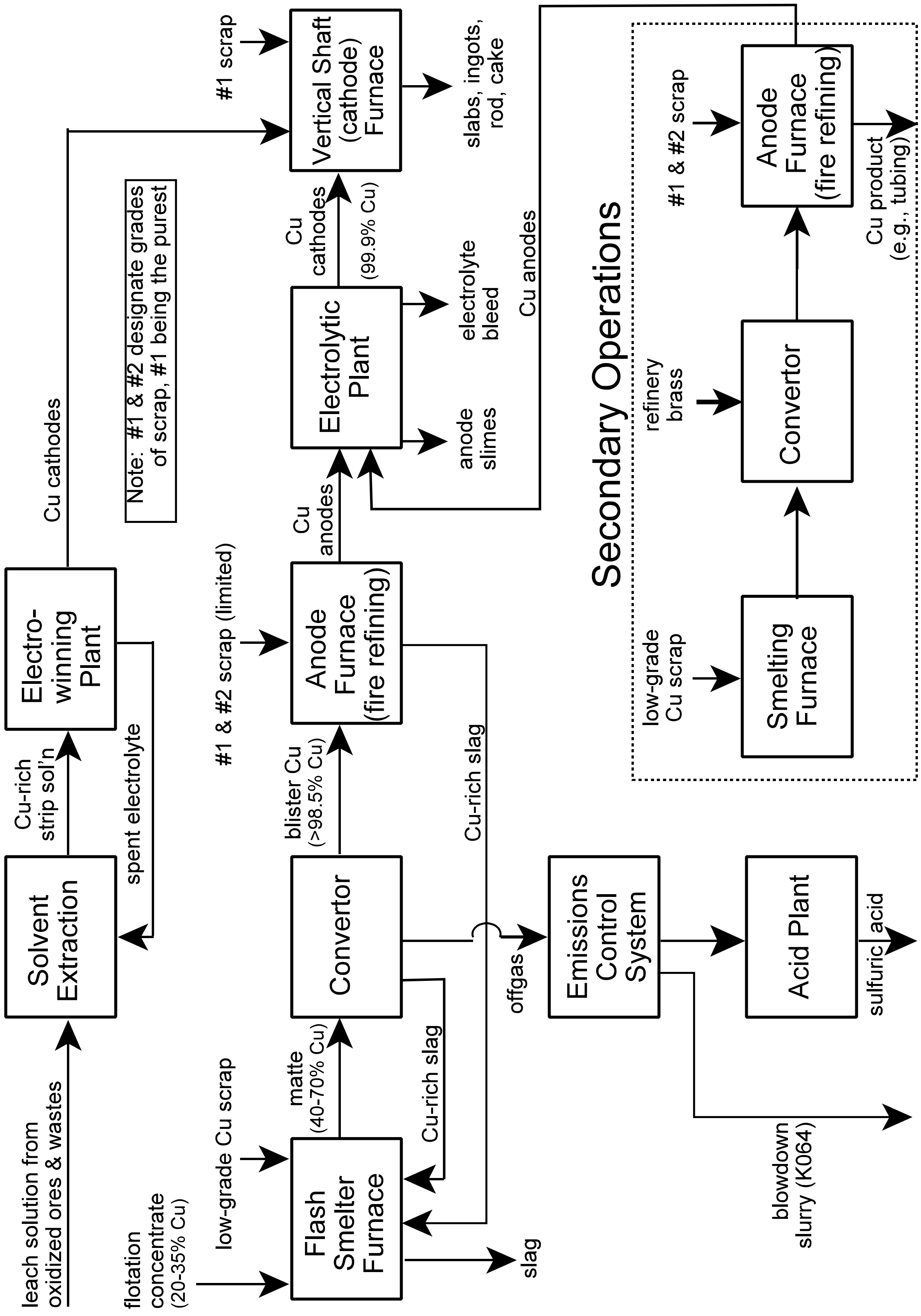

Figure 4.2 Operations in the primary and secondary production of copper

4.2.3 Copper Refining

Copper scrap can enter copper refining and processing operations in a variety of ways, depending on factors such as the quality of the scrap and its alloy content. Some copper scrap is refined by primary producers and some by secondary processors. Copper and copper-alloy scrap can also be remelted at brass mills, ingot makers, or foundries.

Primary producers mainly recover copper from ores by smelting or leaching, while secondary producers recover copper from scrap. Some of the unit operations that are involved in primary and secondary copper production are illustrated in Figure 4.2. As shown in the diagram, low-grade copper scrap can be charged to the flash smelter. Some No. 1 and No. 2 scrap (the highest grades of scrap, which constitute most of the copper scrap generated during the dismantling of a nuclear power plant) can also be charged to the anode furnace.[7] No. 1 scrap can be charged to a vertical shaft furnace where it would be melted into ingots or other copper products. Secondary producers can smelt low-grade copper scrap. In addition, a fire-refining furnace, which can be part of a secondary smelting operation or a free-standing facility, can consume No. 1 and No. 2 scrap. This is a simplified presentation of a complex process which does not attempt to capture all the flow paths and processing steps of the various products and by-products of copper refining and production. Details of the process may differ among different facilities.

In 2000, as noted in Table 4.2, approximately 51% of old copper-base scrap was consumed by smelters and refineries, 7% by brass and wire rod mills, 27% by brass and bronze ingot makers, and the remainder by miscellaneous manufacturers, foundries, and chemical plants. At the end of 2000, there were four primary smelters, one secondary smelter, four electrolytic refineries and four fire refineries operating in the United States (USGS 2001). (The only operating secondary smelter shut down in October 2001.) In addition there were 35 brass mills, 15 wire rod mills, and 600 foundries consuming refined copper and direct melt scrap. Brass mills primarily use new scrap while copper refiners primarily use old scrap.

4.2.3.1 Fire Refining

Fire refining is typically performed in a reverberatory furnace. This furnace is charged by forklift trucks or by charging machines. Impurities are removed by oxidizing the molten metal with air or oxygen and skimming away the resultant slag. The oxygen content of the melt is then reduced to the desired level (e.g., 0.03% to 0.04%) by adding a hydrocarbon source (e.g., natural gas or green logs). The refined copper is cast into shapes such as cakes, billets, or wire bar.

In some cases, melting of copper scrap in a reverberatory furnace may be the only step in the refining process. At one copper tubing manufacturer—Reading Tube Corporation—No. 1 copper scrap is the sole feed. All of the incoming scrap is visually inspected for known forms of suspect copper. An in-depth visual inspection is made of selected samples from the scrap;

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[7] A reverberatory furnace used to produce anodes for electrorefining may be referred to as an "anode furnace," as in the flow diagram depicted in Figure 4.2.

chemical analyses are taken from samples to screen for impurities. Typically, scrap inventories equal one or two days of consumption, but on some occasions may reach five days. The scrap is charged into a 180-t reverberatory furnace, melted, and blown with air or oxygen to oxidize impurities.[8] The oxide slag is skimmed from the melt. The melt is then covered with charcoal and "poled" to remove oxygen. In the poling process, green hardwood logs are thrust into the molten copper bath, where the hydrocarbons react with the oxygen to form CO/CO_2. The molten copper is then laundered. In this process, the copper flows under charcoal into a ladle which is covered with a carbon-based product. The laundering removes additional oxygen from the melt. Final deoxidation is promoted by the addition of phosphorus; the melt is then cast into billets for subsequent fabrication into tubing.[9] About 30% of the copper in the billets is recycled as home scrap.

At Reading Tube, slag is skimmed from the furnace through a door at one end, using steel rakes which are about 3 – 4 m long. Two operators work together with a single rake to skim the slag into a box beneath the furnace door. Slagging takes about two hours, during which time the operators are about 2.5 m from the furnace wall. The steel slag boxes are about 1 m square and 0.3 m deep. One of the furnace operators transports the filled slag box via forklift truck to a temporary storage area, where it is dumped onto the floor. When the slag has cooled, it is broken up with a "thumper" (air hammer) and metallic copper is culled from the slag by hand. The culled slag is moved with a front-end loader to an outside storage bin. This slag, which contains 30% to 35% copper, is sold to an outside processor for recovery of additional copper content. Offgas from the furnace passes through an after-burner to convert CO to CO_2 and to destroy any hydrocarbons; it is then exhausted through a stack. Stack emissions are monitored for total particulates, opacity, and SO_2.

The furnace operates on a 24-hour cycle, comprising the following operations:

- Charging . . . . 4.5 h
- Melting . . . . 4.5 h
- Refining and slagging . . . . 5.5 h
- Poling . . . . 2.5 h
- Casting . . . . 7 h

Slag production in a reverberatory furnace varies as a function of the percentage of copper in the charge. With increasing copper grade (Biswas and Davenport 1976):

- Copper concentration in slag increases
- Slag weight decreases
- Copper loss decreases

[8] Since about 25% of the melt remains in the furnace as a heel for the subsequent heat, the net output is 135 t.

[9] George Burg, Vice-President, Manufacturing, Reading Tube Corporation, private communication with William C. Thurber, SC&A, Inc., May 5, 1999.

4.2.3.2 Electrolytic Refining

The final stage in copper purification employs an electrolytic refining[10] process that yields copper which may contain less than 40 ppm of metallic impurities (Ramachandran and Wildman 1987). During electrorefining, copper anodes and pure copper cathode starter sheets are suspended in a $CuSO_4$-H_2SO_4-H_2O electrolyte, through which an electrical current is passed at a potential of about 0.25 Vdc. The process requires 10 to 14 days to produce a cathode weighing about 150 kg. During electrolysis, the copper dissolves from the anode and deposits on the cathode. Impurities such as Au, Ag, and other precious metals, as well as Pb, Se, and Te, all of which are carried over from copper ore, collect in the anode slimes.[11] These anode slimes are collected and sent to a precious metals refinery (Davenport 1986). Other elements, such as Fe, Ni, and Zn, dissolve in the electrolyte[12] and are removed from the copper electrolysis cells in a bleed stream. The bleed stream is sent to “liberator” cells, where the solution is again electrolyzed and soluble copper is plated out on insoluble lead anodes. The bleed stream is then treated for $NiSO_4$ recovery by concentrating the solution in evaporator vessels, where $NiSO_4$ crystals precipitate. The remaining liquor is called “black acid.” Both the $NiSO_4$ and the black acid may be salable products (Kusik and Kenahan 1978).

Brunson and Stone (1976) estimate that about 15 lb of slimes are generated for each ton of copper that is electrorefined (7.5 kg/t). Over a period of years, the slimes content at the refinery described by these authors has varied from 10 to 19 lb per ton (5 – 9.5 kg/t), depending on the anode purity (Stone and Tuggle 1995).

The Amarillo Copper Refinery of ASARCO, Incorporated, the reference electrolytic refinery for the present analysis, has an annual production of 420 kt of electrolytically refined copper. Fire refining is conducted in a 320-t reverberatory furnace with an annual output of 114 kt of anodes. The normal furnace feed is 81% blister copper from primary producers and 19% No. 2 copper scrap (Ramachandran and Wildman 1987). The combined output from the reverberatory furnace and the anode scrap-melting furnace, a total of 240 kt/y, together with 245 kt/y of purchased anodes, is electrorefined. About 63 kt of spent anodes are recycled to the anode melting furnace. Sulfuric acid recovered from the electrolyte bleed circuit is most likely used for electrolyte makeup; accordingly, it is returned to the process. The nickel sulfate, containing 5% H_2SO_4 and 3% H_2O, is sold to nickel producers for metal recovery. The nickel sulfate also contains contaminants, such as iron and zinc.

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[10] The terms “electrolytic refining” and “electrorefining” are used interchangeably.

[11] According to U.S. patent 4,351,705, a typical slimes composition is 5-10% Cu, 4-8% Ni, 6-8% Sb, 15-25% Sn, 5-12% Pb, 0-2% Ag, and 4-8% As. Smaller quantities of other metals are presumably not listed.

[12] Davenport (1986) states that As, Bi, Co, Fe, Ni, and Sb report to the electrolyte. This characterization of arsenic conflicts with the information in Footnote 11, as well with the results of our own analysis of the behavior of arsenic during electrorefining.

4.2.3.3 Brass and Bronze Smelting

There is no significant refining of the metal during the melting of scrap to produce brass and bronze. Chemical species with high vapor pressures would most likely be volatilized, but the slag-metal reactions typical of fire-refining operations are not likely to occur to a significant degree. According to Licht (2000), remelting of bronze using good practices results in total emissions not exceeding 0.5% of the process weight. However, with brasses containing 15% to 40% Zn, emissions may vary from less than 0.5% to 6% or more of the total mass of metal. As Licht further notes:

> In brass foundries, as much as 98% of the particulate matter contained in the furnace stack gases may be zinc oxide and lead oxide, depending on the composition of the alloy. Constituents of fumes included zinc, lead, tin, copper, cadmium, silicon, and carbon. They are present in varying amounts depending on the composition of the alloy and foundry practice.

Larger foundries that melt brasses and bronzes to produce castings typically use induction furnaces, while smaller foundries may use fuel-fired crucible furnaces (Licht 2000). Ingot makers may use reverberatory furnaces (Anigstein et al. 2001, Appendix C). Pacific Environmental Services (PES 1977, Table 4.5) measured the emissions from 18 shops that melt brass and bronze in induction furnaces without emissions control equipment. Emissions ranged from 0.3 to 20 kg/t, with an average value of 10 kg/t. The emissions from six shops which used baghouses for dust collection ranged from 0.01 to 0.65 kg/t, with an average of 0.35 kg/t. The report does not state the basis for measurement, but elsewhere in the document emissions are cited relative to quantities of feed material processed rather than amount of product. Consequently, it is assumed here that the units of measurement for emissions from brass induction furnaces are kilograms per tonne of feed.

It has been estimated that a well run brass foundry has a 53.8% yield of metal in good, finished castings. Most of the 46.2% loss is recoverable as home scrap (St. John 1958, pp. 88-96). Recoverable home scrap includes, at a minimum, gates, risers, and sprues (33.6%), pigged cold metal (2.0%), reject castings (2.4%), and machine turnings (6.1%).[13] Losses which are not fully recoverable include melting loss, skim and furnace spill, pouring loss, and sand blasting and grinding loss. For a well run foundry, these net losses are about 2.1%, although they could be as high as 12.1% for a poorly run shop, where the product yield could be as low as 27.5%.

Detailed information on furnace sizes used for brass and bronze melting was not found during the course of this study. Edelstein (2002) estimates that refined copper and direct-melt scrap was consumed in 600 foundries, chemical plants, and miscellaneous operations in 2000. In 2000, these facilities consumed 125 kt of brass and bronze ingot, 59.8 kt of refined copper, and 83 kt of

[13] Gates, risers, and sprues are passages in the casting mold which facilitate transport of molten metal to the mold cavity. Metal which freezes in the passages is recovered and returned to the casting process as home scrap. Pigged cold metal is excess metal from the furnace charge which is not required for the particular furnace run and is cast into small ingots (pigs) for subsequent remelting.

copper scrap (Edelstein 2002, Table 12). Based on these data, it is estimated that the average annual consumption of copper-base metals was about 450 t per facility.

4.2.4 Product Use

In addition to the refined metal, by-products of the copper refining operations also have commercial uses. Both types of products are described in this section.

4.2.4.1 Metal Products

The Copper Development Association (CDA) divides the end-use markets for copper and brass into five major areas. CDA (2001, Table 4) presents the annual compilation of market data for 2000, listing the following quantities of copper consumed, in millions of pounds (metric tons in parentheses):

- Building construction (building wire, plumbing and heating, air conditioning and commercial refrigeration, builders hardware, architectural) . . . . 3,740 (1,696 kt)

- Electrical and electronic products (power utilities, telecommunications, business electronics, lighting and wiring devices) . . . . 2,636 (1,196 kt)

- Industrial machinery and equipment (in-plant equipment, industrial valves and fittings, non-electrical instruments, off-highway vehicles, heat exchangers) . . . . 1,010 (458 kt)

- Transportation equipment (automotive, truck and bus, marine, railroad, aircraft and aerospace) . . . . 1,095 (497 kt)

- Consumer and general products (appliances, cord sets, military and commercial ordnance, consumer electronics, fasteners and closures, coinage, utensils and cutlery, miscellaneous) . . . . 1,070 (485 kt)

Of the total consumption of 9,551 million pounds (4,332 kt), all but 490 million pounds (222 kt) was from domestic production. It should be noted that the consumption figures are based on total metal content,[14] not copper content.

CDA 2001 also presents annual consumption data based on types of end products. Summary statistics for 2000 are listed below, in millions of pounds:

- Wire mill products . . . . 4,608 (2,090 kt)
- Other mill products (sheet, tube, pipe, rod, bar, etc.) . . . . 4,022 (1,824 kt)
- Foundry products . . . . 385 (175 kt)

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[14] The total metal content includes, in addition to copper, any alloying elements such as zinc in brass or tin in bronze.

- Powder products . . . . 46 (21 kt)

It can be seen from this summary that, in 2000, wire mill products accounted for 51% of all domestic copper-bearing products and other mill products accounted for 44% of the total. A further breakdown of these two categories is provided below, in millions of pounds:

Wire mill products:

- Bare wire . . . . 370 (168 kt)
- Telecommunications cable . . . . 675 (306 kt)
- Electronic cable and wire . . . . 300 (136 kt)
- Building wire . . . . 1,433 (650 kt)
- Magnet wire . . . . 800 (363 kt)
- Power cable . . . . 320 (145 kt)
- Apparatus wire and cordage . . . . 245 (111 kt)
- Automotive wire and cable (except magnet wire) . . . . 395 (179 kt)
- Other insulated wire and cable . . . . 70 (32 kt)

Other mill products (percentage refers to the fraction comprising unalloyed copper, the balance being copper alloys):

- Strip, sheet, plate, and foil (38%) . . . . 1,425 (646 kt)
- Mechanical wire (22%) . . . . 99 (45 kt)
- Rod and bar (20%) . . . . 1,248 (566 kt)
- Plumbing tube and pipe (100%) . . . . 675 (306 kt)
- Commercial tube and pipe (94%) . . . . 575 (261 kt)

The following amounts of copper are found in various finished vehicular products (ICA n/d):

- Mid-sized automobile . . . . 22.5 kg (including 18 kg of electrical components)
- Typical diesel-electric locomotive . . . . 5,000 kg (large diesel-electric: 7,200 kg)
- Triton-class nuclear submarine . . . . 90,000 kg
- Average motorized farm vehicle . . . . 28 kg
- Average construction vehicle . . . . 30 kg
- Electric forklift . . . . 62 kg
- Electrically powered subway car, trolley, or bus . . . . 280 – 4,100 kg

4.2.4.2 Refinery By-products

One of the by-products of copper refining operations that may have commercial value is the zinc-containing dusts used in fertilizers. On July 24, 2002, EPA (2002) promulgated regulations regarding manufacture of zinc fertilizers from hazardous secondary materials. Because of certain provisions of the new rule, EPA expected that fertilizer manufacturers would begin to use "zinc-rich dusts from brass foundries and fabricators as substitutes for other feedstocks [e.g., baghouse dust from steelmaking EAFs]." EPA estimated that 23 brass fume generators (ingot makers, mills, and foundries) would potentially be affected by the new rule.

Another potentially valuable by-product is slag, which contains 30% to 35% copper. As cited in Section 4.2.3.1, this material may be sold to a specialty processor for metal recovery.

4.3 Mass Fractions and Partitioning Factors for Refining Operations

For the purpose of the present analysis, the material entering a fire-refining reverberatory furnace is distributed into three process streams: metal product, slag, and offgas. The offgas consists of gases and vapors as well as particulates. The particulates and the vapors that condense upon cooling form dust, a portion of which is captured by the baghouse filters or other APCD. The volatile fraction, as well as the particulates that escape the baghouse, are released to the atmosphere. Any impurities (e.g., radionuclides) in the scrap metal are likewise distributed among the metal, slag, dust, and volatile effluent emissions.

During electrorefining the incoming material, including any impurities, is distributed among the metal product, the anode slimes, and the electrolyte bleed.

Very limited information is available in the literature to describe mass fractions of materials produced during brass smelting operations. Slag-metal separations for various elements, which occur during the fire refining of copper, would most likely not occur during brass smelting, where the primary objective is to melt the scrap, not to adjust its composition. Airborne emissions of volatile chemical species can be assumed to be similar to those from a reverberatory furnace.

As shown in Table 4.2, about 22 kt of copper was recovered from old copper-base scrap at brass and wire rod mills in 2000. This represents about 2.6% of the 844 kt of copper recovered from scrap at these facilities, the remainder being from new scrap. Likewise, as shown in Table 4.2, only 6.6% of the copper from old scrap is recovered at brass and wire rod mills. Both statistics indicate that brass production does not play a significant role in the recycling of old copper scrap, such as the scrap that would be cleared from a nuclear facility. Consequently, a more detailed analysis of mass fractions and partitioning factors in brass and bronze smelting was not performed for the current assessment. A scoping analysis was performed, however, to determine if the radiological impacts of cleared scrap processed at such facilities could exceed the impacts from processes that were studied in greater detail. This analysis is discussed briefly in Section 4.6.9 and in greater detail in Appendix N.

4.3.1 Mass Fractions

4.3.1.1 Fire Refining

The weight of slag produced by the reverberatory furnace of the Reading Tube Corporation is estimated to be about 2% to 2.5% of the charge weight.[15] On this basis, the mass fraction of slag

[15] See Footnote 9 on page 4-9.

with respect to scrap charged to the fire-refining furnace was assigned a uniform distribution of 0.020 – 0.025. The slag contains about 40% copper.[15]

EPA 1995 (Table 12.9-1) lists particulate emission factors for a reverberatory furnace used in the secondary smelting of unalloyed copper. The factor for total particulates is 2.6 kg of per tonne of scrap melted, while that for PM-10 emissions[16] is 2.5 kg/t. A baghouse reduces the total emissions to 0.2 kg/t. This is 8% of the unfiltered emissions, implying a baghouse efficiency of 92%.

The factor for unfiltered total emissions is based on PES 1977 and is the average of 12 plants, with a range of 0.4 to 15 kg/t. In the present analysis, the mass fraction of dust with respect to scrap charged to the furnace was assigned a truncated lognormal distribution that is consistent with these statistics. The distribution has an arithmetic mean of 0.0026, an arithmetic standard deviation of 0.002855, a minimum of 0.0004, and a maximum of 0.015.

Reading Tube, which uses an APCD other than a baghouse to control particulate emissions, reports PM-10 emissions corresponding to 0.05 kg per tonne of copper produced.[17] These emissions are about one-fourth of the average total emissions of facilities equipped with baghouses, indicating that, in this instance, the APCD is at least as efficient as a baghouse. Dust collected in these APCDs is shipped off site for recovery of its metal content.

For the purpose of the present analysis, the quantity of metallic copper produced from one furnace heat was calculated by subtracting the amounts of chemically bound copper in the slag and in the dust (i.e., the amount of copper in the form of CuO), from the amount of metal in the furnace charge. Gößling (2001) cites a value of 45.04% Cu_2O in slag from a fire-refining anode furnace at a primary copper smelter, which corresponds to a Cu content of 40.00%. This is in agreement with the estimate for the Reading facility; however, it should be noted that Gößling describes a somewhat different process. The dust is assumed to contain 75% Cu, in the form of CuO. The calculation results in yields of 97.9% –99.2%.

4.3.1.2 Electrolytic Refining

As discussed in Section 4.6.8, detailed probabilistic analyses are not performed on exposure scenarios involving electrolytic refineries. The deterministic scoping analyses described in that section require only point values rather than probability distributions.

A mass fraction of 0.0075 of anode slimes with respect to the metal fed to the electrorefining process is adopted for the scoping analyses, based on the data quoted by Brunson and Stone (1976), as cited in Section 4.2.3.2. Data on the production of nickel sulfate was presented by Anigstein et al. (2001, Section C.5.1.4), who estimate that ASARCO's Amarillo Copper

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[16] "PM-10" is the acronym for particulate matter with AMAD # 10 : m.

[17] Bill Rismiller (Environmental Manager, Reading Tube Division of Cambridge-Lee Industries), private communication to William C. Thurber, SC&A, Inc. (September 3, 2002).

Refinery, which consumes 485 kt/y of copper anodes, would produce about 1,200 t/y of crude nickel sulfate. This value is adopted for the scoping analyses in the present study.

4.3.2 Partitioning Factors

4.3.2.1 Fire Refining

During fire refining, impurities (elements or chemical compounds) partition between the two liquid phases—slag and molten metal—or discharge from the furnace in the offgas. Some of the chemical species that leave the furnace in the offgas remain in the vapor phase while some condense or coalesce into particulates (dust). Impurities found in coarse particulates are captured by the baghouse filter or other APCD. Some of the fine particles and the species in the vapor phase escape in the effluent emissions from the stack.

The partitioning factors developed for the present analysis are intended to represent the expected behavior of impurities during melting in a typical reverberatory furnace. Thermodynamic calculations of the oxidation potential of each element were used in estimating partitioning factors at temperatures typical of reverberatory furnace operation. The calculations were supplemented with other data, such as vapor pressures of the chemical species and observed partitioning based on industry experience and laboratory testing. In the absence of other information, partitioning factors are estimated, based on the behavior of chemically similar elements.

Table 4.5 shows partitioning factors for each element (or its compounds) in fire refining. The development of statistical distributions for each of these factors is described in Section J.5.

4.3.2.2 Electrolytic Refining

During electrorefining, copper preferentially plates out at the cathode while many impurities, such as lead and tin, are left in the anode slimes. Nickel and other metallic impurities accumulate in the electrolyte and are removed in the electrolyte bleed. Extremely low concentrations of many impurities may be difficult to remove from the copper.

Electrode half-cell potentials were used to establish partitioning during electrorefining. Details of the partitioning analyses are presented in Appendix J.

Partitioning factors for electrorefining are presented in Table 4.6.

4.4 Mixing of Cleared Scrap

The concentration of each radionuclide in cleared copper scrap would be reduced by mixing with other materials, including scrap from other sources, prior to smelting. Further mixing occurs during the disposal of refinery by-products. The mixing of cleared scrap and of the products resulting from the refining of the scrap are briefly discussed in this section. The type of mixing factor used in each exposure scenario is listed in Table 4.7.

Table 4.5 Partitioning in fire refining of copper (%)

Elements	Metal product	Dust	Slag	Volatile
H, C	0	0	0	100
Na, Ca, Sc, Cr, Sr, Y, Zr, Nb, Mo, Tc, Ba, Ce, Pm, Sm, Eu, Gd, Tb, Tm, Ta, W, Ra	0.05–0.15	0	99.85–99.95	0
P, S, K	0.05–0.15	10–90	9.85–89.95	0
Cl, I	0	0–10	90–100	0
Mn	2–5	0	95–98	0
Fe	2–25	0	75–98	0
Co, Ni	1–60	0	40–99	0
Zn, Cd	1–26	0–5	74–94	0
As	10–20	10–80	10–70	0
Se, Te, Cs	10–20	80–90	0	0
Ru, Ag, Os, Ir	100	0	0	0
Sn	12–40	0	60–88	0
Sb	1–69	0–5	31–94	0
Tl	10–20	30–60	20–60	0
Pb	6–100	0–5	0–89	0
Bi	90–100	0–10	0	0
Po	1–50	50–99	0	0
Ac, Np, Pu, Am, Cm, Bk, Cf, Es	0.1–1	0	99–99.9	0
Th, Pa, U	0.1–2	0	98–99.9	0

As discussed in Section 4.6, the only melting or refining process subjected to a detailed analysis is fire refining at a secondary producer. Consequently, mixing factors for electrorefining and brass smelting are not presented in this chapter.

4.4.1 Processing Copper Scrap at Scrap Yard

The cleared scrap would be processed at a facility specializing in nonferrous metals. As discussed in Section D.3.1, the mean throughput of such facilities is about 11 kt/y. The average mixing factor of cleared copper scrap, as reflected by the mean value of 10,000 Monte Carlo realizations, is about 5.6×10^{-3}.

4.4.2 Secondary Fire Refining

As stated in Section 4.2.3, there were four fire refineries operating in the United States at the end of 2000. The scrap consumption rate of each of these facilities was estimated on the basis of its production capacity and the mass fraction of the copper product. The facility is selected at random, weighted by its capacity. As discussed in greater detail in Section D.3.2, the amount of cleared scrap includes probabilistically weighted amounts of copper scrap from multiple nuclear power plants undergoing dismantlement during the same year. The results of 10,000 Monte

Carlo realizations of mixing factors have a mean value of 1.1×10^{-3}, with a standard error of the mean of $\pm 7.3 \times 10^{-6}$.[18]

Table 4.6 Partitioning in electrorefining of copper (%)

Elements	Copper cathodes	Anode slimes	Electrolyte bleed
Na, K, Sc, Cr, Sr, Y, Zr, Nb, Mo, Tc, Cd, Cs, Ce, Pm, Sm, Eu, Gd, Tb, Tm, Ta, W, Tl, Ra, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es	0	0	100
P, As	0.1–2	98–99.9	0
S, Se	0.1–0.2	99.8–99.9	0
Cl, I	0	100	0
Ca	0	40–60	40–60
Mn, Fe	1–3	26–46	51–73
Co	0.5–1.5	0	98.5–99.5
Ni	0.3–0.7	0–10	89.7–99.3
Zn	0	0–10	90–100
Ru	3–4	26–32	65–70
Ag	2–6	94–98	0
Sn	0.1–10	90–99.9	0
Sb	0.1–1	0–74.9	25–99
Te	0–33	67–100	0
Ba	0	1–99	1–99
Os, Ir	0	81–84	16–19
Pb	0.15–0.45	99.55–99.85	0
Bi	0.3–1.4	0–74.7	25–98.6
Po	25–75	25–75	0

4.5 Radionuclide Concentrations in Various Media

The refining process redistributes any impurities (such as radionuclides) in the scrap among the various furnace products. As discussed in Section 4.4, this partitioning is dependent on the chemical element in question and applies to all isotopes of that element.

The annual-average radionuclide concentrations in fire-refined copper and in the by-products of the fire refining of copper scrap, as well as the annual activity of each nuclide released to the atmosphere, are calculating by applying the equations listed in Section 3.5.1. The parameters specific to copper are based on the information presented in this chapter. The values adopted for the present analysis are listed in Tables B.4 and B.5.

[18] Because of the skewness of this distribution, the standard error of the mean is a more meaningful metric than the coefficient of variation.

The mean and the 5th, 50th and 95th percentile radionuclide concentrations in the products of fire refining of copper scrap, as well as the annual activities released to the atmosphere, are listed in Appendix K.

4.6 Dose Assessment of Copper Recycling and Disposal Scenarios

The 20 exposure scenarios included in the copper analysis, along with the environmental transport pathways included in each scenario, are listed in Table 4.7. The basis of each scenario is listed in the column headed “CA” (corresponding analysis). Each of the 14 scenarios indicated by the notation “Fe” is based on the corresponding scenario in the steel analysis, which has the same or a similar title. Five other scenarios, indicated by the notation “mod,” are based on similar steel scenarios, but with significant modifications. In addition, there is one new product use scenario: individuals consuming drinking water from copper pipes. Only those aspects of the analysis that are new or significantly different from the corresponding steel analyses are discussed in this section.[19]

4.6.1 Inhalation and Inadvertent Ingestion of Copper Dusts

The U.S. Occupational Safety and Health Administration (OSHA) limits the workplace exposure to copper dusts. The permissible exposure limit (PEL) for copper mists and dusts is 1 mg/m^3 of Cu (29 CFR 1910.1000, Table Z-1). As stipulated by 29 CFR 1910.1000(a)(2): An employee's exposure . . . shall not exceed the Time Weighted Average [(TWA)] given for that substance any 8-hour work shift of a 40-hour work week. The incorporation of these limits into the copper scenarios is discussed in the following sections.

4.6.2 Scrap Processing, and Handling of Fire-refined Copper Product

The workers processing copper scrap at a scrap yard would be exposed to copper dust generated by the shredding and sectioning of copper scrap. Because the OSHA limit applies to any given 8-hour shift, the annual average dust loading would be significantly less than the limit. The 8-hour TWA dust concentration is modeled as a truncated lognormal distribution, with a range of zero to 1 mg/m^3 of Cu and a mean of 0.5 mg/m^3. A similar model is applied to the copper product handling scenario.

[19] All parameter values that are specific to the copper exposure scenarios are listed in Table B.9. All other parameters have the values listed for the steel scenarios in Table B.8.

Table 4.7 Scenario and exposure pathway matrix

Scenario abbreviation	Scenario title	CA[a]	MF[b]	Pathways[c]		
				Ext[d]	Inh	Ing
Handling and Processing						
Scrap yard	Processing copper scrap at scrap yard	mod	SD	20	●	●
Handling metal product	Handling fire-refined copper product	Fe	AA	23	●	●
Handling slag	Handling copper slag at fire-refining facility	Fe	AA	21	●	●
Baghouse maintenance	Reverberatory furnace baghouse maintenance	Fe	AA	22		
Atmospheric Release						
Airborne emissions	Emission of airborne effluents from furnace	Fe	AA	F2	●	●
Transport						
Scrap truck–driver	Truck driver hauling cleared copper scrap	mod	N	26		
Metal product–driver	Truck driver hauling fire-refined copper	mod	AA	29		
Slag truck–driver	Truck driver hauling reverberatory furnace slag	Fe	AA	28	●	●
Dust truck–driver	Truck driver hauling reverberatory furnace dust	Fe	AA	27	●	●
Product Use						
Exposure to small mass	Exposure to small mass of fire-refined copper	Fe	AA	24		
Copper object on body	Small fire-refined copper object on body	Fe	AA	25		
Drinking–copper pipes	Drinking tapwater from copper pipes	new	AA			●
Landfill Disposal						
Scrap disposal–industrial	Handling copper scrap at industrial landfill	Fe	IL	F1		
Scrap disposal–municipal	Handling copper scrap at municipal landfill	Fe	ML	F1		
Slag disposal–industrial	Handling copper slag at industrial landfill	Fe	IL	F1	●	●
Slag disposal–municipal	Handling copper slag at municipal landfill	Fe	ML	F1	●	●
Groundwater Contaminated by Leachate from Landfills						
Leachate–industrial–scrap	Leachate from industrial landfill–scrap	Fe	IL			●
Leachate–municipal–scrap	Leachate from municipal landfill–scrap	Fe	ML			●
Leachate–industrial–dross	Leachate from industrial landfill–slag	mod	IL			●
Leachate–municipal–dross	Leachate from municipal landfill–slag	mod	ML			●

[a] CA = corresponding analysis: Fe = steel, mod = modified from corresponding steel analysis

[b] MF = mixing factor: AA = annual average, IL = industrial landfill, ML = municipal landfill, N = no mixing, SD = scrap dealer (see text—details in Appendix D)

[c] Exposure pathways: Ext = external, Inh = inhalation, Ing = ingestion of food, water, or soil; inadvertent ingestion

[d] External exposure dose factors:

- 20 Scrap pile
- 21 Slag pile
- 22 Baghouse
- 23 Large metal mass
- 24 Small metal mass
- 25 Small object on body
- 26 Scrap truck
- 27 Dust truck
- 28 Slag truck
- 29 Truck loaded with metal product
- F1 Federal Guidance Report # 12: soil contaminated to an infinite depth
- F2 Federal Guidance Report # 12: contaminated ground surface

Because of the controls required to maintain the dust concentrations within acceptable limits, it is likely that the ingestion of copper dust would also be reduced from that in the corresponding steel scenarios. Since the airborne dust concentration limit of 1 mg/m^3 is one-fifth of the 5 mg/m^3 PEL on the respirable fraction of nuisance dusts, it is reasonable to assume that the inadvertent ingestion of dust would be reduced by a similar amount. This is likely to occur because the protective measures used to reduce inhalation exposure would also reduce the oral intake, either by reducing the opportunity for ingestion through the use of respiratory apparatus, or by reducing the amount of finely divided copper in the worker's immediate environment.

Exposure durations of less than eight hours per shift would permit the worker to be exposed to proportionately higher dust concentrations. The doses from internal exposure are calculated to be the same as if the worker were exposed for eight hours to the lower concentration. External exposures are based on the time the worker actually spends on this task.

4.6.3 Handling Copper Slag at Fire Refinery

The slag handling scenario at a secondary copper fire refinery is based on a description of this operation presented by Anigstein et al. (2001, Section 9.3.3). After being skimmed from the molten copper and allowed to cool, the slag is transported to a corner of the building, where it is spread on the floor. A worker breaks up the slag with a pneumatic hammer and culls copper nuggets by hand. This worker would be externally exposed to direct, penetrating radiation from any residual radionuclides that partition to the slag.

The worker would also be exposed to the inhalation of the dust that would be generated during this operation. The inhalation exposure would be limited by the OSHA limit on copper dust. Since Cu comprises 40% of reverberatory furnace slag, the 8-hour TWA limit on slag dust would be 2.5 mg/m^3 (1 mg/m^3 ÷ 0.4 = 2.5). The dust loading is assigned a lognormal distribution, such that the 8-hour TWA would range from zero to 2.5 mg/m^3 of slag, with a mean of 1.25 mg/m^3. As stated earlier, exposure durations of less than eight hours per shift would allow the worker to be exposed to proportionately higher dust concentrations. The doses from the inhalation exposure are calculated to be the same as if the worker were exposed for eight hours to the lower concentration.

Because the worker typically spends about two hours per day on this task, the actual dust concentrations could be significantly higher; therefore, the rate of inadvertent ingestion is assumed to be the same as in the corresponding steel scenarios.

4.6.4 Atmospheric Releases During Fire refining

The only significant difference in the atmospheric release scenario for the fire refining of copper scrap and the comparable scenario for melt-refining of steel scrap is the period of buildup of radionuclides in the soil at the receptor location. In the steel scenario, it was assumed that the activity would build up over a period of 1.7 years, the assumed period of time during which steel scrap would be cleared from a commercial nuclear power plant undergoing dismantlement. Because of the large number of steelmaking facilities which consume iron and steel scrap, it is unlikely that a single melt shop would be recycling scrap from more than one nuclear power reactor. However, the secondary copper industry includes only four fire refineries. Consequently, there is a high likelihood that, if copper cleared from the nuclear plants is destined for recycling, the same refinery would be recycling such scrap in different years. The buildup time was calculated as follows:

$$t_b = \frac{f_{fr}\, m_{Cu}\, n_d\, N_R}{m_0} \left(\frac{m_{fr}}{M_{fr}} \right) \qquad \textbf{4.1}$$

t_b = buildup time of activity in soil (d)

f_{fr} = fraction of Cu scrap consumed by fire-refining furnaces

m_{Cu} = mass of Cu scrap cleared during dismantlement of one reactor

m_{fr} = annual capacity of given fire-refining facility

n_d = days per year

N_R = number of reactors scheduled for dismantlement

m_0 = mass of cleared Cu scrap processed by given fire-refining facility in one year

M_{fr} = combined capacity of all U.S. fire-refining facilities

The numerator of the first term in Equation 4.1 represents the total mass of cleared copper scrap—generated by the dismantlement of all nuclear power reactors scheduled for dismantlement over the next 50 years—that would be processed by all currently operating fire-refining facilities. The denominator represents the mass of cleared scrap processed by the given fire-refining facility in one year. The term in brackets is the ratio of the production capacity of the given facility to that of all such facilities. The expression is thus the nominal time period during which a given fire-refining facility would be processing cleared scrap, assuming the same amount of cleared scrap was processed each year.

Because the models used to calculate doses from the deposition of airborne effluent emissions on soil incorporate a single buildup period, the recycling of cleared scrap at a given facility is assumed to take place over a contiguous period of time. This could lead to a slightly conservative assessment.

4.6.5 Transportation Scenarios

The distances traveled in transporting copper scrap and the by-products of copper refining are based on data for shipments of “Metallic waste and scrap” presented by the Bureau of the Census (1999). These distances are represented by a normal distribution, with a mode of 130 mi (209 km), the average distance listed by the Census Bureau, and a coefficient of variation of 11.6%, as given by the Census Bureau. The lower end of the distribution was truncated at 50 mi (80 km), based on engineering judgement—50 mi at an average speed of 50 mph (80 km/h) results in an average exposure time of one hour. Although shorter trips are possible, the time spent loading and unloading would make it unlikely that a driver would spend less than one hour per load. The average speed of all trips made by a given driver is represented by a triangular distribution with a range of 40 to 60 mph (64 – 97 km/h), and a mode of 50 mph. These speeds are based on engineering judgement and are intended to span the range of average highway speeds throughout the United States.

Because of the small quantity of cleared copper scrap, it is assumed that it would all be transported by one driver, unlike the case for steel scrap discussed in Chapter 3.

The distances traveled by copper products shipped from the refinery are based on shipments of "Nonferrous metal, except precious, in unwrought forms, in finished basic shapes" (Bureau of the Census 1999). These distances are represented by a truncated lognormal distribution, with an arithmetic mean of 393 mi (632 km), the average distance listed by the Census Bureau, and a coefficient of variation of 10.2%, as given by the Census Bureau. The minimum and maximum are set to 50 and 2,000 mi (80 – 3,200 km), based on engineering judgement. Because non-ferrous metal products are typically shipped over greater distances than iron and steel products, it is more likely that a truck equipped with a sleeping compartment would be used for this purpose. The calculation of the duration of external exposure in the sleeper is the same as that presented under the sub-heading "Truck Driver Hauling EAF Dust in a Dump Trailer" in Section 3.7.3.3.

4.6.6 Drinking Tapwater from Copper Pipes

The one entirely new scenario is the use of copper piping made of recycled scrap. Some of the metal, along with any radionuclides from the cleared scrap that partition to the fire-refined metal product, gradually dissolves in the water passing through these pipes. This material would be ingested by individuals drinking tapwater carried by these pipes. Copper piping is one of the major products made from fire-refined copper scrap.

4.6.6.1 Exposure Pathways

The only pathway included in this scenario is the ingestion of radionuclides dissolved in the drinking water. Airborne suspension of particulates from copper piping is unlikely; therefore, the inhalation pathway is not included. Also, the doses from external exposure to copper pipes and fixtures were judged to be small compared to the doses from the ingestion of drinking water; therefore, that pathway was not included in the model.

4.6.6.2 Detailed Description

In common with other product-use scenarios, the exposure assessment spans a one-year period after the plumbing is installed and put into use. The gradual dissolution of the piping is assumed to produce a constant concentration of copper in the tapwater. The dose from the drinking water pathway is expressed as follows:

$$D_{iw} = C_{Cu}\, C_{ip}\, F_{ig}\, I_w\, t_{ys} \left(\frac{e^{-\lambda_i t_s} - e^{-\lambda_i (t_s + t_a)}}{\lambda_i\, t_a} \right) \qquad \textbf{4.2}$$

D_{iw} = dose from ingestion of radionuclide *i* in tapwater during assessment period (: Sv)

C_{Cu} = concentration of copper in tapwater (g/mL)

C_{ip} = undecayed specific activity of radionuclide *i* in copper product (see Equation 3.2) (Bq/g)

F_{ig} = dose conversion factor for ingestion of radionuclide *i* (: Sv/Bq)

I_w = daily consumption of tapwater (mL/d)

t_{ys} = exposure duration (d)

t_s = time from clearance of material to the time the scenario begins (d)

8_i = radioactive decay rate of nuclide *i* (d^{-1})

t_a = assessment period

Equation 4.2 expresses the assumption that any radionuclides that partitioned to the copper during fire refining would dissolve in the tapwater at the same relative rate as the copper. Therefore, the activity concentration of a given nuclide in the water is the product of the concentration of copper in the water and the specific activity of the nuclide in the copper.

In most cases, the scenario begins at the time the copper pipes are installed and put into use. For those nuclides with long-lived progenies, the beginning of the assessment period is adjusted incrementally over the average service life of the copper pipes until the peak year—the 365.25-day period which results in the highest dose—is determined.

4.6.6.3 Concentration of Copper in Tapwater

The Agency for Toxic Substances and Disease Registry (ATSDR 1990) has reported that the use of copper or bronze pipes increases the concentration of copper in drinking water. When water is allowed to remain in the pipes for a period of time, copper can leach from the pipes into the water. Soft water is more corrosive than hard water, enhancing leaching of copper from the pipes. When pipes have not been flushed after a period of disuse, the concentration of copper in tap water may exceed 1.3 ppm (1.3 mg Cu/L), which is the EPA drinking-water limit. The report presents results from a number of different studies. One study found that the copper concentration in treated water in Canada that has not been exposed to copper pipes was generally very low: # 10 ppb (# 10 : g Cu/L). Another study showed the mean copper concentrations in running and standing water from copper pipes in Seattle to be 0.16 and 0.45 ppm, respectively, with an average value of 0.31 ppm (0.31 mg/L). The increase in copper concentration due to leaching of copper from the pipes was 0.3 mg/L. A triangular distribution, with a minimum of 0.16 mg/L, a mode of 0.3 mg/L, and a maximum of 1.3 mg/L was therefore assigned to the parameter C_{Cu} in Equation 4.2.

4.6.7 Well Water Infiltrated by Leachate from Landfills Containing Copper Slag

The exposures of residents drinking water from wells down gradient from landfills used for the disposal of copper slag were patterned after similar scenarios involving the disposal of BOF dust in the steel analysis.

4.6.8 Electrolytic Refineries

Only exposure scenarios involving the fire refining of copper scrap are subjected to detailed, probabilistic analyses. Electrolytic refineries and brass mills were excluded because it is highly unlikely that the processing of copper scrap from nuclear facilities by these producers would lead to higher normalized doses than would result from fire refining by secondary producers.

As shown in Figure 4.2, high-grade (No. 1 and No. 2) copper scrap, the type that would be generated during the dismantlement of a nuclear power plant, can be introduced into the fire-refining anode furnace at an electrolytic refinery. The processes employed at this furnace are essentially the same as the free-standing fire refinery already modeled; consequently, no additional analyses of these processes are needed. The electrolytic plant uses these and other fire-refined anodes and further purifies the copper. Consequently, the metal product contains fewer impurities, and would thus result in lesser impacts from any impurities entering the fire-refining stage.

The same statement may not apply to the by-products of electrorefining: the anode slimes and the electrolyte bleed. Because of the small mass fractions of these waste streams, any impurities that remained in the anodes following fire refining but were removed during electrorefining would be concentrated in one of these two media. Anigstein et al. (2001, Chapter 9) analyzed the external exposure of a tank house operator to (-emitting radionuclides that were concentrated in the anode slimes. A scoping analysis patterned on this scenario shows that it is unlikely that this scenario would give rise to the critical group for any radionuclide in the present study. (The scoping analyses discussed in this and the following section are described in Appendix N of the present report.)

The process of recovering crude nickel sulfate from the electrolyte bleed is reasonably automated, requiring little "up-close and personal attention."[20] Scoping analyses were performed on two workers that could be exposed to radionuclides that concentrate in the nickel sulfate: a forklift operator that transports the filled bags of concentrate and a truck driver that transports the concentrate to a processor for recovery of nickel and other valuable metals. In neither case would such a scenario give rise to a critical group.

Figure 4.2 also indicates that No. 1 scrap can be introduced into the cathode furnace. Since this is a melting rather than a refining furnace, there would be little removal of any residual

[20] Harry Tallert, Tank House Manager, Amarillo Copper Refinery, ASARCO Incorporated, private communication with William C. Thurber, SC&A, Inc., March 7, 2003.

impurities in this scrap. A scoping analysis was performed of the exposure of a worker handling the metal product of this furnace. The results show that this scenario does not lead to a critical group.

4.6.9 Brass Mills

As was discussed in Section 4.2.3.3, scrap melted in brass mills undergoes little or no refining; consequently, any impurities in the scrap most likely remain in the metal. A scoping analysis was performed to determine if individuals playing large brass musical instruments made with cleared copper scrap could constitute a critical group. The results of the scoping analysis show that this is not the case.

4.6.10 Scenario Timing

This section discusses the time periods for each of the copper exposure scenarios. The timing is based on data specific to the copper industry, supplemented by engineering judgment.

4.6.10.1 Scrap Transport and Handling

- Cleared scrap is transported to a scrap dealer or to a landfill. Transportation takes two to six days from the time of clearance.

- The scrap is disposed of in a landfill one to seven days after arrival.

- The scrap is processed and remains at the scrap dealer for a period of one to 30 days after it arrives.

4.6.10.2 Refining and Processing

- The fire-refining process and associated operations at the secondary producer take place one to five days after the scrap is shipped from the scrap dealer.

- Airborne effluent releases from the reverberatory furnace occur at the time the scrap is melted and refined.

- Slag and dust are produced at the time the scrap is refined.

4.6.10.3 Transportation of Products of Fire Refining

- Transport of fire-refined copper occurs three to 30 days after production.

- Dust from the reverberatory furnace is collected monthly and may be sent to a third party for metal recovery. Transportation is assumed to take place 30 to 60 days after the dust is generated.

- Slag may also be sent to a third party for metal recovery. Transportation is assumed to take place two to three days after the slag is generated.

4.6.10.4 Use of Copper Products

- Manufactured items are put into use 10 to 60 days after the refined copper is shipped from the secondary producer. As noted in Section 4.2.2, the average life of copper products is 20 years.

- Copper pipes are installed and put into service between 10 and 270 days after shipment from the secondary producer. This range encompasses replacement plumbing, which might be installed and used as soon as 10 days after shipment, and pipes installed in a new building under construction, which might not be used until nine months later. The average service life of copper pipes is 35 years (Henstock 1997).

4.7 Dose Assessments of Recycling and Disposal of Copper Scrap

As discussed in previous sections of this chapter, the radiological assessment of the clearance of copper scrap from NRC-licensed nuclear facilities evaluates the radiation exposures of individual members of various groups to each of 115 radionuclides and their progenies in 20 exposure scenarios.

4.7.1 Calculation of Effective Dose Equivalents (EDEs)

The groups described by five of these scenarios receive the highest mean normalized EDEs from one year of exposure to cleared copper scrap from all 115 nuclides, one scenario constituting the EDE-critical group for 90 nuclides.[21] Table 4.9 lists the mean and the 5th, 50th, and 95th percentile mass-based normalized EDEs from each radionuclide to its respective critical group, while Table 4.10 lists the corresponding surficial EDEs. Figure 4.3 lists the scenarios describing the EDE-critical groups and displays the number of radionuclides for which each scenario constitutes the critical group. The mean and the 5th, 50th, 90th, and 95th percentile normalized EDEs from all 115 nuclides for all 20 scenarios are tabulated in Appendix G-1.

The scenario giving rise to a critical group for the greatest number of radionuclides comprises workers handling and processing copper slag from a reverberatory furnace at a secondary refinery. The small mass fraction of the reverberatory furnace slag, combined with the significant partitioning of a large majority of radionuclides to the slag, results in very high concentrations of these nuclides in slag relative to their original concentrations in scrap. The slag handling scenario exposes the workers to a large, flat area of slag with no external shielding and little self-shielding, enhancing the external exposures to direct penetrating radiation emitted

[21] As discussed in Chapter 1, the group which receives the highest mean normalized EDE from a given radionuclide is defined as the EDE-critical group for that nuclide.

by those nuclides. These workers are also subjected to internal exposures from inhalation and ingestion of the slag dust generated during this operation.

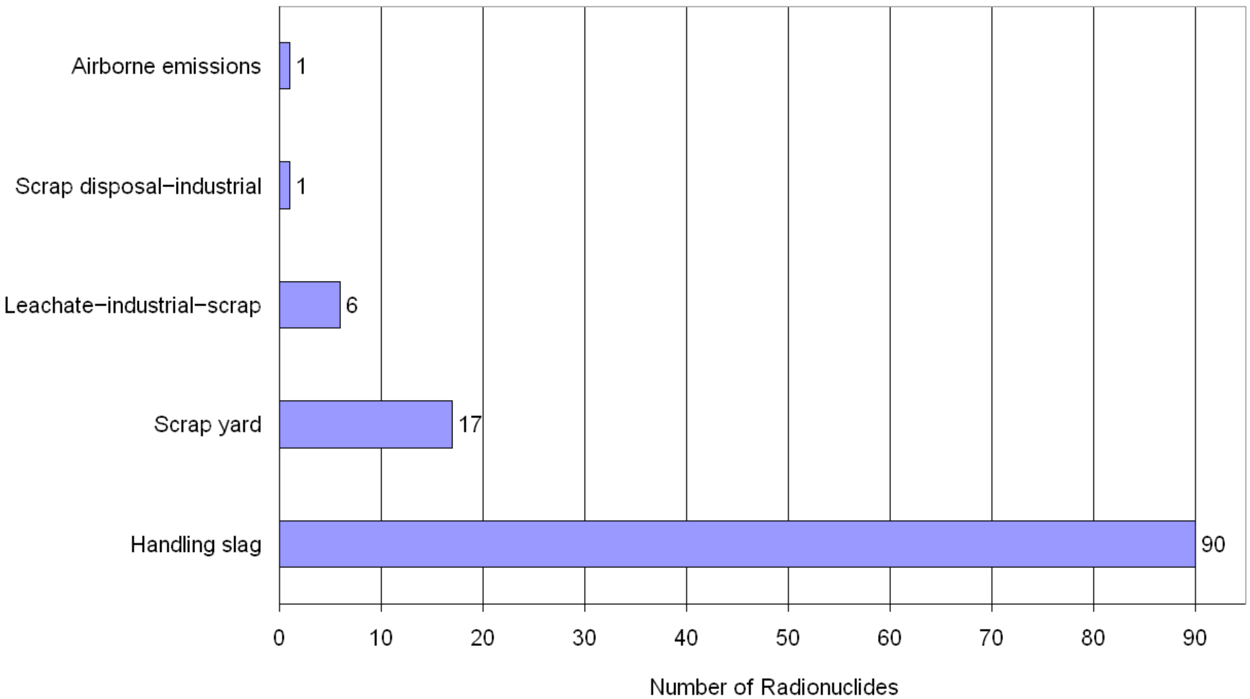

Figure 4.3 Scenarios giving rise to EDE-critical groups for copper

Workers handling and processing copper scrap at a scrap yard constitute the critical group for 17 nuclides. The factors contributing to the exposures of these workers are discussed in Section 3.9.1. Seven of the remaining critical groups stem from the disposal of copper scrap in an industrial landfill as an alternative to recycling. These critical groups comprise either nearby residents drinking water from wells contaminated by leachate or workers at the landfill.

4.7.2 Calculation of Effective Doses

The groups described by the same five scenarios characterizing the EDE-critical groups receive the highest mean normalized effective doses from one year of exposure to cleared copper scrap from all 115 nuclides, the workers handling and processing copper slag constituting the critical group for 86 nuclides. Table 4.11 lists the mean and the 5th, 50th, and 95th percentile mass-based normalized effective doses from each radionuclide to its respective critical group, while Table 4.12 lists the corresponding surficial effective doses. Figure 4.4 lists the scenarios describing the effective dose-critical groups and displays the number of radionuclides for which each scenario constitutes the critical group. The mean and the 5th, 50th, 90th, and 95th percentile normalized effective doses from all 115 nuclides for all 20 scenarios are tabulated in Appendix G-2. The factors leading to the highest effective doses in these scenarios are similar to those giving rise to the EDE-critical groups discussed in Section 4.7.1.

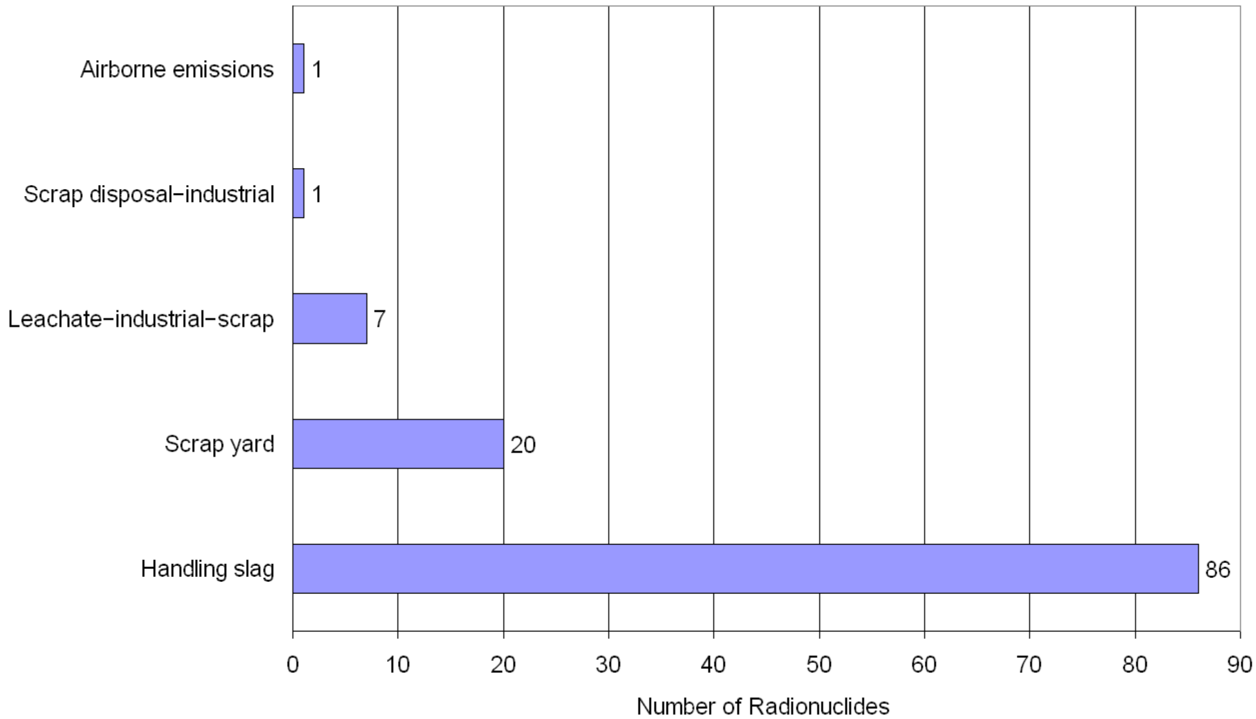

Figure 4.4 Scenarios giving rise to effective-dose critical groups for copper

In the case of one radionuclide—Mo-93—the mean normalized effective dose in the critical group is higher than the 90th percentile effective dose, as listed in Table 4.8. The critical group for this nuclide comprises persons living down gradient from an industrial landfill used for the disposal of cleared copper scrap. (The 90th percentile effective dose is in fact zero, which indicates that, in at least 90% of the Monte Carlo realizations, the activity never reached the well during the 1,000 year assessment period.) The group with the highest EDE for which the mean does not exceed the 90th percentile might be considered as an alternate critical group for that nuclide. This potential alternate critical group is also listed in the table for purposes of comparison.

Table 4.8 Mass-based normalized effective dose from Mo-93 (:Sv/y per Bq/g)

Nuclide[a]	Critical group[b]		Potential alternate critical group[c]		
	Mean	90th %-ile	Mean	90th %-ile	Scenario name
Mo-93	1.2e-03	0.0e+00	4.2e-04	8.7e-04	Handling slag

[a] Nuclide for which mean normalized effective dose exceeds 90th percentile effective dose

[b] Critical group = persons living down gradient from an industrial landfill used for the disposal of cleared copper scrap

[c] Group with maximum mean effective dose which does not exceed 90th percentile effective dose to *that* group

Table 4.9 Normalized mass-based effective dose equivalents to critical groups for copper

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	1.0e-04	0.0e+00	7.6e-08	4.2e-04	3.7e-07	0.0e+00	2.8e-10	1.6e-06	Leachate-industrial-scrap
C-14	2.4e-04	7.5e-05	1.8e-04	6.1e-04	9.0e-07	2.8e-07	6.7e-07	2.3e-06	Airborne emissions
Na-22	1.2e+00	4.1e-01	9.7e-01	2.5e+00	4.3e-03	1.5e-03	3.6e-03	9.4e-03	Handling slag
P-32	7.9e-04	1.2e-04	4.7e-04	2.6e-03	2.9e-06	4.6e-07	1.7e-06	9.5e-06	Scrap yard
S-35	2.7e-05	5.7e-06	2.0e-05	7.2e-05	1.0e-07	2.1e-08	7.6e-08	2.7e-07	Handling slag
Cl-36	2.1e-03	0.0e+00	0.0e+00	8.1e-03	7.6e-06	0.0e+00	0.0e+00	3.0e-05	Leachate-industrial-scrap
K-40	6.5e-02	1.4e-02	4.1e-02	2.0e-01	2.4e-04	5.2e-05	1.5e-04	7.3e-04	Scrap yard
Ca-41	1.1e-03	0.0e+00	0.0e+00	4.8e-03	4.2e-06	0.0e+00	0.0e+00	1.8e-05	Leachate-industrial-scrap
Ca-45	2.2e-04	6.4e-05	1.8e-04	5.2e-04	8.2e-07	2.4e-07	6.5e-07	1.9e-06	Handling slag
Sc-46	9.3e-01	3.2e-01	7.7e-01	2.1e+00	3.5e-03	1.2e-03	2.8e-03	7.6e-03	Handling slag
Cr-51	8.2e-03	2.4e-03	6.5e-03	1.9e-02	3.0e-05	9.0e-06	2.4e-05	7.2e-05	Handling slag
Mn-53	1.4e-05	4.2e-06	1.1e-05	3.1e-05	5.0e-08	1.6e-08	4.0e-08	1.2e-07	Handling slag
Mn-54	4.3e-01	1.5e-01	3.6e-01	9.5e-01	1.6e-03	5.6e-04	1.3e-03	3.5e-03	Handling slag
Fe-55	4.3e-05	1.3e-05	3.4e-05	1.0e-04	1.6e-07	4.6e-08	1.3e-07	3.8e-07	Handling slag
Fe-59	4.4e-01	1.4e-01	3.5e-01	9.8e-01	1.6e-03	5.3e-04	1.3e-03	3.6e-03	Handling slag
Co-56	1.3e+00	4.2e-01	1.0e+00	2.9e+00	4.8e-03	1.6e-03	3.9e-03	1.1e-02	Handling slag
Co-57	1.5e-02	5.0e-03	1.2e-02	3.3e-02	5.5e-05	1.8e-05	4.5e-05	1.2e-04	Handling slag
Co-58	3.5e-01	1.2e-01	2.9e-01	7.9e-01	1.3e-03	4.3e-04	1.1e-03	2.9e-03	Handling slag
Co-60	1.1e+00	3.8e-01	9.2e-01	2.5e+00	4.2e-03	1.4e-03	3.4e-03	9.2e-03	Handling slag
Ni-59	2.8e-05	9.1e-06	2.2e-05	6.2e-05	1.0e-07	3.4e-08	8.3e-08	2.3e-07	Handling slag
Ni-63	5.4e-05	1.6e-05	4.3e-05	1.3e-04	2.0e-07	5.9e-08	1.6e-07	4.7e-07	Handling slag
Zn-65	2.7e-01	9.5e-02	2.3e-01	6.0e-01	1.0e-03	3.5e-04	8.4e-04	2.2e-03	Handling slag
As-73	1.7e-04	6.5e-06	5.1e-05	5.6e-04	6.2e-07	2.4e-08	1.9e-07	2.1e-06	Scrap disposal-industrial
Se-75	6.5e-02	1.4e-02	4.1e-02	2.0e-01	2.4e-04	5.1e-05	1.5e-04	7.3e-04	Scrap yard
Sr-85	2.0e-01	6.9e-02	1.7e-01	4.5e-01	7.5e-04	2.6e-04	6.1e-04	1.7e-03	Handling slag
Sr-89	1.2e-03	3.8e-04	9.4e-04	2.6e-03	4.3e-06	1.4e-06	3.5e-06	9.7e-06	Handling slag
Sr-90	1.3e-02	4.2e-03	1.1e-02	3.1e-02	5.0e-05	1.6e-05	4.0e-05	1.2e-04	Handling slag
Y-91	3.5e-03	1.2e-03	2.8e-03	7.6e-03	1.3e-05	4.5e-06	1.1e-05	2.8e-05	Handling slag
Zr-93	1.7e-03	5.4e-04	1.4e-03	4.1e-03	6.5e-06	2.0e-06	5.2e-06	1.5e-05	Handling slag
Zr-95	4.4e-01	1.6e-01	3.7e-01	9.7e-01	1.6e-03	5.8e-04	1.4e-03	3.6e-03	Handling slag
Nb-93m	6.1e-04	1.9e-04	4.9e-04	1.4e-03	2.3e-06	7.0e-07	1.8e-06	5.3e-06	Handling slag
Nb-94	8.7e-01	3.1e-01	7.2e-01	1.9e+00	3.2e-03	1.1e-03	2.7e-03	7.0e-03	Handling slag
Nb-95	2.8e-01	8.7e-02	2.2e-01	6.3e-01	1.0e-03	3.2e-04	8.2e-04	2.3e-03	Handling slag
Mo-93	6.4e-04	2.0e-04	5.1e-04	1.5e-03	2.4e-06	7.5e-07	1.9e-06	5.5e-06	Handling slag
Tc-97	1.1e-03	0.0e+00	0.0e+00	4.5e-03	4.1e-06	0.0e+00	0.0e+00	1.7e-05	Leachate-industrial-scrap
Tc-97m	1.6e-04	5.4e-05	1.3e-04	3.6e-04	6.0e-07	2.0e-07	4.8e-07	1.3e-06	Handling slag
Tc-99	9.5e-03	0.0e+00	0.0e+00	3.8e-02	3.5e-05	0.0e+00	0.0e+00	1.4e-04	Leachate-industrial-scrap
Ru-103	1.1e-01	2.3e-02	7.2e-02	3.5e-01	4.2e-04	8.6e-05	2.7e-04	1.3e-03	Scrap yard
Ru-106	8.0e-02	1.7e-02	5.0e-02	2.4e-01	2.9e-04	6.4e-05	1.9e-04	8.9e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.9 Normalized mass-based effective dose equivalents to critical groups for copper

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	5.5e-01	1.2e-01	3.5e-01	1.7e+00	2.0e-03	4.4e-04	1.3e-03	6.2e-03	Scrap yard
Ag-110m	9.7e-01	2.1e-01	6.2e-01	2.9e+00	3.6e-03	7.6e-04	2.3e-03	1.1e-02	Scrap yard
Cd-109	1.5e-03	5.0e-04	1.2e-03	3.4e-03	5.6e-06	1.9e-06	4.6e-06	1.3e-05	Handling slag
Sn-113	9.1e-02	3.1e-02	7.5e-02	2.0e-01	3.4e-04	1.2e-04	2.8e-04	7.4e-04	Handling slag
Sb-124	5.8e-01	1.9e-01	4.7e-01	1.3e+00	2.2e-03	6.9e-04	1.7e-03	4.9e-03	Handling slag
Sb-125	1.6e-01	5.2e-02	1.3e-01	3.6e-01	5.9e-04	1.9e-04	4.7e-04	1.3e-03	Handling slag
Te-123m	1.3e-02	2.8e-03	8.5e-03	4.1e-02	5.0e-05	1.1e-05	3.1e-05	1.5e-04	Scrap yard
Te-127m	1.5e-03	3.4e-04	9.3e-04	4.5e-03	5.5e-06	1.2e-06	3.5e-06	1.7e-05	Scrap yard
I-125	1.5e-03	3.7e-04	1.2e-03	3.9e-03	5.7e-06	1.4e-06	4.4e-06	1.4e-05	Handling slag
I-129	4.0e-01	0.0e+00	0.0e+00	1.4e+00	1.5e-03	0.0e+00	0.0e+00	5.3e-03	Leachate-industrial-scrap
I-131	3.6e-02	3.6e-03	2.1e-02	1.2e-01	1.3e-04	1.3e-05	7.9e-05	4.5e-04	Handling slag
Cs-134	5.5e-01	1.2e-01	3.5e-01	1.7e+00	2.0e-03	4.4e-04	1.3e-03	6.2e-03	Scrap yard
Cs-135	8.6e-05	1.4e-05	5.5e-05	2.7e-04	3.2e-07	5.1e-08	2.0e-07	1.0e-06	Scrap yard
Cs-137	2.0e-01	4.3e-02	1.3e-01	6.0e-01	7.4e-04	1.6e-04	4.6e-04	2.2e-03	Scrap yard
Ba-133	1.5e-01	5.4e-02	1.3e-01	3.3e-01	5.7e-04	2.0e-04	4.7e-04	1.2e-03	Handling slag
Ce-139	2.9e-02	1.0e-02	2.4e-02	6.4e-02	1.1e-04	3.8e-05	8.9e-05	2.4e-04	Handling slag
Ce-141	9.1e-03	2.8e-03	7.3e-03	2.1e-02	3.4e-05	1.0e-05	2.7e-05	7.8e-05	Handling slag
Ce-144	3.0e-02	1.1e-02	2.5e-02	6.5e-02	1.1e-04	4.1e-05	9.4e-05	2.4e-04	Handling slag
Pm-147	8.2e-04	2.5e-04	6.6e-04	1.9e-03	3.0e-06	9.4e-07	2.4e-06	7.1e-06	Handling slag
Sm-151	6.2e-04	1.9e-04	5.0e-04	1.5e-03	2.3e-06	7.1e-07	1.8e-06	5.4e-06	Handling slag
Eu-152	6.1e-01	2.1e-01	5.1e-01	1.3e+00	2.3e-03	7.9e-04	1.9e-03	4.9e-03	Handling slag
Eu-154	6.0e-01	2.1e-01	5.0e-01	1.3e+00	2.2e-03	7.8e-04	1.8e-03	4.8e-03	Handling slag
Eu-155	6.2e-03	2.3e-03	5.2e-03	1.3e-02	2.3e-05	8.4e-06	1.9e-05	5.0e-05	Handling slag
Gd-153	6.7e-03	2.4e-03	5.6e-03	1.5e-02	2.5e-05	8.8e-06	2.1e-05	5.4e-05	Handling slag
Tb-160	4.9e-01	1.7e-01	4.0e-01	1.1e+00	1.8e-03	6.2e-04	1.5e-03	4.0e-03	Handling slag
Tm-170	1.1e-03	3.8e-04	8.8e-04	2.3e-03	3.9e-06	1.4e-06	3.2e-06	8.6e-06	Handling slag
Tm-171	2.2e-04	7.1e-05	1.8e-04	5.0e-04	8.1e-07	2.6e-07	6.5e-07	1.8e-06	Handling slag
Ta-182	5.9e-01	2.0e-01	4.8e-01	1.3e+00	2.2e-03	7.6e-04	1.8e-03	4.8e-03	Handling slag
W-181	1.5e-03	5.1e-04	1.2e-03	3.2e-03	5.5e-06	1.9e-06	4.5e-06	1.2e-05	Handling slag
W-185	7.6e-05	1.9e-05	5.9e-05	1.9e-04	2.8e-07	7.2e-08	2.2e-07	7.0e-07	Handling slag
Os-185	2.0e-01	4.2e-02	1.3e-01	6.1e-01	7.4e-04	1.5e-04	4.7e-04	2.3e-03	Scrap yard
Ir-192	1.9e-01	4.0e-02	1.2e-01	5.8e-01	7.0e-04	1.5e-04	4.4e-04	2.2e-03	Scrap yard
Tl-204	1.9e-04	4.7e-05	1.2e-04	5.6e-04	7.0e-07	1.8e-07	4.5e-07	2.1e-06	Scrap yard
Pb-210	3.9e-01	6.8e-02	2.9e-01	1.0e+00	1.4e-03	2.5e-04	1.1e-03	3.8e-03	Handling slag
Bi-207	5.5e-01	1.2e-01	3.5e-01	1.7e+00	2.0e-03	4.4e-04	1.3e-03	6.2e-03	Scrap yard
Po-210	3.9e-02	1.0e-02	2.5e-02	1.2e-01	1.5e-04	3.7e-05	9.2e-05	4.5e-04	Scrap yard
Ra-226	1.1e+00	4.2e-01	9.6e-01	2.5e+00	4.3e-03	1.5e-03	3.6e-03	9.2e-03	Handling slag
Ra-228	7.8e-01	2.8e-01	6.4e-01	1.7e+00	2.9e-03	1.0e-03	2.4e-03	6.3e-03	Handling slag

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.9 Normalized mass-based effective dose equivalents to critical groups for copper

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	2.7e+01	8.4e+00	2.2e+01	6.4e+01	1.0e-01	3.1e-02	8.1e-02	2.4e-01	Handling slag
Th-228	7.6e+00	2.4e+00	6.1e+00	1.8e+01	2.8e-02	8.9e-03	2.3e-02	6.5e-02	Handling slag
Th-229	3.6e+01	1.1e+01	2.8e+01	8.4e+01	1.3e-01	4.0e-02	1.0e-01	3.1e-01	Handling slag
Th-230	5.3e+00	1.6e+00	4.2e+00	1.3e+01	2.0e-02	6.0e-03	1.6e-02	4.6e-02	Handling slag
Th-232	2.4e+01	7.2e+00	1.9e+01	5.6e+01	8.7e-02	2.7e-02	6.9e-02	2.1e-01	Handling slag
Pa-231	1.8e+01	5.5e+00	1.4e+01	4.2e+01	6.6e-02	2.0e-02	5.3e-02	1.5e-01	Handling slag
U-232	1.3e+01	4.1e+00	1.1e+01	3.2e+01	5.0e-02	1.5e-02	4.0e-02	1.2e-01	Handling slag
U-233	2.7e+00	8.3e-01	2.2e+00	6.5e+00	1.0e-02	3.1e-03	8.1e-03	2.4e-02	Handling slag
U-234	2.7e+00	8.1e-01	2.1e+00	6.3e+00	9.9e-03	3.0e-03	7.9e-03	2.3e-02	Handling slag
U-235	2.6e+00	7.9e-01	2.1e+00	6.1e+00	9.6e-03	2.9e-03	7.6e-03	2.2e-02	Handling slag
U-236	2.5e+00	7.7e-01	2.0e+00	6.0e+00	9.4e-03	2.8e-03	7.5e-03	2.2e-02	Handling slag
U-238	2.4e+00	7.3e-01	1.9e+00	5.7e+00	8.9e-03	2.7e-03	7.1e-03	2.1e-02	Handling slag
Np-237	1.1e+01	3.4e+00	8.9e+00	2.6e+01	4.1e-02	1.3e-02	3.3e-02	9.7e-02	Handling slag
Pu-236	2.8e+00	8.6e-01	2.2e+00	6.6e+00	1.0e-02	3.2e-03	8.3e-03	2.4e-02	Handling slag
Pu-238	6.0e+00	1.8e+00	4.7e+00	1.4e+01	2.2e-02	6.7e-03	1.8e-02	5.2e-02	Handling slag
Pu-239	6.4e+00	2.0e+00	5.1e+00	1.5e+01	2.4e-02	7.2e-03	1.9e-02	5.5e-02	Handling slag
Pu-240	6.4e+00	2.0e+00	5.1e+00	1.5e+01	2.4e-02	7.2e-03	1.9e-02	5.5e-02	Handling slag
Pu-241	1.0e-01	3.2e-02	8.3e-02	2.4e-01	3.8e-04	1.2e-04	3.1e-04	9.0e-04	Handling slag
Pu-242	6.1e+00	1.9e+00	4.8e+00	1.4e+01	2.2e-02	6.9e-03	1.8e-02	5.3e-02	Handling slag
Pu-244	6.2e+00	1.9e+00	4.9e+00	1.4e+01	2.3e-02	7.1e-03	1.8e-02	5.3e-02	Handling slag
Am-241	9.1e+00	2.8e+00	7.3e+00	2.2e+01	3.4e-02	1.0e-02	2.7e-02	8.0e-02	Handling slag
Am-242m	9.0e+00	2.8e+00	7.2e+00	2.1e+01	3.3e-02	1.0e-02	2.7e-02	7.9e-02	Handling slag
Am-243	9.1e+00	2.8e+00	7.3e+00	2.1e+01	3.4e-02	1.0e-02	2.7e-02	7.9e-02	Handling slag
Cm-242	3.2e-01	9.9e-02	2.6e-01	7.7e-01	1.2e-03	3.7e-04	9.6e-04	2.8e-03	Handling slag
Cm-243	6.3e+00	1.9e+00	5.1e+00	1.5e+01	2.3e-02	7.2e-03	1.9e-02	5.5e-02	Handling slag
Cm-244	5.1e+00	1.6e+00	4.1e+00	1.2e+01	1.9e-02	5.8e-03	1.5e-02	4.4e-02	Handling slag
Cm-245	9.4e+00	2.9e+00	7.5e+00	2.2e+01	3.5e-02	1.1e-02	2.8e-02	8.2e-02	Handling slag
Cm-246	9.3e+00	2.8e+00	7.4e+00	2.2e+01	3.4e-02	1.0e-02	2.7e-02	8.1e-02	Handling slag
Cm-247	8.7e+00	2.7e+00	6.9e+00	2.0e+01	3.2e-02	9.9e-03	2.6e-02	7.5e-02	Handling slag
Cm-248	3.4e+01	1.0e+01	2.7e+01	8.0e+01	1.3e-01	3.8e-02	1.0e-01	3.0e-01	Handling slag
Bk-249	2.8e-02	8.6e-03	2.2e-02	6.6e-02	1.0e-04	3.2e-05	8.3e-05	2.5e-04	Handling slag
Cf-248	1.0e+00	3.1e-01	8.0e-01	2.4e+00	3.7e-03	1.1e-03	3.0e-03	8.8e-03	Handling slag
Cf-249	8.0e+00	2.5e+00	6.4e+00	1.9e+01	3.0e-02	9.2e-03	2.4e-02	7.0e-02	Handling slag
Cf-250	4.2e+00	1.3e+00	3.4e+00	1.0e+01	1.6e-02	4.8e-03	1.3e-02	3.7e-02	Handling slag
Cf-251	8.1e+00	2.5e+00	6.4e+00	1.9e+01	3.0e-02	9.2e-03	2.4e-02	7.0e-02	Handling slag
Cf-252	3.2e+00	9.7e-01	2.5e+00	7.5e+00	1.2e-02	3.6e-03	9.3e-03	2.8e-02	Handling slag
Cf-254	1.2e+01	4.3e+00	1.0e+01	2.7e+01	4.5e-02	1.6e-02	3.7e-02	9.9e-02	Handling slag
Es-254	1.3e+00	4.5e-01	1.1e+00	2.8e+00	4.7e-03	1.7e-03	3.9e-03	1.1e-02	Handling slag

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.10 Normalized surficial effective dose equivalents to critical groups for copper

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	2.0e-04	0.0e+00	1.5e-07	8.2e-04	7.3e-07	0.0e+00	5.4e-10	3.0e-06	Leachate-industrial-scrap
C-14	4.7e-04	1.4e-04	3.5e-04	1.2e-03	1.7e-06	5.3e-07	1.3e-06	4.4e-06	Airborne emissions
Na-22	2.3e+00	7.7e-01	1.9e+00	5.0e+00	8.3e-03	2.9e-03	6.9e-03	1.8e-02	Handling slag
P-32	1.5e-03	2.4e-04	9.0e-04	4.9e-03	5.7e-06	8.9e-07	3.3e-06	1.8e-05	Scrap yard
S-35	5.3e-05	1.1e-05	3.9e-05	1.4e-04	2.0e-07	4.1e-08	1.4e-07	5.2e-07	Handling slag
Cl-36	4.0e-03	0.0e+00	0.0e+00	1.6e-02	1.5e-05	0.0e+00	0.0e+00	5.8e-05	Leachate-industrial-scrap
K-40	1.3e-01	2.7e-02	7.9e-02	3.7e-01	4.7e-04	9.9e-05	2.9e-04	1.4e-03	Scrap yard
Ca-41	2.2e-03	0.0e+00	0.0e+00	9.2e-03	8.2e-06	0.0e+00	0.0e+00	3.4e-05	Leachate-industrial-scrap
Ca-45	4.3e-04	1.2e-04	3.4e-04	1.0e-03	1.6e-06	4.5e-07	1.3e-06	3.8e-06	Handling slag
Sc-46	1.8e+00	6.1e-01	1.5e+00	4.0e+00	6.7e-03	2.3e-03	5.5e-03	1.5e-02	Handling slag
Cr-51	1.6e-02	4.7e-03	1.3e-02	3.8e-02	5.9e-05	1.7e-05	4.7e-05	1.4e-04	Handling slag
Mn-53	2.6e-05	8.1e-06	2.1e-05	6.1e-05	9.7e-08	3.0e-08	7.7e-08	2.3e-07	Handling slag
Mn-54	8.4e-01	2.9e-01	6.9e-01	1.9e+00	3.1e-03	1.1e-03	2.6e-03	6.9e-03	Handling slag
Fe-55	8.4e-05	2.4e-05	6.6e-05	2.0e-04	3.1e-07	8.8e-08	2.4e-07	7.4e-07	Handling slag
Fe-59	8.4e-01	2.7e-01	6.8e-01	1.9e+00	3.1e-03	1.0e-03	2.5e-03	7.1e-03	Handling slag
Co-56	2.5e+00	8.0e-01	2.0e+00	5.6e+00	9.3e-03	3.0e-03	7.5e-03	2.1e-02	Handling slag
Co-57	2.9e-02	9.5e-03	2.4e-02	6.5e-02	1.1e-04	3.5e-05	8.8e-05	2.4e-04	Handling slag
Co-58	6.8e-01	2.2e-01	5.5e-01	1.5e+00	2.5e-03	8.1e-04	2.0e-03	5.7e-03	Handling slag
Co-60	2.2e+00	7.2e-01	1.8e+00	4.9e+00	8.1e-03	2.7e-03	6.6e-03	1.8e-02	Handling slag
Ni-59	5.4e-05	1.7e-05	4.3e-05	1.2e-04	2.0e-07	6.4e-08	1.6e-07	4.5e-07	Handling slag
Ni-63	1.0e-04	3.1e-05	8.2e-05	2.5e-04	3.9e-07	1.1e-07	3.0e-07	9.1e-07	Handling slag
Zn-65	5.3e-01	1.8e-01	4.4e-01	1.2e+00	2.0e-03	6.7e-04	1.6e-03	4.3e-03	Handling slag
As-73	3.2e-04	1.2e-05	9.9e-05	1.1e-03	1.2e-06	4.5e-08	3.7e-07	4.2e-06	Scrap disposal-industrial
Se-75	1.3e-01	2.6e-02	8.0e-02	3.8e-01	4.7e-04	9.8e-05	2.9e-04	1.4e-03	Scrap yard
Sr-85	3.9e-01	1.3e-01	3.2e-01	8.8e-01	1.4e-03	4.8e-04	1.2e-03	3.2e-03	Handling slag
Sr-89	2.2e-03	7.3e-04	1.8e-03	5.2e-03	8.3e-06	2.7e-06	6.7e-06	1.9e-05	Handling slag
Sr-90	2.6e-02	8.0e-03	2.1e-02	6.0e-02	9.7e-05	3.0e-05	7.7e-05	2.2e-04	Handling slag
Y-91	6.7e-03	2.3e-03	5.5e-03	1.5e-02	2.5e-05	8.5e-06	2.0e-05	5.6e-05	Handling slag
Zr-93	3.4e-03	1.0e-03	2.7e-03	8.0e-03	1.3e-05	3.8e-06	1.0e-05	3.0e-05	Handling slag
Zr-95	8.6e-01	3.0e-01	7.1e-01	1.9e+00	3.2e-03	1.1e-03	2.6e-03	7.0e-03	Handling slag
Nb-93m	1.2e-03	3.6e-04	9.4e-04	2.8e-03	4.4e-06	1.3e-06	3.5e-06	1.0e-05	Handling slag
Nb-94	1.7e+00	5.8e-01	1.4e+00	3.7e+00	6.2e-03	2.1e-03	5.2e-03	1.4e-02	Handling slag
Nb-95	5.3e-01	1.7e-01	4.3e-01	1.2e+00	2.0e-03	6.2e-04	1.6e-03	4.6e-03	Handling slag
Mo-93	1.2e-03	3.9e-04	9.9e-04	2.9e-03	4.6e-06	1.4e-06	3.7e-06	1.1e-05	Handling slag
Tc-97	2.1e-03	0.0e+00	0.0e+00	8.7e-03	8.0e-06	0.0e+00	0.0e+00	3.2e-05	Leachate-industrial-scrap
Tc-97m	3.1e-04	1.0e-04	2.5e-04	7.1e-04	1.2e-06	3.8e-07	9.4e-07	2.6e-06	Handling slag
Tc-99	1.8e-02	0.0e+00	0.0e+00	7.5e-02	6.8e-05	0.0e+00	0.0e+00	2.8e-04	Leachate-industrial-scrap
Ru-103	2.2e-01	4.4e-02	1.4e-01	6.8e-01	8.2e-04	1.6e-04	5.1e-04	2.5e-03	Scrap yard
Ru-106	1.5e-01	3.3e-02	9.8e-02	4.5e-01	5.7e-04	1.2e-04	3.6e-04	1.7e-03	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.10 Normalized surficial effective dose equivalents to critical groups for copper

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	1.1e+00	2.3e-01	6.7e-01	3.2e+00	3.9e-03	8.3e-04	2.5e-03	1.2e-02	Scrap yard
Ag-110m	1.9e+00	4.0e-01	1.2e+00	5.6e+00	7.0e-03	1.5e-03	4.4e-03	2.1e-02	Scrap yard
Cd-109	2.9e-03	9.6e-04	2.4e-03	6.7e-03	1.1e-05	3.5e-06	8.7e-06	2.5e-05	Handling slag
Sn-113	1.8e-01	6.0e-02	1.4e-01	3.9e-01	6.5e-04	2.2e-04	5.4e-04	1.4e-03	Handling slag
Sb-124	1.1e+00	3.5e-01	9.0e-01	2.6e+00	4.2e-03	1.3e-03	3.3e-03	9.7e-03	Handling slag
Sb-125	3.1e-01	9.9e-02	2.5e-01	7.0e-01	1.1e-03	3.7e-04	9.1e-04	2.6e-03	Handling slag
Te-123m	2.6e-02	5.5e-03	1.6e-02	7.7e-02	9.6e-05	2.0e-05	6.1e-05	2.9e-04	Scrap yard
Te-127m	2.9e-03	6.5e-04	1.8e-03	8.6e-03	1.1e-05	2.4e-06	6.7e-06	3.2e-05	Scrap yard
I-125	3.0e-03	7.1e-04	2.3e-03	7.6e-03	1.1e-05	2.6e-06	8.4e-06	2.8e-05	Handling slag
I-129	7.8e-01	0.0e+00	0.0e+00	2.7e+00	2.9e-03	0.0e+00	0.0e+00	1.0e-02	Leachate-industrial-scrap
I-131	7.1e-02	6.9e-03	4.1e-02	2.3e-01	2.6e-04	2.5e-05	1.5e-04	8.7e-04	Handling slag
Cs-134	1.1e+00	2.2e-01	6.7e-01	3.1e+00	3.9e-03	8.3e-04	2.5e-03	1.2e-02	Scrap yard
Cs-135	1.7e-04	2.6e-05	1.1e-04	5.2e-04	6.2e-07	9.8e-08	3.9e-07	1.9e-06	Scrap yard
Cs-137	3.9e-01	8.1e-02	2.4e-01	1.1e+00	1.4e-03	3.0e-04	9.0e-04	4.2e-03	Scrap yard
Ba-133	3.0e-01	1.0e-01	2.5e-01	6.5e-01	1.1e-03	3.8e-04	9.1e-04	2.4e-03	Handling slag
Ce-139	5.6e-02	1.9e-02	4.6e-02	1.2e-01	2.1e-04	7.1e-05	1.7e-04	4.6e-04	Handling slag
Ce-141	1.8e-02	5.5e-03	1.4e-02	4.1e-02	6.5e-05	2.0e-05	5.2e-05	1.5e-04	Handling slag
Ce-144	5.9e-02	2.1e-02	4.9e-02	1.3e-01	2.2e-04	7.8e-05	1.8e-04	4.7e-04	Handling slag
Pm-147	1.6e-03	4.9e-04	1.3e-03	3.7e-03	5.9e-06	1.8e-06	4.7e-06	1.4e-05	Handling slag
Sm-151	1.2e-03	3.7e-04	9.6e-04	2.8e-03	4.5e-06	1.4e-06	3.5e-06	1.1e-05	Handling slag
Eu-152	1.2e+00	4.0e-01	9.7e-01	2.6e+00	4.4e-03	1.5e-03	3.6e-03	9.6e-03	Handling slag
Eu-154	1.2e+00	4.0e-01	9.5e-01	2.5e+00	4.3e-03	1.5e-03	3.5e-03	9.4e-03	Handling slag
Eu-155	1.2e-02	4.3e-03	1.0e-02	2.6e-02	4.5e-05	1.6e-05	3.7e-05	9.7e-05	Handling slag
Gd-153	1.3e-02	4.5e-03	1.1e-02	2.9e-02	4.8e-05	1.7e-05	4.0e-05	1.1e-04	Handling slag
Tb-160	9.4e-01	3.2e-01	7.7e-01	2.1e+00	3.5e-03	1.2e-03	2.9e-03	7.8e-03	Handling slag
Tm-170	2.1e-03	7.1e-04	1.7e-03	4.6e-03	7.6e-06	2.6e-06	6.3e-06	1.7e-05	Handling slag
Tm-171	4.2e-04	1.4e-04	3.4e-04	9.8e-04	1.6e-06	5.1e-07	1.3e-06	3.6e-06	Handling slag
Ta-182	1.1e+00	3.9e-01	9.4e-01	2.5e+00	4.2e-03	1.4e-03	3.5e-03	9.3e-03	Handling slag
W-181	2.9e-03	9.7e-04	2.4e-03	6.3e-03	1.1e-05	3.6e-06	8.7e-06	2.3e-05	Handling slag
W-185	1.5e-04	3.7e-05	1.1e-04	3.7e-04	5.5e-07	1.4e-07	4.2e-07	1.4e-06	Handling slag
Os-185	3.9e-01	8.1e-02	2.4e-01	1.2e+00	1.4e-03	3.0e-04	9.0e-04	4.3e-03	Scrap yard
Ir-192	3.7e-01	7.6e-02	2.3e-01	1.1e+00	1.4e-03	2.8e-04	8.6e-04	4.1e-03	Scrap yard
Tl-204	3.7e-04	9.1e-05	2.3e-04	1.1e-03	1.4e-06	3.3e-07	8.7e-07	4.1e-06	Scrap yard
Pb-210	7.5e-01	1.3e-01	5.6e-01	2.0e+00	2.8e-03	4.7e-04	2.1e-03	7.3e-03	Handling slag
Bi-207	1.1e+00	2.3e-01	6.7e-01	3.2e+00	4.0e-03	8.3e-04	2.5e-03	1.2e-02	Scrap yard
Po-210	7.7e-02	1.9e-02	4.8e-02	2.3e-01	2.8e-04	7.1e-05	1.8e-04	8.7e-04	Scrap yard
Ra-226	2.2e+00	7.9e-01	1.8e+00	4.8e+00	8.2e-03	2.9e-03	6.8e-03	1.8e-02	Handling slag
Ra-228	1.5e+00	5.2e-01	1.2e+00	3.3e+00	5.6e-03	1.9e-03	4.6e-03	1.2e-02	Handling slag

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.10 Normalized surficial effective dose equivalents to critical groups for copper

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	5.3e+01	1.6e+01	4.2e+01	1.2e+02	2.0e-01	5.9e-02	1.6e-01	4.6e-01	Handling slag
Th-228	1.5e+01	4.6e+00	1.2e+01	3.4e+01	5.4e-02	1.7e-02	4.3e-02	1.3e-01	Handling slag
Th-229	6.9e+01	2.1e+01	5.5e+01	1.6e+02	2.5e-01	7.7e-02	2.0e-01	6.0e-01	Handling slag
Th-230	1.0e+01	3.1e+00	8.2e+00	2.4e+01	3.8e-02	1.1e-02	3.0e-02	9.0e-02	Handling slag
Th-232	4.6e+01	1.4e+01	3.6e+01	1.1e+02	1.7e-01	5.1e-02	1.3e-01	4.0e-01	Handling slag
Pa-231	3.4e+01	1.0e+01	2.7e+01	8.2e+01	1.3e-01	3.9e-02	1.0e-01	3.0e-01	Handling slag
U-232	2.6e+01	7.9e+00	2.1e+01	6.2e+01	9.7e-02	2.9e-02	7.7e-02	2.3e-01	Handling slag
U-233	5.3e+00	1.6e+00	4.2e+00	1.3e+01	2.0e-02	5.9e-03	1.6e-02	4.7e-02	Handling slag
U-234	5.2e+00	1.6e+00	4.1e+00	1.2e+01	1.9e-02	5.8e-03	1.5e-02	4.6e-02	Handling slag
U-235	5.0e+00	1.5e+00	4.0e+00	1.2e+01	1.9e-02	5.6e-03	1.5e-02	4.4e-02	Handling slag
U-236	4.9e+00	1.5e+00	3.9e+00	1.2e+01	1.8e-02	5.5e-03	1.4e-02	4.3e-02	Handling slag
U-238	4.7e+00	1.4e+00	3.7e+00	1.1e+01	1.7e-02	5.2e-03	1.4e-02	4.1e-02	Handling slag
Np-237	2.2e+01	6.6e+00	1.7e+01	5.1e+01	8.0e-02	2.4e-02	6.4e-02	1.9e-01	Handling slag
Pu-236	5.4e+00	1.6e+00	4.3e+00	1.3e+01	2.0e-02	6.1e-03	1.6e-02	4.8e-02	Handling slag
Pu-238	1.2e+01	3.5e+00	9.2e+00	2.7e+01	4.3e-02	1.3e-02	3.4e-02	1.0e-01	Handling slag
Pu-239	1.2e+01	3.7e+00	9.8e+00	2.9e+01	4.6e-02	1.4e-02	3.6e-02	1.1e-01	Handling slag
Pu-240	1.2e+01	3.7e+00	9.8e+00	2.9e+01	4.6e-02	1.4e-02	3.6e-02	1.1e-01	Handling slag
Pu-241	2.0e-01	6.1e-02	1.6e-01	4.7e-01	7.4e-04	2.3e-04	5.9e-04	1.8e-03	Handling slag
Pu-242	1.2e+01	3.6e+00	9.3e+00	2.8e+01	4.3e-02	1.3e-02	3.4e-02	1.0e-01	Handling slag
Pu-244	1.2e+01	3.7e+00	9.5e+00	2.8e+01	4.4e-02	1.4e-02	3.5e-02	1.0e-01	Handling slag
Am-241	1.8e+01	5.4e+00	1.4e+01	4.2e+01	6.5e-02	2.0e-02	5.2e-02	1.5e-01	Handling slag
Am-242m	1.8e+01	5.3e+00	1.4e+01	4.2e+01	6.5e-02	2.0e-02	5.1e-02	1.5e-01	Handling slag
Am-243	1.8e+01	5.3e+00	1.4e+01	4.2e+01	6.5e-02	2.0e-02	5.2e-02	1.5e-01	Handling slag
Cm-242	6.3e-01	1.9e-01	5.0e-01	1.5e+00	2.3e-03	7.0e-04	1.9e-03	5.5e-03	Handling slag
Cm-243	1.2e+01	3.7e+00	9.7e+00	2.9e+01	4.5e-02	1.4e-02	3.6e-02	1.1e-01	Handling slag
Cm-244	9.8e+00	3.0e+00	7.8e+00	2.3e+01	3.6e-02	1.1e-02	2.9e-02	8.6e-02	Handling slag
Cm-245	1.8e+01	5.5e+00	1.4e+01	4.3e+01	6.7e-02	2.0e-02	5.3e-02	1.6e-01	Handling slag
Cm-246	1.8e+01	5.5e+00	1.4e+01	4.3e+01	6.6e-02	2.0e-02	5.3e-02	1.6e-01	Handling slag
Cm-247	1.7e+01	5.1e+00	1.3e+01	4.0e+01	6.2e-02	1.9e-02	4.9e-02	1.5e-01	Handling slag
Cm-248	6.6e+01	2.0e+01	5.2e+01	1.6e+02	2.4e-01	7.4e-02	1.9e-01	5.8e-01	Handling slag
Bk-249	5.4e-02	1.6e-02	4.3e-02	1.3e-01	2.0e-04	6.1e-05	1.6e-04	4.8e-04	Handling slag
Cf-248	1.9e+00	5.9e-01	1.5e+00	4.6e+00	7.2e-03	2.2e-03	5.7e-03	1.7e-02	Handling slag
Cf-249	1.6e+01	4.8e+00	1.2e+01	3.7e+01	5.8e-02	1.8e-02	4.6e-02	1.4e-01	Handling slag
Cf-250	8.2e+00	2.5e+00	6.5e+00	1.9e+01	3.0e-02	9.2e-03	2.4e-02	7.2e-02	Handling slag
Cf-251	1.6e+01	4.7e+00	1.2e+01	3.7e+01	5.8e-02	1.8e-02	4.6e-02	1.4e-01	Handling slag
Cf-252	6.1e+00	1.9e+00	4.9e+00	1.5e+01	2.3e-02	6.8e-03	1.8e-02	5.4e-02	Handling slag
Cf-254	2.4e+01	8.2e+00	1.9e+01	5.3e+01	8.8e-02	3.0e-02	7.2e-02	2.0e-01	Handling slag
Es-254	2.5e+00	8.6e-01	2.0e+00	5.5e+00	9.2e-03	3.2e-03	7.5e-03	2.1e-02	Handling slag

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.11 Normalized mass-based effective doses to critical groups for copper

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	1.1e-04	0.0e+00	7.9e-08	4.4e-04	3.9e-07	0.0e+00	2.9e-10	1.6e-06	Leachate-industrial-scrap
C-14	2.5e-04	7.7e-05	1.9e-04	6.3e-04	9.2e-07	2.8e-07	6.9e-07	2.3e-06	Airborne emissions
Na-22	1.1e+00	4.0e-01	9.4e-01	2.5e+00	4.2e-03	1.5e-03	3.5e-03	9.2e-03	Handling slag
P-32	7.8e-04	1.2e-04	4.6e-04	2.5e-03	2.9e-06	4.5e-07	1.7e-06	9.4e-06	Scrap yard
S-35	4.2e-05	8.8e-06	3.1e-05	1.1e-04	1.5e-07	3.3e-08	1.2e-07	4.1e-07	Handling slag
Cl-36	2.3e-03	0.0e+00	0.0e+00	9.2e-03	8.7e-06	0.0e+00	0.0e+00	3.4e-05	Leachate-industrial-scrap
K-40	6.5e-02	1.4e-02	4.1e-02	2.0e-01	2.4e-04	5.2e-05	1.5e-04	7.3e-04	Scrap yard
Ca-41	9.5e-04	0.0e+00	0.0e+00	4.0e-03	3.5e-06	0.0e+00	0.0e+00	1.5e-05	Leachate-industrial-scrap
Ca-45	2.5e-04	7.5e-05	2.0e-04	5.7e-04	9.1e-07	2.8e-07	7.3e-07	2.1e-06	Handling slag
Sc-46	9.1e-01	3.1e-01	7.5e-01	2.0e+00	3.4e-03	1.2e-03	2.8e-03	7.4e-03	Handling slag
Cr-51	7.9e-03	2.4e-03	6.3e-03	1.9e-02	2.9e-05	8.7e-06	2.3e-05	7.0e-05	Handling slag
Mn-53	6.3e-06	1.6e-06	4.9e-06	1.5e-05	2.3e-08	5.9e-09	1.8e-08	5.7e-08	Handling slag
Mn-54	4.2e-01	1.5e-01	3.5e-01	9.2e-01	1.6e-03	5.5e-04	1.3e-03	3.4e-03	Handling slag
Fe-55	6.0e-05	1.4e-05	4.6e-05	1.5e-04	2.2e-07	5.3e-08	1.7e-07	5.5e-07	Handling slag
Fe-59	4.3e-01	1.4e-01	3.4e-01	9.6e-01	1.6e-03	5.2e-04	1.3e-03	3.6e-03	Handling slag
Co-56	1.3e+00	4.2e-01	1.0e+00	2.8e+00	4.7e-03	1.5e-03	3.8e-03	1.0e-02	Handling slag
Co-57	1.5e-02	4.8e-03	1.2e-02	3.2e-02	5.4e-05	1.8e-05	4.4e-05	1.2e-04	Handling slag
Co-58	3.4e-01	1.1e-01	2.8e-01	7.7e-01	1.3e-03	4.1e-04	1.0e-03	2.8e-03	Handling slag
Co-60	1.1e+00	3.7e-01	9.0e-01	2.4e+00	4.1e-03	1.4e-03	3.3e-03	9.1e-03	Handling slag
Ni-59	1.9e-05	5.9e-06	1.5e-05	4.3e-05	6.9e-08	2.2e-08	5.5e-08	1.6e-07	Handling slag
Ni-63	3.4e-05	9.4e-06	2.7e-05	8.2e-05	1.3e-07	3.5e-08	9.9e-08	3.0e-07	Handling slag
Zn-65	2.7e-01	9.3e-02	2.2e-01	5.8e-01	9.9e-04	3.4e-04	8.2e-04	2.2e-03	Handling slag
As-73	1.4e-04	5.4e-06	4.3e-05	4.7e-04	5.2e-07	2.0e-08	1.6e-07	1.7e-06	Scrap disposal-industrial
Se-75	6.5e-02	1.4e-02	4.1e-02	2.0e-01	2.4e-04	5.0e-05	1.5e-04	7.3e-04	Scrap yard
Sr-85	2.0e-01	6.7e-02	1.6e-01	4.4e-01	7.3e-04	2.5e-04	6.0e-04	1.6e-03	Handling slag
Sr-89	1.1e-03	3.7e-04	9.1e-04	2.6e-03	4.1e-06	1.4e-06	3.4e-06	9.4e-06	Handling slag
Sr-90	9.4e-03	2.9e-03	7.4e-03	2.2e-02	3.5e-05	1.1e-05	2.8e-05	8.0e-05	Handling slag
Y-91	3.0e-03	1.0e-03	2.4e-03	6.6e-03	1.1e-05	3.8e-06	9.0e-06	2.4e-05	Handling slag
Zr-93	5.3e-04	1.7e-04	4.3e-04	1.2e-03	2.0e-06	6.1e-07	1.6e-06	4.6e-06	Handling slag
Zr-95	4.3e-01	1.5e-01	3.6e-01	9.5e-01	1.6e-03	5.7e-04	1.3e-03	3.5e-03	Handling slag
Nb-93m	8.1e-05	2.6e-05	6.5e-05	1.9e-04	3.0e-07	9.6e-08	2.4e-07	6.9e-07	Handling slag
Nb-94	8.4e-01	3.0e-01	7.0e-01	1.8e+00	3.1e-03	1.1e-03	2.6e-03	6.8e-03	Handling slag
Nb-95	2.7e-01	8.5e-02	2.2e-01	6.2e-01	9.9e-04	3.1e-04	8.0e-04	2.3e-03	Handling slag
Mo-93	1.2e-03	0.0e+00	0.0e+00	1.4e-03	4.5e-06	0.0e+00	0.0e+00	5.2e-06	Leachate-industrial-scrap
Tc-97	2.0e-03	0.0e+00	0.0e+00	8.1e-03	7.4e-06	0.0e+00	0.0e+00	3.0e-05	Leachate-industrial-scrap
Tc-97m	2.8e-04	8.9e-05	2.2e-04	6.3e-04	1.0e-06	3.3e-07	8.2e-07	2.3e-06	Handling slag
Tc-99	1.9e-02	0.0e+00	0.0e+00	7.6e-02	6.9e-05	0.0e+00	0.0e+00	2.8e-04	Leachate-industrial-scrap
Ru-103	1.1e-01	2.3e-02	7.1e-02	3.5e-01	4.2e-04	8.4e-05	2.6e-04	1.3e-03	Scrap yard
Ru-106	7.8e-02	1.7e-02	4.9e-02	2.4e-01	2.9e-04	6.2e-05	1.8e-04	8.8e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.11 Normalized mass-based effective doses to critical groups for copper

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	5.4e-01	1.2e-01	3.4e-01	1.7e+00	2.0e-03	4.3e-04	1.3e-03	6.1e-03	Scrap yard
Ag-110m	9.6e-01	2.0e-01	6.1e-01	2.9e+00	3.6e-03	7.5e-04	2.3e-03	1.1e-02	Scrap yard
Cd-109	8.0e-04	2.7e-04	6.6e-04	1.8e-03	3.0e-06	1.0e-06	2.4e-06	6.6e-06	Handling slag
Sn-113	8.8e-02	3.1e-02	7.3e-02	1.9e-01	3.3e-04	1.1e-04	2.7e-04	7.2e-04	Handling slag
Sb-124	5.7e-01	1.2e-01	3.6e-01	1.8e+00	2.1e-03	4.4e-04	1.3e-03	6.5e-03	Scrap yard
Sb-125	1.5e-01	5.1e-02	1.3e-01	3.5e-01	5.7e-04	1.9e-04	4.6e-04	1.3e-03	Handling slag
Te-123m	1.3e-02	2.8e-03	8.4e-03	4.1e-02	4.9e-05	1.0e-05	3.1e-05	1.5e-04	Scrap yard
Te-127m	1.5e-03	3.4e-04	9.4e-04	4.5e-03	5.5e-06	1.3e-06	3.5e-06	1.7e-05	Scrap yard
I-125	2.0e-03	4.1e-04	1.5e-03	5.1e-03	7.2e-06	1.5e-06	5.4e-06	1.9e-05	Handling slag
I-129	5.9e-01	0.0e+00	0.0e+00	2.1e+00	2.2e-03	0.0e+00	0.0e+00	7.9e-03	Leachate-industrial-scrap
I-131	3.6e-02	3.5e-03	2.1e-02	1.2e-01	1.3e-04	1.3e-05	7.7e-05	4.4e-04	Handling slag
Cs-134	5.4e-01	1.2e-01	3.4e-01	1.7e+00	2.0e-03	4.3e-04	1.3e-03	6.1e-03	Scrap yard
Cs-135	8.4e-05	1.1e-05	5.3e-05	2.7e-04	3.1e-07	4.2e-08	2.0e-07	9.8e-07	Scrap yard
Cs-137	2.0e-01	4.2e-02	1.2e-01	6.0e-01	7.3e-04	1.6e-04	4.6e-04	2.2e-03	Scrap yard
Ba-133	1.5e-01	5.2e-02	1.2e-01	3.2e-01	5.5e-04	1.9e-04	4.6e-04	1.2e-03	Handling slag
Ce-139	2.8e-02	9.8e-03	2.3e-02	6.1e-02	1.0e-04	3.6e-05	8.6e-05	2.3e-04	Handling slag
Ce-141	8.9e-03	2.8e-03	7.1e-03	2.1e-02	3.3e-05	1.0e-05	2.6e-05	7.6e-05	Handling slag
Ce-144	2.5e-02	8.8e-03	2.1e-02	5.3e-02	9.1e-05	3.3e-05	7.6e-05	2.0e-04	Handling slag
Pm-147	2.7e-04	8.6e-05	2.2e-04	6.3e-04	1.0e-06	3.2e-07	8.1e-07	2.3e-06	Handling slag
Sm-151	2.1e-04	6.5e-05	1.7e-04	4.9e-04	7.7e-07	2.4e-07	6.2e-07	1.8e-06	Handling slag
Eu-152	5.9e-01	2.1e-01	4.9e-01	1.3e+00	2.2e-03	7.7e-04	1.8e-03	4.8e-03	Handling slag
Eu-154	5.8e-01	2.0e-01	4.8e-01	1.3e+00	2.1e-03	7.5e-04	1.8e-03	4.7e-03	Handling slag
Eu-155	5.6e-03	2.0e-03	4.6e-03	1.2e-02	2.1e-05	7.4e-06	1.7e-05	4.5e-05	Handling slag
Gd-153	6.4e-03	2.2e-03	5.3e-03	1.4e-02	2.4e-05	8.3e-06	2.0e-05	5.1e-05	Handling slag
Tb-160	4.7e-01	1.6e-01	3.9e-01	1.1e+00	1.8e-03	6.0e-04	1.4e-03	3.9e-03	Handling slag
Tm-170	9.1e-04	3.2e-04	7.5e-04	2.0e-03	3.4e-06	1.2e-06	2.8e-06	7.3e-06	Handling slag
Tm-171	1.0e-04	3.5e-05	8.3e-05	2.3e-04	3.7e-07	1.3e-07	3.1e-07	8.4e-07	Handling slag
Ta-182	5.7e-01	2.0e-01	4.7e-01	1.3e+00	2.1e-03	7.4e-04	1.8e-03	4.7e-03	Handling slag
W-181	1.4e-03	4.8e-04	1.1e-03	3.0e-03	5.1e-06	1.8e-06	4.2e-06	1.1e-05	Handling slag
W-185	7.8e-05	2.0e-05	6.0e-05	1.9e-04	2.9e-07	7.3e-08	2.2e-07	7.1e-07	Handling slag
Os-185	2.0e-01	4.1e-02	1.2e-01	6.0e-01	7.3e-04	1.5e-04	4.6e-04	2.2e-03	Scrap yard
Ir-192	1.9e-01	3.9e-02	1.2e-01	5.8e-01	7.0e-04	1.4e-04	4.4e-04	2.1e-03	Scrap yard
Tl-204	2.0e-04	5.0e-05	1.3e-04	6.0e-04	7.5e-07	1.9e-07	4.8e-07	2.2e-06	Scrap yard
Pb-210	2.4e-01	4.2e-02	1.8e-01	6.2e-01	8.8e-04	1.6e-04	6.6e-04	2.3e-03	Handling slag
Bi-207	5.5e-01	1.2e-01	3.4e-01	1.7e+00	2.0e-03	4.3e-04	1.3e-03	6.2e-03	Scrap yard
Po-210	3.7e-02	1.0e-02	2.4e-02	1.1e-01	1.4e-04	3.8e-05	8.7e-05	4.2e-04	Scrap yard
Ra-226	1.1e+00	4.0e-01	9.3e-01	2.4e+00	4.1e-03	1.5e-03	3.4e-03	8.8e-03	Handling slag
Ra-228	7.3e-01	2.6e-01	6.1e-01	1.6e+00	2.7e-03	9.7e-04	2.3e-03	5.9e-03	Handling slag

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.11 Normalized mass-based effective doses to critical groups for copper

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	5.1e+00	1.6e+00	4.1e+00	1.2e+01	1.9e-02	5.8e-03	1.5e-02	4.4e-02	Handling slag
Th-228	3.3e+00	1.1e+00	2.7e+00	7.4e+00	1.2e-02	4.1e-03	9.8e-03	2.7e-02	Handling slag
Th-229	4.8e+00	1.5e+00	3.8e+00	1.1e+01	1.8e-02	5.4e-03	1.4e-02	4.1e-02	Handling slag
Th-230	5.5e-01	1.7e-01	4.4e-01	1.3e+00	2.0e-03	6.2e-04	1.6e-03	4.8e-03	Handling slag
Th-232	9.9e-01	3.0e-01	7.9e-01	2.3e+00	3.7e-03	1.1e-03	2.9e-03	8.6e-03	Handling slag
Pa-231	1.4e+00	3.9e-01	9.0e-01	4.4e+00	5.3e-03	1.4e-03	3.3e-03	1.6e-02	Scrap yard
U-232	2.0e+00	6.2e-01	1.6e+00	4.8e+00	7.5e-03	2.3e-03	6.0e-03	1.8e-02	Handling slag
U-233	5.2e-01	1.6e-01	4.1e-01	1.2e+00	1.9e-03	5.8e-04	1.5e-03	4.5e-03	Handling slag
U-234	5.1e-01	1.5e-01	4.1e-01	1.2e+00	1.9e-03	5.7e-04	1.5e-03	4.5e-03	Handling slag
U-235	5.1e-01	1.6e-01	4.1e-01	1.2e+00	1.9e-03	6.0e-04	1.5e-03	4.4e-03	Handling slag
U-236	4.7e-01	1.4e-01	3.8e-01	1.1e+00	1.7e-03	5.3e-04	1.4e-03	4.1e-03	Handling slag
U-238	4.4e-01	1.4e-01	3.5e-01	1.0e+00	1.6e-03	5.0e-04	1.3e-03	3.8e-03	Handling slag
Np-237	1.2e+00	3.9e-01	9.8e-01	2.8e+00	4.5e-03	1.4e-03	3.6e-03	1.1e-02	Handling slag
Pu-236	6.3e-01	2.0e-01	5.0e-01	1.5e+00	2.3e-03	7.2e-04	1.9e-03	5.5e-03	Handling slag
Pu-238	8.5e-01	2.6e-01	6.8e-01	2.0e+00	3.2e-03	9.7e-04	2.5e-03	7.4e-03	Handling slag
Pu-239	6.5e-01	2.0e-01	5.2e-01	1.5e+00	2.4e-03	7.5e-04	1.9e-03	5.7e-03	Handling slag
Pu-240	6.5e-01	2.0e-01	5.2e-01	1.5e+00	2.4e-03	7.5e-04	1.9e-03	5.7e-03	Handling slag
Pu-241	9.4e-03	2.5e-03	5.9e-03	2.8e-02	3.5e-05	9.3e-06	2.2e-05	1.1e-04	Scrap yard
Pu-242	6.1e-01	1.9e-01	4.9e-01	1.4e+00	2.2e-03	7.0e-04	1.8e-03	5.3e-03	Handling slag
Pu-244	7.5e-01	2.6e-01	6.1e-01	1.7e+00	2.8e-03	9.5e-04	2.3e-03	6.3e-03	Handling slag
Am-241	2.1e+00	6.3e-01	1.6e+00	4.8e+00	7.6e-03	2.3e-03	6.1e-03	1.8e-02	Handling slag
Am-242m	2.1e+00	6.5e-01	1.7e+00	5.0e+00	7.9e-03	2.4e-03	6.3e-03	1.9e-02	Handling slag
Am-243	2.1e+00	6.5e-01	1.7e+00	4.9e+00	7.8e-03	2.4e-03	6.2e-03	1.8e-02	Handling slag
Cm-242	2.5e-01	7.7e-02	2.0e-01	6.0e-01	9.4e-04	2.9e-04	7.5e-04	2.2e-03	Handling slag
Cm-243	1.6e+00	4.8e-01	1.2e+00	3.6e+00	5.7e-03	1.8e-03	4.6e-03	1.3e-02	Handling slag
Cm-244	1.3e+00	3.9e-01	1.0e+00	3.0e+00	4.8e-03	1.5e-03	3.8e-03	1.1e-02	Handling slag
Cm-245	2.1e+00	6.3e-01	1.6e+00	4.9e+00	7.6e-03	2.3e-03	6.1e-03	1.8e-02	Handling slag
Cm-246	2.1e+00	6.3e-01	1.6e+00	4.8e+00	7.6e-03	2.3e-03	6.1e-03	1.8e-02	Handling slag
Cm-247	2.0e+00	6.5e-01	1.6e+00	4.8e+00	7.6e-03	2.4e-03	6.1e-03	1.8e-02	Handling slag
Cm-248	7.2e+00	2.2e+00	5.8e+00	1.7e+01	2.7e-02	8.2e-03	2.1e-02	6.3e-02	Handling slag
Bk-249	7.7e-03	2.4e-03	6.1e-03	1.8e-02	2.8e-05	8.7e-06	2.3e-05	6.7e-05	Handling slag
Cf-248	4.4e-01	1.3e-01	3.5e-01	1.0e+00	1.6e-03	5.0e-04	1.3e-03	3.9e-03	Handling slag
Cf-249	3.6e+00	1.1e+00	2.9e+00	8.3e+00	1.3e-02	4.1e-03	1.1e-02	3.1e-02	Handling slag
Cf-250	1.7e+00	5.1e-01	1.3e+00	3.9e+00	6.2e-03	1.9e-03	4.9e-03	1.5e-02	Handling slag
Cf-251	3.5e+00	1.1e+00	2.8e+00	8.3e+00	1.3e-02	4.0e-03	1.0e-02	3.1e-02	Handling slag
Cf-252	9.7e-01	3.0e-01	7.7e-01	2.3e+00	3.6e-03	1.1e-03	2.9e-03	8.5e-03	Handling slag
Cf-254	8.7e+00	3.1e+00	7.2e+00	1.9e+01	3.2e-02	1.1e-02	2.7e-02	7.1e-02	Handling slag
Es-254	8.9e-01	3.3e-01	7.4e-01	1.9e+00	3.3e-03	1.2e-03	2.7e-03	7.2e-03	Handling slag

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.12 Normalized surficial effective doses to critical groups for copper

Radionuclide	:Sv/y per Bq/cm²				mrem/y per pCi/cm²				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	2.0e-04	0.0e+00	1.5e-07	8.5e-04	7.6e-07	0.0e+00	5.6e-10	3.1e-06	Leachate-industrial-scrap
C-14	4.8e-04	1.5e-04	3.6e-04	1.2e-03	1.8e-06	5.4e-07	1.3e-06	4.6e-06	Airborne emissions
Na-22	2.2e+00	7.6e-01	1.8e+00	4.9e+00	8.2e-03	2.8e-03	6.8e-03	1.8e-02	Handling slag
P-32	1.5e-03	2.3e-04	8.9e-04	4.9e-03	5.6e-06	8.7e-07	3.3e-06	1.8e-05	Scrap yard
S-35	8.1e-05	1.7e-05	6.0e-05	2.2e-04	3.0e-07	6.2e-08	2.2e-07	8.0e-07	Handling slag
Cl-36	4.5e-03	0.0e+00	0.0e+00	1.8e-02	1.7e-05	0.0e+00	0.0e+00	6.6e-05	Leachate-industrial-scrap
K-40	1.3e-01	2.7e-02	7.9e-02	3.7e-01	4.6e-04	9.8e-05	2.9e-04	1.4e-03	Scrap yard
Ca-41	1.9e-03	0.0e+00	0.0e+00	7.8e-03	6.9e-06	0.0e+00	0.0e+00	2.9e-05	Leachate-industrial-scrap
Ca-45	4.8e-04	1.4e-04	3.8e-04	1.1e-03	1.8e-06	5.3e-07	1.4e-06	4.1e-06	Handling slag
Sc-46	1.8e+00	6.0e-01	1.5e+00	3.9e+00	6.5e-03	2.2e-03	5.4e-03	1.5e-02	Handling slag
Cr-51	1.5e-02	4.5e-03	1.2e-02	3.7e-02	5.7e-05	1.7e-05	4.5e-05	1.4e-04	Handling slag
Mn-53	1.2e-05	3.0e-06	9.5e-06	3.0e-05	4.5e-08	1.1e-08	3.5e-08	1.1e-07	Handling slag
Mn-54	8.2e-01	2.8e-01	6.8e-01	1.8e+00	3.0e-03	1.0e-03	2.5e-03	6.7e-03	Handling slag
Fe-55	1.2e-04	2.7e-05	8.9e-05	2.9e-04	4.3e-07	1.0e-07	3.3e-07	1.1e-06	Handling slag
Fe-59	8.3e-01	2.7e-01	6.7e-01	1.9e+00	3.1e-03	9.9e-04	2.5e-03	6.9e-03	Handling slag
Co-56	2.5e+00	7.9e-01	2.0e+00	5.5e+00	9.1e-03	2.9e-03	7.4e-03	2.0e-02	Handling slag
Co-57	2.8e-02	9.3e-03	2.3e-02	6.3e-02	1.0e-04	3.4e-05	8.5e-05	2.3e-04	Handling slag
Co-58	6.6e-01	2.1e-01	5.4e-01	1.5e+00	2.5e-03	7.9e-04	2.0e-03	5.6e-03	Handling slag
Co-60	2.1e+00	7.0e-01	1.8e+00	4.8e+00	7.9e-03	2.6e-03	6.5e-03	1.8e-02	Handling slag
Ni-59	3.6e-05	1.1e-05	2.9e-05	8.4e-05	1.3e-07	4.2e-08	1.1e-07	3.1e-07	Handling slag
Ni-63	6.6e-05	1.8e-05	5.1e-05	1.6e-04	2.4e-07	6.6e-08	1.9e-07	5.9e-07	Handling slag
Zn-65	5.2e-01	1.8e-01	4.3e-01	1.1e+00	1.9e-03	6.5e-04	1.6e-03	4.2e-03	Handling slag
As-73	2.7e-04	1.0e-05	8.3e-05	9.4e-04	1.0e-06	3.8e-08	3.1e-07	3.5e-06	Scrap disposal-industrial
Se-75	1.3e-01	2.6e-02	7.9e-02	3.7e-01	4.6e-04	9.7e-05	2.9e-04	1.4e-03	Scrap yard
Sr-85	3.8e-01	1.3e-01	3.1e-01	8.6e-01	1.4e-03	4.7e-04	1.2e-03	3.2e-03	Handling slag
Sr-89	2.2e-03	7.0e-04	1.8e-03	5.1e-03	8.0e-06	2.6e-06	6.5e-06	1.9e-05	Handling slag
Sr-90	1.8e-02	5.6e-03	1.4e-02	4.2e-02	6.7e-05	2.1e-05	5.3e-05	1.6e-04	Handling slag
Y-91	5.8e-03	2.0e-03	4.7e-03	1.3e-02	2.1e-05	7.2e-06	1.7e-05	4.8e-05	Handling slag
Zr-93	1.0e-03	3.2e-04	8.2e-04	2.4e-03	3.8e-06	1.2e-06	3.0e-06	9.0e-06	Handling slag
Zr-95	8.4e-01	2.9e-01	6.9e-01	1.9e+00	3.1e-03	1.1e-03	2.6e-03	6.9e-03	Handling slag
Nb-93m	1.6e-04	4.9e-05	1.3e-04	3.7e-04	5.8e-07	1.8e-07	4.7e-07	1.4e-06	Handling slag
Nb-94	1.6e+00	5.6e-01	1.3e+00	3.6e+00	6.0e-03	2.1e-03	5.0e-03	1.3e-02	Handling slag
Nb-95	5.2e-01	1.6e-01	4.2e-01	1.2e+00	1.9e-03	6.0e-04	1.5e-03	4.5e-03	Handling slag
Mo-93	2.4e-03	0.0e+00	0.0e+00	2.7e-03	8.8e-06	0.0e+00	0.0e+00	1.0e-05	Leachate-industrial-scrap
Tc-97	3.9e-03	0.0e+00	0.0e+00	1.6e-02	1.4e-05	0.0e+00	0.0e+00	5.8e-05	Leachate-industrial-scrap
Tc-97m	5.3e-04	1.7e-04	4.3e-04	1.2e-03	2.0e-06	6.2e-07	1.6e-06	4.6e-06	Handling slag
Tc-99	3.6e-02	0.0e+00	0.0e+00	1.5e-01	1.3e-04	0.0e+00	0.0e+00	5.4e-04	Leachate-industrial-scrap
Ru-103	2.2e-01	4.4e-02	1.4e-01	6.7e-01	8.1e-04	1.6e-04	5.1e-04	2.5e-03	Scrap yard
Ru-106	1.5e-01	3.2e-02	9.6e-02	4.5e-01	5.6e-04	1.2e-04	3.5e-04	1.7e-03	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.12 Normalized surficial effective doses to critical groups for copper

Radionuclide	:Sv/y per Bq/cm²				mrem/y per pCi/cm²				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	1.1e+00	2.2e-01	6.7e-01	3.1e+00	3.9e-03	8.2e-04	2.5e-03	1.2e-02	Scrap yard
Ag-110m	1.9e+00	3.9e-01	1.2e+00	5.5e+00	6.9e-03	1.5e-03	4.4e-03	2.0e-02	Scrap yard
Cd-109	1.6e-03	5.2e-04	1.3e-03	3.5e-03	5.8e-06	1.9e-06	4.7e-06	1.3e-05	Handling slag
Sn-113	1.7e-01	5.8e-02	1.4e-01	3.8e-01	6.3e-04	2.2e-04	5.2e-04	1.4e-03	Handling slag
Sb-124	1.1e+00	2.3e-01	7.0e-01	3.3e+00	4.1e-03	8.5e-04	2.6e-03	1.2e-02	Scrap yard
Sb-125	3.0e-01	9.7e-02	2.4e-01	6.8e-01	1.1e-03	3.6e-04	8.9e-04	2.5e-03	Handling slag
Te-123m	2.6e-02	5.4e-03	1.6e-02	7.7e-02	9.6e-05	2.0e-05	6.0e-05	2.8e-04	Scrap yard
Te-127m	2.9e-03	6.5e-04	1.8e-03	8.6e-03	1.1e-05	2.4e-06	6.7e-06	3.2e-05	Scrap yard
I-125	3.8e-03	7.8e-04	2.8e-03	9.9e-03	1.4e-05	2.9e-06	1.0e-05	3.6e-05	Handling slag
I-129	1.2e+00	0.0e+00	0.0e+00	4.0e+00	4.3e-03	0.0e+00	0.0e+00	1.5e-02	Leachate-industrial-scrap
I-131	6.9e-02	6.7e-03	4.0e-02	2.3e-01	2.6e-04	2.5e-05	1.5e-04	8.5e-04	Handling slag
Cs-134	1.1e+00	2.2e-01	6.7e-01	3.1e+00	3.9e-03	8.2e-04	2.5e-03	1.1e-02	Scrap yard
Cs-135	1.6e-04	2.2e-05	1.0e-04	5.1e-04	6.0e-07	8.0e-08	3.8e-07	1.9e-06	Scrap yard
Cs-137	3.8e-01	8.1e-02	2.4e-01	1.1e+00	1.4e-03	3.0e-04	8.9e-04	4.2e-03	Scrap yard
Ba-133	2.9e-01	9.9e-02	2.4e-01	6.3e-01	1.1e-03	3.6e-04	8.8e-04	2.3e-03	Handling slag
Ce-139	5.4e-02	1.9e-02	4.5e-02	1.2e-01	2.0e-04	6.9e-05	1.7e-04	4.4e-04	Handling slag
Ce-141	1.7e-02	5.3e-03	1.4e-02	4.0e-02	6.4e-05	2.0e-05	5.1e-05	1.5e-04	Handling slag
Ce-144	4.8e-02	1.7e-02	4.0e-02	1.0e-01	1.8e-04	6.2e-05	1.5e-04	3.9e-04	Handling slag
Pm-147	5.2e-04	1.7e-04	4.2e-04	1.2e-03	1.9e-06	6.1e-07	1.6e-06	4.5e-06	Handling slag
Sm-151	4.0e-04	1.2e-04	3.2e-04	9.5e-04	1.5e-06	4.6e-07	1.2e-06	3.5e-06	Handling slag
Eu-152	1.1e+00	3.9e-01	9.5e-01	2.5e+00	4.2e-03	1.5e-03	3.5e-03	9.3e-03	Handling slag
Eu-154	1.1e+00	3.8e-01	9.3e-01	2.5e+00	4.2e-03	1.4e-03	3.4e-03	9.1e-03	Handling slag
Eu-155	1.1e-02	3.8e-03	8.9e-03	2.4e-02	4.0e-05	1.4e-05	3.3e-05	8.7e-05	Handling slag
Gd-153	1.2e-02	4.3e-03	1.0e-02	2.7e-02	4.6e-05	1.6e-05	3.8e-05	1.0e-04	Handling slag
Tb-160	9.2e-01	3.1e-01	7.5e-01	2.1e+00	3.4e-03	1.1e-03	2.8e-03	7.6e-03	Handling slag
Tm-170	1.8e-03	6.1e-04	1.4e-03	3.9e-03	6.5e-06	2.3e-06	5.3e-06	1.4e-05	Handling slag
Tm-171	2.0e-04	6.6e-05	1.6e-04	4.4e-04	7.2e-07	2.4e-07	5.9e-07	1.6e-06	Handling slag
Ta-182	1.1e+00	3.8e-01	9.1e-01	2.5e+00	4.1e-03	1.4e-03	3.4e-03	9.1e-03	Handling slag
W-181	2.7e-03	9.2e-04	2.2e-03	6.0e-03	9.9e-06	3.4e-06	8.2e-06	2.2e-05	Handling slag
W-185	1.5e-04	3.8e-05	1.2e-04	3.8e-04	5.6e-07	1.4e-07	4.3e-07	1.4e-06	Handling slag
Os-185	3.8e-01	8.0e-02	2.4e-01	1.1e+00	1.4e-03	2.9e-04	8.9e-04	4.2e-03	Scrap yard
Ir-192	3.6e-01	7.6e-02	2.3e-01	1.1e+00	1.3e-03	2.8e-04	8.5e-04	4.1e-03	Scrap yard
Tl-204	3.9e-04	9.7e-05	2.5e-04	1.2e-03	1.4e-06	3.6e-07	9.2e-07	4.4e-06	Scrap yard
Pb-210	4.6e-01	8.0e-02	3.5e-01	1.2e+00	1.7e-03	3.0e-04	1.3e-03	4.5e-03	Handling slag
Bi-207	1.1e+00	2.2e-01	6.7e-01	3.1e+00	3.9e-03	8.3e-04	2.5e-03	1.2e-02	Scrap yard
Po-210	7.2e-02	2.0e-02	4.5e-02	2.2e-01	2.7e-04	7.3e-05	1.7e-04	8.2e-04	Scrap yard
Ra-226	2.1e+00	7.7e-01	1.8e+00	4.7e+00	7.9e-03	2.8e-03	6.6e-03	1.7e-02	Handling slag
Ra-228	1.4e+00	5.0e-01	1.2e+00	3.1e+00	5.2e-03	1.9e-03	4.3e-03	1.2e-02	Handling slag

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 4.12 Normalized surficial effective doses to critical groups for copper

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	9.8e+00	3.0e+00	7.8e+00	2.3e+01	3.6e-02	1.1e-02	2.9e-02	8.5e-02	Handling slag
Th-228	6.3e+00	2.1e+00	5.1e+00	1.5e+01	2.3e-02	7.7e-03	1.9e-02	5.4e-02	Handling slag
Th-229	9.2e+00	2.8e+00	7.4e+00	2.2e+01	3.4e-02	1.0e-02	2.7e-02	8.1e-02	Handling slag
Th-230	1.1e+00	3.2e-01	8.5e-01	2.5e+00	3.9e-03	1.2e-03	3.1e-03	9.3e-03	Handling slag
Th-232	1.9e+00	5.9e-01	1.5e+00	4.6e+00	7.1e-03	2.2e-03	5.6e-03	1.7e-02	Handling slag
Pa-231	2.8e+00	7.4e-01	1.7e+00	8.5e+00	1.0e-02	2.7e-03	6.4e-03	3.1e-02	Scrap yard
U-232	3.9e+00	1.2e+00	3.1e+00	9.3e+00	1.4e-02	4.4e-03	1.1e-02	3.5e-02	Handling slag
U-233	1.0e+00	3.0e-01	8.0e-01	2.4e+00	3.7e-03	1.1e-03	2.9e-03	8.8e-03	Handling slag
U-234	9.9e-01	3.0e-01	7.8e-01	2.3e+00	3.7e-03	1.1e-03	2.9e-03	8.7e-03	Handling slag
U-235	9.9e-01	3.1e-01	7.9e-01	2.3e+00	3.7e-03	1.1e-03	2.9e-03	8.6e-03	Handling slag
U-236	9.1e-01	2.8e-01	7.3e-01	2.2e+00	3.4e-03	1.0e-03	2.7e-03	8.0e-03	Handling slag
U-238	8.5e-01	2.6e-01	6.8e-01	2.0e+00	3.2e-03	9.7e-04	2.5e-03	7.5e-03	Handling slag
Np-237	2.4e+00	7.4e-01	1.9e+00	5.5e+00	8.7e-03	2.7e-03	7.0e-03	2.0e-02	Handling slag
Pu-236	1.2e+00	3.8e-01	9.7e-01	2.9e+00	4.5e-03	1.4e-03	3.6e-03	1.1e-02	Handling slag
Pu-238	1.7e+00	5.1e-01	1.3e+00	3.9e+00	6.1e-03	1.9e-03	4.9e-03	1.4e-02	Handling slag
Pu-239	1.3e+00	3.9e-01	1.0e+00	3.0e+00	4.7e-03	1.4e-03	3.7e-03	1.1e-02	Handling slag
Pu-240	1.3e+00	3.9e-01	1.0e+00	3.0e+00	4.7e-03	1.4e-03	3.7e-03	1.1e-02	Handling slag
Pu-241	1.8e-02	4.8e-03	1.1e-02	5.5e-02	6.7e-05	1.8e-05	4.2e-05	2.0e-04	Scrap yard
Pu-242	1.2e+00	3.6e-01	9.4e-01	2.8e+00	4.4e-03	1.3e-03	3.5e-03	1.0e-02	Handling slag
Pu-244	1.5e+00	4.9e-01	1.2e+00	3.3e+00	5.4e-03	1.8e-03	4.4e-03	1.2e-02	Handling slag
Am-241	4.0e+00	1.2e+00	3.2e+00	9.4e+00	1.5e-02	4.5e-03	1.2e-02	3.5e-02	Handling slag
Am-242m	4.1e+00	1.2e+00	3.3e+00	9.8e+00	1.5e-02	4.6e-03	1.2e-02	3.6e-02	Handling slag
Am-243	4.1e+00	1.2e+00	3.2e+00	9.6e+00	1.5e-02	4.6e-03	1.2e-02	3.5e-02	Handling slag
Cm-242	4.9e-01	1.5e-01	3.9e-01	1.2e+00	1.8e-03	5.5e-04	1.4e-03	4.3e-03	Handling slag
Cm-243	3.0e+00	9.2e-01	2.4e+00	7.1e+00	1.1e-02	3.4e-03	8.8e-03	2.6e-02	Handling slag
Cm-244	2.5e+00	7.6e-01	2.0e+00	5.9e+00	9.2e-03	2.8e-03	7.3e-03	2.2e-02	Handling slag
Cm-245	4.0e+00	1.2e+00	3.2e+00	9.5e+00	1.5e-02	4.5e-03	1.2e-02	3.5e-02	Handling slag
Cm-246	4.0e+00	1.2e+00	3.2e+00	9.4e+00	1.5e-02	4.5e-03	1.2e-02	3.5e-02	Handling slag
Cm-247	4.0e+00	1.2e+00	3.2e+00	9.3e+00	1.5e-02	4.6e-03	1.2e-02	3.4e-02	Handling slag
Cm-248	1.4e+01	4.2e+00	1.1e+01	3.3e+01	5.2e-02	1.6e-02	4.1e-02	1.2e-01	Handling slag
Bk-249	1.5e-02	4.5e-03	1.2e-02	3.5e-02	5.5e-05	1.7e-05	4.4e-05	1.3e-04	Handling slag
Cf-248	8.6e-01	2.6e-01	6.8e-01	2.0e+00	3.2e-03	9.6e-04	2.5e-03	7.5e-03	Handling slag
Cf-249	6.9e+00	2.1e+00	5.5e+00	1.6e+01	2.6e-02	7.9e-03	2.0e-02	6.0e-02	Handling slag
Cf-250	3.2e+00	9.8e-01	2.6e+00	7.6e+00	1.2e-02	3.6e-03	9.5e-03	2.8e-02	Handling slag
Cf-251	6.8e+00	2.1e+00	5.4e+00	1.6e+01	2.5e-02	7.7e-03	2.0e-02	6.0e-02	Handling slag
Cf-252	1.9e+00	5.7e-01	1.5e+00	4.5e+00	7.0e-03	2.1e-03	5.5e-03	1.6e-02	Handling slag
Cf-254	1.7e+01	5.8e+00	1.4e+01	3.8e+01	6.2e-02	2.1e-02	5.1e-02	1.4e-01	Handling slag
Es-254	1.7e+00	6.2e-01	1.4e+00	3.8e+00	6.4e-03	2.3e-03	5.3e-03	1.4e-02	Handling slag

[a] 5th percentile to 95th percentile = 90% confidence interval

References

Agency for Toxic Substances and Disease Registry (ATSDR). 1990. *Toxicological Profile for Copper*. Atlanta: U.S. Department of Health and Human Services, Public Health Services.

Anigstein, R., et al. 2001. “Technical Support Document: Potential Recycling of Scrap Metal from Nuclear Facilities, Part I: Radiological Assessment of Exposed Individuals.” Washington, DC: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air. http://www.epa.gov/radiation/cleanmetals/docs/tsd (August 12, 2002).

Biswas, A. K., and W. G. Davenport. 1976. *Extractive Metallurgy of Copper*. Oxford: Pergamon Press.

Brunson, W. W., and D. R. Stone. 1976. “Electrorefining at the Copper Division of Southwire Company, Carrollton, Georgia, U.S.A.” *Transactions of the Institution of Mining and Metallurgy*, Section C, vol. 85, C150–C156.

Bryan, R. H., and I. T. Dudley. 1974. “Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant,” ORNL-TM-4515. Oak Ridge, TN: Oak Ridge National Laboratory.

Bureau of the Census (U.S.). 1999. “1997 Economic Census: Transportation—1997 Commodity Flow Survey.” U.S. Department of Transportation, Bureau of Transportation Statistics; U.S. Department of Commerce, Economics and Statistics Administration. http://199.79.179.77/ntda/cfs/97tcf-us.pdf (March 4, 2002).

CDA (Copper Development Association) 2001. “Annual Data 2001: Copper Supply & Consumption, 1980–2000.” http://marketdata.copper.org/annual_00/annual_00.pdf (March 25, 2003).

Code of Federal Regulations, *Title 29, Labor*, Part 1910, “Occupational Safety and Health Standards,” Subpart Z, “Toxic and Hazardous Substances,” 1910.1000, “Air Contaminants,” Table Z-1, “Limits for Air Contaminants” (29 CFR 1910.1000). http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9992&p_text_version=FALSE (March 18, 2003).

Davenport, W. G. 1986. “Copper Production.” In M. B. Bever (Ed.), *Encyclopedia of Materials Science and Engineering*. Vol 2 (pp. 841-848). Oxford: Pergamon Press.

Edelstein, D. E. 2002. “Copper.” In *Minerals Yearbook—2000.* U.S. Geological Survey http://minerals.usgs.gov/minerals/pubs/commodity/copper/240400.pdf (March 3, 2003).

Environmental Protection Agency (U.S.) (EPA). 1995. “Compilation of Air Pollutant Emission Factors,” AP-42. 5th ed. Vol. 1, “Stationary Point and Area Sources.” Washington DC: Author. http://www.epa.gov/ttn/chief/ap42/ch12/final/c12s09.pdf (March 3, 2003).

Environmental Protection Agency (U.S.) (EPA). 2002. "Zinc Fertilizers Made from Recycled Hazardous Secondary Materials." *Federal Register*, Vol. 67, No. 142: pp. 48393–48415. July 24, 2002.

Gößling, S. 2001. "Entropy Balance of Industrial Copper Production: A Measure for Resource Use: First Results for Flash Smelting, Converting and Refining." http://www.desy.de/~stefang/beschreibung.html (September 13, 2000).

Henstock, M. E. 1997. "The Potential and the Limitations of Copper Recycling." *Proceedings of The World Conference on Copper Recycling*. Lisbon: International Copper Study Group.

International Copper Association (ICA). (n/d). "Copper Info." http://www.copperinfo.com/cproducts/transportation.shtml (October 7, 2002).

Jolly, J. L. W. 1997. "World Copper Scrap Markets and Trends." *Proceedings of The World Conference on Copper Recycling*. Lisbon: International Copper Study Group.

Kusik, C. L., and C. B. Kenahan. 1978. "Energy Use Patterns for Metal Recycling," Information Circular 8781. U.S. Bureau of Mines.

Licht, C. A. 2000. "Secondary Brass and Bronze Melting Processes." In W. T. Davis (Ed.), *Air Pollution Engineering Manual*, 2nd ed. (pp. 626–631). New York: John Wiley & Sons, Inc.

Pacific Environmental Services, Inc. (PES) 1977. "Emission Factors and Emission Source Information for Primary and Secondary Copper Smelters," EPA-450/3-77-051. Research Triangle Park, NC: U.S. Environmental Protection Agency.

Ramachandran, V., and V. L. Wildman. 1987. "Current Operations at the Amarillo Copper Refinery." In J. E. Hoffman et al. (Eds.), *The Electrorefining and Winning of Copper* (pp. 387–396). Warrendale, PA: The Metallurgical Society/AIME.

St. John, H. M. 1958. *Brass and Bronze Foundry Practice.* Cleveland, OH: Penton Publishing Company.

Stone, D. R., and J. P. Tuggle. 1995. "Process, Productivity, and Quality Improvements at the Copper Division of Southwire" In *Proceedings of Copper 95-Cobre 95 International Conference: Vol. 3. Electrorefining and Hydrometallurgy of Copper* (pp. 103–111). The Metallurgical Society of CIM.

"Trends in U.S. Copper and Scrap and Effects of Product Shifts." 1997. Presented at The World Conference on Copper Recycling, Brussels (March 3–4, 1997). http://environment.copper.org/trends/Scrap.html (October 7, 2002).

U.S. Geological Survey (USGS). 2001. "Copper." In "Mineral Commodity Summaries, January 2001." http://minerals.usgs.gov/minerals/pubs/commodity/copper/240301.pdf (March 3, 2003).

5 RECYCLING AND DISPOSAL OF ALUMINUM SCRAP

Assessments have been performed of the potential radiation doses to individuals from the recycling or disposal of aluminum scrap that could be cleared from nuclear facilities. The assessment addresses 21 scenarios that depict exposures resulting from the handling and processing of cleared scrap and the products of melt-refining this scrap at secondary aluminum smelters, emission of airborne effluents from these facilities, transportation of scrap and smelter products, the use of aluminum products, the landfill disposal of cleared scrap and aluminum dross, and the infiltration of well water by leachate from landfills containing cleared scrap or dross. The analysis utilizes data on secondary aluminum smelters in the United States, and on contemporary U.S. work practices and living habits.

The critical group for the largest number of radionuclides, accounting for most of the 115 radionuclides in the analysis, consists of workers processing scrap at a scrap yard. Scenarios involving the use of aluminum products—the owner-operator of a taxi with an aluminum engine block or a person using an aluminum cooking utensil—give rise to most of the remaining critical groups.

Mean values of mass-based normalized EDEs to critical groups range from a high of 0.51 :Sv/y per Bq/g (1.9e-3 mrem/y per pCi/g) from Th-229 to a low of 6.7e-7 :Sv/y per Bq/g (2.5e-9 mrem/y per pCi/g) from Mn-53. The corresponding surficial EDEs are 0.56 and 7.4e-7 :Sv/y per Bq/cm^2, respectively. Mean values of mass-based normalized effective doses range from a high of 0.25 :Sv/y per Bq/g (9.3e-4 mrem/y per pCi/g) from Co-60 to a low of 6.8e-7 :Sv/y per Bq/g (2.5e-9 mrem/y per pCi/g) from Mn-53. The corresponding surficial effective doses are 0.28 and 7.6e-7 :Sv/y per Bq/cm^2, respectively. The critical group for Th-229 is the scrap yard workers, for Mn-53 it is the users of aluminum cooking ware, while for Co-60 it is the drivers of taxis with aluminum engine blocks.

This chapter describes the radiological assessment of the recycling and/or disposal of aluminum scrap that could be cleared from NRC-licensed facilities. This assessment is based on a realistic appraisal of the recycling of aluminum scrap into consumer or industrial products, or of disposing of the scrap in an industrial or municipal landfill.

5.1 Introduction to Analysis

As was the case with the other metals, the evaluation of the potential doses from cleared aluminum scrap consists of two main parts. The first step is characterizing the flow of cleared scrap through the normal recycling process, beginning with the generation of scrap, through melting or smelting, manufacturing, and product use, as well as disposal as an alternative to recycling. This enables the calculation of radionuclide concentrations in products and by-products of the smelting of aluminum scrap.

The second step is the development and analysis of exposure scenarios. All but one of the 21 scenarios in the aluminum analysis were modeled on corresponding scenarios for iron and steel or copper scrap. The new scenario is discussed in Section 5.6.3.

5.2 Flow of Aluminum Scrap

This section presents an overview of the U.S. secondary aluminum industry. Its purpose is: (1) to serve as a source of information required for the present analysis, and (2) to present a context for those aspects of the recycling and disposal of aluminum scrap that are addressed by the analysis. It thus includes some data which are not directly utilized by the analysis.

Figure 5.1 presents a schematic diagram of the flow of aluminum scrap, as characterized in the present analysis. As is the case in the analysis of other cleared materials, this is a simplified idealization of the actual process. The diagram depicts the sequence of steps that are represented by the exposure scenarios in the present analysis. Intermediate steps, not represented by exposure scenarios, are indicated by dashed lines or boxes. Other steps and processes are discussed in the following sections of this chapter.

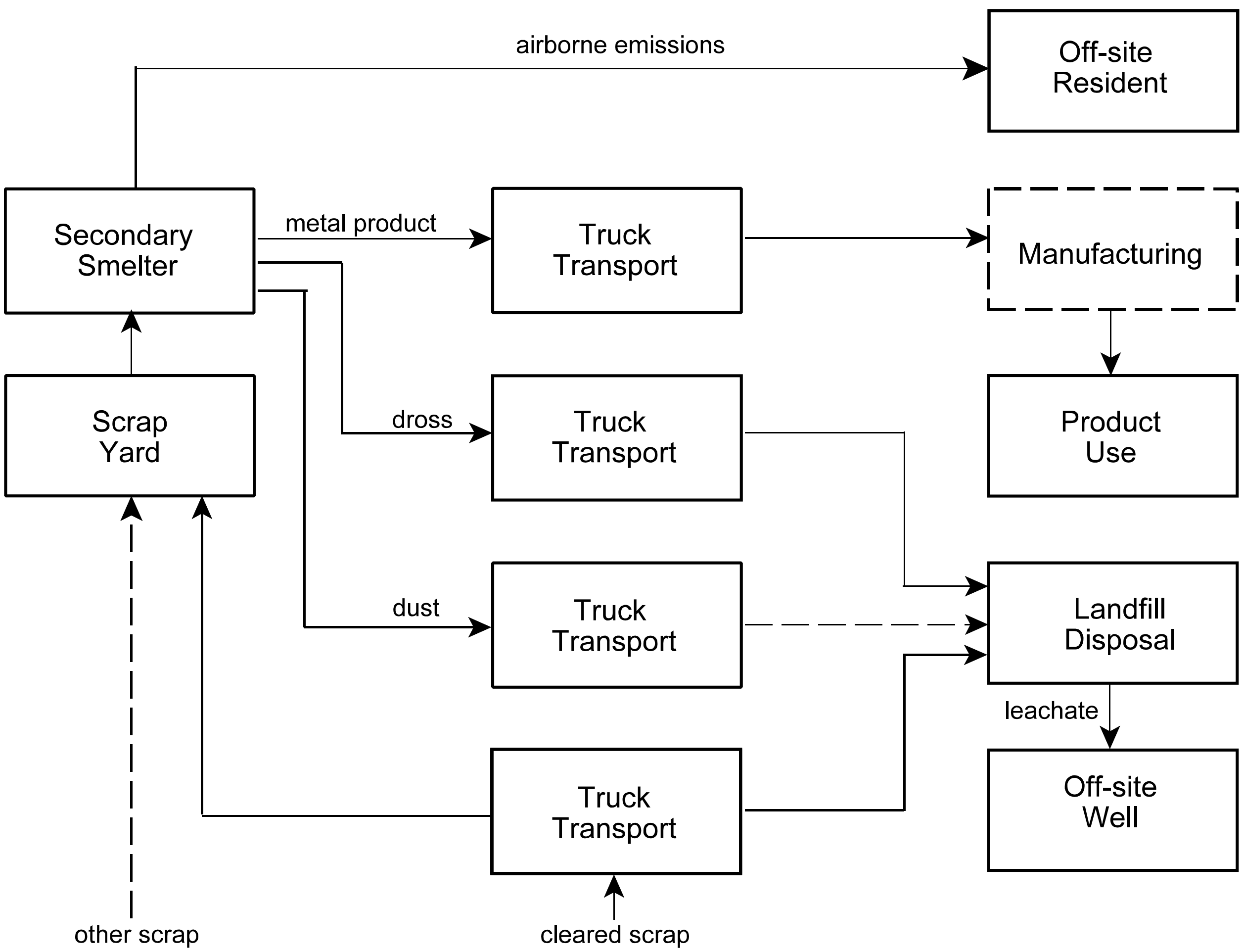

Figure 5.1 Flow of aluminum scrap

The process begins with the release of cleared scrap from an NRC-licensed facility. It is assumed that the scrap is shipped by truck[1] for processing at a scrap yard operated by a scrap metals dealer.[2] The scrap dealer then ships the processed scrap to a secondary aluminum smelter, where it is melt-refined to produce aluminum alloys, which are typically cast into ingots.[3]

Alternatively, the licensee or demolition contractor may elect to dispose of the scrap in an industrial or municipal solid waste (MSW) landfill. As another alternative, depending on the nature of the scrap and other economic factors, the scrap might be processed at the generator facility and shipped directly to the smelter.[4]

Smelter by-products include dross and offgas. Dross, which is analogous to slag in the melt-refining of steel and copper, is a mixture of flux added to the melt, and metallic chlorides and oxides. The dross is transported by truck for disposal in a landfill. Alternatively, in many cases, it is sent to processors for metal recovery.

Offgas consists of the fumes and particulates evolved during melting which are captured by the facility's emission control system. After cooling, most of the offgas is collected in the baghouse in the form of dust, which is sent to a landfill for disposal. Gases, vapors, and some of the particulates escape the filtration system and are released to the atmosphere. These airborne effluents may be transported by air currents to a nearby residence.

The aluminum alloys produced at the smelter are usually shipped in the form of ingots; however, as discussed on page 5-7, the product may also be shipped as molten metal in insulated crucibles.

Aluminum alloys produced by secondary smelters are used to make a vast array of finished products. The present analysis examines four such products. Two are generic shapes that can represent a number of individual products. In addition, two specific products—an aluminum engine block in an automobile and an aluminum cooking utensil—are included in the analysis.

5.2.1 Sources of Material

As is the case for steel and copper scrap, the main generators of aluminum scrap addressed in this study are NRC-licensed facilities—primarily commercial power plants, test and research reactors, and industrial nuclear facilities. According to Bryan and Dudley (1974), a 1000-MWe

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[1] Scrap and smelter products can also be shipped by rail or waterway.

[2] Some scrap is conveyed directly to a smelter and processed at the facility (Gary Huddleston, environmental manager, Wabash Alloys LLC, private communication with Robert Anigstein, SC&A Inc., October 16, 2002).

[3] Alternate types of processing facilities are discussed in Section 5.2.2.

[4] Processing scrap at the nuclear facility is outside the scope the analysis. Such processing would most likely be performed by radiation workers whose occupational exposures are controlled under current regulations.

PWR contains 18.1 t of aluminum. As shown in Table A.10, which presents the results of a detailed analysis of materials in a PWR, 5.4 t of aluminum is associated with reactor equipment, reactor auxiliaries, and fuel storage—systems that would most likely be too contaminated to be candidates for clearance. A total of 10.7 t is associated with site improvements, miscellaneous buildings, electric plant equipment, and miscellaneous equipment. These systems are not impacted by radioactive materials and therefore not subject to clearance. This leaves 1.2 to 2.0 t of aluminum (depending on whether or not the 0.8 t of aluminum in the turbine building falls into the impacted or nonimpacted category) that would be subject to clearance.

A discussion of the mass-to-surface ratios of the aluminum components of a nuclear power plant is presented in Section A.6.4. The data in that section describe all of the aluminum components, while the parameter required for the present analysis is the overall mass-to-surface ratio of the components likely to be cleared. A probability distribution of mass-to-surface ratios of the cleared scrap was determined as follows. As stated in Section A.6.4, most of the aluminum is assumed to be in the form of sheet metal or thin-walled tubing, ranging in thickness from 0.062 to 0.25 inch (0.159 – 0.635 cm). It is assumed that the individual components are equally likely to have one of eight standard thicknesses of commercial aluminum sheets in this range, as shown in Table 5.1. The overall mass-to-surface ratio is generated by randomly assigning a frequency (uniformly distributed over the arbitrary range 0 – 1) to each thickness. We then calculate a frequency-weighted-average thickness, from which we obtain the mass-to-surface ratio. The results of 10,000 Monte Carlo realizations have a mean value of 0.90 g/cm^2 and a coefficient of variability of 0.10.

Table 5.1 Mass-to-surface ratios of commercial aluminum sheets

Thickness[a]		Mass-to-surface ratio (g/cm^2)[b]
inch	cm	
0.063	0.160	0.432
0.08	0.203	0.549
0.09	0.229	0.617
0.1	0.254	0.686
0.125	0.318	0.857
0.16	0.406	1.097
0.19	0.483	1.303
0.25	0.635	1.715

[a] Sizes listed for 5052-H32 aluminum flat sheet, a common alloy (Cygnet [n/d])
[b] Calculated, assuming density = 2.7 g/cm^3

5.2.2 Recycling of Aluminum Scrap

Section 3.2.2 describes the three types of scrap metal used in iron- and steelmaking: home, new, and old. Aluminum scrap falls into the same three categories. Just as the other metals, aluminum scrap cleared from NRC-licensed facilities would be old scrap. Statistical data on the consumption of aluminum scrap and its recovery in aluminum products are presented in

Table 5.2. Most of these data were compiled by Plunkert (2002), but are based on information furnished to that author by The Aluminum Association.[5]

Used aluminum beverage cans (UBC) are typically processed in dedicated facilities that return product to the can industry. This insures that the particular alloys used for cans remain segregated and are processed without being commingled with general grades of scrap. This material is not part of the general stream of old scrap that would be mixed with scrap cleared from NRC-licensed facilities. On the other hand, a broad range of old aluminum scrap is processed by the secondary aluminum recycling industry, primarily to produce foundry alloys.

Table 5.2 lists five types of facilities that recycle aluminum scrap. The first column of numbers lists the total scrap consumption of each of these industries, based on published data. The next column lists data on the consumption of old scrap. The quantities of old scrap consumed by the four categories of secondary producers, other than secondary smelters, are estimated on the basis of the reported data on the sums of old scrap and new scrap consumed by the facilities in these four categories lumped together. It is assumed that the same ratio of old to new scrap applies to each category individually. Furthermore, it is assumed that the fractional recovery of metal is the same for old and new scrap. The non-UBC scrap consumed by secondary smelters was calculated by subtracting the 88 kt of UBC scrap toll-treated[6] for primary producers from the listed amount of old scrap processed at these facilities. Finally, the amount of non-UBC old scrap consumed by each of the four categories—other than secondary smelters—was estimated by prorating the total amount of UBC scrap consumed by these four categories according to the total amount of scrap consumed by each category.

5.2.3 Secondary Smelters

By far the largest consumers of non-UBC old scrap are secondary smelters producing foundry alloys. It is therefore most likely that aluminum scrap cleared from an NRC-licensed facility and destined for recycling would be consumed by one of these smelters.

EPA (1995a) reported that the secondary aluminum industry operated about 68 plants and employed about 3,600 workers.[7] Another source, Novelli 1997, states that the North American industry involves 46 companies with 81 smelting operations. More recently, The Aluminum Association (2002) reported that, in 2001, 75 plants produced secondary ingot. Total ingot shipments from both primary and secondary sources were 5,886 million pounds (2,670 kt). As listed in Table 5.2, secondary smelters consumed about 1,965 kt of scrap and recovered 1,450 kt

[5] Nicholas A. Adams, Jr., Director, Statistics & Economics and Staff Executive, Recycling Division, The Aluminum Association, Incorporated, private communication with Robert Anigstein, SC&A, Inc., October 16, 2002.

[6] In some cases a beverage can producer retains ownership of the UBC scrap but has the scrap processed by a primary producer into new beverage can stock. The primary producer bills the scrap owner a per-ton tolling charge to remelt and reprocess the scrap metal.

[7] This total probably includes plants dedicated to UBC remelting.

of metal in 2000. This scrap was from a mixture of old and new sources and included a small amount (88 kt) of UBC scrap toll-treated for primary producers. About 70% of the metal recovery in secondary smelters was from new scrap (Plunkert 2002, Table 4).

Table 5.2 U.S. industrial consumption and recovery from purchased aluminum scrap in 2000 (kt)

	Consumption				Recovery		
	Total	Old scrap[a]		New scrap	Total	Old scrap[a,b]	New scrap[b]
		Total	non-UBC				
Secondary smelters	1965[c]	593[d]	***505***[e]	1370	1450	***440***	***1010***
Integrated producers	1062[c]	***496***	***99***		930	***434***	***496***
Independent mill fabricators	800	***373***	***74***		736	***344***	***392***
Foundries	95.6	***44.6***	***8.9***	1050	85.8	***40.1***	***45.7***
Other consumers	14.6	***6.8***	***1.4***		14.6	***6.8***	***7.8***
Subtotal (excludes secondary smelters)	1972	920	183		1766	825	942
Total	3936[c]	***1514***	***688***	2420	3220	***1270***	***1950***
Adjusted total[f]	4223[c]	***1624***	***738***	2590	3450[c]	1372[c]	2078[c]

Source: Plunkert 2002, unless otherwise noted

Notes: Includes imported scrap
Total metal content, scrap . 93.3% Al
Most data rounded to no more than three significant figures, may not add to totals shown.

[a] Old scrap includes sweated pig[8]

[b] Calculated from ratio of old scrap to new scrap *consumed*

[c] Aluminum Association 2001

[d] Includes 88,000 t of UBC scrap toll-treated for primary producers

[e] Figures in bold italics derived by present authors from published data

[f] Adjusted by multiplying "totals" by factor of 1.073 to estimate full industry coverage (4223 ÷ 3936 = 1.073)[9]

Figure 5.2 depicts a flow diagram for the processing of aluminum scrap at a typical secondary smelter. Such a smelter most commonly uses an oil- or gas-fired reverberatory furnace of 40,000- to 220,000-lb (18-to 100-t) capacity (Viland 1990). The input material is usually aluminum scrap and small amounts of additives such as silicon and zinc. Halide salts (such as mixtures of NaCl, KCl, and NaF) are added to form a cover over the melt and reduce oxidation. For casting alloys, 2% to 13% silicon is added in the secondary smelting process to promote casting alloy fluidity. The fumes that are generated during smelting are captured by the primary exhaust hood and transported via a duct system to a baghouse. Occasionally, dirty aluminum scrap undergoes pretreatment to remove iron, oil, and water. Pretreatment consists of crushing

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[8] "To facilitate handling, a significant proportion of the old aluminum scrap, and in some cases new scrap, is simply melted to form sweated pig that must be processed further to make specification-grade ingot" (EPA 1995a). This is also called remelt secondary ingot (RSI) by the aluminum industry. Because of its quality and pedigree, it is unlikely that aluminum scrap from licensed facilities would follow this route.

[9] Since some members of the aluminum industry did not respond to USGS surveys, Plunkert (2002) scaled the sums of the reported values to estimate the actual totals for the entire industry.

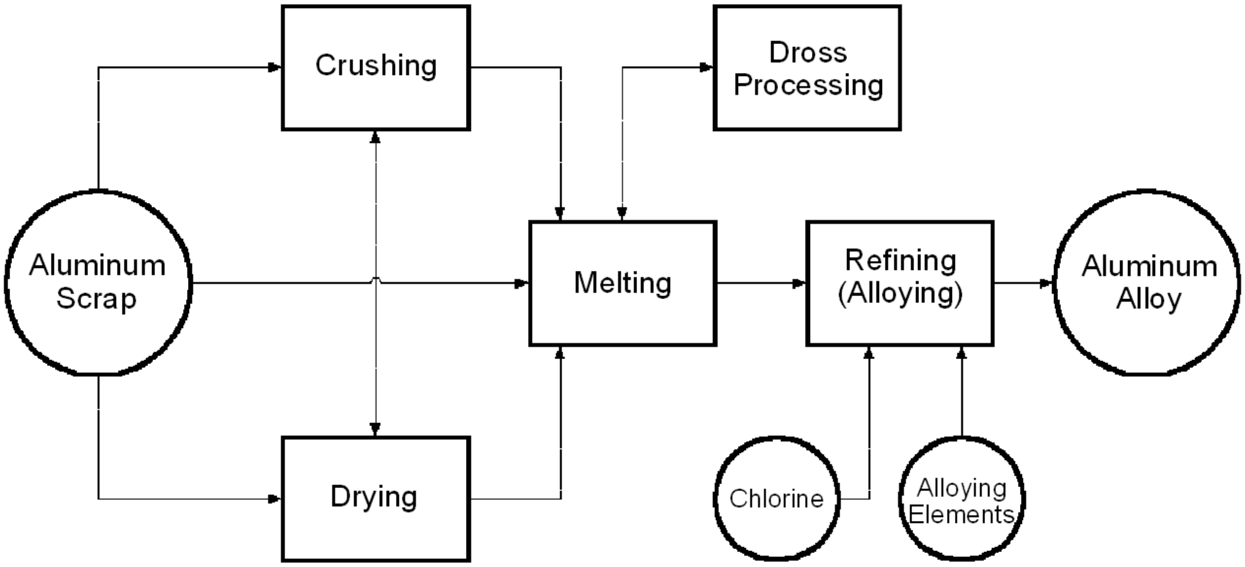

Figure 5.2 Processing and melting of aluminum scrap at typical secondary smelter

and/or drying (using an afterburner). The dust produced during pretreatment is collected in a baghouse, either the same one used for the furnace or a similar facility. When the dust is removed from the baghouse, it is tested for hazardous components to determine if it needs to be handled as hazardous waste. About 99% of the dust produced during the recycling of aluminum is considered nonhazardous.

During each of the refining steps, the feed material separates into different product streams. Each of these products undergoes different treatment, use, and disposal.

Aluminum dross is not classified as a hazardous waste; therefore, it can be recycled, reprocessed, or disposed of in a landfill. After dross is removed from the furnace and cooled, it is stored outdoors in piles at the smelter until it is either re-used by the smelter or transported to a processor for metal recovery. Dross processing may involve physical methods, such as hammer mills and screens, or thermal methods, such as melting in rotary salt furnaces. After processing, the dross residue is generally disposed of in solid waste landfills (Viland 1990). DOE (1999) estimated that 2 billion pounds (~1.8 Mt) of dross and saltcake[10] materials are landfilled annually, after processing for aluminum recovery. Processes are being developed to reduce the quantity of material destined for landfills by beneficially recovering oxide components.

The aluminum alloys produced at the secondary smelters are typically cast into ingots that are shipped to foundries for casting into end-user products. A significant quantity of product from the secondary smelters is shipped as molten metal in insulated crucibles. An example of this practice is the operations of one secondary smelter in Tennessee. Some of the metal is tapped

[10] Saltcake is a general term for the residues of dross processing in rotary furnaces or by other means.

from the furnace into 30,000-lb (14-t) hot metal transporters. These cylindrical containers are made with a steel shell and a castable lightweight refractory. The hot containers are manipulated with an overhead crane which spans the tapping area and is used to load the containers onto flatbed trucks for shipment. These containers can keep metal in the molten state for five to six hours. Up to eight containers may be temporarily stored in the tapping area prior to shipment. Shipments are typically to plants in the immediate area. Approximately 500 million pounds (~230 kt) per year of molten metal was shipped in crucibles on trucks in North America[11] (Viland 1990). This may be compared to about 15 *billion* pounds (~68 Mt) per year of total aluminum shipments in the United States alone in the late 1980's, presumably the time period of the Viland data. Thus, the molten aluminum represents less than 3% of the total aluminum shipments at that time.

According to Viland (1990), typical end-use markets for the castings include:

- Direct automotive 22%
- Automotive-related 44%
- Small engine 8%
- Appliance 7%
- Other 19%

The Aluminum Association (1998) has estimated that the automotive industry consumes 65% to 70% of foundry ingot, which is consistent with the above estimates.

5.2.4 Product Use

Finished aluminum products are used in many applications, including containers and packaging, building and construction, transportation, electrical products, consumer durables, and machinery and equipment. However, as noted above, most non-UBC scrap is used to produce various types of casting alloys.

The total aluminum market and the market for aluminum ingot (both primary and secondary) in 2001 are summarized in Table 5.3. It can be seen from the table that nearly 70% of ingots (the main product of secondary smelters) are shipped to transportation-related markets. Passenger cars account for more than 60% of the total market for aluminum ingot. According to Accomet Corporation (n/d) (a supplier of aluminum alloys to the automotive industry): “The average car produced today contains over 250 pounds [> 110 kg] of aluminum in the form of various motor mounts, pistons, heat exchangers, air conditioners, transmission housings, wheels, exteriors, fenders, load floors and suspension components.” About 60% of this aluminum is from recycled metal.

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[11] Insight into the U.S. share of North American production may be gained by noting that the United States produced 72% of the *primary* aluminum made in North America in 1990, dropping to 61% in 2000, the balance being made in Canada. Mexico, whose primary aluminum production equals about 1% of the North American total, is classified as part of Latin America (The Aluminum Association 2001).

Further details on end-use products for aluminum ingots are presented below (in millions of pounds) (Aluminum Association 2002):

- Windows, doors, and screens . . . . 23 (10 kt)
- Manufactured housing . . . . 3 (1.4 kt)
- Bridge, street, and highway . . . . 16 (7.3 kt)
- Trucks and buses . . . . 348 (158 kt)
- Passenger cars . . . . 3,584 (1,626 kt)
- Trailers and semi-trailers . . . . 38 (17.2 kt)
- Air conditioners, freezers, refrigerators . . . . 47 (21 kt)
- Portable appliances . . . . 24 (11 kt)
- Cooking utensils . . . . 21 (9.5 kt)

Table 5.3 Product net shipments by major market in 2001

Market	Total aluminum			Ingot		
	10^6 lb	kt	Fraction	10^6 lb	kt	Fraction
Building & construction	2,895	1,313	13.5%	79	36	1.3%
Transportation	6,646	3,015	30.9%	4,052	1,838	68.8%
Consumer durables	1,444	655	6.7%	336	152	5.7%
Electrical	1,361	617	6.3%	185	84	3.1%
Machinery & equipment	1,299	589	6.0%	509	231	8.6%
Containers & packaging	4,851	2,200	22.6%	--	0	0.0%
Other	545	247	2.5%	255	116	4.3%
Domestic total	19,041	8,637	88.7%	5416	2,457	92.0%
Exports	2,435	1,105	11.3%	470	213	8.0%
Grand total	21,476	9,742	100.0%	5,886	2,670	100.0%

Source: Aluminum Association 2002

5.3 Mass Fractions and Partitioning Factors for Smelter Operations

For the purpose of the present analysis, the material entering a reverberatory furnace is distributed into three process streams: metal product, dross, and offgas. The offgas consists of gases and vapors as well as particulates. The particulates and the vapors that condense upon cooling form dust, a portion of which is captured by the baghouse filters. The volatile fraction, as well as the particulates that escape the baghouse, is released to the atmosphere. Any impurities (e.g., radionuclides) in the scrap metal are likewise distributed among the metal, dross, dust, and volatile effluent emissions.

5.3.1 Mass Fractions

The melting cycle for a typical reverberatory furnace consists of charging scrap into the forewell of the furnace, blending and mixing alloying materials, adding fluxing salts, removing magnesium ("demagging"),[12] removing gases, skimming off the dross, and pouring. A heel consisting of 20% to 40% of the furnace capacity is generally left in the furnace to shorten the melting cycle.[13] Scrap is charged to the furnace, either with a front-end loader or a belt conveyor, over a 16- to 18-hour period. Demagging and gas removal require two to four hours, and tapping requires an additional three to four hours, resulting in a total cycle of about 24 hours.

Dross is a mixture of flux added to the melt, metal chlorides from demagging, and metal oxides. At the Dickson, TN, plant of Wabash Alloys LLC, a major producer of secondary aluminum, the mass of the dross is about 15% of the mass of the metal charge.[14] Another source estimated that 40% to 90% of the metal mass entering the furnace ends up in the metal product.[15] If cleaner scrap (new scrap) is used, the yield is close to 90%. It is expected that any aluminum scrap cleared from an NRC-licensed facility would be of high quality and would be mixed with scrap of similar quality, in which case yields would approach 90%. Viland (1990) noted that "For every 1 million pounds[16] of scrap processed, 760,000 pounds of secondary aluminum is produced, and 240,000 pounds of dross residues, and 3,000 pounds of baghouse dusts are generated." Garbay and Chapuis (1991), who described French recycling practices, have stated that a medium-sized plant melts 14 kt of aluminous waste and produces 11 kt of aluminum alloy, 3.3 kt of dross and 30 t of dust. Karvelas et al. (1991) quoted processing results from secondary aluminum smelters in the United States in 1988. For each 1,100 tons[16] of aluminum produced, 114 tons of dross, and 10 tons of baghouse dust were generated. The composition of the dross was 12% – 20% Al, 20% – 25% NaCl, 20% – 25% KCl, 20% - 50% Al_2O_3, and 2% – 5% other compounds.

The mass fraction of dust cited by Viland (1990) is consistent with EPA 1995b, which cites a value of 2.15 kilograms of dust per tonne of metal processed, with a standard deviation of 1.75 kg/t, for uncontrolled emissions from 10 reverberatory furnace source tests. Controlled emissions employing a baghouse for these sources averaged 0.65 kg/t, with a standard deviation of 0.15 kg/t. EPA 1995b notes: This factor may be lower if a coated baghouse is used. Under a new rule promulgated by EPA (2000), particulate emissions from secondary aluminum smelters will be limited to 0.4 lb per ton (0.2 kg/t) of material charged, which is lower than the measured values cited in EPA 1995b. Existing smelters have until March 2003 to comply with this rule.

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[12] Demagging is accomplished by injecting chlorine gas or another gaseous halogen into the melt.

[13] Patricia Plunkert, U.S. Bureau of Mines, private communication with William C. Thurber, SC&A, Inc., September 20, 1995.

[14] Robert H. Graham, plant manager, Wabash Alloys LLC, Dickson, TN, private communication with William C. Thurber, SC&A, Inc., May 2, 1997.

[15] Jim Bopp, Alchem Aluminum, private communication with Mary Anderson, SAIC, May 23, 1997.

[16] Since these nominal values are cited solely to determine ratios of product streams, they would be the same in metric units.

Particulate emissions have also been measured from melt furnaces at Alcan Aluminum's recycling facility in Berea, KY (EPA 1990). Average particulate emissions were calculated to be 0.95 lb per ton of scrap (0.48 kg/t). This operation is typical of aluminum beverage can recycling rather than of recycling old scrap for foundry alloys.

These mass fractions are summarized in Table 5.4.

Table 5.4 Comparison of mass fractions in secondary aluminum smelting

Source	Metal	Dust	Dross
Viland 1990	0.76	3e-03	0.24
Garbay and Chapuis 1991	0.79	2e-03	0.24
Anigstein et al. 2001	0.94		0.15
Alchem Aluminum (Footnote 15)	0.4 – 0.9		
EPA 1990		4.8e-04	
EPA 1995b		2.15e-03 ± 1.75e-03	
Karvelas et al. 1991	0.95 – 0.97	8.6e-03 to 8.8e-03	0.09 – 0.10

It is apparent that some of the data in Table 5.4 are inconsistent with a materials balance. For instance, Viland's values (neglecting the small amount of dust) show the sum of the fractions to be unity, which can only be true if dross is 100% aluminum or if there are other losses that are not accounted for.

5.3.1.1 Adopted Values

The quantity of metallic aluminum produced from a given heat was calculated by subtracting the amounts of chemically bound aluminum in the dross and in the dust (i.e., the amount of aluminum in the form of Al_2O_3), from the amount of metal in the furnace charge. The fraction of Al_2O_3 in dross was assigned a uniform distribution of 0.2 – 0.5, based on the values reported by Karvelas et al. (1991) cited above. The mass fraction of aluminum in dust was assigned a fixed value of 0.394, calculated from the relative concentrations of metallic elements in air samples collected near furnaces at a secondary aluminum smelter (Kiefer et al. 1995), assuming that the metals were in the form of oxides. The mass fraction of the metal product—an intermediate result calculated separately during each realization, and thus not tabulated—is the ratio of mass of molten metal to the mass of metal in the furnace charge.

The mass fraction of dross was assigned a triangular distribution, with a range of 0.09 – 0.24, spanning the range of values listed in Table 5.4, and a most likely value of 0.15, based on the practice at the Wabash Alloys plant in Dickson, TN. The dust fraction was assigned a normal distribution with a mean of 2.15×10^{-3} and a standard deviation of 1.75×10^{-3}, as reported in EPA 1995b, but truncated at the lower end at 4.8×10^{-4}, the value reported in EPA 1990 (see Table 5.4). The latter is a reasonable minimum value for the present analysis since it is the emission factor measured during the smelting of UBC scrap, which is relatively clean.

The fraction of dust released to the atmosphere is assigned a normal distribution, with a mean of 6.5×10^{-4} and a standard deviation of 1.5×10^{-4}, based on the data reported in EPA 1995b. Although these emissions are expected to go down as a result of the limits mandated by EPA (2000), these data, representing the most recent published measurements, were adopted for the present analysis.

These data, together with additional parameters used to characterize the mass fractions in the present analysis, are presented in Table B.7.

5.3.2 Partitioning Factors

This section presents a summary of the expected partitioning of impurities among the dross, the metal, and the furnace emissions (particulate and gaseous) during the secondary smelting of aluminum. A more detailed discussion is presented in Section J.3.1, from which the following text is excerpted.

A major operation during the smelting of aluminum scrap involves the injection of chlorine gas or other gaseous halogen into the melt to remove detrimental excess magnesium. Other impurities in aluminum scrap may be transferred to the dross during this demagging operation, depending on the relative thermodynamic stability of the respective chloride species. The following reaction is assumed to be representative of transfer of selected metals from the melt to the dross during demagging:

$$\frac{x}{y} M + \frac{1}{2} Cl_2 = \frac{1}{y} M_x Cl_y$$

M = metal dissolved in liquid aluminum

x = number of atoms of M in chloride salt

y = number of atoms of Cl in chloride salt

Values for the free energy of formation for this reaction at 1,000 K (a typical pouring temperature for aluminum) were evaluated for various potential impurities in the scrap metal. Assuming that the above equation represents the governing chemistry, that equilibrium is obtained, and that the dilute solutions behave as pure substances, it is expected that all the elements whose chlorides have free energies of formation more negative than $AlCl_3$ will be transferred to the dross, and that those less negative than $AlCl_3$ will tend to remain with the aluminum (see Table J.23). Hydrogen should also be substantially but not totally removed from the melt and released to the atmosphere. Hydrogen removal occurs by solution in the chlorine rather than by HCl formation, which is thermodynamically unfavorable. Although thermodynamic equilibria based on pure substances suggest that solute elements with standard free energies of formation of the solute metal chlorides higher (less negative) than that of $AlCl_3$ will remain in the melt, there is little information available on activity coefficients for the same substances in dilute solutions. Thus, the thermochemical calculations provide only rough guidelines as to the expected partitioning of trace impurities during melting.

Many chlorides are volatile at low temperatures; this attribute may play a role in the partitioning process. Addition of chlorine to the melt for demagging and hydrogen removal could result in the formation of volatile chlorides. The possibility also exists that some species expected to be transferred to the dross would also volatilize to some extent and either condense on the ducting or be collected in the baghouse dust.

Table 5.5 shows the ranges of partitioning factors adopted for each element represented by one or more of the radionuclides addressed in the present analysis. Detailed data on the uncertainty distributions of these partitioning factors are presented in Table B.7.

Table 5.5 Partitioning of contaminants in aluminum smelting (%)

Elements	Metal product	Dross	Baghouse dust	Volatile
H	0–20	0	0	80–100
C, Na, K, Ce	1–10	90–99	0	0
P, Cr, As, Se, Mo, Tc, Sn, Sb, Te, Ta, W, Os, Ir, Tl, Pb, Bi, Po, Pa	50–100	0–25	0–25	0
S, Ru, Ag	100	0	0	0
Cl, Sc, Y, Cs, Pm, Sm, Eu, Gd, Tb, Tm, Ra	0	100	0	0
Ca, Sr	1–25	75–99	0	0
Mn, Fe, Co, Ni, Zn, Nb	80–98	1–10	1–10	0
Zr	0–100	0–100	0–100	0
Cd	90–99	0	1–10	0
I	0	50–100	0	0–50
Ba	0	90–99	1–10	0
Ac, Th, Np, Am, Cm, Bk, Cf, Es	1–50	50–99	0	0
U, Pu	1–50	50–89	0–10	0

5.4 Mixing of Cleared Scrap

The concentration of each radionuclide in cleared aluminum scrap would be reduced by mixing with other materials, including scrap from other sources, prior to smelting. Further mixing occurs during the disposal of smelter by-products. The mixing of cleared scrap and of the products resulting from the smelting of the scrap are briefly discussed in this section. The type of mixing factor used in each exposure scenario is listed in Table 5.6. A more detailed discussion of mixing is presented in Section D.4.

5.4.1 Transport of Aluminum Scrap

Because of the small quantity of aluminum scrap that would be generated during the dismantlement of a commercial nuclear power plant, it is assumed that all of this scrap would be shipped off site as a single truck-load. It is further assumed that the cleared scrap in the truck would be mixed with aluminum scrap from nonimpacted areas of the plant, or from other sources. The mass of cleared scrap, which is represented by a uniform probability distribution with a range of 1.2 to 2.0 t, is mixed into a 20-t load of scrap. The resulting mixing factors have a range of 0.06 – 0.1.

5.4.2 Processing Aluminum Scrap at Scrap Yard

The aluminum scrap would be processed at a facility specializing in nonferrous metals. Such scrap processing facilities are discussed in Chapter 4 and analyzed in greater detail in Section D.3.1, which presents a probability distribution of the throughput of the nonferrous metal scrap processors. The mean throughput is about 11 kt/y, yielding an average mixing factor of cleared aluminum scrap, as reflected by the mean value of 10,000 Monte Carlo realizations, of about 2.3×10^{-4}.

5.4.3 Secondary Smelter Operations

5.4.3.1 Annual-Average Mixing Factors

As is discussed in the next section, the cleared scrap would most likely be processed and charged to the reverberatory furnace in a single batch. However, for the purpose of assessing the doses of individuals exposed to a continuous stream of smelter products over the course of a year, it is useful to calculate annual-average mixing factors. A longer discussion of this concept is presented in Section D.1. The annual-average mixing factor for products of the secondary smelter is calculated as the ratio of the mass of cleared scrap to the annual production capacity of the smelter. The capacity is sampled from the distribution of aluminum smelter capacities described in Section D.4.2.1, yielding an average mixing factor (the mean value of 10,000 Monte Carlo realizations) of about 1.8×10^{-5}.

5.4.3.2 Single-Heat Mixing Factors

The two tonnes (or less) of aluminum scrap that would be cleared from an NRC-licensed facility is much less than the capacity of a reverberatory furnace at a secondary aluminum smelter. As confirmed by a staff member of Wabash Alloys LLC, it is most likely that all of the cleared scrap would charged to the furnace in a single heat.[17] Consequently, the mixing factor for all of the product use scenarios was calculated as the ratio of the scrap cleared during the dismantlement of a single nuclear power plant to the capacity of a reverberatory furnace, resulting in an average mixing factor (the mean value of 10,000 Monte Carlo realizations) of about 2.0%. Additional details are presented in Section D.4.2.2.

[17] Gary Huddleston, environmental manager, Wabash Alloys LLC, private communication with Robert Anigstein, SC&A, Inc., January, 2003.

5.5 Radionuclide Concentrations in Various Media

The smelting process redistributes any impurities (such as radionuclides) in the scrap among the various furnace products. This partitioning is dependent on the chemical element in question and applies to all isotopes of that element.

The annual-average radionuclide concentrations in refined aluminum and in the by-products of the smelting/melting of aluminum scrap in a reverberatory furnace, as well as the annual activity of each nuclide released to the atmosphere, employ the equations listed in Section 3.5.1. The parameters specific to aluminum are based on the available information on the secondary aluminum industry presented in Section 5.2. The values adopted for the present analysis are listed in Tables B.6 and B.7.

The radionuclide concentrations in the metal product, based on the single-heat mixing factors discussed in Section 5.4.3.2, were calculated as follows:

$$S_{ip} = \frac{C_{io}\, f_{ip}\, f_{mc}}{f_p}$$

S_{ip} = concentration of nuclide *i* in metal produced from maximum single heat

C_{io} = initial concentration of nuclide *i* in cleared scrap

f_{ip} = partition factor of nuclide *i* in metal product (see Table 5.5)

f_{mc} = single-heat mixing factor

$= \frac{m_{Al}}{M_f}$

m_{Al} = mass of aluminum scrap cleared from a single nuclear power plant
M_f = capacity of reverberatory furnace (details in Appendix D)

f_p = mass fraction of metal product (see Section 5.3.1.1)

The mean and the 5th, 50th, and 95th percentile radionuclide concentrations in the products of the secondary smelter, as well as the annual activities released to the atmosphere, are listed in Appendix K.

5.6 Aluminum Recycling and Disposal Scenarios

The 21 exposure scenarios included in the aluminum analysis, along with the environmental transport pathways included in each scenario, are listed in Table 5.6. The basis of each scenario is listed in the column headed "CA" (corresponding analysis). Each of the 14 scenarios indicated by the notation "Fe" is based on the corresponding scenario in the steel analysis, which has the same or a similar title. One of these scenarios, indicated by "Fe-mod," involves a significant modification of the corresponding steel scenario, as discussed later in this section.

Six more scenarios, noted "Cu," are based on corresponding copper scenarios. (Aluminum scenarios involving dross correspond to steel or copper scenarios involving slag.) In addition, there is one new product use scenario: a person using a cooking utensil made from recycled aluminum. Only those aspects of the analysis that are new or significantly different than the corresponding steel or copper analyses are discussed in this section.[18]

5.6.1 Inhalation of Aluminum Dusts

There are no specific OSHA limits on the inhalation of aluminum dusts. Such dusts therefore come under the general category of nuisance dusts. The permissible exposure limit (PEL) for such dusts is 5 mg/m^3 of respirable particles. The mass loading of dust from aluminum processing, handling, and disposal was modeled in the same manner as for steel slag, described in Section 3.7.1.2. These dust concentrations are used in all the handling, processing, and disposal scenarios which include the inhalation pathway, as indicated in Table 5.6. The dust concentrations in the dross and dust transportation scenarios are the same as in the corresponding scenarios in the steel and copper analyses.

5.6.2 Handling Dross at Secondary Smelter

It is assumed that an average of about 500 t of dross is stored at a secondary smelter. It is more realistic to model this as a mound, with a worker engaged in activities in its vicinity, rather than as an essentially infinite plane, as was done in the corresponding slag handling scenario in the steel analysis. The dross handling scenario thus corresponds more closely to the scenario that models the processing of steel slag for use in road construction.

5.6.3 Use of Aluminum Cooking Ware

A person cooking food in an aluminum pot would be exposed to direct penetrating radiation from any residual radionuclide concentrations in the metal, in addition to eating food which may be contaminated with radionuclides that have leached from the pan.

5.6.3.1 External Exposure

The duration of external exposure was modeled as a lognormal distribution, with a mean of ~52 min/d, an arithmetic standard deviation of ~53 min/d, and truncated at the lower end at one minute per day. These values are based on the time spent on food preparation in a given 24-hour period by all survey respondents, reported in EPA 1997, Table 15-88. Since these include respondents who spent as little as one minute per day on food preparation, it is reasonable to assume that these are daily averages that would apply to an entire year.

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[18] All parameter values that are specific to the aluminum exposure scenarios are listed in Table B.10. All other parameters have the values listed for the corresponding steel scenarios in Table B.8 or the similar copper scenarios in Table B.9.

Table 5.6 Scenario and exposure pathway matrix

Scenario abbreviation	Scenario title	MF[a]	CA[b]	Pathways[c]		
				Ext[d]	Inh	Ing
Handling and Processing						
Scrap yard	Processing aluminum scrap at scrap yard	SD	Cu	30	●	●
Handling metal product	Handling metal product at secondary smelter	AA	Fe	33	●	●
Handling dross	Handling dross at secondary smelter	AA	Fe-mod	31	●	●
Baghouse maintenance	Baghouse maintenance at secondary smelter	AA	Fe	32		
Atmospheric Release						
Airborne emissions	Emission of airborne effluents from smelter	AA	Fe	F2	●	●
Transportation						
Scrap truck–driver	Truck driver hauling cleared aluminum scrap	ST	Cu	35		
Metal product–driver	Truck driver hauling metal product from smelter	AA	Fe	38		
Dross truck–driver	Truck driver hauling dross from smelter	AA	Cu	36	●	●
Dust truck–driver	Truck driver hauling dust from smelter	AA	Cu	37	●	●
Product Use						
Exposure to large mass	Exposure to large metal mass	SH	Fe	33		
Exposure to small mass	Exposure to small metal mass	SH	Fe	34		
Driver–engine block	Driver of taxi with aluminum engine block	SH	Fe	39		
Aluminum cookware	Use of aluminum cooking ware	SH	New	40		●
Landfill Disposal						
Scrap disposal–industrial	Handling aluminum scrap at industrial landfill	IL	Fe	F1		
Scrap disposal–municipal	Handling aluminum scrap at municipal landfill	ML	Fe	F1		
Dross disposal–industrial	Handling dross at industrial landfill	IL	Fe	F1	●	●
Dross disposal–municipal	Handling dross at municipal landfill	ML	Fe	F1	●	●
Groundwater Contaminated by Leachate from Landfills						
Leachate–industrial–scrap	Leachate from industrial landfill–scrap	IL	Fe			●
Leachate–municipal–scrap	Leachate from municipal landfill–scrap	ML	Fe			●
Leachate–industrial–dross	Leachate from industrial landfill–dross	IL	Cu			●
Leachate–municipal–dross	Leachate from municipal landfill–dross	ML	Cu			●

[a] MF = mixing factor: AA = annual average, IL = industrial landfill, ML = municipal landfill, SD = scrap dealer, SH = single heat, ST = scrap truck (see text—details in Appendix D)

[b] CA = corresponding analysis: Fe = steel, Cu = copper

[c] Exposure pathways: Ext = external, Inh = inhalation, Ing = ingestion of food, water, or soil; inadvertent ingestion

[d] External exposure dose factors:
- 30 Scrap pile
- 31 Dross pile
- 32 Baghouse
- 33 Large metal object
- 34 Small metal object
- 35 Scrap truck
- 36 Dross truck
- 37 Dust truck
- 38 Truck loaded with metal product
- 39 Auto—aluminum engine block
- 40 Cooking pot
- F1 Soil contaminated to an infinite depth (Eckerman and Ryman 1993)
- F2 Contaminated ground surface (Eckerman and Ryman 1993)

5.6.3.2 Ingestion Exposure

Blumenthal (1990) wrote that ". . . a person using uncoated aluminum pans for all cooking and food storage every day would take in an estimated 3.5 milligrams of aluminum daily." This was the only quantitative estimate of total intake of aluminum from kitchen utensils that was found in the literature, and was adopted as the fixed value for the present analysis. Again, since this is a daily average, it is assumed that the exposure would occur each day of the year. The dose from the ingestion pathway is expressed as follows:

$$D_{ic} = C_{ip} F_{ig} m_{Al} t_{ys} \left(\frac{e^{-\lambda_i t_s} - e^{-\lambda_i (t_s + t_a)}}{\lambda_i t_a} \right) \qquad \textbf{5.1}$$

D_{ic} = dose from ingestion of radionuclide *i* in cooking ware during assessment period (:Sv)

C_{ip} = undecayed specific activity of radionuclide *i* in metal product[19] (Bq/g)

F_{ig} = dose conversion factor for ingestion of radionuclide *i* (:Sv/Bq)

m_{Al} = intake of aluminum from cooking ware
= 0.0035 g/d

t_{ys} = exposure duration (d)

t_s = time from clearance of material to the time the scenario begins (d)

8_i = radioactive decay rate of nuclide *i* (d^{-1})

t_a = period of assessment

Equation 5.1 expresses the assumption that any radionuclides that partitioned to the aluminum during smelting would leach into the food at the same relative rate as the aluminum. Therefore, the daily intake of a given nuclide in the aluminum pot is the product of the daily intake of aluminum and the specific activity of the nuclide in the aluminum.

5.6.4 Scenario Timing

This section presents the basic assumptions used in defining the time periods for each of the aluminum exposure scenarios.

5.6.4.1 Scrap Transport and Handling

- All cleared scrap is assumed to be initially transported to a scrap dealer. Transportation takes place two to six days after clearance.

[19] An exact expression for this quantity is presented in Section 3.5.2.

- Disposal in a landfill occurs three to 13 days after clearance.

- The scrap is processed and remains at the scrap dealer for a period of one to 30 days after it arrives.

5.6.4.2 Refining and Processing

- The operations at the secondary smelter take place one to 15 days after the scrap is shipped from the scrap dealer.

- Atmospheric releases from the furnace occur at the time the scrap is smelted.

- Dross and dust are produced at the time the scrap is smelted.

5.6.4.3 Transportation of Smelter Products

- The metal is assumed to be transported three to 30 days after it is produced.[20]

- Dross and dust from the reverberatory furnace are collected periodically and sent to a third party for metal recovery. Transportation is assumed to take place 30 to 60 days after the dust and dross are generated.

5.6.4.4 Use of Aluminum Products

- Manufactured items are put into use 10 to 60 days after the aluminum is shipped from the secondary smelter.

- Generic aluminum products are assumed to have a useful life of 30 years. There are two specific aluminum products in the present analysis: an aluminum engine block and an aluminum cooking pot. The engine block is assumed to be in a taxicab which is driven by its owner an average of about 2,500 hours per year. In addition, it may be leased to other drivers when the owner is off duty. Due to heavy use, the engine is assumed to have a service life of three years.[21] An aluminum pot is assumed to have a service life of 20 years.

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[20] Molten metal is transported immediately after being poured from the furnace. However, the scenario modeled in the present analysis is the transport of cast ingots, which would typically take place a few days after production. As discussed in Section 5.2.3, molten aluminum shipments are a small fraction of total aluminum production.

[21] As an example, the New York City Taxi and Limousine Commission requires medallion taxis (cabs allowed to pick up passengers on the street) to be replaced every three years.

5.7 Dose Assessments of Recycling and Disposal of Aluminum Scrap

As discussed in previous sections of this chapter, the radiological assessment of the clearance of aluminum scrap from NRC-licensed nuclear facilities evaluates the radiation exposures of individual members of various groups to each of 115 radionuclides and their progenies in 21 exposure scenarios.

5.7.1 Calculation of Effective Dose Equivalents (EDEs)

The groups described by four scenarios receive the highest mean normalized EDEs from one year of exposure to cleared aluminum scrap from all 115 nuclides, one scenario constituting the EDE-critical group for 78 nuclides.[22] Table 5.7 lists the mean and the 5th, 50th, and 95th percentile mass-based normalized EDEs from each radionuclide to its respective critical group, while Table 5.8 lists the corresponding surficial EDEs. Figure 5.3 lists the scenarios describing the EDE-critical groups and displays the number of radionuclides for which each scenario constitutes the critical group. The mean and the 5th, 50th, 90th, and 95th percentile normalized EDEs from all 115 nuclides for all 21 scenarios are tabulated in Appendix H-1.

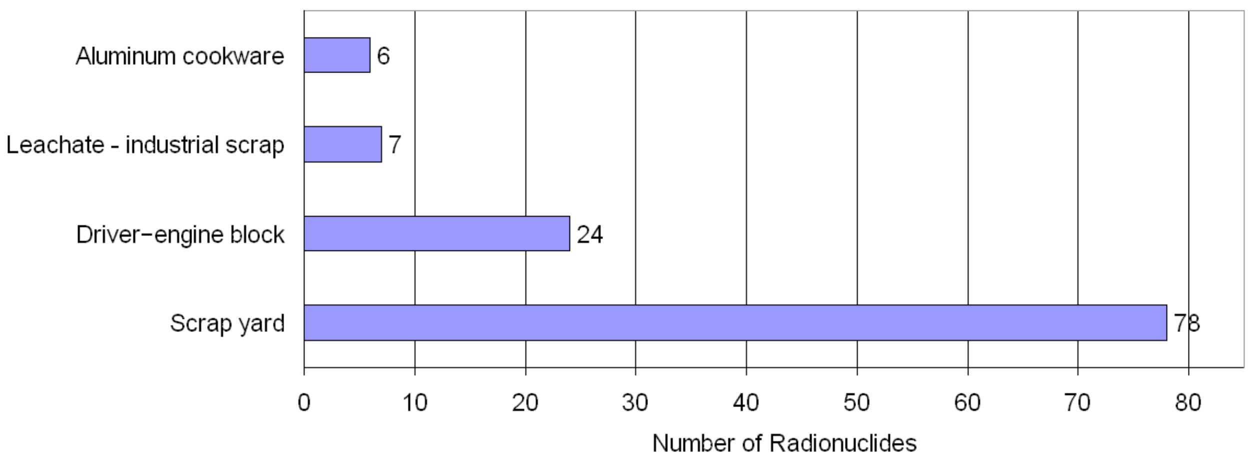

Figure 5.3 Scenarios giving rise to EDE-critical groups for aluminum

The scrap yard worker scenario gives rise to the critical group for the largest number of radionuclides. Since this scenario includes all three principal environmental pathways—external exposure, inhalation, and inadvertent ingestion—it leads to potential doses from nuclides which are strong photon emitters, as well as from those that deliver their primary dose via alpha or beta emission.

The drivers of taxicabs with aluminum engine blocks constitute the critical group for a number of nuclides that partition strongly to the metal during smelting and are strong external emitters. Several factors account for this being the critical group for 24 radionuclides. First is the average

[22] As discussed in Chapter 1, the group which receives the highest mean normalized EDE from a given radionuclide is defined as the EDE-critical group for that nuclide.

mixing factor of 2.0%, as cited in Section 5.4.3.2. Second is the long exposure duration—the driver spends an average of about nine hours per day, six days a week in his taxi. (A detailed discussion of the exposure duration in this scenario is presented in Section 3.7.5.5.)

5.7.2 Calculation of Effective Doses

The groups described by five scenarios receive the highest mean normalized effective doses from one year of exposure to cleared aluminum scrap from all 115 nuclides, the scrap yard workers constituting the critical group for 77 nuclides. Table 5.9 lists the mean and the 5th, 50th, and 95th percentile mass-based normalized effective doses from each radionuclide to its respective critical group, while Table 5.10 lists the corresponding surficial effective doses. Figure 5.4 lists the scenarios describing the effective dose-critical groups and displays the number of radionuclides for which each scenario constitutes the critical group. The mean and the 5th, 50th, 90th, and 95th percentile normalized effective doses from all 115 nuclides for all 21 scenarios are tabulated in Appendix H-2.

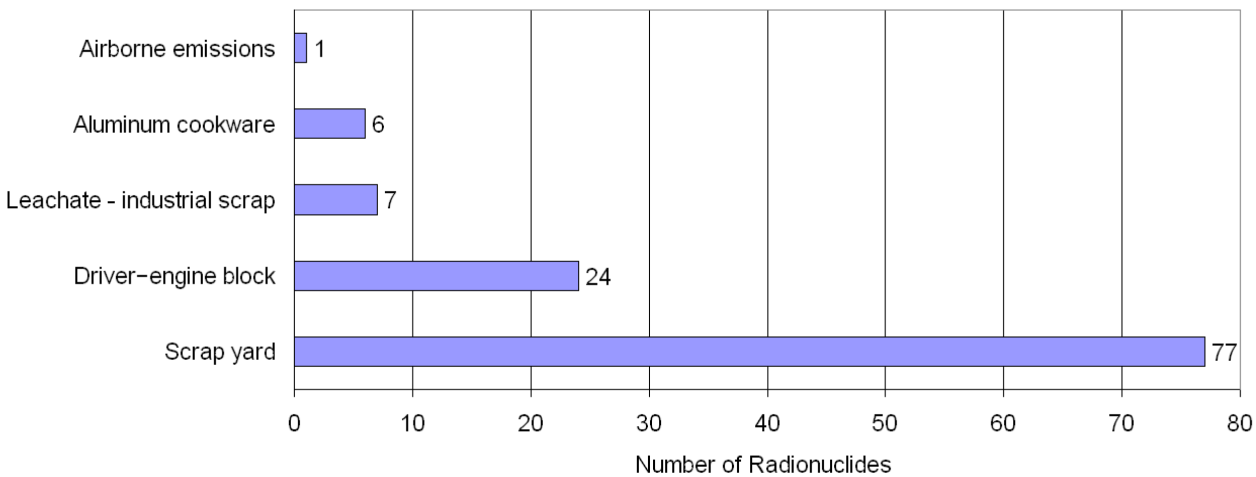

Figure 5.4 Scenarios giving rise to effective dose-critical groups for aluminum

The factors leading to the highest effective doses in these scenarios are similar to those giving rise to the EDE-critical groups discussed in Section 5.7.1.

Table 5.7 Normalized mass-based effective dose equivalents to critical groups for aluminum

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	2.8e-06	0.0e+00	2.6e-09	1.0e-05	1.0e-08	0.0e+00	9.5e-12	3.8e-08	Leachate-industrial-scrap
C-14	4.5e-06	0.0e+00	0.0e+00	8.5e-06	1.7e-08	0.0e+00	0.0e+00	3.1e-08	Leachate-industrial-scrap
Na-22	2.9e-02	7.2e-03	1.8e-02	8.6e-02	1.1e-04	2.7e-05	6.8e-05	3.2e-04	Scrap yard
P-32	2.1e-05	3.8e-06	1.3e-05	6.8e-05	7.9e-08	1.4e-08	4.8e-08	2.5e-07	Scrap yard
S-35	8.2e-07	2.0e-07	5.2e-07	2.5e-06	3.1e-09	7.5e-10	1.9e-09	9.2e-09	Scrap yard
Cl-36	5.9e-05	0.0e+00	0.0e+00	2.4e-04	2.2e-07	0.0e+00	0.0e+00	8.9e-07	Leachate-industrial-scrap
K-40	2.2e-03	5.5e-04	1.4e-03	6.6e-03	8.2e-06	2.0e-06	5.2e-06	2.4e-05	Scrap yard
Ca-41	2.9e-05	0.0e+00	0.0e+00	1.2e-04	1.1e-07	0.0e+00	0.0e+00	4.6e-07	Leachate-industrial-scrap
Ca-45	3.8e-06	8.0e-07	2.4e-06	1.2e-05	1.4e-08	3.0e-09	8.9e-09	4.5e-08	Scrap yard
Sc-46	2.3e-02	5.8e-03	1.5e-02	7.1e-02	8.7e-05	2.1e-05	5.5e-05	2.6e-04	Scrap yard
Cr-51	2.4e-04	5.4e-05	1.5e-04	7.4e-04	8.8e-07	2.0e-07	5.5e-07	2.7e-06	Scrap yard
Mn-53	6.7e-07	4.4e-07	6.1e-07	1.2e-06	2.5e-09	1.6e-09	2.3e-09	4.6e-09	Aluminum cookware
Mn-54	5.6e-02	3.1e-02	5.1e-02	1.0e-01	2.1e-04	1.2e-04	1.9e-04	3.8e-04	Driver-engine block
Fe-55	3.1e-06	2.1e-06	2.9e-06	5.8e-06	1.2e-08	7.6e-09	1.1e-08	2.1e-08	Aluminum cookware
Fe-59	1.2e-02	2.9e-03	7.7e-03	3.7e-02	4.5e-05	1.1e-05	2.9e-05	1.4e-04	Scrap yard
Co-56	4.8e-02	1.6e-02	4.0e-02	1.0e-01	1.8e-04	6.1e-05	1.5e-04	3.8e-04	Driver-engine block
Co-57	7.2e-03	3.9e-03	6.5e-03	1.3e-02	2.7e-05	1.4e-05	2.4e-05	4.9e-05	Driver-engine block
Co-58	1.3e-02	3.9e-03	1.0e-02	2.8e-02	4.6e-05	1.5e-05	3.8e-05	1.0e-04	Driver-engine block
Co-60	2.6e-01	1.5e-01	2.4e-01	4.7e-01	9.6e-04	5.5e-04	8.7e-04	1.7e-03	Driver-engine block
Ni-59	2.2e-06	1.3e-06	2.0e-06	4.0e-06	8.1e-09	4.7e-09	7.4e-09	1.5e-08	Driver-engine block
Ni-63	3.5e-06	2.3e-06	3.2e-06	6.6e-06	1.3e-08	8.7e-09	1.2e-08	2.4e-08	Aluminum cookware
Zn-65	3.1e-02	1.7e-02	2.8e-02	5.8e-02	1.2e-04	6.2e-05	1.0e-04	2.1e-04	Driver-engine block
As-73	1.8e-05	6.0e-06	1.5e-05	3.8e-05	6.5e-08	2.2e-08	5.5e-08	1.4e-07	Driver-engine block
Se-75	1.0e-02	4.4e-03	9.0e-03	2.0e-02	3.8e-05	1.6e-05	3.3e-05	7.4e-05	Driver-engine block
Sr-85	5.1e-03	1.3e-03	3.3e-03	1.6e-02	1.9e-05	4.6e-06	1.2e-05	5.8e-05	Scrap yard
Sr-89	2.9e-05	7.6e-06	1.9e-05	8.9e-05	1.1e-07	2.8e-08	6.9e-08	3.3e-07	Scrap yard
Sr-90	2.6e-04	6.3e-05	1.6e-04	7.9e-04	9.5e-07	2.3e-07	6.0e-07	2.9e-06	Scrap yard
Y-91	7.9e-05	2.1e-05	5.0e-05	2.4e-04	2.9e-07	7.7e-08	1.9e-07	8.8e-07	Scrap yard
Zr-93	2.1e-05	5.2e-06	1.3e-05	6.3e-05	7.6e-08	1.9e-08	4.8e-08	2.3e-07	Scrap yard
Zr-95	1.1e-02	2.7e-03	6.8e-03	3.2e-02	4.0e-05	9.8e-06	2.5e-05	1.2e-04	Scrap yard
Nb-93m	7.3e-06	1.9e-06	4.6e-06	2.2e-05	2.7e-08	6.9e-09	1.7e-08	8.2e-08	Scrap yard
Nb-94	2.0e-01	1.1e-01	1.8e-01	3.6e-01	7.3e-04	4.3e-04	6.7e-04	1.3e-03	Driver-engine block
Nb-95	7.1e-03	1.7e-03	4.5e-03	2.2e-02	2.6e-05	6.1e-06	1.6e-05	8.0e-05	Scrap yard
Mo-93	9.0e-06	5.6e-06	8.2e-06	1.7e-05	3.3e-08	2.1e-08	3.0e-08	6.2e-08	Aluminum cookware
Tc-97	3.0e-05	0.0e+00	0.0e+00	1.3e-04	1.1e-07	0.0e+00	0.0e+00	4.7e-07	Leachate-industrial-scrap
Tc-97m	4.6e-06	1.2e-06	2.9e-06	1.4e-05	1.7e-08	4.6e-09	1.1e-08	5.0e-08	Scrap yard
Tc-99	2.5e-04	0.0e+00	0.0e+00	1.1e-03	9.4e-07	0.0e+00	0.0e+00	4.0e-06	Leachate-industrial-scrap
Ru-103	4.5e-03	1.1e-03	2.9e-03	1.4e-02	1.7e-05	4.0e-06	1.1e-05	5.1e-05	Scrap yard
Ru-106	1.9e-02	1.1e-02	1.8e-02	3.5e-02	7.2e-05	4.0e-05	6.5e-05	1.3e-04	Driver-engine block

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.7 Normalized mass-based effective dose equivalents to critical groups for aluminum

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	2.4e-01	1.4e-01	2.2e-01	4.3e-01	8.9e-04	5.2e-04	8.1e-04	1.6e-03	Driver-engine block
Ag-110m	1.7e-01	9.4e-02	1.6e-01	3.2e-01	6.5e-04	3.5e-04	5.8e-04	1.2e-03	Driver-engine block
Cd-109	2.0e-04	1.1e-04	1.8e-04	3.7e-04	7.5e-07	4.2e-07	6.7e-07	1.4e-06	Driver-engine block
Sn-113	6.6e-03	2.8e-03	5.8e-03	1.3e-02	2.5e-05	1.0e-05	2.1e-05	4.8e-05	Driver-engine block
Sb-124	2.0e-02	4.9e-03	1.3e-02	6.1e-02	7.5e-05	1.8e-05	4.7e-05	2.3e-04	Scrap yard
Sb-125	4.0e-02	2.3e-02	3.7e-02	7.3e-02	1.5e-04	8.3e-05	1.4e-04	2.7e-04	Driver-engine block
Te-123m	3.5e-03	1.5e-03	3.1e-03	6.8e-03	1.3e-05	5.6e-06	1.1e-05	2.5e-05	Driver-engine block
Te-127m	1.3e-04	5.2e-05	1.1e-04	2.5e-04	4.7e-07	1.9e-07	4.1e-07	9.3e-07	Driver-engine block
I-125	4.8e-05	1.1e-05	3.0e-05	1.5e-04	1.8e-07	4.1e-08	1.1e-07	5.4e-07	Scrap yard
I-129	1.2e-02	0.0e+00	0.0e+00	4.4e-02	4.5e-05	0.0e+00	0.0e+00	1.6e-04	Leachate-industrial-scrap
I-131	1.2e-03	1.1e-04	6.0e-04	4.1e-03	4.5e-06	4.1e-07	2.2e-06	1.5e-05	Scrap yard
Cs-134	2.0e-02	5.0e-03	1.3e-02	6.1e-02	7.5e-05	1.9e-05	4.8e-05	2.2e-04	Scrap yard
Cs-135	6.8e-06	9.8e-07	4.2e-06	2.2e-05	2.5e-08	3.6e-09	1.6e-08	8.1e-08	Scrap yard
Cs-137	7.4e-03	1.8e-03	4.7e-03	2.2e-02	2.8e-05	6.8e-06	1.8e-05	8.2e-05	Scrap yard
Ba-133	4.2e-03	1.0e-03	2.7e-03	1.3e-02	1.6e-05	3.9e-06	9.9e-06	4.6e-05	Scrap yard
Ce-139	1.2e-03	2.9e-04	7.5e-04	3.6e-03	4.4e-06	1.1e-06	2.8e-06	1.3e-05	Scrap yard
Ce-141	4.4e-04	1.0e-04	2.8e-04	1.3e-03	1.6e-06	3.8e-07	1.0e-06	5.0e-06	Scrap yard
Ce-144	7.3e-04	1.9e-04	4.6e-04	2.2e-03	2.7e-06	7.1e-07	1.7e-06	8.1e-06	Scrap yard
Pm-147	9.9e-06	2.5e-06	6.2e-06	3.0e-05	3.6e-08	9.4e-09	2.3e-08	1.1e-07	Scrap yard
Sm-151	7.2e-06	1.8e-06	4.5e-06	2.2e-05	2.7e-08	6.8e-09	1.7e-08	8.2e-08	Scrap yard
Eu-152	1.5e-02	3.8e-03	9.7e-03	4.6e-02	5.7e-05	1.4e-05	3.6e-05	1.7e-04	Scrap yard
Eu-154	1.5e-02	3.7e-03	9.5e-03	4.4e-02	5.5e-05	1.4e-05	3.5e-05	1.6e-04	Scrap yard
Eu-155	3.4e-04	8.6e-05	2.2e-04	1.0e-03	1.3e-06	3.2e-07	8.1e-07	3.8e-06	Scrap yard
Gd-153	4.3e-04	1.1e-04	2.7e-04	1.3e-03	1.6e-06	3.9e-07	1.0e-06	4.7e-06	Scrap yard
Tb-160	1.2e-02	3.1e-03	7.9e-03	3.8e-02	4.6e-05	1.1e-05	2.9e-05	1.4e-04	Scrap yard
Tm-170	3.1e-05	8.5e-06	2.0e-05	9.1e-05	1.1e-07	3.1e-08	7.3e-08	3.4e-07	Scrap yard
Tm-171	4.1e-06	1.2e-06	2.6e-06	1.2e-05	1.5e-08	4.3e-09	9.7e-09	4.5e-08	Scrap yard
Ta-182	2.7e-02	1.1e-02	2.4e-02	5.3e-02	1.0e-04	4.2e-05	8.7e-05	2.0e-04	Driver-engine block
W-181	3.1e-04	1.3e-04	2.7e-04	6.0e-04	1.1e-06	4.9e-07	1.0e-06	2.2e-06	Driver-engine block
W-185	2.1e-06	4.9e-07	1.3e-06	6.5e-06	7.8e-09	1.8e-09	4.9e-09	2.4e-08	Scrap yard
Os-185	1.2e-02	4.5e-03	1.0e-02	2.4e-02	4.4e-05	1.7e-05	3.8e-05	9.0e-05	Driver-engine block
Ir-192	1.1e-02	3.4e-03	8.9e-03	2.4e-02	3.9e-05	1.2e-05	3.3e-05	8.8e-05	Driver-engine block
Tl-204	1.0e-04	5.6e-05	9.1e-05	1.8e-04	3.7e-07	2.1e-07	3.4e-07	6.8e-07	Driver-engine block
Pb-210	3.7e-02	2.4e-02	3.4e-02	6.9e-02	1.4e-04	8.7e-05	1.3e-04	2.5e-04	Aluminum cookware
Bi-207	1.6e-01	8.8e-02	1.4e-01	2.9e-01	5.8e-04	3.3e-04	5.3e-04	1.1e-03	Driver-engine block
Po-210	3.1e-03	1.8e-03	2.8e-03	5.8e-03	1.2e-05	6.5e-06	1.0e-05	2.2e-05	Aluminum cookware
Ra-226	2.6e-02	6.9e-03	1.7e-02	7.8e-02	9.7e-05	2.5e-05	6.2e-05	2.9e-04	Scrap yard
Ra-228	1.5e-02	4.1e-03	9.7e-03	4.5e-02	5.6e-05	1.5e-05	3.6e-05	1.7e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.7 Normalized mass-based effective dose equivalents to critical groups for aluminum

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a] 5th	50th	95th	Mean	Percentile[a] 5th	50th	95th	
Ac-227	3.2e-01	8.1e-02	2.0e-01	9.7e-01	1.2e-03	3.0e-04	7.4e-04	3.6e-03	Scrap yard
Th-228	7.7e-02	2.1e-02	4.9e-02	2.4e-01	2.8e-04	7.8e-05	1.8e-04	8.7e-04	Scrap yard
Th-229	5.1e-01	1.3e-01	3.2e-01	1.5e+00	1.9e-03	4.7e-04	1.2e-03	5.7e-03	Scrap yard
Th-230	7.6e-02	1.9e-02	4.7e-02	2.3e-01	2.8e-04	7.0e-05	1.8e-04	8.5e-04	Scrap yard
Th-232	3.8e-01	9.5e-02	2.4e-01	1.2e+00	1.4e-03	3.5e-04	8.8e-04	4.3e-03	Scrap yard
Pa-231	3.1e-01	7.7e-02	1.9e-01	9.3e-01	1.1e-03	2.9e-04	7.1e-04	3.4e-03	Scrap yard
U-232	1.5e-01	3.9e-02	9.7e-02	4.7e-01	5.7e-04	1.4e-04	3.6e-04	1.7e-03	Scrap yard
U-233	3.1e-02	7.9e-03	2.0e-02	9.6e-02	1.2e-04	2.9e-05	7.3e-05	3.5e-04	Scrap yard
U-234	3.1e-02	7.7e-03	1.9e-02	9.4e-02	1.1e-04	2.9e-05	7.1e-05	3.5e-04	Scrap yard
U-235	3.0e-02	7.8e-03	1.9e-02	9.3e-02	1.1e-04	2.9e-05	7.0e-05	3.4e-04	Scrap yard
U-236	2.9e-02	7.3e-03	1.8e-02	8.9e-02	1.1e-04	2.7e-05	6.8e-05	3.3e-04	Scrap yard
U-238	2.8e-02	7.0e-03	1.8e-02	8.5e-02	1.0e-04	2.6e-05	6.5e-05	3.1e-04	Scrap yard
Np-237	1.3e-01	3.3e-02	8.2e-02	4.0e-01	4.8e-04	1.2e-04	3.0e-04	1.5e-03	Scrap yard
Pu-236	3.4e-02	8.6e-03	2.1e-02	1.0e-01	1.3e-04	3.2e-05	7.9e-05	3.8e-04	Scrap yard
Pu-238	9.3e-02	2.4e-02	5.8e-02	2.8e-01	3.4e-04	8.7e-05	2.2e-04	1.0e-03	Scrap yard
Pu-239	1.0e-01	2.6e-02	6.4e-02	3.1e-01	3.8e-04	9.5e-05	2.4e-04	1.1e-03	Scrap yard
Pu-240	1.0e-01	2.6e-02	6.4e-02	3.1e-01	3.8e-04	9.5e-05	2.4e-04	1.1e-03	Scrap yard
Pu-241	2.0e-03	5.0e-04	1.2e-03	6.0e-03	7.3e-06	1.8e-06	4.5e-06	2.2e-05	Scrap yard
Pu-242	9.7e-02	2.5e-02	6.1e-02	3.0e-01	3.6e-04	9.1e-05	2.3e-04	1.1e-03	Scrap yard
Pu-244	1.0e-01	2.6e-02	6.3e-02	3.1e-01	3.7e-04	9.5e-05	2.3e-04	1.1e-03	Scrap yard
Am-241	1.1e-01	2.7e-02	6.6e-02	3.2e-01	3.9e-04	9.9e-05	2.4e-04	1.2e-03	Scrap yard
Am-242m	1.0e-01	2.6e-02	6.5e-02	3.2e-01	3.9e-04	9.8e-05	2.4e-04	1.2e-03	Scrap yard
Am-243	1.1e-01	2.7e-02	6.7e-02	3.2e-01	3.9e-04	1.0e-04	2.5e-04	1.2e-03	Scrap yard
Cm-242	3.8e-03	9.5e-04	2.4e-03	1.2e-02	1.4e-05	3.5e-06	8.8e-06	4.3e-05	Scrap yard
Cm-243	7.4e-02	1.9e-02	4.6e-02	2.3e-01	2.7e-04	7.0e-05	1.7e-04	8.3e-04	Scrap yard
Cm-244	5.9e-02	1.5e-02	3.7e-02	1.8e-01	2.2e-04	5.5e-05	1.4e-04	6.6e-04	Scrap yard
Cm-245	1.1e-01	2.8e-02	6.8e-02	3.3e-01	4.0e-04	1.0e-04	2.5e-04	1.2e-03	Scrap yard
Cm-246	1.1e-01	2.7e-02	6.7e-02	3.3e-01	4.0e-04	1.0e-04	2.5e-04	1.2e-03	Scrap yard
Cm-247	1.0e-01	2.6e-02	6.4e-02	3.1e-01	3.8e-04	9.7e-05	2.4e-04	1.2e-03	Scrap yard
Cm-248	3.9e-01	9.9e-02	2.5e-01	1.2e+00	1.5e-03	3.7e-04	9.1e-04	4.4e-03	Scrap yard
Bk-249	3.3e-04	8.3e-05	2.0e-04	1.0e-03	1.2e-06	3.1e-07	7.6e-07	3.7e-06	Scrap yard
Cf-248	1.2e-02	2.9e-03	7.3e-03	3.6e-02	4.3e-05	1.1e-05	2.7e-05	1.3e-04	Scrap yard
Cf-249	9.6e-02	2.5e-02	6.0e-02	2.9e-01	3.5e-04	9.1e-05	2.2e-04	1.1e-03	Scrap yard
Cf-250	4.9e-02	1.2e-02	3.1e-02	1.5e-01	1.8e-04	4.6e-05	1.1e-04	5.5e-04	Scrap yard
Cf-251	9.4e-02	2.4e-02	5.9e-02	2.9e-01	3.5e-04	8.9e-05	2.2e-04	1.1e-03	Scrap yard
Cf-252	3.7e-02	9.2e-03	2.3e-02	1.1e-01	1.4e-04	3.4e-05	8.5e-05	4.1e-04	Scrap yard
Cf-254	2.5e-01	6.6e-02	1.6e-01	7.3e-01	9.1e-04	2.4e-04	5.8e-04	2.7e-03	Scrap yard
Es-254	2.1e-02	5.9e-03	1.3e-02	6.2e-02	7.8e-05	2.2e-05	4.9e-05	2.3e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.8 Normalized surficial effective dose equivalents to critical groups for aluminum

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	3.1e-06	0.0e+00	2.9e-09	1.1e-05	1.1e-08	0.0e+00	1.1e-11	4.2e-08	Leachate-industrial-scrap
C-14	5.0e-06	0.0e+00	0.0e+00	9.2e-06	1.8e-08	0.0e+00	0.0e+00	3.4e-08	Leachate-industrial-scrap
Na-22	3.2e-02	7.8e-03	2.0e-02	9.7e-02	1.2e-04	2.9e-05	7.5e-05	3.6e-04	Scrap yard
P-32	2.4e-05	4.2e-06	1.4e-05	7.4e-05	8.8e-08	1.5e-08	5.2e-08	2.7e-07	Scrap yard
S-35	9.2e-07	2.2e-07	5.8e-07	2.8e-06	3.4e-09	8.2e-10	2.1e-09	1.0e-08	Scrap yard
Cl-36	6.6e-05	0.0e+00	0.0e+00	2.6e-04	2.5e-07	0.0e+00	0.0e+00	9.8e-07	Leachate-industrial-scrap
K-40	2.5e-03	6.0e-04	1.6e-03	7.4e-03	9.1e-06	2.2e-06	5.7e-06	2.7e-05	Scrap yard
Ca-41	3.2e-05	0.0e+00	0.0e+00	1.4e-04	1.2e-07	0.0e+00	0.0e+00	5.1e-07	Leachate-industrial-scrap
Ca-45	4.3e-06	8.8e-07	2.7e-06	1.3e-05	1.6e-08	3.3e-09	9.9e-09	4.9e-08	Scrap yard
Sc-46	2.6e-02	6.3e-03	1.6e-02	7.8e-02	9.7e-05	2.3e-05	6.1e-05	2.9e-04	Scrap yard
Cr-51	2.7e-04	5.9e-05	1.7e-04	8.2e-04	9.9e-07	2.2e-07	6.1e-07	3.0e-06	Scrap yard
Mn-53	7.4e-07	4.7e-07	6.7e-07	1.4e-06	2.7e-09	1.7e-09	2.5e-09	5.1e-09	Aluminum cookware
Mn-54	6.3e-02	3.4e-02	5.7e-02	1.2e-01	2.3e-04	1.2e-04	2.1e-04	4.3e-04	Driver-engine block
Fe-55	3.5e-06	2.2e-06	3.2e-06	6.5e-06	1.3e-08	8.1e-09	1.2e-08	2.4e-08	Aluminum cookware
Fe-59	1.4e-02	3.2e-03	8.6e-03	4.2e-02	5.0e-05	1.2e-05	3.2e-05	1.5e-04	Scrap yard
Co-56	5.3e-02	1.8e-02	4.5e-02	1.2e-01	2.0e-04	6.7e-05	1.7e-04	4.3e-04	Driver-engine block
Co-57	8.0e-03	4.2e-03	7.2e-03	1.5e-02	3.0e-05	1.6e-05	2.7e-05	5.5e-05	Driver-engine block
Co-58	1.4e-02	4.3e-03	1.2e-02	3.1e-02	5.2e-05	1.6e-05	4.3e-05	1.2e-04	Driver-engine block
Co-60	2.9e-01	1.6e-01	2.6e-01	5.3e-01	1.1e-03	5.9e-04	9.6e-04	1.9e-03	Driver-engine block
Ni-59	2.5e-06	1.4e-06	2.2e-06	4.5e-06	9.1e-09	5.1e-09	8.2e-09	1.7e-08	Driver-engine block
Ni-63	3.9e-06	2.5e-06	3.6e-06	7.3e-06	1.5e-08	9.3e-09	1.3e-08	2.7e-08	Aluminum cookware
Zn-65	3.5e-02	1.8e-02	3.1e-02	6.4e-02	1.3e-04	6.7e-05	1.2e-04	2.4e-04	Driver-engine block
As-73	2.0e-05	6.6e-06	1.6e-05	4.2e-05	7.2e-08	2.4e-08	6.1e-08	1.6e-07	Driver-engine block
Se-75	1.1e-02	4.8e-03	9.9e-03	2.2e-02	4.2e-05	1.8e-05	3.7e-05	8.3e-05	Driver-engine block
Sr-85	5.7e-03	1.4e-03	3.6e-03	1.7e-02	2.1e-05	5.1e-06	1.3e-05	6.4e-05	Scrap yard
Sr-89	3.3e-05	8.3e-06	2.1e-05	9.8e-05	1.2e-07	3.1e-08	7.6e-08	3.6e-07	Scrap yard
Sr-90	2.9e-04	6.9e-05	1.8e-04	8.9e-04	1.1e-06	2.5e-07	6.7e-07	3.3e-06	Scrap yard
Y-91	8.8e-05	2.3e-05	5.6e-05	2.6e-04	3.3e-07	8.4e-08	2.1e-07	9.8e-07	Scrap yard
Zr-93	2.3e-05	5.7e-06	1.4e-05	7.0e-05	8.5e-08	2.1e-08	5.3e-08	2.6e-07	Scrap yard
Zr-95	1.2e-02	2.9e-03	7.5e-03	3.6e-02	4.4e-05	1.1e-05	2.8e-05	1.3e-04	Scrap yard
Nb-93m	8.1e-06	2.0e-06	5.1e-06	2.5e-05	3.0e-08	7.6e-09	1.9e-08	9.1e-08	Scrap yard
Nb-94	2.2e-01	1.2e-01	2.0e-01	4.0e-01	8.2e-04	4.6e-04	7.4e-04	1.5e-03	Driver-engine block
Nb-95	7.9e-03	1.8e-03	4.9e-03	2.4e-02	2.9e-05	6.7e-06	1.8e-05	8.9e-05	Scrap yard
Mo-93	1.0e-05	6.0e-06	9.1e-06	1.9e-05	3.7e-08	2.2e-08	3.4e-08	6.9e-08	Aluminum cookware
Tc-97	3.3e-05	0.0e+00	0.0e+00	1.4e-04	1.2e-07	0.0e+00	0.0e+00	5.1e-07	Leachate-industrial-scrap
Tc-97m	5.1e-06	1.4e-06	3.2e-06	1.5e-05	1.9e-08	5.0e-09	1.2e-08	5.6e-08	Scrap yard
Tc-99	2.8e-04	0.0e+00	0.0e+00	1.2e-03	1.1e-06	0.0e+00	0.0e+00	4.4e-06	Leachate-industrial-scrap
Ru-103	5.1e-03	1.2e-03	3.2e-03	1.5e-02	1.9e-05	4.4e-06	1.2e-05	5.7e-05	Scrap yard
Ru-106	2.2e-02	1.2e-02	2.0e-02	4.0e-02	8.0e-05	4.4e-05	7.2e-05	1.5e-04	Driver-engine block

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.8 Normalized surficial effective dose equivalents to critical groups for aluminum

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	2.7e-01	1.5e-01	2.4e-01	4.9e-01	9.9e-04	5.5e-04	8.9e-04	1.8e-03	Driver-engine block
Ag-110m	1.9e-01	1.0e-01	1.7e-01	3.6e-01	7.2e-04	3.8e-04	6.5e-04	1.3e-03	Driver-engine block
Cd-109	2.2e-04	1.2e-04	2.0e-04	4.1e-04	8.3e-07	4.6e-07	7.5e-07	1.5e-06	Driver-engine block
Sn-113	7.4e-03	3.1e-03	6.4e-03	1.5e-02	2.7e-05	1.1e-05	2.4e-05	5.4e-05	Driver-engine block
Sb-124	2.3e-02	5.4e-03	1.4e-02	6.9e-02	8.3e-05	2.0e-05	5.3e-05	2.5e-04	Scrap yard
Sb-125	4.5e-02	2.4e-02	4.0e-02	8.2e-02	1.7e-04	9.0e-05	1.5e-04	3.1e-04	Driver-engine block
Te-123m	3.9e-03	1.6e-03	3.4e-03	7.7e-03	1.4e-05	6.1e-06	1.3e-05	2.9e-05	Driver-engine block
Te-127m	1.4e-04	5.7e-05	1.2e-04	2.8e-04	5.2e-07	2.1e-07	4.5e-07	1.0e-06	Driver-engine block
I-125	5.3e-05	1.2e-05	3.4e-05	1.6e-04	2.0e-07	4.5e-08	1.2e-07	6.1e-07	Scrap yard
I-129	1.4e-02	0.0e+00	0.0e+00	4.9e-02	5.0e-05	0.0e+00	0.0e+00	1.8e-04	Leachate-industrial-scrap
I-131	1.3e-03	1.2e-04	6.7e-04	4.6e-03	5.0e-06	4.5e-07	2.5e-06	1.7e-05	Scrap yard
Cs-134	2.3e-02	5.5e-03	1.4e-02	6.8e-02	8.4e-05	2.0e-05	5.3e-05	2.5e-04	Scrap yard
Cs-135	7.6e-06	1.1e-06	4.7e-06	2.4e-05	2.8e-08	4.0e-09	1.7e-08	9.0e-08	Scrap yard
Cs-137	8.3e-03	2.0e-03	5.2e-03	2.5e-02	3.1e-05	7.5e-06	1.9e-05	9.2e-05	Scrap yard
Ba-133	4.7e-03	1.1e-03	3.0e-03	1.4e-02	1.7e-05	4.2e-06	1.1e-05	5.2e-05	Scrap yard
Ce-139	1.3e-03	3.2e-04	8.3e-04	3.9e-03	4.9e-06	1.2e-06	3.1e-06	1.5e-05	Scrap yard
Ce-141	4.9e-04	1.1e-04	3.0e-04	1.5e-03	1.8e-06	4.2e-07	1.1e-06	5.5e-06	Scrap yard
Ce-144	8.1e-04	2.1e-04	5.1e-04	2.4e-03	3.0e-06	7.8e-07	1.9e-06	8.9e-06	Scrap yard
Pm-147	1.1e-05	2.8e-06	6.9e-06	3.3e-05	4.1e-08	1.0e-08	2.5e-08	1.2e-07	Scrap yard
Sm-151	8.0e-06	2.0e-06	5.0e-06	2.4e-05	3.0e-08	7.4e-09	1.9e-08	9.0e-08	Scrap yard
Eu-152	1.7e-02	4.1e-03	1.1e-02	5.1e-02	6.3e-05	1.5e-05	4.0e-05	1.9e-04	Scrap yard
Eu-154	1.7e-02	4.0e-03	1.0e-02	5.0e-02	6.1e-05	1.5e-05	3.9e-05	1.8e-04	Scrap yard
Eu-155	3.8e-04	9.5e-05	2.4e-04	1.1e-03	1.4e-06	3.5e-07	9.0e-07	4.3e-06	Scrap yard
Gd-153	4.7e-04	1.2e-04	3.0e-04	1.4e-03	1.8e-06	4.3e-07	1.1e-06	5.2e-06	Scrap yard
Tb-160	1.4e-02	3.3e-03	8.8e-03	4.2e-02	5.1e-05	1.2e-05	3.2e-05	1.6e-04	Scrap yard
Tm-170	3.4e-05	9.2e-06	2.2e-05	1.0e-04	1.3e-07	3.4e-08	8.1e-08	3.8e-07	Scrap yard
Tm-171	4.6e-06	1.3e-06	2.9e-06	1.4e-05	1.7e-08	4.7e-09	1.1e-08	5.0e-08	Scrap yard
Ta-182	3.0e-02	1.3e-02	2.6e-02	5.9e-02	1.1e-04	4.6e-05	9.7e-05	2.2e-04	Driver-engine block
W-181	3.4e-04	1.5e-04	3.0e-04	6.7e-04	1.3e-06	5.4e-07	1.1e-06	2.5e-06	Driver-engine block
W-185	2.3e-06	5.4e-07	1.5e-06	7.2e-06	8.6e-09	2.0e-09	5.4e-09	2.6e-08	Scrap yard
Os-185	1.3e-02	4.9e-03	1.1e-02	2.7e-02	4.9e-05	1.8e-05	4.2e-05	1.0e-04	Driver-engine block
Ir-192	1.2e-02	3.7e-03	9.9e-03	2.7e-02	4.4e-05	1.4e-05	3.7e-05	9.9e-05	Driver-engine block
Tl-204	1.1e-04	6.1e-05	1.0e-04	2.1e-04	4.2e-07	2.3e-07	3.7e-07	7.7e-07	Driver-engine block
Pb-210	4.2e-02	2.5e-02	3.8e-02	7.6e-02	1.5e-04	9.4e-05	1.4e-04	2.8e-04	Aluminum cookware
Bi-207	1.8e-01	9.5e-02	1.6e-01	3.2e-01	6.5e-04	3.5e-04	5.9e-04	1.2e-03	Driver-engine block
Po-210	3.5e-03	1.9e-03	3.1e-03	6.5e-03	1.3e-05	7.0e-06	1.2e-05	2.4e-05	Aluminum cookware
Ra-226	2.9e-02	7.5e-03	1.9e-02	8.7e-02	1.1e-04	2.8e-05	6.8e-05	3.2e-04	Scrap yard
Ra-228	1.7e-02	4.5e-03	1.1e-02	5.0e-02	6.3e-05	1.7e-05	4.0e-05	1.8e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.8 Normalized surficial effective dose equivalents to critical groups for aluminum

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	3.6e-01	8.9e-02	2.2e-01	1.1e+00	1.3e-03	3.3e-04	8.2e-04	4.0e-03	Scrap yard
Th-228	8.6e-02	2.3e-02	5.4e-02	2.6e-01	3.2e-04	8.5e-05	2.0e-04	9.6e-04	Scrap yard
Th-229	5.6e-01	1.4e-01	3.5e-01	1.7e+00	2.1e-03	5.1e-04	1.3e-03	6.4e-03	Scrap yard
Th-230	8.4e-02	2.1e-02	5.3e-02	2.6e-01	3.1e-04	7.6e-05	1.9e-04	9.6e-04	Scrap yard
Th-232	4.2e-01	1.0e-01	2.6e-01	1.3e+00	1.6e-03	3.8e-04	9.8e-04	4.8e-03	Scrap yard
Pa-231	3.4e-01	8.4e-02	2.1e-01	1.0e+00	1.3e-03	3.1e-04	7.9e-04	3.8e-03	Scrap yard
U-232	1.7e-01	4.2e-02	1.1e-01	5.3e-01	6.4e-04	1.6e-04	4.0e-04	2.0e-03	Scrap yard
U-233	3.5e-02	8.6e-03	2.2e-02	1.1e-01	1.3e-04	3.2e-05	8.1e-05	4.0e-04	Scrap yard
U-234	3.4e-02	8.4e-03	2.1e-02	1.1e-01	1.3e-04	3.1e-05	7.9e-05	3.9e-04	Scrap yard
U-235	3.4e-02	8.4e-03	2.1e-02	1.0e-01	1.2e-04	3.1e-05	7.8e-05	3.8e-04	Scrap yard
U-236	3.2e-02	8.0e-03	2.0e-02	1.0e-01	1.2e-04	2.9e-05	7.5e-05	3.7e-04	Scrap yard
U-238	3.1e-02	7.7e-03	1.9e-02	9.5e-02	1.1e-04	2.8e-05	7.2e-05	3.5e-04	Scrap yard
Np-237	1.5e-01	3.6e-02	9.1e-02	4.4e-01	5.4e-04	1.3e-04	3.4e-04	1.6e-03	Scrap yard
Pu-236	3.8e-02	9.3e-03	2.4e-02	1.2e-01	1.4e-04	3.5e-05	8.7e-05	4.3e-04	Scrap yard
Pu-238	1.0e-01	2.6e-02	6.5e-02	3.2e-01	3.8e-04	9.5e-05	2.4e-04	1.2e-03	Scrap yard
Pu-239	1.1e-01	2.8e-02	7.1e-02	3.5e-01	4.2e-04	1.0e-04	2.6e-04	1.3e-03	Scrap yard
Pu-240	1.1e-01	2.8e-02	7.1e-02	3.5e-01	4.2e-04	1.0e-04	2.6e-04	1.3e-03	Scrap yard
Pu-241	2.2e-03	5.4e-04	1.4e-03	6.7e-03	8.1e-06	2.0e-06	5.0e-06	2.5e-05	Scrap yard
Pu-242	1.1e-01	2.7e-02	6.8e-02	3.3e-01	4.0e-04	9.9e-05	2.5e-04	1.2e-03	Scrap yard
Pu-244	1.1e-01	2.8e-02	7.0e-02	3.4e-01	4.1e-04	1.0e-04	2.6e-04	1.3e-03	Scrap yard
Am-241	1.2e-01	2.9e-02	7.3e-02	3.6e-01	4.3e-04	1.1e-04	2.7e-04	1.3e-03	Scrap yard
Am-242m	1.2e-01	2.9e-02	7.3e-02	3.5e-01	4.3e-04	1.1e-04	2.7e-04	1.3e-03	Scrap yard
Am-243	1.2e-01	2.9e-02	7.4e-02	3.6e-01	4.4e-04	1.1e-04	2.7e-04	1.3e-03	Scrap yard
Cm-242	4.2e-03	1.0e-03	2.6e-03	1.3e-02	1.6e-05	3.8e-06	9.7e-06	4.8e-05	Scrap yard
Cm-243	8.2e-02	2.0e-02	5.1e-02	2.5e-01	3.0e-04	7.6e-05	1.9e-04	9.3e-04	Scrap yard
Cm-244	6.5e-02	1.6e-02	4.1e-02	2.0e-01	2.4e-04	6.0e-05	1.5e-04	7.4e-04	Scrap yard
Cm-245	1.2e-01	3.0e-02	7.6e-02	3.7e-01	4.5e-04	1.1e-04	2.8e-04	1.4e-03	Scrap yard
Cm-246	1.2e-01	2.9e-02	7.4e-02	3.6e-01	4.4e-04	1.1e-04	2.8e-04	1.3e-03	Scrap yard
Cm-247	1.1e-01	2.9e-02	7.1e-02	3.5e-01	4.2e-04	1.1e-04	2.6e-04	1.3e-03	Scrap yard
Cm-248	4.4e-01	1.1e-01	2.7e-01	1.3e+00	1.6e-03	4.0e-04	1.0e-03	4.9e-03	Scrap yard
Bk-249	3.6e-04	9.0e-05	2.3e-04	1.1e-03	1.3e-06	3.3e-07	8.4e-07	4.1e-06	Scrap yard
Cf-248	1.3e-02	3.2e-03	8.1e-03	4.0e-02	4.8e-05	1.2e-05	3.0e-05	1.5e-04	Scrap yard
Cf-249	1.1e-01	2.7e-02	6.7e-02	3.2e-01	3.9e-04	9.9e-05	2.5e-04	1.2e-03	Scrap yard
Cf-250	5.5e-02	1.4e-02	3.4e-02	1.7e-01	2.0e-04	5.0e-05	1.3e-04	6.2e-04	Scrap yard
Cf-251	1.1e-01	2.6e-02	6.6e-02	3.2e-01	3.9e-04	9.7e-05	2.4e-04	1.2e-03	Scrap yard
Cf-252	4.1e-02	1.0e-02	2.5e-02	1.2e-01	1.5e-04	3.7e-05	9.4e-05	4.6e-04	Scrap yard
Cf-254	2.7e-01	7.1e-02	1.7e-01	8.2e-01	1.0e-03	2.6e-04	6.5e-04	3.0e-03	Scrap yard
Es-254	2.3e-02	6.4e-03	1.5e-02	6.9e-02	8.7e-05	2.4e-05	5.5e-05	2.6e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.9 Normalized mass-based effective doses to critical groups for aluminum

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	2.9e-06	0.0e+00	2.7e-09	1.1e-05	1.1e-08	0.0e+00	9.9e-12	3.9e-08	Leachate-industrial-scrap
C-14	4.6e-06	0.0e+00	0.0e+00	8.7e-06	1.7e-08	0.0e+00	0.0e+00	3.2e-08	Leachate-industrial-scrap
Na-22	2.9e-02	7.1e-03	1.8e-02	8.6e-02	1.1e-04	2.6e-05	6.7e-05	3.2e-04	Scrap yard
P-32	2.1e-05	3.8e-06	1.3e-05	6.7e-05	7.7e-08	1.4e-08	4.7e-08	2.5e-07	Scrap yard
S-35	1.3e-06	3.4e-07	8.3e-07	4.0e-06	4.9e-09	1.3e-09	3.1e-09	1.5e-08	Scrap yard
Cl-36	6.7e-05	0.0e+00	0.0e+00	2.7e-04	2.5e-07	0.0e+00	0.0e+00	1.0e-06	Leachate-industrial-scrap
K-40	2.2e-03	5.5e-04	1.4e-03	6.6e-03	8.2e-06	2.0e-06	5.2e-06	2.4e-05	Scrap yard
Ca-41	2.4e-05	0.0e+00	0.0e+00	1.0e-04	8.9e-08	0.0e+00	0.0e+00	3.9e-07	Leachate-industrial-scrap
Ca-45	4.3e-06	1.0e-06	2.7e-06	1.3e-05	1.6e-08	3.7e-09	1.0e-08	4.9e-08	Scrap yard
Sc-46	2.3e-02	5.7e-03	1.5e-02	7.1e-02	8.6e-05	2.1e-05	5.5e-05	2.6e-04	Scrap yard
Cr-51	2.4e-04	5.4e-05	1.5e-04	7.4e-04	8.8e-07	2.0e-07	5.5e-07	2.7e-06	Scrap yard
Mn-53	6.8e-07	4.5e-07	6.3e-07	1.3e-06	2.5e-09	1.7e-09	2.3e-09	4.7e-09	Aluminum cookware
Mn-54	5.5e-02	3.0e-02	4.9e-02	1.0e-01	2.0e-04	1.1e-04	1.8e-04	3.7e-04	Driver-engine block
Fe-55	6.3e-06	4.1e-06	5.8e-06	1.2e-05	2.3e-08	1.5e-08	2.1e-08	4.3e-08	Aluminum cookware
Fe-59	1.2e-02	2.9e-03	7.7e-03	3.7e-02	4.5e-05	1.1e-05	2.8e-05	1.4e-04	Scrap yard
Co-56	4.7e-02	1.6e-02	3.9e-02	1.0e-01	1.7e-04	5.9e-05	1.5e-04	3.7e-04	Driver-engine block
Co-57	7.0e-03	3.8e-03	6.3e-03	1.3e-02	2.6e-05	1.4e-05	2.3e-05	4.8e-05	Driver-engine block
Co-58	1.2e-02	3.8e-03	1.0e-02	2.7e-02	4.5e-05	1.4e-05	3.7e-05	1.0e-04	Driver-engine block
Co-60	2.5e-01	1.5e-01	2.3e-01	4.5e-01	9.3e-04	5.4e-04	8.5e-04	1.7e-03	Driver-engine block
Ni-59	2.1e-06	1.2e-06	1.9e-06	3.9e-06	7.9e-09	4.5e-09	7.2e-09	1.4e-08	Driver-engine block
Ni-63	3.4e-06	2.2e-06	3.1e-06	6.4e-06	1.3e-08	8.3e-09	1.2e-08	2.4e-08	Aluminum cookware
Zn-65	3.0e-02	1.6e-02	2.7e-02	5.6e-02	1.1e-04	6.0e-05	1.0e-04	2.1e-04	Driver-engine block
As-73	1.6e-05	5.6e-06	1.4e-05	3.6e-05	6.1e-08	2.1e-08	5.1e-08	1.3e-07	Driver-engine block
Se-75	1.0e-02	4.3e-03	8.7e-03	1.9e-02	3.7e-05	1.6e-05	3.2e-05	7.2e-05	Driver-engine block
Sr-85	5.1e-03	1.2e-03	3.2e-03	1.5e-02	1.9e-05	4.6e-06	1.2e-05	5.7e-05	Scrap yard
Sr-89	2.9e-05	7.5e-06	1.8e-05	8.8e-05	1.1e-07	2.8e-08	6.8e-08	3.2e-07	Scrap yard
Sr-90	1.9e-04	4.6e-05	1.2e-04	5.9e-04	7.1e-07	1.7e-07	4.5e-07	2.2e-06	Scrap yard
Y-91	7.5e-05	1.9e-05	4.8e-05	2.3e-04	2.8e-07	7.2e-08	1.8e-07	8.4e-07	Scrap yard
Zr-93	9.0e-06	2.3e-06	5.6e-06	2.7e-05	3.3e-08	8.5e-09	2.1e-08	1.0e-07	Scrap yard
Zr-95	1.1e-02	2.6e-03	6.7e-03	3.2e-02	3.9e-05	9.7e-06	2.5e-05	1.2e-04	Scrap yard
Nb-93m	2.7e-06	1.8e-06	2.5e-06	5.1e-06	1.0e-08	6.7e-09	9.3e-09	1.9e-08	Aluminum cookware
Nb-94	1.9e-01	1.1e-01	1.7e-01	3.5e-01	7.1e-04	4.1e-04	6.5e-04	1.3e-03	Driver-engine block
Nb-95	7.0e-03	1.6e-03	4.4e-03	2.1e-02	2.6e-05	6.1e-06	1.6e-05	7.9e-05	Scrap yard
Mo-93	5.2e-05	3.3e-05	4.8e-05	9.6e-05	1.9e-07	1.2e-07	1.8e-07	3.5e-07	Aluminum cookware
Tc-97	5.3e-05	0.0e+00	0.0e+00	2.3e-04	2.0e-07	0.0e+00	0.0e+00	8.5e-07	Leachate-industrial-scrap
Tc-97m	6.4e-06	1.7e-06	4.0e-06	1.9e-05	2.4e-08	6.4e-09	1.5e-08	7.0e-08	Scrap yard
Tc-99	5.0e-04	0.0e+00	0.0e+00	2.2e-03	1.9e-06	0.0e+00	0.0e+00	8.0e-06	Leachate-industrial-scrap
Ru-103	4.5e-03	1.1e-03	2.8e-03	1.4e-02	1.7e-05	3.9e-06	1.1e-05	5.1e-05	Scrap yard
Ru-106	1.9e-02	1.1e-02	1.7e-02	3.4e-02	7.0e-05	3.9e-05	6.3e-05	1.3e-04	Driver-engine block

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.9 Normalized mass-based effective doses to critical groups for aluminum

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	2.3e-01	1.4e-01	2.1e-01	4.2e-01	8.6e-04	5.0e-04	7.8e-04	1.6e-03	Driver-engine block
Ag-110m	1.7e-01	9.2e-02	1.5e-01	3.1e-01	6.3e-04	3.4e-04	5.6e-04	1.2e-03	Driver-engine block
Cd-109	2.0e-04	1.1e-04	1.8e-04	3.6e-04	7.3e-07	4.1e-07	6.6e-07	1.3e-06	Driver-engine block
Sn-113	6.4e-03	2.7e-03	5.6e-03	1.3e-02	2.4e-05	1.0e-05	2.1e-05	4.7e-05	Driver-engine block
Sb-124	2.0e-02	4.9e-03	1.3e-02	6.1e-02	7.5e-05	1.8e-05	4.7e-05	2.3e-04	Scrap yard
Sb-125	3.9e-02	2.2e-02	3.5e-02	7.1e-02	1.4e-04	8.1e-05	1.3e-04	2.6e-04	Driver-engine block
Te-123m	3.4e-03	1.5e-03	3.0e-03	6.6e-03	1.3e-05	5.4e-06	1.1e-05	2.5e-05	Driver-engine block
Te-127m	1.2e-04	5.1e-05	1.1e-04	2.4e-04	4.5e-07	1.9e-07	4.0e-07	9.1e-07	Driver-engine block
I-125	6.3e-05	1.4e-05	5.1e-05	1.5e-04	2.3e-07	5.1e-08	1.9e-07	5.6e-07	Airborne emissions
I-129	1.8e-02	0.0e+00	0.0e+00	6.4e-02	6.7e-05	0.0e+00	0.0e+00	2.4e-04	Leachate-industrial-scrap
I-131	1.2e-03	1.1e-04	6.0e-04	4.1e-03	4.5e-06	4.1e-07	2.2e-06	1.5e-05	Scrap yard
Cs-134	2.0e-02	5.0e-03	1.3e-02	6.0e-02	7.4e-05	1.9e-05	4.7e-05	2.2e-04	Scrap yard
Cs-135	6.6e-06	8.0e-07	4.1e-06	2.1e-05	2.4e-08	3.0e-09	1.5e-08	8.0e-08	Scrap yard
Cs-137	7.4e-03	1.8e-03	4.7e-03	2.2e-02	2.7e-05	6.8e-06	1.7e-05	8.2e-05	Scrap yard
Ba-133	4.2e-03	1.0e-03	2.7e-03	1.2e-02	1.5e-05	3.8e-06	9.8e-06	4.6e-05	Scrap yard
Ce-139	1.2e-03	2.9e-04	7.5e-04	3.6e-03	4.4e-06	1.1e-06	2.8e-06	1.3e-05	Scrap yard
Ce-141	4.4e-04	1.0e-04	2.7e-04	1.3e-03	1.6e-06	3.8e-07	1.0e-06	5.0e-06	Scrap yard
Ce-144	6.9e-04	1.8e-04	4.4e-04	2.1e-03	2.5e-06	6.5e-07	1.6e-06	7.7e-06	Scrap yard
Pm-147	4.7e-06	1.2e-06	3.0e-06	1.4e-05	1.8e-08	4.6e-09	1.1e-08	5.3e-08	Scrap yard
Sm-151	3.4e-06	8.8e-07	2.2e-06	1.0e-05	1.3e-08	3.3e-09	8.0e-09	3.8e-08	Scrap yard
Eu-152	1.5e-02	3.8e-03	9.6e-03	4.5e-02	5.6e-05	1.4e-05	3.6e-05	1.7e-04	Scrap yard
Eu-154	1.5e-02	3.7e-03	9.4e-03	4.4e-02	5.5e-05	1.4e-05	3.5e-05	1.6e-04	Scrap yard
Eu-155	3.4e-04	8.5e-05	2.2e-04	1.0e-03	1.3e-06	3.1e-07	8.0e-07	3.8e-06	Scrap yard
Gd-153	4.2e-04	1.0e-04	2.7e-04	1.3e-03	1.6e-06	3.9e-07	9.9e-07	4.7e-06	Scrap yard
Tb-160	1.2e-02	3.0e-03	7.9e-03	3.8e-02	4.6e-05	1.1e-05	2.9e-05	1.4e-04	Scrap yard
Tm-170	3.0e-05	8.3e-06	1.9e-05	8.9e-05	1.1e-07	3.1e-08	7.1e-08	3.3e-07	Scrap yard
Tm-171	3.1e-06	8.7e-07	1.9e-06	9.1e-06	1.1e-08	3.2e-09	7.2e-09	3.4e-08	Scrap yard
Ta-182	2.6e-02	1.1e-02	2.3e-02	5.1e-02	9.7e-05	4.1e-05	8.5e-05	1.9e-04	Driver-engine block
W-181	2.9e-04	1.3e-04	2.6e-04	5.8e-04	1.1e-06	4.7e-07	9.6e-07	2.1e-06	Driver-engine block
W-185	2.1e-06	4.7e-07	1.3e-06	6.4e-06	7.7e-09	1.8e-09	4.8e-09	2.4e-08	Scrap yard
Os-185	1.1e-02	4.4e-03	9.9e-03	2.4e-02	4.2e-05	1.6e-05	3.7e-05	8.8e-05	Driver-engine block
Ir-192	1.0e-02	3.3e-03	8.6e-03	2.3e-02	3.8e-05	1.2e-05	3.2e-05	8.5e-05	Driver-engine block
Tl-204	9.8e-05	5.5e-05	8.9e-05	1.8e-04	3.6e-07	2.0e-07	3.3e-07	6.6e-07	Driver-engine block
Pb-210	1.8e-02	1.1e-02	1.6e-02	3.2e-02	6.5e-05	4.1e-05	5.9e-05	1.2e-04	Aluminum cookware
Bi-207	1.5e-01	8.6e-02	1.4e-01	2.8e-01	5.7e-04	3.2e-04	5.1e-04	1.0e-03	Driver-engine block
Po-210	3.0e-03	7.6e-04	1.9e-03	9.0e-03	1.1e-05	2.8e-06	6.9e-06	3.3e-05	Scrap yard
Ra-226	2.7e-02	7.1e-03	1.7e-02	8.0e-02	9.9e-05	2.6e-05	6.3e-05	3.0e-04	Scrap yard
Ra-228	1.6e-02	4.5e-03	1.0e-02	4.9e-02	6.1e-05	1.7e-05	3.9e-05	1.8e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.9 Normalized mass-based effective doses to critical groups for aluminum

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	7.7e-02	2.0e-02	4.8e-02	2.3e-01	2.8e-04	7.4e-05	1.8e-04	8.7e-04	Scrap yard
Th-228	4.8e-02	1.3e-02	3.0e-02	1.4e-01	1.8e-04	4.9e-05	1.1e-04	5.3e-04	Scrap yard
Th-229	1.0e-01	2.6e-02	6.4e-02	3.1e-01	3.7e-04	9.6e-05	2.4e-04	1.1e-03	Scrap yard
Th-230	3.5e-02	8.8e-03	2.2e-02	1.1e-01	1.3e-04	3.2e-05	8.1e-05	3.9e-04	Scrap yard
Th-232	3.7e-02	9.2e-03	2.3e-02	1.1e-01	1.4e-04	3.4e-05	8.5e-05	4.1e-04	Scrap yard
Pa-231	1.1e-01	2.9e-02	7.1e-02	3.5e-01	4.2e-04	1.1e-04	2.6e-04	1.3e-03	Scrap yard
U-232	3.2e-02	8.1e-03	2.0e-02	9.7e-02	1.2e-04	3.0e-05	7.4e-05	3.6e-04	Scrap yard
U-233	7.6e-03	1.9e-03	4.7e-03	2.3e-02	2.8e-05	7.1e-06	1.8e-05	8.5e-05	Scrap yard
U-234	7.4e-03	1.9e-03	4.6e-03	2.3e-02	2.7e-05	6.9e-06	1.7e-05	8.3e-05	Scrap yard
U-235	8.4e-03	2.3e-03	5.3e-03	2.6e-02	3.1e-05	8.3e-06	2.0e-05	9.5e-05	Scrap yard
U-236	6.9e-03	1.7e-03	4.3e-03	2.1e-02	2.5e-05	6.4e-06	1.6e-05	7.8e-05	Scrap yard
U-238	6.7e-03	1.7e-03	4.2e-03	2.1e-02	2.5e-05	6.4e-06	1.6e-05	7.6e-05	Scrap yard
Np-237	2.1e-02	5.4e-03	1.3e-02	6.3e-02	7.7e-05	2.0e-05	4.8e-05	2.3e-04	Scrap yard
Pu-236	1.5e-02	3.9e-03	9.7e-03	4.7e-02	5.7e-05	1.4e-05	3.6e-05	1.7e-04	Scrap yard
Pu-238	3.7e-02	9.4e-03	2.3e-02	1.1e-01	1.4e-04	3.5e-05	8.7e-05	4.2e-04	Scrap yard
Pu-239	4.1e-02	1.0e-02	2.6e-02	1.2e-01	1.5e-04	3.8e-05	9.5e-05	4.6e-04	Scrap yard
Pu-240	4.1e-02	1.0e-02	2.6e-02	1.2e-01	1.5e-04	3.8e-05	9.5e-05	4.6e-04	Scrap yard
Pu-241	7.4e-04	1.9e-04	4.6e-04	2.3e-03	2.7e-06	6.9e-07	1.7e-06	8.4e-06	Scrap yard
Pu-242	3.8e-02	9.6e-03	2.4e-02	1.2e-01	1.4e-04	3.6e-05	8.9e-05	4.3e-04	Scrap yard
Pu-244	4.2e-02	1.1e-02	2.7e-02	1.3e-01	1.6e-04	4.1e-05	9.9e-05	4.8e-04	Scrap yard
Am-241	3.4e-02	8.6e-03	2.1e-02	1.0e-01	1.3e-04	3.2e-05	7.9e-05	3.8e-04	Scrap yard
Am-242m	3.4e-02	8.6e-03	2.1e-02	1.0e-01	1.3e-04	3.2e-05	7.9e-05	3.8e-04	Scrap yard
Am-243	3.6e-02	9.2e-03	2.2e-02	1.1e-01	1.3e-04	3.4e-05	8.3e-05	4.1e-04	Scrap yard
Cm-242	3.8e-03	9.5e-04	2.4e-03	1.2e-02	1.4e-05	3.5e-06	8.9e-06	4.3e-05	Scrap yard
Cm-243	2.6e-02	6.8e-03	1.7e-02	8.1e-02	9.7e-05	2.5e-05	6.1e-05	3.0e-04	Scrap yard
Cm-244	2.2e-02	5.4e-03	1.4e-02	6.6e-02	8.0e-05	2.0e-05	5.0e-05	2.4e-04	Scrap yard
Cm-245	3.6e-02	9.0e-03	2.2e-02	1.1e-01	1.3e-04	3.3e-05	8.3e-05	4.0e-04	Scrap yard
Cm-246	3.5e-02	8.8e-03	2.2e-02	1.1e-01	1.3e-04	3.2e-05	8.1e-05	3.9e-04	Scrap yard
Cm-247	3.5e-02	9.3e-03	2.2e-02	1.1e-01	1.3e-04	3.4e-05	8.2e-05	4.0e-04	Scrap yard
Cm-248	1.2e-01	3.1e-02	7.6e-02	3.7e-01	4.5e-04	1.1e-04	2.8e-04	1.4e-03	Scrap yard
Bk-249	1.3e-04	3.3e-05	8.3e-05	4.0e-04	4.9e-07	1.2e-07	3.1e-07	1.5e-06	Scrap yard
Cf-248	6.8e-03	1.7e-03	4.3e-03	2.1e-02	2.5e-05	6.4e-06	1.6e-05	7.8e-05	Scrap yard
Cf-249	6.1e-02	1.6e-02	3.8e-02	1.9e-01	2.3e-04	5.8e-05	1.4e-04	6.9e-04	Scrap yard
Cf-250	2.8e-02	7.0e-03	1.7e-02	8.4e-02	1.0e-04	2.6e-05	6.4e-05	3.1e-04	Scrap yard
Cf-251	5.9e-02	1.5e-02	3.7e-02	1.8e-01	2.2e-04	5.6e-05	1.4e-04	6.7e-04	Scrap yard
Cf-252	1.5e-02	3.9e-03	9.7e-03	4.7e-02	5.7e-05	1.4e-05	3.6e-05	1.7e-04	Scrap yard
Cf-254	2.2e-01	5.5e-02	1.4e-01	6.4e-01	8.0e-04	2.1e-04	5.1e-04	2.4e-03	Scrap yard
Es-254	1.8e-02	5.1e-03	1.2e-02	5.4e-02	6.7e-05	1.9e-05	4.3e-05	2.0e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.10 Normalized surficial effective doses to critical groups for aluminum

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	3.2e-06	0.0e+00	3.0e-09	1.2e-05	1.2e-08	0.0e+00	1.1e-11	4.4e-08	Leachate-industrial-scrap
C-14	5.1e-06	0.0e+00	0.0e+00	9.4e-06	1.9e-08	0.0e+00	0.0e+00	3.5e-08	Leachate-industrial-scrap
Na-22	3.2e-02	7.7e-03	2.0e-02	9.6e-02	1.2e-04	2.9e-05	7.5e-05	3.5e-04	Scrap yard
P-32	2.3e-05	4.1e-06	1.4e-05	7.3e-05	8.6e-08	1.5e-08	5.2e-08	2.7e-07	Scrap yard
S-35	1.5e-06	3.7e-07	9.3e-07	4.5e-06	5.5e-09	1.4e-09	3.4e-09	1.7e-08	Scrap yard
Cl-36	7.5e-05	0.0e+00	0.0e+00	3.0e-04	2.8e-07	0.0e+00	0.0e+00	1.1e-06	Leachate-industrial-scrap
K-40	2.5e-03	6.0e-04	1.6e-03	7.4e-03	9.1e-06	2.2e-06	5.7e-06	2.7e-05	Scrap yard
Ca-41	2.7e-05	0.0e+00	0.0e+00	1.2e-04	9.9e-08	0.0e+00	0.0e+00	4.3e-07	Leachate-industrial-scrap
Ca-45	4.8e-06	1.1e-06	3.0e-06	1.5e-05	1.8e-08	4.0e-09	1.1e-08	5.4e-08	Scrap yard
Sc-46	2.6e-02	6.3e-03	1.6e-02	7.8e-02	9.6e-05	2.3e-05	6.1e-05	2.9e-04	Scrap yard
Cr-51	2.7e-04	5.9e-05	1.7e-04	8.2e-04	9.9e-07	2.2e-07	6.1e-07	3.0e-06	Scrap yard
Mn-53	7.6e-07	4.8e-07	6.9e-07	1.4e-06	2.8e-09	1.8e-09	2.6e-09	5.2e-09	Aluminum cookware
Mn-54	6.1e-02	3.3e-02	5.5e-02	1.1e-01	2.3e-04	1.2e-04	2.0e-04	4.1e-04	Driver-engine block
Fe-55	7.0e-06	4.4e-06	6.4e-06	1.3e-05	2.6e-08	1.6e-08	2.3e-08	4.8e-08	Aluminum cookware
Fe-59	1.3e-02	3.2e-03	8.5e-03	4.2e-02	5.0e-05	1.2e-05	3.1e-05	1.5e-04	Scrap yard
Co-56	5.2e-02	1.8e-02	4.4e-02	1.1e-01	1.9e-04	6.5e-05	1.6e-04	4.2e-04	Driver-engine block
Co-57	7.8e-03	4.1e-03	7.0e-03	1.4e-02	2.9e-05	1.5e-05	2.6e-05	5.3e-05	Driver-engine block
Co-58	1.4e-02	4.2e-03	1.1e-02	3.0e-02	5.0e-05	1.5e-05	4.1e-05	1.1e-04	Driver-engine block
Co-60	2.8e-01	1.6e-01	2.5e-01	5.1e-01	1.0e-03	5.8e-04	9.4e-04	1.9e-03	Driver-engine block
Ni-59	2.4e-06	1.3e-06	2.1e-06	4.3e-06	8.8e-09	4.9e-09	7.9e-09	1.6e-08	Driver-engine block
Ni-63	3.8e-06	2.4e-06	3.4e-06	7.0e-06	1.4e-08	8.9e-09	1.3e-08	2.6e-08	Aluminum cookware
Zn-65	3.4e-02	1.8e-02	3.0e-02	6.2e-02	1.3e-04	6.5e-05	1.1e-04	2.3e-04	Driver-engine block
As-73	1.8e-05	6.2e-06	1.5e-05	4.0e-05	6.8e-08	2.3e-08	5.7e-08	1.5e-07	Driver-engine block
Se-75	1.1e-02	4.7e-03	9.7e-03	2.2e-02	4.1e-05	1.7e-05	3.6e-05	8.0e-05	Driver-engine block
Sr-85	5.7e-03	1.4e-03	3.6e-03	1.7e-02	2.1e-05	5.0e-06	1.3e-05	6.4e-05	Scrap yard
Sr-89	3.2e-05	8.2e-06	2.0e-05	9.7e-05	1.2e-07	3.0e-08	7.5e-08	3.6e-07	Scrap yard
Sr-90	2.1e-04	5.1e-05	1.3e-04	6.6e-04	7.9e-07	1.9e-07	5.0e-07	2.4e-06	Scrap yard
Y-91	8.4e-05	2.1e-05	5.3e-05	2.5e-04	3.1e-07	7.9e-08	2.0e-07	9.3e-07	Scrap yard
Zr-93	1.0e-05	2.5e-06	6.3e-06	3.1e-05	3.7e-08	9.3e-09	2.3e-08	1.1e-07	Scrap yard
Zr-95	1.2e-02	2.9e-03	7.5e-03	3.6e-02	4.4e-05	1.1e-05	2.8e-05	1.3e-04	Scrap yard
Nb-93m	3.1e-06	1.9e-06	2.8e-06	5.7e-06	1.1e-08	7.2e-09	1.0e-08	2.1e-08	Aluminum cookware
Nb-94	2.1e-01	1.2e-01	1.9e-01	3.9e-01	7.9e-04	4.4e-04	7.2e-04	1.5e-03	Driver-engine block
Nb-95	7.8e-03	1.8e-03	4.9e-03	2.4e-02	2.9e-05	6.7e-06	1.8e-05	8.8e-05	Scrap yard
Mo-93	5.8e-05	3.5e-05	5.3e-05	1.1e-04	2.1e-07	1.3e-07	2.0e-07	4.0e-07	Aluminum cookware
Tc-97	6.0e-05	0.0e+00	0.0e+00	2.5e-04	2.2e-07	0.0e+00	0.0e+00	9.2e-07	Leachate-industrial-scrap
Tc-97m	7.1e-06	1.9e-06	4.5e-06	2.1e-05	2.6e-08	7.0e-09	1.7e-08	7.8e-08	Scrap yard
Tc-99	5.6e-04	0.0e+00	0.0e+00	2.3e-03	2.1e-06	0.0e+00	0.0e+00	8.6e-06	Leachate-industrial-scrap
Ru-103	5.0e-03	1.2e-03	3.2e-03	1.5e-02	1.9e-05	4.3e-06	1.2e-05	5.7e-05	Scrap yard
Ru-106	2.1e-02	1.1e-02	1.9e-02	3.9e-02	7.8e-05	4.2e-05	7.0e-05	1.4e-04	Driver-engine block

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.10 Normalized surficial effective doses to critical groups for aluminum

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	2.6e-01	1.5e-01	2.3e-01	4.7e-01	9.6e-04	5.4e-04	8.7e-04	1.7e-03	Driver-engine block
Ag-110m	1.9e-01	9.9e-02	1.7e-01	3.5e-01	7.0e-04	3.7e-04	6.3e-04	1.3e-03	Driver-engine block
Cd-109	2.2e-04	1.2e-04	2.0e-04	4.0e-04	8.1e-07	4.5e-07	7.3e-07	1.5e-06	Driver-engine block
Sn-113	7.2e-03	3.0e-03	6.2e-03	1.4e-02	2.7e-05	1.1e-05	2.3e-05	5.3e-05	Driver-engine block
Sb-124	2.2e-02	5.4e-03	1.4e-02	6.8e-02	8.3e-05	2.0e-05	5.3e-05	2.5e-04	Scrap yard
Sb-125	4.3e-02	2.3e-02	3.9e-02	8.0e-02	1.6e-04	8.7e-05	1.4e-04	3.0e-04	Driver-engine block
Te-123m	3.8e-03	1.6e-03	3.3e-03	7.5e-03	1.4e-05	5.9e-06	1.2e-05	2.8e-05	Driver-engine block
Te-127m	1.4e-04	5.5e-05	1.2e-04	2.8e-04	5.0e-07	2.0e-07	4.4e-07	1.0e-06	Driver-engine block
I-125	7.0e-05	1.5e-05	5.6e-05	1.7e-04	2.6e-07	5.5e-08	2.1e-07	6.2e-07	Airborne emissions
I-129	2.0e-02	0.0e+00	0.0e+00	7.2e-02	7.4e-05	0.0e+00	0.0e+00	2.7e-04	Leachate-industrial-scrap
I-131	1.3e-03	1.2e-04	6.7e-04	4.6e-03	5.0e-06	4.5e-07	2.5e-06	1.7e-05	Scrap yard
Cs-134	2.2e-02	5.5e-03	1.4e-02	6.7e-02	8.3e-05	2.0e-05	5.2e-05	2.5e-04	Scrap yard
Cs-135	7.4e-06	8.8e-07	4.5e-06	2.4e-05	2.7e-08	3.3e-09	1.7e-08	8.8e-08	Scrap yard
Cs-137	8.2e-03	2.0e-03	5.2e-03	2.5e-02	3.0e-05	7.4e-06	1.9e-05	9.2e-05	Scrap yard
Ba-133	4.7e-03	1.1e-03	2.9e-03	1.4e-02	1.7e-05	4.2e-06	1.1e-05	5.2e-05	Scrap yard
Ce-139	1.3e-03	3.2e-04	8.3e-04	3.9e-03	4.9e-06	1.2e-06	3.1e-06	1.5e-05	Scrap yard
Ce-141	4.9e-04	1.1e-04	3.0e-04	1.5e-03	1.8e-06	4.1e-07	1.1e-06	5.5e-06	Scrap yard
Ce-144	7.7e-04	1.9e-04	4.8e-04	2.3e-03	2.8e-06	7.2e-07	1.8e-06	8.4e-06	Scrap yard
Pm-147	5.3e-06	1.4e-06	3.3e-06	1.6e-05	2.0e-08	5.0e-09	1.2e-08	5.9e-08	Scrap yard
Sm-151	3.8e-06	9.6e-07	2.4e-06	1.2e-05	1.4e-08	3.6e-09	8.9e-09	4.3e-08	Scrap yard
Eu-152	1.7e-02	4.1e-03	1.1e-02	5.1e-02	6.2e-05	1.5e-05	3.9e-05	1.9e-04	Scrap yard
Eu-154	1.6e-02	4.0e-03	1.0e-02	4.9e-02	6.1e-05	1.5e-05	3.8e-05	1.8e-04	Scrap yard
Eu-155	3.8e-04	9.3e-05	2.4e-04	1.1e-03	1.4e-06	3.4e-07	8.9e-07	4.2e-06	Scrap yard
Gd-153	4.7e-04	1.1e-04	3.0e-04	1.4e-03	1.7e-06	4.2e-07	1.1e-06	5.2e-06	Scrap yard
Tb-160	1.4e-02	3.3e-03	8.7e-03	4.2e-02	5.1e-05	1.2e-05	3.2e-05	1.5e-04	Scrap yard
Tm-170	3.4e-05	9.0e-06	2.1e-05	9.9e-05	1.2e-07	3.3e-08	7.9e-08	3.7e-07	Scrap yard
Tm-171	3.4e-06	9.5e-07	2.2e-06	1.0e-05	1.3e-08	3.5e-09	8.0e-09	3.7e-08	Scrap yard
Ta-182	2.9e-02	1.2e-02	2.5e-02	5.8e-02	1.1e-04	4.5e-05	9.4e-05	2.1e-04	Driver-engine block
W-181	3.3e-04	1.4e-04	2.9e-04	6.4e-04	1.2e-06	5.1e-07	1.1e-06	2.4e-06	Driver-engine block
W-185	2.3e-06	5.2e-07	1.5e-06	7.1e-06	8.6e-09	1.9e-09	5.4e-09	2.6e-08	Scrap yard
Os-185	1.3e-02	4.8e-03	1.1e-02	2.7e-02	4.7e-05	1.8e-05	4.0e-05	9.8e-05	Driver-engine block
Ir-192	1.2e-02	3.6e-03	9.6e-03	2.6e-02	4.3e-05	1.3e-05	3.5e-05	9.6e-05	Driver-engine block
Tl-204	1.1e-04	5.9e-05	9.8e-05	2.0e-04	4.0e-07	2.2e-07	3.6e-07	7.5e-07	Driver-engine block
Pb-210	2.0e-02	1.2e-02	1.8e-02	3.6e-02	7.2e-05	4.4e-05	6.6e-05	1.3e-04	Aluminum cookware
Bi-207	1.7e-01	9.3e-02	1.5e-01	3.2e-01	6.3e-04	3.4e-04	5.7e-04	1.2e-03	Driver-engine block
Po-210	3.3e-03	8.3e-04	2.1e-03	9.9e-03	1.2e-05	3.1e-06	7.6e-06	3.7e-05	Scrap yard
Ra-226	3.0e-02	7.7e-03	1.9e-02	8.8e-02	1.1e-04	2.8e-05	7.0e-05	3.2e-04	Scrap yard
Ra-228	1.8e-02	5.0e-03	1.2e-02	5.4e-02	6.8e-05	1.8e-05	4.3e-05	2.0e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 5.10 Normalized surficial effective doses to critical groups for aluminum

Radionuclide	:Sv/y per Bq/cm²				mrem/y per pCi/cm²				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	8.5e-02	2.2e-02	5.3e-02	2.6e-01	3.2e-04	8.0e-05	2.0e-04	9.6e-04	Scrap yard
Th-228	5.3e-02	1.5e-02	3.4e-02	1.6e-01	2.0e-04	5.4e-05	1.2e-04	5.8e-04	Scrap yard
Th-229	1.1e-01	2.8e-02	7.0e-02	3.5e-01	4.2e-04	1.0e-04	2.6e-04	1.3e-03	Scrap yard
Th-230	3.9e-02	9.5e-03	2.4e-02	1.2e-01	1.4e-04	3.5e-05	8.9e-05	4.4e-04	Scrap yard
Th-232	4.1e-02	1.0e-02	2.5e-02	1.2e-01	1.5e-04	3.7e-05	9.4e-05	4.6e-04	Scrap yard
Pa-231	1.3e-01	3.1e-02	7.9e-02	3.9e-01	4.7e-04	1.2e-04	2.9e-04	1.4e-03	Scrap yard
U-232	3.5e-02	8.8e-03	2.2e-02	1.1e-01	1.3e-04	3.3e-05	8.2e-05	4.0e-04	Scrap yard
U-233	8.4e-03	2.1e-03	5.3e-03	2.6e-02	3.1e-05	7.7e-06	1.9e-05	9.6e-05	Scrap yard
U-234	8.2e-03	2.0e-03	5.1e-03	2.5e-02	3.1e-05	7.5e-06	1.9e-05	9.3e-05	Scrap yard
U-235	9.3e-03	2.5e-03	5.9e-03	2.8e-02	3.5e-05	9.1e-06	2.2e-05	1.0e-04	Scrap yard
U-236	7.7e-03	1.9e-03	4.8e-03	2.3e-02	2.8e-05	7.0e-06	1.8e-05	8.7e-05	Scrap yard
U-238	7.5e-03	1.9e-03	4.7e-03	2.3e-02	2.8e-05	7.0e-06	1.7e-05	8.5e-05	Scrap yard
Np-237	2.3e-02	5.9e-03	1.4e-02	7.0e-02	8.5e-05	2.2e-05	5.4e-05	2.6e-04	Scrap yard
Pu-236	1.7e-02	4.2e-03	1.1e-02	5.3e-02	6.4e-05	1.6e-05	4.0e-05	1.9e-04	Scrap yard
Pu-238	4.2e-02	1.0e-02	2.6e-02	1.3e-01	1.5e-04	3.8e-05	9.6e-05	4.7e-04	Scrap yard
Pu-239	4.6e-02	1.1e-02	2.8e-02	1.4e-01	1.7e-04	4.1e-05	1.1e-04	5.2e-04	Scrap yard
Pu-240	4.6e-02	1.1e-02	2.8e-02	1.4e-01	1.7e-04	4.1e-05	1.1e-04	5.2e-04	Scrap yard
Pu-241	8.2e-04	2.0e-04	5.1e-04	2.5e-03	3.1e-06	7.5e-07	1.9e-06	9.3e-06	Scrap yard
Pu-242	4.3e-02	1.0e-02	2.7e-02	1.3e-01	1.6e-04	3.9e-05	9.8e-05	4.8e-04	Scrap yard
Pu-244	4.7e-02	1.2e-02	3.0e-02	1.5e-01	1.8e-04	4.5e-05	1.1e-04	5.4e-04	Scrap yard
Am-241	3.8e-02	9.3e-03	2.4e-02	1.2e-01	1.4e-04	3.4e-05	8.7e-05	4.3e-04	Scrap yard
Am-242m	3.8e-02	9.3e-03	2.4e-02	1.2e-01	1.4e-04	3.5e-05	8.7e-05	4.3e-04	Scrap yard
Am-243	4.0e-02	1.0e-02	2.5e-02	1.2e-01	1.5e-04	3.7e-05	9.2e-05	4.5e-04	Scrap yard
Cm-242	4.3e-03	1.0e-03	2.7e-03	1.3e-02	1.6e-05	3.8e-06	9.8e-06	4.8e-05	Scrap yard
Cm-243	2.9e-02	7.3e-03	1.8e-02	9.0e-02	1.1e-04	2.7e-05	6.8e-05	3.3e-04	Scrap yard
Cm-244	2.4e-02	5.9e-03	1.5e-02	7.4e-02	8.9e-05	2.2e-05	5.6e-05	2.7e-04	Scrap yard
Cm-245	4.0e-02	9.8e-03	2.5e-02	1.2e-01	1.5e-04	3.6e-05	9.1e-05	4.5e-04	Scrap yard
Cm-246	3.9e-02	9.5e-03	2.4e-02	1.2e-01	1.4e-04	3.5e-05	8.9e-05	4.4e-04	Scrap yard
Cm-247	3.9e-02	1.0e-02	2.5e-02	1.2e-01	1.5e-04	3.7e-05	9.1e-05	4.4e-04	Scrap yard
Cm-248	1.4e-01	3.3e-02	8.5e-02	4.2e-01	5.0e-04	1.2e-04	3.1e-04	1.5e-03	Scrap yard
Bk-249	1.5e-04	3.6e-05	9.2e-05	4.5e-04	5.4e-07	1.3e-07	3.4e-07	1.7e-06	Scrap yard
Cf-248	7.6e-03	1.9e-03	4.8e-03	2.3e-02	2.8e-05	6.9e-06	1.8e-05	8.6e-05	Scrap yard
Cf-249	6.8e-02	1.7e-02	4.3e-02	2.1e-01	2.5e-04	6.4e-05	1.6e-04	7.7e-04	Scrap yard
Cf-250	3.1e-02	7.6e-03	1.9e-02	9.5e-02	1.1e-04	2.8e-05	7.1e-05	3.5e-04	Scrap yard
Cf-251	6.6e-02	1.6e-02	4.1e-02	2.0e-01	2.4e-04	6.0e-05	1.5e-04	7.5e-04	Scrap yard
Cf-252	1.7e-02	4.2e-03	1.1e-02	5.3e-02	6.4e-05	1.6e-05	4.0e-05	1.9e-04	Scrap yard
Cf-254	2.4e-01	6.1e-02	1.5e-01	7.2e-01	8.9e-04	2.2e-04	5.6e-04	2.7e-03	Scrap yard
Es-254	2.0e-02	5.5e-03	1.3e-02	6.0e-02	7.5e-05	2.0e-05	4.8e-05	2.2e-04	Scrap yard

[a] 5th percentile to 95th percentile = 90% confidence interval

References

Accomet Corporation. (n/d). “Secondary Aluminum.” http://www.accomet.com/Secondary.htm (September 12, 2002).

The Aluminum Association, Inc. 1998. “Aluminum Recycling Casebook.” Washington, DC: Author.

The Aluminum Association, Inc. 2001. “Aluminum Statistical Review for 2000.” Washington, DC: Author.

The Aluminum Association, Inc. 2002. “Aluminum Statistical Review for 2001.” Washington, DC: Author.

Anigstein, R., et al. 2001. “Technical Support Document: Potential Recycling of Scrap Metal from Nuclear Facilities, Part I: Radiological Assessment of Exposed Individuals.” Washington, DC: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air. http://www.epa.gov/radiation/cleanmetals/docs/tsd (August 12, 2002).

Blumenthal, D. 1990. “Is That Newfangled Cookware Safe?” *FDA Consumer, 24*(8), 12. http://www.fda.gov/bbs/topics/CONSUMER/CON00036.html (October 16, 2002).

Bryan, R. H. and I. T. Dudley. 1974. “Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant,” ORNL-TM-4515. Oak Ridge, TN: Oak Ridge National Laboratory.

Cygnet Stamping & Fabricating, Inc. (n/d). “Common Materials: 5052 Aluminum Sheet.” http://www.cygnetstamping.com/commonMaterials/5052.html (April 2, 2003).

Department of Energy (U.S.), Office of Industrial Technologies (DOE). 1999. “Recycling of Aluminum Dross/Saltcake,” DOE/GO-10099-730, Aluminum Project Fact Sheet. Washington, DC: Author. http://www.oit.doe.gov/nice3/factsheets/alumitech.pdf (October 27, 2002).

Eckerman, K. F., and J. C. Ryman. 1993. “External Exposure to Radionuclides in Air, Water, and Soil,” Federal Guidance Report No. 12, EPA 402-R-93-081. Washington, DC: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air.

Environmental Protection Agency (U.S.) (EPA). 1990. Letter from R. Shafer, Alcan Recycling, to J. Dills, Permit Review Branch, Division of Air Quality, Kentucky Department for Environmental Protection, enclosing report: “Compliance Emission Testing on the Melt Furnace, Decoater, Hold Furnace, Alpur Filter, Dross Baghouse, Hot and Cold Baghouses at the Alcan Ingot and Recycling in Berea, Kentucky.” Docket A-92-61, II-D-11.

Environmental Protection Agency (U.S.) (EPA). 1995a. "Profile of the Nonferrous Metals Industry," EPA 310-R-95-010. Washington, DC: Author.

Environmental Protection Agency (U.S.) (EPA). 1995b. “Compilation of Air Pollutant Emission Factors,” AP-42. 5th ed. Vol. 1, “Stationary Point and Area Sources.” Washington DC: Author. http://www.epa.gov/ttn/chief/ap42/ch12/final/c12s09.pdf (October 27, 2002).

Environmental Protection Agency (U.S.) (EPA). 1997. “Exposure Factors Handbook,” EPA/600/P-95/002Fa. Washington, DC: Author.

Environmental Protection Agency (U.S.) (EPA). 2000. “National Emission Standards for Hazardous Air Pollutants for Secondary Aluminum Production; Final Rule.“ *Federal Register,* Vol. 65, No. 57: pp. 15689–15737. March 23, 2000. http://www.epa.gov/fedrgstr/EPA-AIR/2000/March/Day-23/a4143.htm (June 5, 2003)

Garbay, H., and A. M. Chapuis. 1991. “Radiological Impact of Very Slightly Radioactive Copper and Aluminum Recovered from Dismantled Nuclear Facilities,” Final Report, EUR-13160-FR. Commission of the European Communities, Nuclear Sciences and Technology.

Karvelas, D., et al. 1991. "An Economic and Technical Assessment of Black-Dross- and Salt-Cake-Recycling Systems for Application in the Secondary Aluminum Industry," ANL/ESD-11. Argonne, IL: Argonne National Laboratory.

Kiefer, M., et al., 1995. "Health Hazard Evaluation Report: Arkansas Aluminum Alloys Inc., Hot Springs, Arkansas," HETA 95-0244-2550. National Institute for Occupational Health and Safety. (NTIS No. PB96210067.)

Novelli, L. R. 1997. “The Fate of Secondary Aluminum Smelting,” *Scrap*, *54*(6), 49–58.

Plunkert, P. A. 2002. “Aluminum.” In *Minerals Yearbook—2000*. U.S. Geological Survey. http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/050400.pdf (June 4, 2003).

Viland, J. S. 1990. “A Secondary’s View of Recycling.” In J. H. L. van Linden et al. (Eds.) *Second International Symposium: Recycling of Metals and Engineered Materials*. Warrendale, PA: The Minerals, Metals & Materials Society.

6 RECYCLING AND DISPOSAL OF CONCRETE RUBBLE

Assessments have been performed of the potential radiation doses to individuals from the recycling or disposal of concrete rubble that could be cleared from nuclear facilities. The assessment addresses eight scenarios that depict exposures resulting from the handling and processing of cleared concrete rubble, transportation of the rubble, the use of recycled concrete in road construction, the landfill disposal of concrete rubble, and the infiltration of well water by leachate from landfills containing concrete rubble. The analysis utilizes data on concrete recycling and disposal, as currently practiced in the United States, and on contemporary U.S. work practices and living habits.

The critical group for almost one-half of the 115 radionuclides addressed by the present analysis consists of workers processing concrete rubble for recycling or disposal. Workers building a road with recycled concrete constitute the critical group for most of the remaining nuclides.

Mean values of mass-based normalized EDEs to critical groups range from a high of 1,400 :Sv/y per Bq/g (5.1 mrem/y per pCi/g) from Cf-254 to a low of 1.5e-3 :Sv/y per Bq/g (5.7e-6 mrem/y per pCi/g) from Mn-53. The corresponding surficial EDEs are 4.9 and 5.5e-6 :Sv/y per Bq/cm^2, respectively. Mean values of mass-based normalized effective doses range from a high of 1,400 :Sv/y per Bq/g (5.1 mrem/y per pCi/g) from Cf-254 to a low of 1.6e-3 :Sv/y per Bq/g (5.8e-6 mrem/y per pCi/g) from Mn-53. The corresponding surficial effective doses are 4.9 and 5.6e-6 :Sv/y per Bq/cm^2, respectively. The critical group for Cf-254 is the workers processing concrete rubble, while that for Mn-53 comprises persons drinking water from wells down gradient from an industrial landfill containing cleared concrete rubble.

This chapter describes the radiological assessment of the recycling and/or disposal of concrete rubble that could be cleared from NRC-licensed facilities. Similar to the assessments of scrap metals described in Chapters 3 – 5, the models created for the present analysis are based on realistic appraisals of the use of recycled concrete in road construction, or of disposal of the rubble in an industrial or municipal landfill.

6.1 Introduction to Analysis

As was the case with scrap metals, the evaluation of normalized effective dose equivalents (EDEs) and effective doses from one year of exposure to cleared concrete rubble consists of two main parts. The first step is characterizing the flow of cleared concrete through the normal recycling process, beginning with the generation of rubble, through processing and use in road building, as well as disposal as an alternative to recycling.

The second step is the development and analysis of exposure scenarios. The eight scenarios in the concrete analysis are based on corresponding scenarios for iron and steel scrap. Essential differences between the two sets of scenarios are discussed in Section 6.3.

6.2 Flow of Concrete Rubble

This section presents an overview of the recycling and disposal of concrete rubble in the United States. Its aim is: (1) to serve as a source of information required for the present analysis, and

(2) to provide an overall perspective on the fate of rubble generated during the demolition of concrete structures. It thus includes some data which are not directly utilized by the analysis.

Figure 6.1 presents a schematic diagram of the flow of recycled and disposed concrete. As is the case in the analysis of other cleared materials, this is a simplified idealization of the actual process. The diagram depicts the sequence of steps that is represented by the exposure scenarios in the present analysis. Other steps and processes are discussed in the following sections of this chapter.

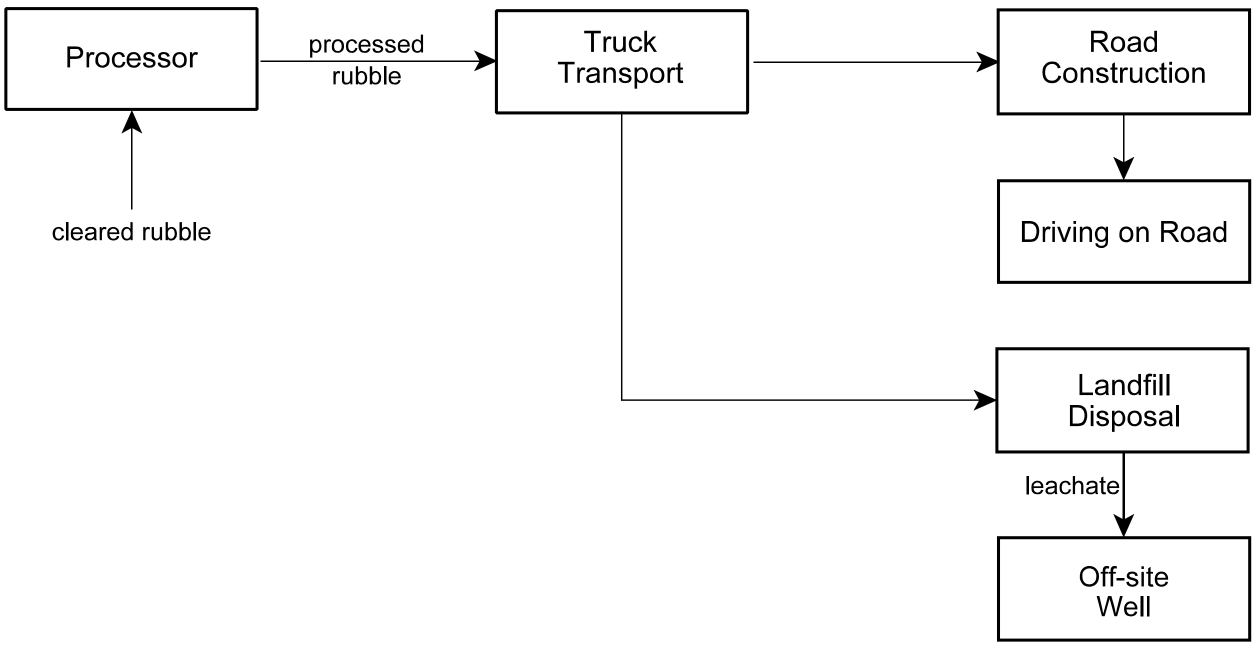

Figure 6.1 Flow of concrete rubble

6.2.1 Sources of Material

The generators of concrete rubble addressed in this study are NRC-licensed facilities: primarily commercial power plants, test and research reactors, and industrial nuclear facilities. As presented in Section A.2.3.3, the reference 1,000 MWe BWR commercial nuclear power plant contains about 355,000 t of concrete. About 73,600 t is associated with non-impacted areas of the plant. An estimated 51.4 m^3 (123 t) of surface-contaminated concrete would be removed by scabbling during dismantlement and decontamination. In addition, an estimated 73.3 m^3 (176 t) would have become neutron-activated during the operation of the plant. All of this contaminated material would be disposed of as low-level waste. The balance—approximately 281,000 t—would be subject to clearance.

According to Table A.10, the reference 1,000 MWe PWR nuclear power plant contains approximately 180,000 t of concrete. About 36,900 t of concrete is associated with non-impacted areas of the plant. The remaining concrete is associated with the reactor building, reactor auxiliaries, fuel storage, turbine building, turbine plant equipment, and reactor plant equipment. About 284 t of this material is likely to be surface-contaminated and would therefore be removed by scabbling; an indeterminate but small additional amount would be neutron-activated. The balance—about 143,000 t—would be subject to clearance.

6.2.1.1 Mass-to-Surface Ratio

A discussion of the mass-to-surface ratio of concrete rubble cleared from commercial nuclear power plants is presented in Section A.6.2. In the case of the PWR, data on the components which would be subject to clearance were excerpted from Section A.6.2.1 and reproduced in Table 6.1. The total mass of the listed components is about 96% of the estimated mass of cleared material; data on surface areas were not available for some components.

Table 6.1 Concrete mass-to-surface ratios for components of reference 1,000 MWe PWR

System	Component	Area (m^2)[a]	Mass (t)	Ratio (g/cm^2)
Reactor building	Structural concrete	697	12,860	1,846
	Cylindrical wall	5,760	20,208	351
	Dome	2,787	7,348	264
	Interior	4,645	13,778	297
Turbine building	Concrete fill	4,905	1,837	37
	Structural concrete	4,088	11,941	292
	Superstructure	2,508	2,021	81
Reactor auxiliaries	Structural concrete	13,471	33,067	245
Fuel Storage	Structural concrete	1,301	5,511	424
	Superstructure	650	919	141
Turbine plant equipment	Concrete fill - foundation mat	307	1,837	599
	Foundation mat	307	3,674	1,198
	Support	1,626	5,879	362
	Intake/discharge	1,161	2,756	237
	Warming line	46	129	277
	Discharge tunnel	1,858	4,042	218
	Discharge canal	2,323	8,267	356
	De-icing pump pit structure	557	1,286	231
Total		48,999	137,358	280

[a] Assumes that only one side is contaminated

Comparable data are not available for the reference BWR. The mass-to-surface ratios for a BWR were therefore assumed to be the same as those for a PWR. The distribution of mass-to-thickness ratios, averaged over the total amount of concrete cleared during one year of dismantlement activities, was created in a similar manner to that for the steel components described in Chapter 3. The resulting distribution spans a range of 235 to 348 g/cm^2, with a mean of 281 g/cm^2.

6.2.2 Transportation and Processing

Because of the large quantities of concrete rubble generated during the dismantlement of a nuclear power plant, and the high cost of transportation relative to its intrinsic value, the material would most likely be processed at or near the site of the plant; furthermore, the processed rubble would most likely be utilized and/or disposed of at nearby locations. Trucks are typically used for transportation over these relatively short distances.

Prior to use, concrete rubble must be crushed and sorted. Any steel rebar in the concrete would be separated and sent to a ferrous metal scrap dealer.[1] Prior to being crushed, the concrete is reduced to blocks, approximately 1.5 × 1.5 × 0.8 m in size. During crushing, water is sprayed on the concrete to suppress dust. Franklin Associates (1998) estimate that there are more than 1,000 asphalt and concrete crushing facilities in the United States.

As described by the Turner-Fairbank Highway Research Center (TFHRC 1997):

> RCM [reclaimed concrete material] is generated through the demolition of portland cement concrete elements of roads, runways, and structures during road reconstruction, utility excavations, or demolition operations.
>
> In many metropolitan areas, the RCM source is from existing portland cement concrete curb, sidewalk and driveway sections that may or may not be lightly reinforced. The RCM is usually removed with a backhoe or payloader and is loaded into dump trucks for removal from the site. The RCM excavation may include 10 to 30 percent subbase soil material and asphalt pavement. Therefore, the RCM is not pure portland cement concrete, but a mixture of concrete, soil, and small quantities of bituminous concrete.
>
> The excavated concrete that will be recycled is typically hauled to a central facility for stockpiling and processing or, in some cases (such as large reconstruction projects), processed on site using a mobile plant. At the central processing facility, crushing, screening, and ferrous metal recovery operations occur. Present crushing systems, with magnetic separators, are capable of removing reinforcing steel without much difficulty. Welded wire mesh reinforcement, however, may be difficult or impossible to remove effectively.

The U.S. Geological Survey (2000) has estimated that 200 million tonnes of potentially recyclable aggregates are generated annually from the demolition of roads and buildings:

> Demolished infrastructure can either be disposed in landfills or recycled. The decision is usually made by the demolition contractor, taking into consideration regional economics, contract terms, and legal mandates.

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[1] It is assumed that concrete rubble destined for landfill disposal would also be processed to remove the rebar.

6.2.3 Use of Recycled Concrete

According to USGS 2000, about 100 Mt of concrete aggregate is recycled annually, which represents about 5% of the 2-Gt annual aggregate market. A breakdown of the applications for recycled aggregate is as follows:

- Road base 68%
- New concrete mixes 6%
- Asphalt hot mixes 9%
- High-value riprap 3%
- Low-value products (e.g., general fill) . 7%
- Other applications 7%

It is apparent from the above tabulation that use of recycled concrete as aggregate in new concrete mixes is limited (i.e., about 6%). TFHRC (1997) has reported that concrete incorporating more than 10% to 20% recycled concrete as fine aggregate can have quality problems because of the large amount of water required to maintain workability of the mix. The report provides a list of uses for RCM that is similar to that of USGS 2000, including:

- Aggregate in cement-treated or lean concrete bases
- Concrete aggregate
- Aggregate for flowable fill
- Aggregate in asphaltic concrete
- Bulk fill on land and water
- Shoreline protection material (riprap)
- Gabion basket fill[2]
- Granular aggregate for base
- Trench backfill

TFHRC (1997) also reports that

> . . . disposal in landfills, near the right-of-way, and in borrow pits or depleted quarries has historically been the most common method of managing RCM. However, recycling has become a more attractive option, particularly in aggregate-scarce areas and in large urban areas where gathering and distribution networks for RCM have been developed.

Recycling can eliminate the costs of haulage to landfills—$0.15 per ton-mile (~$0.10 per t-km)—and disposal—about $100 per ton (~$110/t). RCM is used as road base in 44 states (AGC 2002).

[2] Gabion: A bottomless basket of wickerwork or metal iron filled with earth or stones; used in building fieldworks or as revetments in mining (Parker 1994).

While recycled concrete is used to a limited extent as an aggregate in portland cement concrete for highway construction, no general usage of this recycled material as an aggregate for concrete used in *building construction* was identified in the course of the present analysis. A representative of Southern Crushed Concrete Inc.—a company that recycles concrete—knew of no use of RCM as aggregate in new concrete mixes for buildings. He believed that recycled aggregate was not used in buildings because of structural concerns as compared to concrete with virgin aggregate. The company had been involved in a highway project in Texas, where 30% of the virgin aggregate was replaced with aggregate from recycled concrete.[3] The view that reclaimed concrete was not used as an aggregate in concrete used to construct buildings was confirmed by an official of the Construction Materials Recycling Association.[4]

According to the Texas Department of Transportation (TxDOT 1999), one highway construction project near Houston has used 100% recycled concrete aggregate (coarse and fine) in new pavement concrete. Construction crews observed that the concrete was not consistent and that it sometimes set too quickly. In spite of these concerns, pavement performance has been good.

6.2.4 Disposal

Concrete rubble that is not suitable for recycling, or that the licensee elects not to recycle, is sent directly to a landfill. The following discussion of construction and demolition (C&D) debris is based on Franklin Associates 1998.

While the definition of C&D debris varies from state to state, concrete is a significant component of debris from all sources; it is the largest component of building demolition debris. The most common management practice for C&D debris is landfilling, which may be done in C&D landfills,[5] municipal solid waste (MSW) landfills, or at unpermitted sites. In 1996, an estimated 35% to 45% of C&D debris was placed in C&D landfills, while another 30% to 40% was managed on site, at MSW landfills, or at unpermitted landfills. Most of the balance was recycled. There were 1,900 active C&D landfills in the United States in 1994, with 280 in Florida and more than 100 each in Louisiana, North Carolina, Ohio, Kentucky, Mississippi, and South Dakota.

State regulation of C&D landfills is highly variable. In 11 states, the C&D landfill must meet MSW landfill requirements, while in 24 states the regulatory requirements for C&D landfills are separate from MSW landfill requirements. In addition, eight states have separate requirements for off-site and on-site landfills, while seven states exempt on-site C&D landfills from regulation.

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[3] Jim Miller, Sales & Estimating Dept., Southern Crushed Concrete Inc., private communication with William C. Thurber, SC&A, Inc., December, 2001.

[4] William Turley, Executive Director, Construction Materials Recycling Association, private communication with William C. Thurber, SC&A, Inc., January 7, 2002.

[5] In the present report, C&D landfills are subsumed under the more general category of industrial landfills.

6.3 Concrete Recycling and Disposal Scenarios

The eight exposure scenarios included in the concrete analysis, along with the mixing factors and environmental transport pathways included in each scenario, are listed in Table 6.2. These scenarios were adapted from the corresponding steel scenarios described in Chapter 3. The parameter values specific to concrete are listed in Table B.11. Only those aspects of the scenarios that are significantly different from the corresponding steel scenarios are described in the present section.

Table 6.2 Scenario and exposure pathway matrix

Scenario abbreviation	Scenario title	MF[a]	Exposure pathways[b]		
			Ext[c]	Inh	Ing
Handling and Processing					
Processing concrete	Processing concrete rubble at satellite facility	N	50	●	●
Transport					
Truck driver	Truck driver hauling concrete rubble	N	51	●	●
Product Use					
Road building	Building road using recycled concrete	N	F1	●	●
Driving on road	Driving on road built with recycled concrete	RS	F1		
Landfill Disposal					
Disposal–industrial	Handling concrete rubble at industrial landfill	IL	F1	●	●
Disposal–MSW	Handling concrete rubble at municipal landfill	ML	F1	●	●
Groundwater Contaminated by Leachate from Landfills					
Leachate–industrial	Leachate from industrial landfill	IL			●
Leachate–MSW	Leachate from municipal landfill	ML			●

[a] MF = mixing factor: IL = industrial landfill, ML = municipal landfill, N = no mixing, RS = road surface (see text) (additional details on mixing in landfills in Appendix D)

[b] Ext = external, Inh = inhalation, Ing = inadvertent ingestion; ingestion of drinking water

[c] External exposure dose factors:
- 50 Concrete pile
- 51 Concrete truck
- F1 Soil contaminated to an infinite depth (Eckerman and Ryman 1993)

6.3.1 Inhalation of Dust

The exposures of construction workers to inhalation of concrete dust are governed by OSHA standards. These standards are specified in 29 CFR 1926.55(a), which states in part:

> Exposure of employees to inhalation, ingestion, skin absorption, or contact with any material or substance at a concentration above those specified in the "Threshold Limit Values of Airborne Contaminants for 1970" of the American Conference of Governmental Industrial Hygienists, shall be avoided. See Appendix A to this section.

More detailed guidance is provided in 29 CFR 1910.1000(c):

> "Table Z-3." An employee's exposure to any substance listed in Table Z-3, in any 8-hour work shift of a 40-hour work week, shall not exceed the 8-hour time weighted average [(TWA)] limit given for that substance in the table.

Table Z-3, entitled "Mineral Dusts," includes a formula for calculating the TWA limits of dusts containing crystalline silica, a category which includes concrete aerosols. The table presents the limit in terms of the number of particles per unit volume, as well as in terms of mass loading (used to model inhalation exposure in the present analysis). The latter limits are calculated as follows:

$$\chi_d = \frac{10\ \text{mg/m}^3}{\%\text{SiO}_2 + 2} \qquad \textbf{6.1}$$

P_d = 8-h TWA level of respirable dust containing crystalline silica in the form of quartz
= $0.14\ \text{mg/m}^3$

$\%SiO_2$ = percentage of crystalline SiO_2
= 67.5% (see below)

In the present analysis, the fraction of SiO_2 in concrete is calculated from the elemental composition of concrete listed by the American Nuclear Society (1987),[6] assuming that all of the silicon is in the form of silica. In all scenarios which include the inhalation exposure pathway, it is assumed that dust suppression techniques (e.g., water sprays) will be employed in order that these TWA values are not exceeded.

The SiO_2 in concrete is primarily in the form of quartz. According to Prof. T. Taylor Eighmy:

> Quartz is a very common aggregate constituent, and is almost always present in naturally derived fine aggregate sources that are mined or produced in rock crushing operations. The nature of the parent rock will control for the presence of quartz, but since quartz is so durable, it is usually in the surviving fraction for many parent rock systems. Quartz is also present in quite a few coarse aggregate sources. Since coarse and fine aggregates make up 70 to 85 percent of the concrete volume, the biggest (and potentially only) source of quartz would be the aggregates in the portland cement concrete made with portland cement alone.[7]

This is confirmed by Riala (n/d), who observes: Although cement does not contain quartz, concrete dust most often contains quartz due to the quartz content of the stone aggregate.

[6] These data are from an ANSI/ANS standard for performing radiation transport calculations for nuclear reactors. They were adopted as fixed values in the present analysis.

[7] T. Taylor Eighmy, Director, Recycled Materials Resource Center, University of New Hampshire, private communication with Robert Anigstein, SC&A, Inc., March 21, 2003.

For the purpose of the present analysis, it is assumed that the silica in concrete is crystalline quartz, and that workers' exposures to concrete dust would be subject to the applicable OSHA limits.

6.3.2 Processing Concrete Rubble at Satellite Facility

The analyses of the recycling of scrap metals described in Chapters 3 – 5 assumed that the cleared scrap would be processed at a commercial scrap yard. Because of the much greater mass of cleared concrete, coupled with a much smaller commercial value per unit mass, transporting the concrete over large distances would not be economically feasible. It is more likely that the concrete would be processed at a dedicated facility at or near the site of the nuclear plant being dismantled. Consequently, the processing scenario assumes no mixing of the cleared concrete with other materials.

The exposure of workers to the inhalation of concrete dust is subject to the 8-hour TWA limit of 0.14 mg/m^3, derived in Section 6.3.1. Because the OSHA limits apply to any given 8-hour shift, the long-term average dust loading would be significantly less than this limit. The 8-hour TWA dust concentration is therefore modeled as a truncated lognormal distribution, with a range of zero to 0.014 mg/m^3 and a mean of 0.07 mg/m^3, one-half the limit.

Exposure durations of less than eight hours per shift would permit the worker to be exposed to proportionately higher dust concentrations. The inhalation doses are calculated to be the same as if the worker were exposed for eight hours to the lower concentration. Doses from external exposure and secondary ingestion are based on the time the worker actually spends on this task.

6.3.3 Transport of Concrete Rubble

The distances for shipments of concrete rubble were based on shipment distances of "nonmetallic waste and scrap" tabulated in Bureau of the Census 1999. These distances are represented by a normal distribution, with a mode of 231 mi (372 km), the average distance listed by the Census Bureau, and a coefficient of variation of 10.5%, as given by the Census Bureau. Because of the relatively short distances involved, it was assumed that the truck would have a "day cab" (i.e., no sleeper). The driver would be exposed to inhalation of dust during loading and unloading, as well as to the inadvertent ingestion of settled particulates. The 8-hour TWA dust concentration is based on the same distribution as is used in the concrete processing scenario described in Section 6.3.2. Since the actual exposure duration is assumed to be 15 – 30 minutes per trip, the actual dust concentration during the loading and unloading could be much greater than the 8-hour TWA concentration. However, they would not be higher than the dust concentrations that were modeled for the loading and unloading of a truck transporting steel slag, discussed in Chapter 3.

6.3.4 Landfill Disposal Workers

The inhalation exposures of landfill disposal workers are also subject to the OSHA limits on crystalline silica. However, since the workers handle materials other than the cleared concrete, the percentage of crystalline SiO_2 in Equation 6.1 is adjusted by multiplying the silica in concrete (67.5%) by the amount of cleared concrete (in a given realization) as a fraction of the total waste stream to a given landfill.[8] The distribution representing the 8-hour TWA dust concentration is adjusted in the same manner.

6.3.5 Concrete Road Scenarios

In both scenarios involving roads built with recycled concrete—"building road using recycled concrete" and "driving on road built with recycled concrete"—the fraction of RCM used in the asphaltic concrete of the road surface has a range of 10% to 80%, with a most probable value of 24%. As in the corresponding scenarios in the steel analysis, aggregate is assumed to constitute 80% of the pavement. The low end of the distribution is based on the observation of TFHRC (1997), cited in Section 6.2.3, that concrete incorporating more than 10% to 20% recycled concrete as fine aggregate can have quality problems. The maximum value is based on the use of 100% RCM as aggregate, as cited by TxDOT 1997, while the probable value was based on the experience of Southern Crushed Concrete, which used RCM as 30% of the aggregate ($0.3 \times 0.8 = 0.24$).

The inhalation exposures of the road construction workers are modeled in the same way as those of the concrete processing workers, described in Section 6.3.2.

6.3.6 Scenario Timing

The following basic assumptions are adopted to estimate the timing for the scenarios:

- Processing of cleared rubble occurs between two and 30 days following clearance.
- Transportation to a road-building site or a landfill takes place one to 30 days after processing.
- Disposal activities take place between one and seven days after the concrete arrives at the landfill.
- Road-building activities occur between one and 30 days after the concrete arrives on site.
- Use of the roadway begins one day after the road is constructed.

6.4 Dose Assessments of Recycling and Disposal of Concrete Rubble

As discussed in previous sections of this chapter, the radiological assessment of the clearance of concrete rubble from NRC-licensed nuclear facilities evaluates the radiation exposures of

[8] The annual flow of waste to various landfills is discussed in Section D.2.1.1.

individual members of various groups to each of 115 radionuclides and their progenies in eight exposure scenarios.

6.4.1 Calculation of Effective Dose Equivalents (EDEs)

The groups described by four of these scenarios receive the highest mean normalized EDEs from one year of exposure to cleared concrete rubble from one or more nuclides. One of these groups, workers processing concrete rubble for recycling or disposal, constitutes the EDE-critical group for 52 nuclides.[9] Table 6.5 lists the mean and the 5th, 50th, and 95th percentile mass-based normalized EDEs from each radionuclide to its respective critical group, while Table 6.6 lists the corresponding surficial EDEs. Figure 6.2 lists the scenarios describing the EDE-critical groups and displays the number of radionuclides for which each scenario constitutes the critical group. The mean and the 5th, 50th, 90th, and 95th percentile normalized EDEs from all 115 nuclides from all eight scenarios are tabulated in Appendix I-1.

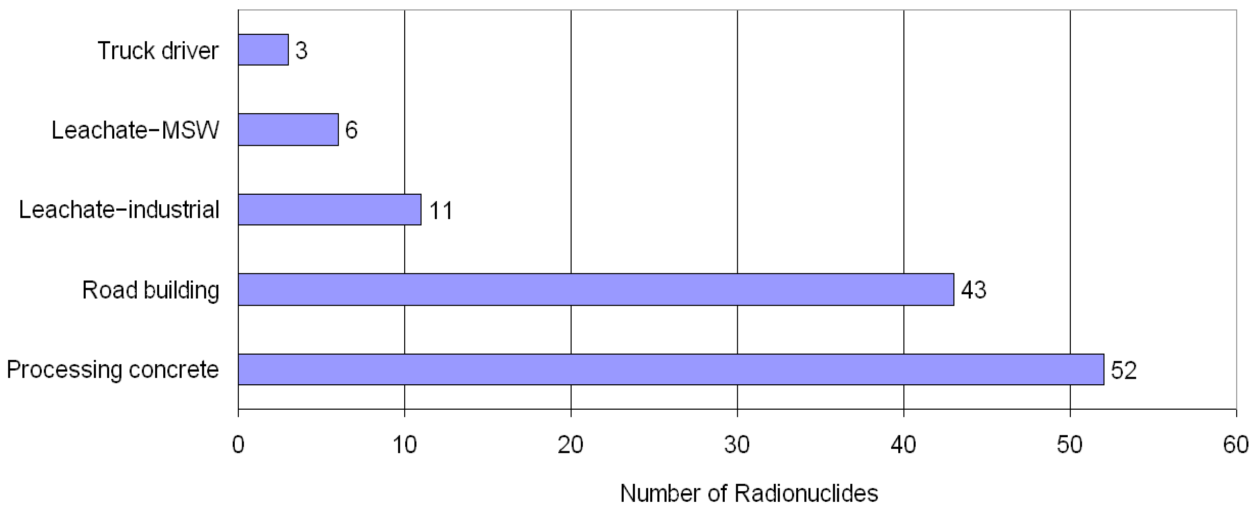

Figure 6.2 Scenarios giving rise to EDE-critical groups for concrete

In the case of the 11 radionuclides listed in Table 6.3, the mean normalized EDE in the critical group was higher than the 90th percentile EDE. The critical group for each of these nuclides comprises persons drinking water from wells down gradient from an industrial or MSW landfill containing cleared concrete rubble. The group with the highest EDE for which the mean does not exceed the 90th percentile might be considered as the alternate critical group for that nuclide. These potential alternate critical groups are listed in Table 6.3.

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9 As discussed in Chapter 1, the group which receives the highest mean normalized EDE from a given radionuclide is defined as the EDE-critical group for that nuclide.

Table 6.3 Normalized mass-based EDE from selected nuclides (:Sv/y per Bq/g)

Nuclide[a]	Critical group			Potential alternate critical group[b]		
	Mean	90^{th} %-ile	Scenario	Mean	90^{th} %-ile	Scenario
C-14	1.2e-01	0.0e+00	Leachate–industrial	7.3e-03	1.3e-02	Processing concrete
Mn-53	1.5e-03	0.0e+00	Leachate–industrial	3.9e-04	6.8e-04	Processing concrete
Sr-90	1.5e+00	0.0e+00	Leachate–industrial	9.1e-01	1.4e+00	Processing concrete
Mo-93	1.7e-01	0.0e+00	Leachate–industrial	1.4e-02	2.3e-02	Road building
Cs-135	2.6e-02	0.0e+00	Leachate–MSW	2.5e-02	4.4e-02	Processing concrete
U-233	3.2e+01	0.0e+00	Leachate–MSW	7.1e+00	9.9e+00	Processing concrete
U-234	2.3e+01	0.0e+00	Leachate–MSW	7.0e+00	9.7e+00	Processing concrete
U-235	3.3e+01	0.0e+00	Leachate–MSW	1.8e+01	2.3e+01	Processing concrete
U-236	2.2e+01	0.0e+00	Leachate–MSW	6.6e+00	9.2e+00	Processing concrete
U-238	2.1e+01	0.0e+00	Leachate–MSW	8.6e+00	1.1e+01	Processing concrete
Np-237	1.1e+03	2.0e+02	Leachate–industrial	5.6e+01	7.3e+01	Processing concrete

[a] Nuclides from which mean normalized EDE exceeds 90th percentile EDE
[b] Group with maximum mean EDE which does not exceed 90th percentile EDE to *that* group

6.4.2 Calculation of Effective Doses

The groups described by five of the exposure scenarios receive the highest mean normalized effective doses from one year of exposure to cleared concrete rubble from one or more nuclides. One group, workers processing concrete rubble for recycling or disposal, constitutes the effective dose-critical group for 56 nuclides. Table 6.7 lists the mean and the 5th, 50th, and 95th percentile mass-based normalized effective doses from each radionuclide to its respective critical group, while Table 6.8 lists the corresponding surficial effective doses. Figure 6.3 lists the scenarios describing the effective dose-critical groups and displays the number of radionuclides for which each scenario constitutes the critical group. The mean and the 5th, 50th, 90th, and 95th percentile normalized effective doses from all 115 nuclides from all eight scenarios are tabulated in Appendix I-2.

In the case of the 12 radionuclides listed in Table 6.4, the mean normalized effective dose in the critical group was higher than the 90th percentile effective dose. The critical group for each of these nuclides again comprises persons drinking water from wells down gradient from an industrial or MSW landfill containing cleared concrete rubble. The potential alternate critical groups are listed in Table 6.4.

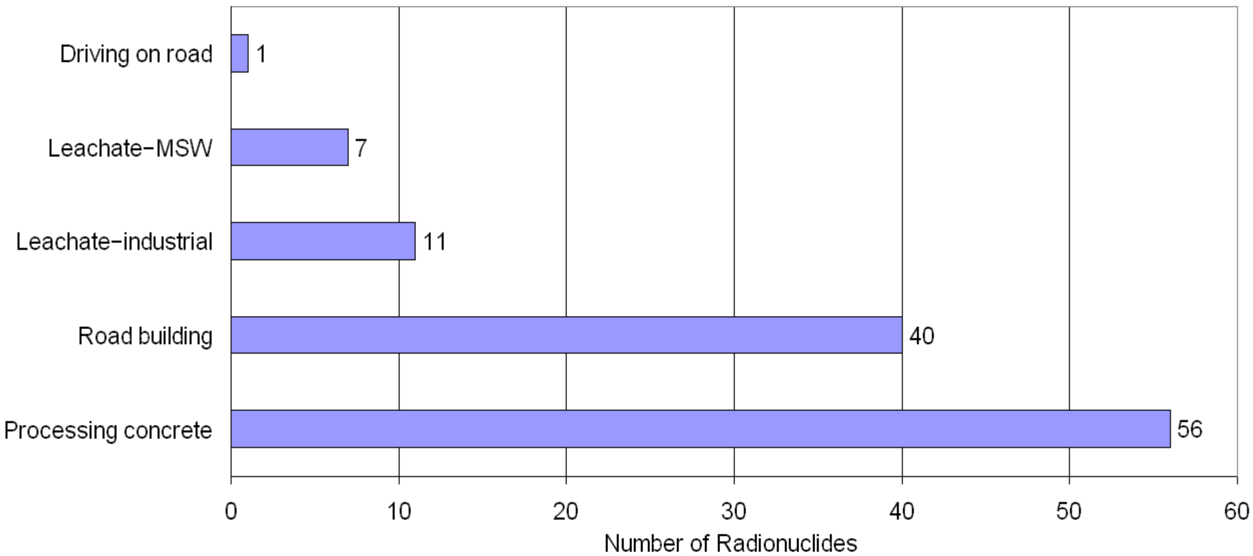

Figure 6.3 Scenarios giving rise to effective dose-critical groups for concrete

Table 6.4 Normalized mass-based effective doses from selected nuclides (: Sv/y per Bq/g)

Nuclide[a]	Critical group			Potential alternate critical group[b]		
	Mean	90^{th} %-ile	Scenario	Mean	90^{th} %-ile	Scenario
C-14	1.2e-01	0.0e+00	Leachate–industrial	7.5e-03	1.3e-02	Processing concrete
Mn-53	1.6e-03	0.0e+00	Leachate–industrial	3.8e-04	6.8e-04	Processing concrete
Sr-90	1.1e+00	0.0e+00	Leachate–industrial	9.7e-01	1.6e+00	Road building
Mo-93	9.0e-01	0.0e+00	Leachate–industrial	3.9e-02	6.5e-02	Processing concrete
Cs-135	2.7e-02	0.0e+00	Leachate–MSW	2.6e-02	4.6e-02	Processing concrete
U-232	2.9e+01	0.0e+00	Leachate–MSW	2.0e+01	3.5e+01	Driving on road
U-233	2.0e+01	0.0e+00	Leachate–MSW	1.8e+00	2.5e+00	Processing concrete
U-234	1.5e+01	0.0e+00	Leachate–MSW	1.8e+00	2.4e+00	Processing concrete
U-235	1.7e+01	0.0e+00	Leachate–MSW	1.3e+01	2.2e+01	Road building
U-236	1.4e+01	0.0e+00	Leachate–MSW	1.6e+00	2.3e+00	Processing concrete
U-238	1.4e+01	0.0e+00	Leachate–MSW	3.9e+00	4.9e+00	Processing concrete
Np-237	9.9e+01	1.8e+01	Leachate–industrial	2.1e+01	2.7e+01	Processing concrete

[a] Nuclides from which mean normalized effective dose exceeds 90th percentile effective dose

[b] Group with maximum mean effective dose which does not exceed 90th percentile effective dose to *that* group

Table 6.5 Normalized mass-based effective dose equivalents to critical groups for concrete

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	6.6e-02	0.0e+00	4.4e-05	2.9e-01	2.4e-04	0.0e+00	1.6e-07	1.1e-03	Leachate-industrial
C-14	1.2e-01	0.0e+00	0.0e+00	2.8e-01	4.3e-04	0.0e+00	0.0e+00	1.0e-03	Leachate-industrial
Na-22	2.4e+02	1.2e+02	2.1e+02	4.6e+02	8.8e-01	4.3e-01	7.7e-01	1.7e+00	Road building
P-32	1.1e-01	4.4e-02	9.5e-02	2.0e-01	3.9e-04	1.6e-04	3.5e-04	7.5e-04	Processing concrete
S-35	1.6e-03	3.8e-04	1.6e-03	2.9e-03	5.9e-06	1.4e-06	5.8e-06	1.1e-05	Processing concrete
Cl-36	1.3e+00	0.0e+00	0.0e+00	6.2e+00	4.8e-03	0.0e+00	0.0e+00	2.3e-02	Leachate-industrial
K-40	1.9e+01	9.1e+00	1.6e+01	3.6e+01	6.9e-02	3.4e-02	6.1e-02	1.3e-01	Road building
Ca-41	7.2e-01	0.0e+00	0.0e+00	3.7e+00	2.7e-03	0.0e+00	0.0e+00	1.4e-02	Leachate-industrial
Ca-45	1.1e-02	2.0e-03	1.1e-02	2.1e-02	4.1e-05	7.3e-06	4.0e-05	7.7e-05	Processing concrete
Sc-46	1.7e+02	7.5e+01	1.4e+02	3.3e+02	6.2e-01	2.8e-01	5.3e-01	1.2e+00	Road building
Cr-51	1.8e+00	9.3e-01	1.7e+00	2.8e+00	6.5e-03	3.4e-03	6.2e-03	1.0e-02	Processing concrete
Mn-53	1.5e-03	0.0e+00	0.0e+00	0.0e+00	5.7e-06	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial
Mn-54	8.5e+01	4.1e+01	7.4e+01	1.6e+02	3.1e-01	1.5e-01	2.7e-01	6.0e-01	Road building
Fe-55	2.1e-03	3.1e-04	2.1e-03	4.1e-03	7.9e-06	1.1e-06	7.8e-06	1.5e-05	Processing concrete
Fe-59	8.8e+01	5.1e+01	8.6e+01	1.3e+02	3.3e-01	1.9e-01	3.2e-01	5.0e-01	Processing concrete
Co-56	3.0e+02	1.4e+02	2.6e+02	6.1e+02	1.1e+00	5.0e-01	9.7e-01	2.2e+00	Road building
Co-57	8.1e+00	4.0e+00	7.1e+00	1.6e+01	3.0e-02	1.5e-02	2.6e-02	5.8e-02	Road building
Co-58	7.5e+01	4.5e+01	7.4e+01	1.1e+02	2.8e-01	1.7e-01	2.7e-01	4.1e-01	Processing concrete
Co-60	2.9e+02	1.4e+02	2.5e+02	5.5e+02	1.1e+00	5.2e-01	9.3e-01	2.0e+00	Road building
Ni-59	2.1e-03	1.2e-03	2.1e-03	3.1e-03	7.9e-06	4.5e-06	7.8e-06	1.2e-05	Processing concrete
Ni-63	2.1e-03	3.2e-04	2.1e-03	4.0e-03	7.7e-06	1.2e-06	7.6e-06	1.5e-05	Processing concrete
Zn-65	5.9e+01	2.9e+01	5.2e+01	1.1e+02	2.2e-01	1.1e-01	1.9e-01	4.2e-01	Road building
As-73	1.2e-01	5.5e-02	1.1e-01	2.5e-01	4.6e-04	2.0e-04	3.9e-04	9.1e-04	Road building
Se-75	2.8e+01	1.3e+01	2.5e+01	5.5e+01	1.1e-01	5.0e-02	9.2e-02	2.0e-01	Road building
Sr-85	3.6e+01	2.1e+01	3.5e+01	5.3e+01	1.3e-01	7.8e-02	1.3e-01	2.0e-01	Processing concrete
Sr-89	1.4e-01	8.3e-02	1.4e-01	2.1e-01	5.2e-04	3.1e-04	5.0e-04	7.7e-04	Processing concrete
Sr-90	1.5e+00	0.0e+00	0.0e+00	2.7e-06	5.4e-03	0.0e+00	0.0e+00	9.9e-09	Leachate-industrial
Y-91	4.3e-01	2.6e-01	4.2e-01	6.4e-01	1.6e-03	9.6e-04	1.6e-03	2.4e-03	Processing concrete
Zr-93	9.4e-03	3.9e-03	9.3e-03	1.5e-02	3.5e-05	1.4e-05	3.4e-05	5.6e-05	Processing concrete
Zr-95	8.6e+01	4.2e+01	7.5e+01	1.6e+02	3.2e-01	1.6e-01	2.8e-01	6.1e-01	Road building
Nb-93m	3.8e-03	2.0e-03	3.8e-03	5.8e-03	1.4e-05	7.6e-06	1.4e-05	2.1e-05	Processing concrete
Nb-94	1.7e+02	8.5e+01	1.5e+02	3.3e+02	6.4e-01	3.1e-01	5.6e-01	1.2e+00	Road building
Nb-95	5.1e+01	2.8e+01	4.9e+01	8.0e+01	1.9e-01	1.0e-01	1.8e-01	2.9e-01	Processing concrete
Mo-93	1.7e-01	0.0e+00	0.0e+00	2.4e-01	6.4e-04	0.0e+00	0.0e+00	8.8e-04	Leachate-industrial
Tc-97	7.1e-01	0.0e+00	0.0e+00	3.3e+00	2.6e-03	0.0e+00	0.0e+00	1.2e-02	Leachate-industrial
Tc-97m	2.7e-02	1.3e-02	2.4e-02	5.4e-02	1.0e-04	4.6e-05	8.8e-05	2.0e-04	Road building
Tc-99	6.1e+00	0.0e+00	0.0e+00	2.8e+01	2.2e-02	0.0e+00	0.0e+00	1.1e-01	Leachate-industrial
Ru-103	3.2e+01	1.8e+01	3.2e+01	5.0e+01	1.2e-01	6.8e-02	1.2e-01	1.9e-01	Processing concrete
Ru-106	2.2e+01	1.1e+01	1.9e+01	4.1e+01	8.0e-02	3.9e-02	7.0e-02	1.5e-01	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.5 Normalized mass-based effective dose equivalents to critical groups for concrete

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	1.7e+02	8.4e+01	1.5e+02	3.3e+02	6.4e-01	3.1e-01	5.6e-01	1.2e+00	Road building
Ag-110m	2.8e+02	1.3e+02	2.4e+02	5.3e+02	1.0e+00	5.0e-01	8.9e-01	2.0e+00	Road building
Cd-109	4.8e-01	2.4e-01	4.2e-01	9.0e-01	1.8e-03	8.7e-04	1.5e-03	3.3e-03	Road building
Sn-113	2.1e+01	9.8e+00	1.8e+01	4.1e+01	7.7e-02	3.6e-02	6.7e-02	1.5e-01	Road building
Sb-124	1.5e+02	8.6e+01	1.4e+02	2.2e+02	5.4e-01	3.2e-01	5.3e-01	8.0e-01	Processing concrete
Sb-125	4.3e+01	2.1e+01	3.7e+01	8.2e+01	1.6e-01	7.7e-02	1.4e-01	3.0e-01	Road building
Te-123m	9.0e+00	4.2e+00	7.9e+00	1.8e+01	3.3e-02	1.6e-02	2.9e-02	6.5e-02	Road building
Te-127m	4.8e-01	2.3e-01	4.2e-01	9.4e-01	1.8e-03	8.4e-04	1.6e-03	3.5e-03	Road building
I-125	2.5e-01	1.0e-01	2.1e-01	5.1e-01	9.1e-04	3.8e-04	7.9e-04	1.9e-03	Road building
I-129	2.9e+02	0.0e+00	0.0e+00	1.3e+03	1.1e+00	0.0e+00	0.0e+00	4.8e+00	Leachate-industrial
I-131	1.0e+01	2.3e+00	7.7e+00	2.5e+01	3.7e-02	8.6e-03	2.9e-02	9.4e-02	Processing concrete
Cs-134	1.6e+02	8.0e+01	1.4e+02	3.1e+02	6.1e-01	3.0e-01	5.3e-01	1.2e+00	Road building
Cs-135	2.6e-02	0.0e+00	0.0e+00	0.0e+00	9.5e-05	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
Cs-137	6.1e+01	3.0e+01	5.3e+01	1.2e+02	2.3e-01	1.1e-01	2.0e-01	4.3e-01	Road building
Ba-133	3.5e+01	1.7e+01	3.1e+01	6.7e+01	1.3e-01	6.4e-02	1.1e-01	2.5e-01	Road building
Ce-139	9.4e+00	4.5e+00	8.2e+00	1.8e+01	3.5e-02	1.7e-02	3.0e-02	6.8e-02	Road building
Ce-141	3.2e+00	1.8e+00	3.1e+00	5.1e+00	1.2e-02	6.5e-03	1.1e-02	1.9e-02	Processing concrete
Ce-144	5.3e+00	2.6e+00	4.6e+00	1.0e+01	1.9e-02	9.5e-03	1.7e-02	3.7e-02	Road building
Pm-147	5.9e-03	2.6e-03	5.8e-03	9.5e-03	2.2e-05	9.5e-06	2.2e-05	3.5e-05	Processing concrete
Sm-151	2.7e-03	1.3e-03	2.7e-03	4.2e-03	9.9e-06	4.7e-06	9.9e-06	1.5e-05	Processing concrete
Eu-152	1.2e+02	6.1e+01	1.1e+02	2.4e+02	4.6e-01	2.3e-01	4.0e-01	8.8e-01	Road building
Eu-154	1.4e+02	6.7e+01	1.2e+02	2.6e+02	5.0e-01	2.5e-01	4.4e-01	9.6e-01	Road building
Eu-155	3.2e+00	1.6e+00	2.8e+00	6.1e+00	1.2e-02	5.8e-03	1.0e-02	2.3e-02	Road building
Gd-153	3.9e+00	1.9e+00	3.4e+00	7.5e+00	1.5e-02	7.1e-03	1.3e-02	2.8e-02	Road building
Tb-160	8.8e+01	5.2e+01	8.6e+01	1.3e+02	3.2e-01	1.9e-01	3.2e-01	4.8e-01	Processing concrete
Tm-170	2.3e-01	1.1e-01	2.0e-01	4.4e-01	8.4e-04	4.0e-04	7.3e-04	1.6e-03	Road building
Tm-171	2.0e-02	1.0e-02	1.8e-02	3.9e-02	7.5e-05	3.7e-05	6.6e-05	1.4e-04	Road building
Ta-182	1.1e+02	5.3e+01	9.8e+01	2.2e+02	4.2e-01	2.0e-01	3.6e-01	8.1e-01	Road building
W-181	1.1e+00	5.2e-01	9.6e-01	2.1e+00	4.1e-03	1.9e-03	3.5e-03	7.9e-03	Road building
W-185	9.7e-03	4.7e-03	9.5e-03	1.5e-02	3.6e-05	1.8e-05	3.5e-05	5.6e-05	Processing concrete
Os-185	5.6e+01	2.6e+01	4.9e+01	1.1e+02	2.1e-01	9.6e-02	1.8e-01	4.1e-01	Road building
Ir-192	5.8e+01	2.6e+01	5.1e+01	1.2e+02	2.2e-01	9.5e-02	1.9e-01	4.3e-01	Road building
Tl-204	7.8e-02	3.9e-02	6.8e-02	1.5e-01	2.9e-04	1.4e-04	2.5e-04	5.5e-04	Road building
Pb-210	2.5e+01	3.3e+00	2.5e+01	5.0e+01	9.4e-02	1.2e-02	9.3e-02	1.8e-01	Processing concrete
Bi-207	1.7e+02	8.2e+01	1.5e+02	3.2e+02	6.2e-01	3.0e-01	5.4e-01	1.2e+00	Road building
Po-210	6.3e+00	9.1e-01	6.1e+00	1.2e+01	2.3e-02	3.4e-03	2.3e-02	4.5e-02	Processing concrete
Ra-226	2.0e+02	1.0e+02	1.8e+02	3.9e+02	7.5e-01	3.7e-01	6.6e-01	1.4e+00	Road building
Ra-228	1.2e+02	5.7e+01	1.0e+02	2.2e+02	4.3e-01	2.1e-01	3.8e-01	8.2e-01	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.5 Normalized mass-based effective dose equivalents to critical groups for concrete

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a] 5th	Percentile[a] 50th	Percentile[a] 95th	Mean	Percentile[a] 5th	Percentile[a] 50th	Percentile[a] 95th	
Ac-227	1.4e+02	8.3e+01	1.4e+02	2.0e+02	5.2e-01	3.1e-01	5.1e-01	7.4e-01	Processing concrete
Th-228	1.8e+02	9.1e+01	1.6e+02	3.5e+02	6.8e-01	3.3e-01	5.9e-01	1.3e+00	Road building
Th-229	1.3e+02	8.6e+01	1.3e+02	1.9e+02	4.9e-01	3.2e-01	4.8e-01	7.2e-01	Processing concrete
Th-230	1.8e+01	9.7e+00	1.7e+01	2.9e+01	6.6e-02	3.6e-02	6.2e-02	1.1e-01	Truck driver
Th-232	8.9e+01	4.9e+01	8.5e+01	1.5e+02	3.3e-01	1.8e-01	3.1e-01	5.4e-01	Truck driver
Pa-231	9.7e+01	5.2e+01	9.5e+01	1.5e+02	3.6e-01	1.9e-01	3.5e-01	5.4e-01	Processing concrete
U-232	3.7e+01	2.0e+01	3.5e+01	6.0e+01	1.4e-01	7.6e-02	1.3e-01	2.2e-01	Truck driver
U-233	3.2e+01	0.0e+00	0.0e+00	0.0e+00	1.2e-01	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-234	2.3e+01	0.0e+00	0.0e+00	0.0e+00	8.5e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-235	3.3e+01	0.0e+00	0.0e+00	0.0e+00	1.2e-01	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-236	2.1e+01	0.0e+00	0.0e+00	0.0e+00	7.9e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-238	2.1e+01	0.0e+00	0.0e+00	0.0e+00	7.9e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
Np-237	1.1e+03	0.0e+00	0.0e+00	2.4e+03	4.0e+00	0.0e+00	0.0e+00	8.7e+00	Leachate-industrial
Pu-236	1.0e+01	5.5e+00	1.0e+01	1.6e+01	3.8e-02	2.0e-02	3.8e-02	5.8e-02	Processing concrete
Pu-238	2.9e+01	1.5e+01	2.8e+01	4.3e+01	1.1e-01	5.5e-02	1.0e-01	1.6e-01	Processing concrete
Pu-239	3.1e+01	1.6e+01	3.1e+01	4.8e+01	1.2e-01	6.1e-02	1.1e-01	1.8e-01	Processing concrete
Pu-240	3.1e+01	1.6e+01	3.1e+01	4.8e+01	1.2e-01	6.1e-02	1.1e-01	1.8e-01	Processing concrete
Pu-241	6.1e-01	3.2e-01	6.0e-01	9.2e-01	2.2e-03	1.2e-03	2.2e-03	3.4e-03	Processing concrete
Pu-242	3.0e+01	1.6e+01	3.0e+01	4.5e+01	1.1e-01	5.8e-02	1.1e-01	1.7e-01	Processing concrete
Pu-244	5.8e+01	3.9e+01	5.8e+01	7.9e+01	2.2e-01	1.5e-01	2.1e-01	2.9e-01	Processing concrete
Am-241	3.3e+01	1.8e+01	3.2e+01	5.0e+01	1.2e-01	6.5e-02	1.2e-01	1.8e-01	Processing concrete
Am-242m	3.3e+01	1.8e+01	3.3e+01	5.0e+01	1.2e-01	6.6e-02	1.2e-01	1.8e-01	Processing concrete
Am-243	4.5e+01	2.9e+01	4.5e+01	6.3e+01	1.7e-01	1.1e-01	1.7e-01	2.3e-01	Processing concrete
Cm-242	1.1e+00	6.0e-01	1.1e+00	1.7e+00	4.1e-03	2.2e-03	4.0e-03	6.2e-03	Processing concrete
Cm-243	3.0e+01	1.9e+01	3.0e+01	4.3e+01	1.1e-01	7.1e-02	1.1e-01	1.6e-01	Processing concrete
Cm-244	1.8e+01	9.5e+00	1.8e+01	2.7e+01	6.7e-02	3.5e-02	6.6e-02	1.0e-01	Processing concrete
Cm-245	3.8e+01	2.2e+01	3.8e+01	5.6e+01	1.4e-01	8.3e-02	1.4e-01	2.1e-01	Processing concrete
Cm-246	3.3e+01	1.7e+01	3.2e+01	5.0e+01	1.2e-01	6.4e-02	1.2e-01	1.8e-01	Processing concrete
Cm-247	5.7e+01	3.9e+01	5.7e+01	7.7e+01	2.1e-01	1.4e-01	2.1e-01	2.9e-01	Processing concrete
Cm-248	1.2e+02	6.3e+01	1.2e+02	1.8e+02	4.5e-01	2.3e-01	4.4e-01	6.8e-01	Processing concrete
Bk-249	1.0e-01	5.5e-02	1.0e-01	1.6e-01	3.9e-04	2.0e-04	3.8e-04	5.9e-04	Processing concrete
Cf-248	3.3e+00	1.8e+00	3.3e+00	5.0e+00	1.2e-02	6.7e-03	1.2e-02	1.9e-02	Processing concrete
Cf-249	6.0e+01	3.9e+01	5.9e+01	8.2e+01	2.2e-01	1.4e-01	2.2e-01	3.0e-01	Processing concrete
Cf-250	1.6e+01	8.2e+00	1.6e+01	2.5e+01	6.1e-02	3.1e-02	6.0e-02	9.3e-02	Processing concrete
Cf-251	4.1e+01	2.3e+01	4.1e+01	6.0e+01	1.5e-01	8.4e-02	1.5e-01	2.2e-01	Processing concrete
Cf-252	1.1e+01	5.8e+00	1.0e+01	1.6e+01	3.9e-02	2.1e-02	3.9e-02	5.9e-02	Processing concrete
Cf-254	1.4e+03	8.1e+02	1.3e+03	2.0e+03	5.1e+00	3.0e+00	5.0e+00	7.5e+00	Processing concrete
Es-254	9.2e+01	4.5e+01	8.0e+01	1.8e+02	3.4e-01	1.7e-01	3.0e-01	6.5e-01	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.6 Normalized surficial effective dose equivalents to critical groups for concrete

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	2.4e-04	0.0e+00	1.6e-07	1.0e-03	8.7e-07	0.0e+00	5.8e-10	3.8e-06	Leachate-industrial
C-14	4.1e-04	0.0e+00	0.0e+00	9.8e-04	1.5e-06	0.0e+00	0.0e+00	3.6e-06	Leachate-industrial
Na-22	8.5e-01	4.1e-01	7.4e-01	1.6e+00	3.1e-03	1.5e-03	2.7e-03	6.0e-03	Road building
P-32	3.8e-04	1.6e-04	3.4e-04	7.2e-04	1.4e-06	5.8e-07	1.3e-06	2.7e-06	Processing concrete
S-35	5.7e-06	1.4e-06	5.6e-06	1.0e-05	2.1e-08	5.0e-09	2.1e-08	3.9e-08	Processing concrete
Cl-36	4.7e-03	0.0e+00	0.0e+00	2.2e-02	1.7e-05	0.0e+00	0.0e+00	8.2e-05	Leachate-industrial
K-40	6.7e-02	3.3e-02	5.8e-02	1.3e-01	2.5e-04	1.2e-04	2.2e-04	4.7e-04	Road building
Ca-41	2.6e-03	0.0e+00	0.0e+00	1.3e-02	9.5e-06	0.0e+00	0.0e+00	4.9e-05	Leachate-industrial
Ca-45	3.9e-05	7.0e-06	3.9e-05	7.5e-05	1.5e-07	2.6e-08	1.4e-07	2.8e-07	Processing concrete
Sc-46	5.9e-01	2.7e-01	5.2e-01	1.2e+00	2.2e-03	9.9e-04	1.9e-03	4.4e-03	Road building
Cr-51	6.3e-03	3.3e-03	6.0e-03	1.0e-02	2.3e-05	1.2e-05	2.2e-05	3.8e-05	Processing concrete
Mn-53	5.5e-06	0.0e+00	0.0e+00	0.0e+00	2.0e-08	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial
Mn-54	3.0e-01	1.5e-01	2.6e-01	5.8e-01	1.1e-03	5.4e-04	9.8e-04	2.2e-03	Road building
Fe-55	7.6e-06	1.1e-06	7.5e-06	1.5e-05	2.8e-08	4.0e-09	2.8e-08	5.5e-08	Processing concrete
Fe-59	3.1e-01	1.8e-01	3.1e-01	4.8e-01	1.2e-03	6.7e-04	1.1e-03	1.8e-03	Processing concrete
Co-56	1.1e+00	4.8e-01	9.4e-01	2.1e+00	4.0e-03	1.8e-03	3.5e-03	8.0e-03	Road building
Co-57	2.9e-02	1.4e-02	2.5e-02	5.6e-02	1.1e-04	5.2e-05	9.3e-05	2.1e-04	Road building
Co-58	2.7e-01	1.6e-01	2.6e-01	4.0e-01	9.9e-04	5.9e-04	9.7e-04	1.5e-03	Processing concrete
Co-60	1.0e+00	5.0e-01	8.9e-01	2.0e+00	3.8e-03	1.8e-03	3.3e-03	7.3e-03	Road building
Ni-59	7.6e-06	4.3e-06	7.5e-06	1.1e-05	2.8e-08	1.6e-08	2.8e-08	4.2e-08	Processing concrete
Ni-63	7.4e-06	1.1e-06	7.3e-06	1.4e-05	2.7e-08	4.2e-09	2.7e-08	5.3e-08	Processing concrete
Zn-65	2.1e-01	1.0e-01	1.8e-01	4.1e-01	7.8e-04	3.8e-04	6.8e-04	1.5e-03	Road building
As-73	4.4e-04	2.0e-04	3.8e-04	8.7e-04	1.6e-06	7.3e-07	1.4e-06	3.2e-06	Road building
Se-75	1.0e-01	4.8e-02	8.9e-02	2.0e-01	3.8e-04	1.8e-04	3.3e-04	7.3e-04	Road building
Sr-85	1.3e-01	7.5e-02	1.3e-01	1.9e-01	4.7e-04	2.8e-04	4.6e-04	7.1e-04	Processing concrete
Sr-89	5.0e-04	2.9e-04	4.9e-04	7.5e-04	1.8e-06	1.1e-06	1.8e-06	2.8e-06	Processing concrete
Sr-90	5.2e-03	0.0e+00	0.0e+00	9.4e-09	1.9e-05	0.0e+00	0.0e+00	3.5e-11	Leachate-industrial
Y-91	1.5e-03	9.2e-04	1.5e-03	2.3e-03	5.7e-06	3.4e-06	5.6e-06	8.5e-06	Processing concrete
Zr-93	3.3e-05	1.4e-05	3.3e-05	5.4e-05	1.2e-07	5.1e-08	1.2e-07	2.0e-07	Processing concrete
Zr-95	3.1e-01	1.5e-01	2.7e-01	5.9e-01	1.1e-03	5.5e-04	9.9e-04	2.2e-03	Road building
Nb-93m	1.4e-05	7.3e-06	1.4e-05	2.1e-05	5.1e-08	2.7e-08	5.0e-08	7.7e-08	Processing concrete
Nb-94	6.2e-01	3.0e-01	5.4e-01	1.2e+00	2.3e-03	1.1e-03	2.0e-03	4.4e-03	Road building
Nb-95	1.8e-01	1.0e-01	1.8e-01	2.9e-01	6.7e-04	3.7e-04	6.5e-04	1.1e-03	Processing concrete
Mo-93	6.1e-04	0.0e+00	0.0e+00	8.4e-04	2.3e-06	0.0e+00	0.0e+00	3.1e-06	Leachate-industrial
Tc-97	2.5e-03	0.0e+00	0.0e+00	1.2e-02	9.4e-06	0.0e+00	0.0e+00	4.4e-05	Leachate-industrial
Tc-97m	9.7e-05	4.5e-05	8.5e-05	1.9e-04	3.6e-07	1.7e-07	3.1e-07	7.0e-07	Road building
Tc-99	2.2e-02	0.0e+00	0.0e+00	1.0e-01	8.0e-05	0.0e+00	0.0e+00	3.8e-04	Leachate-industrial
Ru-103	1.2e-01	6.5e-02	1.1e-01	1.8e-01	4.3e-04	2.4e-04	4.2e-04	6.7e-04	Processing concrete
Ru-106	7.7e-02	3.7e-02	6.7e-02	1.5e-01	2.8e-04	1.4e-04	2.5e-04	5.5e-04	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.6 Normalized surficial effective dose equivalents to critical groups for concrete

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	6.2e-01	3.0e-01	5.4e-01	1.2e+00	2.3e-03	1.1e-03	2.0e-03	4.4e-03	Road building
Ag-110m	9.8e-01	4.8e-01	8.6e-01	1.9e+00	3.6e-03	1.8e-03	3.2e-03	7.0e-03	Road building
Cd-109	1.7e-03	8.4e-04	1.5e-03	3.2e-03	6.3e-06	3.1e-06	5.5e-06	1.2e-05	Road building
Sn-113	7.4e-02	3.5e-02	6.5e-02	1.5e-01	2.8e-04	1.3e-04	2.4e-04	5.4e-04	Road building
Sb-124	5.2e-01	3.0e-01	5.1e-01	7.8e-01	1.9e-03	1.1e-03	1.9e-03	2.9e-03	Processing concrete
Sb-125	1.5e-01	7.4e-02	1.3e-01	2.9e-01	5.6e-04	2.8e-04	4.9e-04	1.1e-03	Road building
Te-123m	3.2e-02	1.5e-02	2.8e-02	6.3e-02	1.2e-04	5.6e-05	1.0e-04	2.3e-04	Road building
Te-127m	1.7e-03	8.1e-04	1.5e-03	3.4e-03	6.4e-06	3.0e-06	5.6e-06	1.2e-05	Road building
I-125	8.8e-04	3.7e-04	7.6e-04	1.8e-03	3.3e-06	1.4e-06	2.8e-06	6.7e-06	Road building
I-129	1.0e+00	0.0e+00	0.0e+00	4.6e+00	3.9e-03	0.0e+00	0.0e+00	1.7e-02	Leachate-industrial
I-131	3.6e-02	8.3e-03	2.8e-02	9.1e-02	1.3e-04	3.1e-05	1.0e-04	3.4e-04	Processing concrete
Cs-134	5.8e-01	2.8e-01	5.1e-01	1.1e+00	2.2e-03	1.1e-03	1.9e-03	4.2e-03	Road building
Cs-135	9.3e-05	0.0e+00	0.0e+00	0.0e+00	3.5e-07	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
Cs-137	2.2e-01	1.1e-01	1.9e-01	4.2e-01	8.0e-04	3.9e-04	7.0e-04	1.5e-03	Road building
Ba-133	1.3e-01	6.1e-02	1.1e-01	2.4e-01	4.6e-04	2.3e-04	4.1e-04	9.0e-04	Road building
Ce-139	3.4e-02	1.6e-02	2.9e-02	6.5e-02	1.2e-04	5.9e-05	1.1e-04	2.4e-04	Road building
Ce-141	1.1e-02	6.2e-03	1.1e-02	1.8e-02	4.2e-05	2.3e-05	4.1e-05	6.7e-05	Processing concrete
Ce-144	1.9e-02	9.1e-03	1.6e-02	3.6e-02	7.0e-05	3.4e-05	6.1e-05	1.3e-04	Road building
Pm-147	2.1e-05	9.1e-06	2.1e-05	3.4e-05	7.8e-08	3.4e-08	7.7e-08	1.3e-07	Processing concrete
Sm-151	9.5e-06	4.5e-06	9.5e-06	1.5e-05	3.5e-08	1.7e-08	3.5e-08	5.5e-08	Processing concrete
Eu-152	4.4e-01	2.2e-01	3.9e-01	8.6e-01	1.6e-03	8.0e-04	1.4e-03	3.2e-03	Road building
Eu-154	4.9e-01	2.4e-01	4.3e-01	9.4e-01	1.8e-03	8.8e-04	1.6e-03	3.5e-03	Road building
Eu-155	1.1e-02	5.6e-03	1.0e-02	2.2e-02	4.2e-05	2.1e-05	3.7e-05	8.2e-05	Road building
Gd-153	1.4e-02	6.8e-03	1.2e-02	2.7e-02	5.2e-05	2.5e-05	4.5e-05	1.0e-04	Road building
Tb-160	3.1e-01	1.8e-01	3.1e-01	4.7e-01	1.2e-03	6.8e-04	1.1e-03	1.7e-03	Processing concrete
Tm-170	8.1e-04	3.9e-04	7.1e-04	1.6e-03	3.0e-06	1.4e-06	2.6e-06	5.8e-06	Road building
Tm-171	7.2e-05	3.6e-05	6.3e-05	1.4e-04	2.7e-07	1.3e-07	2.3e-07	5.1e-07	Road building
Ta-182	4.0e-01	1.9e-01	3.5e-01	7.9e-01	1.5e-03	7.0e-04	1.3e-03	2.9e-03	Road building
W-181	3.9e-03	1.9e-03	3.4e-03	7.7e-03	1.5e-05	6.9e-06	1.3e-05	2.8e-05	Road building
W-185	3.4e-05	1.7e-05	3.4e-05	5.5e-05	1.3e-07	6.2e-08	1.2e-07	2.0e-07	Processing concrete
Os-185	2.0e-01	9.2e-02	1.8e-01	4.0e-01	7.4e-04	3.4e-04	6.5e-04	1.5e-03	Road building
Ir-192	2.1e-01	9.2e-02	1.8e-01	4.1e-01	7.7e-04	3.4e-04	6.7e-04	1.5e-03	Road building
Tl-204	2.8e-04	1.4e-04	2.4e-04	5.3e-04	1.0e-06	5.1e-07	9.0e-07	2.0e-06	Road building
Pb-210	9.1e-02	1.2e-02	8.9e-02	1.8e-01	3.4e-04	4.4e-05	3.3e-04	6.6e-04	Processing concrete
Bi-207	6.0e-01	2.9e-01	5.2e-01	1.2e+00	2.2e-03	1.1e-03	1.9e-03	4.3e-03	Road building
Po-210	2.2e-02	3.2e-03	2.2e-02	4.3e-02	8.3e-05	1.2e-05	8.1e-05	1.6e-04	Processing concrete
Ra-226	7.2e-01	3.5e-01	6.3e-01	1.4e+00	2.7e-03	1.3e-03	2.3e-03	5.1e-03	Road building
Ra-228	4.1e-01	2.0e-01	3.6e-01	7.9e-01	1.5e-03	7.5e-04	1.3e-03	2.9e-03	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.6 Normalized surficial effective dose equivalents to critical groups for concrete

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	5.0e-01	2.9e-01	4.9e-01	7.3e-01	1.8e-03	1.1e-03	1.8e-03	2.7e-03	Processing concrete
Th-228	6.5e-01	3.2e-01	5.7e-01	1.2e+00	2.4e-03	1.2e-03	2.1e-03	4.6e-03	Road building
Th-229	4.8e-01	3.0e-01	4.6e-01	7.0e-01	1.8e-03	1.1e-03	1.7e-03	2.6e-03	Processing concrete
Th-230	6.3e-02	3.4e-02	6.0e-02	1.0e-01	2.3e-04	1.3e-04	2.2e-04	3.8e-04	Truck driver
Th-232	3.2e-01	1.7e-01	3.0e-01	5.2e-01	1.2e-03	6.4e-04	1.1e-03	1.9e-03	Truck driver
Pa-231	3.4e-01	1.8e-01	3.4e-01	5.2e-01	1.3e-03	6.8e-04	1.3e-03	1.9e-03	Processing concrete
U-232	1.3e-01	7.3e-02	1.3e-01	2.1e-01	4.9e-04	2.7e-04	4.6e-04	7.9e-04	Truck driver
U-233	1.1e-01	0.0e+00	0.0e+00	0.0e+00	4.1e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-234	8.1e-02	0.0e+00	0.0e+00	0.0e+00	3.0e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-235	1.2e-01	0.0e+00	0.0e+00	0.0e+00	4.3e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-236	7.5e-02	0.0e+00	0.0e+00	0.0e+00	2.8e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-238	7.5e-02	0.0e+00	0.0e+00	0.0e+00	2.8e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
Np-237	3.8e+00	0.0e+00	0.0e+00	8.5e+00	1.4e-02	0.0e+00	0.0e+00	3.2e-02	Leachate-industrial
Pu-236	3.7e-02	1.9e-02	3.7e-02	5.6e-02	1.4e-04	7.2e-05	1.4e-04	2.1e-04	Processing concrete
Pu-238	1.0e-01	5.3e-02	1.0e-01	1.6e-01	3.8e-04	2.0e-04	3.7e-04	5.7e-04	Processing concrete
Pu-239	1.1e-01	5.8e-02	1.1e-01	1.7e-01	4.1e-04	2.2e-04	4.1e-04	6.3e-04	Processing concrete
Pu-240	1.1e-01	5.8e-02	1.1e-01	1.7e-01	4.1e-04	2.2e-04	4.1e-04	6.3e-04	Processing concrete
Pu-241	2.2e-03	1.1e-03	2.1e-03	3.3e-03	8.0e-06	4.2e-06	7.9e-06	1.2e-05	Processing concrete
Pu-242	1.1e-01	5.6e-02	1.1e-01	1.6e-01	3.9e-04	2.1e-04	3.9e-04	6.0e-04	Processing concrete
Pu-244	2.1e-01	1.4e-01	2.1e-01	2.8e-01	7.7e-04	5.2e-04	7.6e-04	1.0e-03	Processing concrete
Am-241	1.2e-01	6.2e-02	1.2e-01	1.8e-01	4.3e-04	2.3e-04	4.3e-04	6.6e-04	Processing concrete
Am-242m	1.2e-01	6.3e-02	1.2e-01	1.8e-01	4.4e-04	2.3e-04	4.3e-04	6.6e-04	Processing concrete
Am-243	1.6e-01	1.0e-01	1.6e-01	2.3e-01	5.9e-04	3.8e-04	5.9e-04	8.4e-04	Processing concrete
Cm-242	3.9e-03	2.1e-03	3.9e-03	6.0e-03	1.5e-05	7.9e-06	1.4e-05	2.2e-05	Processing concrete
Cm-243	1.1e-01	6.8e-02	1.1e-01	1.5e-01	4.0e-04	2.5e-04	4.0e-04	5.7e-04	Processing concrete
Cm-244	6.4e-02	3.4e-02	6.3e-02	9.8e-02	2.4e-04	1.2e-04	2.3e-04	3.6e-04	Processing concrete
Cm-245	1.4e-01	7.9e-02	1.4e-01	2.0e-01	5.1e-04	2.9e-04	5.0e-04	7.4e-04	Processing concrete
Cm-246	1.2e-01	6.1e-02	1.2e-01	1.8e-01	4.3e-04	2.3e-04	4.3e-04	6.6e-04	Processing concrete
Cm-247	2.0e-01	1.4e-01	2.0e-01	2.8e-01	7.6e-04	5.1e-04	7.5e-04	1.0e-03	Processing concrete
Cm-248	4.3e-01	2.3e-01	4.3e-01	6.6e-01	1.6e-03	8.3e-04	1.6e-03	2.4e-03	Processing concrete
Bk-249	3.7e-04	2.0e-04	3.7e-04	5.7e-04	1.4e-06	7.3e-07	1.4e-06	2.1e-06	Processing concrete
Cf-248	1.2e-02	6.5e-03	1.2e-02	1.8e-02	4.4e-05	2.4e-05	4.3e-05	6.7e-05	Processing concrete
Cf-249	2.1e-01	1.4e-01	2.1e-01	3.0e-01	7.9e-04	5.1e-04	7.8e-04	1.1e-03	Processing concrete
Cf-250	5.9e-02	2.9e-02	5.8e-02	9.1e-02	2.2e-04	1.1e-04	2.2e-04	3.3e-04	Processing concrete
Cf-251	1.5e-01	8.1e-02	1.4e-01	2.2e-01	5.4e-04	3.0e-04	5.3e-04	8.0e-04	Processing concrete
Cf-252	3.8e-02	2.0e-02	3.7e-02	5.7e-02	1.4e-04	7.6e-05	1.4e-04	2.1e-04	Processing concrete
Cf-254	4.9e+00	2.9e+00	4.8e+00	7.3e+00	1.8e-02	1.1e-02	1.8e-02	2.7e-02	Processing concrete
Es-254	3.3e-01	1.6e-01	2.9e-01	6.3e-01	1.2e-03	5.9e-04	1.1e-03	2.3e-03	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.7 Normalized mass-based effective doses to critical groups for concrete

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
H-3	6.9e-02	0.0e+00	4.6e-05	3.0e-01	2.5e-04	0.0e+00	1.7e-07	1.1e-03	Leachate-industrial
C-14	1.2e-01	0.0e+00	0.0e+00	2.9e-01	4.4e-04	0.0e+00	0.0e+00	1.1e-03	Leachate-industrial
Na-22	2.2e+02	1.1e+02	2.0e+02	4.3e+02	8.3e-01	4.1e-01	7.3e-01	1.6e+00	Road building
P-32	1.1e-01	4.4e-02	9.6e-02	2.0e-01	4.0e-04	1.6e-04	3.5e-04	7.5e-04	Processing concrete
S-35	1.9e-03	4.8e-04	1.8e-03	3.4e-03	6.9e-06	1.8e-06	6.8e-06	1.3e-05	Processing concrete
Cl-36	1.5e+00	0.0e+00	0.0e+00	7.0e+00	5.5e-03	0.0e+00	0.0e+00	2.6e-02	Leachate-industrial
K-40	1.8e+01	8.7e+00	1.6e+01	3.4e+01	6.6e-02	3.2e-02	5.8e-02	1.3e-01	Road building
Ca-41	6.1e-01	0.0e+00	0.0e+00	3.1e+00	2.2e-03	0.0e+00	0.0e+00	1.2e-02	Leachate-industrial
Ca-45	1.0e-02	2.0e-03	9.8e-03	1.9e-02	3.7e-05	7.4e-06	3.6e-05	7.0e-05	Processing concrete
Sc-46	1.7e+02	9.9e+01	1.6e+02	2.4e+02	6.1e-01	3.7e-01	6.0e-01	9.0e-01	Processing concrete
Cr-51	1.8e+00	9.4e-01	1.7e+00	2.9e+00	6.5e-03	3.5e-03	6.2e-03	1.1e-02	Processing concrete
Mn-53	1.6e-03	0.0e+00	0.0e+00	0.0e+00	5.8e-06	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial
Mn-54	8.0e+01	3.9e+01	7.0e+01	1.5e+02	3.0e-01	1.4e-01	2.6e-01	5.7e-01	Road building
Fe-55	4.2e-03	5.2e-04	4.1e-03	8.2e-03	1.6e-05	1.9e-06	1.5e-05	3.0e-05	Processing concrete
Fe-59	8.9e+01	5.1e+01	8.7e+01	1.4e+02	3.3e-01	1.9e-01	3.2e-01	5.0e-01	Processing concrete
Co-56	3.0e+02	1.8e+02	2.9e+02	4.4e+02	1.1e+00	6.6e-01	1.1e+00	1.6e+00	Processing concrete
Co-57	7.4e+00	3.6e+00	6.5e+00	1.4e+01	2.7e-02	1.3e-02	2.4e-02	5.3e-02	Road building
Co-58	7.6e+01	4.5e+01	7.5e+01	1.1e+02	2.8e-01	1.7e-01	2.8e-01	4.2e-01	Processing concrete
Co-60	2.7e+02	1.3e+02	2.4e+02	5.2e+02	1.0e+00	4.9e-01	8.8e-01	1.9e+00	Road building
Ni-59	2.2e-03	1.2e-03	2.2e-03	3.3e-03	8.2e-06	4.6e-06	8.1e-06	1.2e-05	Processing concrete
Ni-63	2.0e-03	2.6e-04	1.9e-03	3.8e-03	7.2e-06	9.6e-07	7.1e-06	1.4e-05	Processing concrete
Zn-65	5.6e+01	2.7e+01	4.9e+01	1.1e+02	2.1e-01	1.0e-01	1.8e-01	4.0e-01	Road building
As-73	1.0e-01	4.6e-02	9.0e-02	2.1e-01	3.8e-04	1.7e-04	3.3e-04	7.6e-04	Road building
Se-75	2.6e+01	1.2e+01	2.3e+01	5.1e+01	9.7e-02	4.6e-02	8.5e-02	1.9e-01	Road building
Sr-85	3.6e+01	2.1e+01	3.6e+01	5.4e+01	1.3e-01	7.9e-02	1.3e-01	2.0e-01	Processing concrete
Sr-89	1.8e-01	7.0e-02	1.5e-01	3.7e-01	6.5e-04	2.6e-04	5.6e-04	1.4e-03	Road building
Sr-90	1.1e+00	0.0e+00	0.0e+00	2.0e-06	4.0e-03	0.0e+00	0.0e+00	7.3e-09	Leachate-industrial
Y-91	4.5e-01	1.9e-01	3.9e-01	9.3e-01	1.7e-03	7.0e-04	1.4e-03	3.4e-03	Road building
Zr-93	4.6e-03	1.4e-03	4.6e-03	8.1e-03	1.7e-05	5.2e-06	1.7e-05	3.0e-05	Processing concrete
Zr-95	8.1e+01	3.9e+01	7.1e+01	1.5e+02	3.0e-01	1.5e-01	2.6e-01	5.7e-01	Road building
Nb-93m	2.8e-03	1.3e-03	2.7e-03	4.4e-03	1.0e-05	4.8e-06	1.0e-05	1.6e-05	Processing concrete
Nb-94	1.6e+02	8.0e+01	1.4e+02	3.1e+02	6.0e-01	3.0e-01	5.3e-01	1.2e+00	Road building
Nb-95	5.1e+01	2.9e+01	5.0e+01	8.0e+01	1.9e-01	1.1e-01	1.8e-01	3.0e-01	Processing concrete
Mo-93	9.0e-01	0.0e+00	0.0e+00	1.2e+00	3.3e-03	0.0e+00	0.0e+00	4.6e-03	Leachate-industrial
Tc-97	1.3e+00	0.0e+00	0.0e+00	6.0e+00	4.7e-03	0.0e+00	0.0e+00	2.2e-02	Leachate-industrial
Tc-97m	2.8e-02	1.6e-02	2.7e-02	4.0e-02	1.0e-04	6.1e-05	1.0e-04	1.5e-04	Processing concrete
Tc-99	1.2e+01	0.0e+00	0.0e+00	5.6e+01	4.4e-02	0.0e+00	0.0e+00	2.1e-01	Leachate-industrial
Ru-103	3.3e+01	1.8e+01	3.2e+01	5.0e+01	1.2e-01	6.8e-02	1.2e-01	1.9e-01	Processing concrete
Ru-106	2.1e+01	1.0e+01	1.8e+01	4.0e+01	7.7e-02	3.8e-02	6.7e-02	1.5e-01	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.7 Normalized mass-based effective doses to critical groups for concrete

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	1.6e+02	7.9e+01	1.4e+02	3.1e+02	6.0e-01	2.9e-01	5.2e-01	1.1e+00	Road building
Ag-110m	2.6e+02	1.3e+02	2.3e+02	5.0e+02	9.6e-01	4.7e-01	8.4e-01	1.9e+00	Road building
Cd-109	3.9e-01	1.9e-01	3.5e-01	7.5e-01	1.5e-03	7.2e-04	1.3e-03	2.8e-03	Road building
Sn-113	2.0e+01	1.2e+01	1.9e+01	2.9e+01	7.2e-02	4.4e-02	7.1e-02	1.1e-01	Processing concrete
Sb-124	1.5e+02	8.6e+01	1.4e+02	2.2e+02	5.4e-01	3.2e-01	5.3e-01	8.1e-01	Processing concrete
Sb-125	4.0e+01	1.9e+01	3.5e+01	7.6e+01	1.5e-01	7.2e-02	1.3e-01	2.8e-01	Road building
Te-123m	8.2e+00	3.9e+00	7.2e+00	1.6e+01	3.0e-02	1.4e-02	2.7e-02	5.9e-02	Road building
Te-127m	4.6e-01	2.8e-01	4.5e-01	6.6e-01	1.7e-03	1.0e-03	1.7e-03	2.5e-03	Processing concrete
I-125	3.1e-01	1.4e-01	3.0e-01	4.9e-01	1.1e-03	5.3e-04	1.1e-03	1.8e-03	Processing concrete
I-129	4.3e+02	0.0e+00	0.0e+00	1.9e+03	1.6e+00	0.0e+00	0.0e+00	7.1e+00	Leachate-industrial
I-131	1.0e+01	2.4e+00	7.8e+00	2.6e+01	3.8e-02	8.7e-03	2.9e-02	9.5e-02	Processing concrete
Cs-134	1.5e+02	7.5e+01	1.3e+02	2.9e+02	5.7e-01	2.8e-01	5.0e-01	1.1e+00	Road building
Cs-135	2.7e-02	0.0e+00	0.0e+00	0.0e+00	1.0e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
Cs-137	5.7e+01	2.8e+01	5.0e+01	1.1e+02	2.1e-01	1.0e-01	1.9e-01	4.0e-01	Road building
Ba-133	3.2e+01	1.6e+01	2.8e+01	6.2e+01	1.2e-01	5.8e-02	1.0e-01	2.3e-01	Road building
Ce-139	8.6e+00	4.1e+00	7.5e+00	1.7e+01	3.2e-02	1.5e-02	2.8e-02	6.2e-02	Road building
Ce-141	3.2e+00	1.8e+00	3.1e+00	5.1e+00	1.2e-02	6.5e-03	1.1e-02	1.9e-02	Processing concrete
Ce-144	5.4e+00	2.6e+00	4.7e+00	1.0e+01	2.0e-02	9.7e-03	1.7e-02	3.8e-02	Road building
Pm-147	4.4e-03	1.5e-03	4.3e-03	7.6e-03	1.6e-05	5.5e-06	1.6e-05	2.8e-05	Processing concrete
Sm-151	1.7e-03	5.4e-04	1.7e-03	2.9e-03	6.2e-06	2.0e-06	6.1e-06	1.1e-05	Processing concrete
Eu-152	1.2e+02	5.8e+01	1.0e+02	2.3e+02	4.4e-01	2.1e-01	3.8e-01	8.3e-01	Road building
Eu-154	1.3e+02	6.3e+01	1.1e+02	2.5e+02	4.8e-01	2.3e-01	4.2e-01	9.1e-01	Road building
Eu-155	2.9e+00	1.4e+00	2.5e+00	5.5e+00	1.1e-02	5.2e-03	9.3e-03	2.0e-02	Road building
Gd-153	3.4e+00	1.7e+00	3.0e+00	6.6e+00	1.3e-02	6.1e-03	1.1e-02	2.4e-02	Road building
Tb-160	8.8e+01	5.2e+01	8.7e+01	1.3e+02	3.3e-01	1.9e-01	3.2e-01	4.8e-01	Processing concrete
Tm-170	2.1e-01	1.0e-01	1.9e-01	4.1e-01	7.9e-04	3.8e-04	6.9e-04	1.5e-03	Road building
Tm-171	1.7e-02	8.5e-03	1.5e-02	3.2e-02	6.3e-05	3.1e-05	5.5e-05	1.2e-04	Road building
Ta-182	1.1e+02	5.0e+01	9.3e+01	2.1e+02	4.0e-01	1.9e-01	3.4e-01	7.7e-01	Road building
W-181	9.4e-01	4.4e-01	8.2e-01	1.8e+00	3.5e-03	1.6e-03	3.0e-03	6.8e-03	Road building
W-185	9.8e-03	4.8e-03	9.6e-03	1.6e-02	3.6e-05	1.8e-05	3.6e-05	5.8e-05	Processing concrete
Os-185	5.3e+01	2.4e+01	4.6e+01	1.0e+02	2.0e-01	9.0e-02	1.7e-01	3.9e-01	Road building
Ir-192	5.8e+01	3.5e+01	5.7e+01	8.6e+01	2.2e-01	1.3e-01	2.1e-01	3.2e-01	Processing concrete
Tl-204	7.8e-02	3.9e-02	6.8e-02	1.5e-01	2.9e-04	1.4e-04	2.5e-04	5.5e-04	Road building
Pb-210	1.2e+01	1.7e+00	1.2e+01	2.3e+01	4.5e-02	6.2e-03	4.4e-02	8.7e-02	Processing concrete
Bi-207	1.6e+02	7.7e+01	1.4e+02	3.0e+02	5.8e-01	2.9e-01	5.1e-01	1.1e+00	Road building
Po-210	3.1e+00	5.9e-01	3.0e+00	5.8e+00	1.1e-02	2.2e-03	1.1e-02	2.2e-02	Processing concrete
Ra-226	1.9e+02	9.4e+01	1.7e+02	3.7e+02	7.1e-01	3.5e-01	6.2e-01	1.4e+00	Road building
Ra-228	1.1e+02	5.5e+01	9.8e+01	2.1e+02	4.1e-01	2.0e-01	3.6e-01	7.9e-01	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.7 Normalized mass-based effective doses to critical groups for concrete

Radionuclide	:Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	5.6e+01	3.6e+01	5.6e+01	7.8e+01	2.1e-01	1.3e-01	2.1e-01	2.9e-01	Processing concrete
Th-228	1.7e+02	8.4e+01	1.5e+02	3.2e+02	6.3e-01	3.1e-01	5.5e-01	1.2e+00	Road building
Th-229	4.3e+01	2.9e+01	4.3e+01	5.8e+01	1.6e-01	1.1e-01	1.6e-01	2.1e-01	Processing concrete
Th-230	7.3e+00	3.9e+00	7.2e+00	1.1e+01	2.7e-02	1.5e-02	2.7e-02	4.1e-02	Processing concrete
Th-232	3.3e+01	5.5e+00	3.0e+01	7.5e+01	1.2e-01	2.0e-02	1.1e-01	2.8e-01	Driving on road
Pa-231	2.6e+01	1.5e+01	2.6e+01	3.9e+01	9.8e-02	5.6e-02	9.6e-02	1.4e-01	Processing concrete
U-232	2.9e+01	0.0e+00	0.0e+00	0.0e+00	1.1e-01	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-233	2.0e+01	0.0e+00	0.0e+00	0.0e+00	7.3e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-234	1.5e+01	0.0e+00	0.0e+00	0.0e+00	5.5e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-235	1.7e+01	0.0e+00	0.0e+00	0.0e+00	6.3e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-236	1.4e+01	0.0e+00	0.0e+00	0.0e+00	5.0e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-238	1.4e+01	0.0e+00	0.0e+00	0.0e+00	5.2e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
Np-237	9.9e+01	0.0e+00	0.0e+00	2.2e+02	3.7e-01	0.0e+00	0.0e+00	8.1e-01	Leachate-industrial
Pu-236	3.2e+00	1.8e+00	3.2e+00	4.9e+00	1.2e-02	6.5e-03	1.2e-02	1.8e-02	Processing concrete
Pu-238	7.9e+00	4.2e+00	7.8e+00	1.2e+01	2.9e-02	1.6e-02	2.9e-02	4.4e-02	Processing concrete
Pu-239	8.5e+00	4.5e+00	8.4e+00	1.3e+01	3.1e-02	1.7e-02	3.1e-02	4.8e-02	Processing concrete
Pu-240	8.5e+00	4.5e+00	8.4e+00	1.3e+01	3.1e-02	1.7e-02	3.1e-02	4.7e-02	Processing concrete
Pu-241	1.6e-01	8.2e-02	1.5e-01	2.4e-01	5.8e-04	3.0e-04	5.7e-04	8.7e-04	Processing concrete
Pu-242	8.2e+00	4.4e+00	8.1e+00	1.2e+01	3.0e-02	1.6e-02	3.0e-02	4.6e-02	Processing concrete
Pu-244	3.9e+01	1.9e+01	3.4e+01	7.3e+01	1.4e-01	7.2e-02	1.2e-01	2.7e-01	Road building
Am-241	7.5e+00	4.3e+00	7.5e+00	1.1e+01	2.8e-02	1.6e-02	2.8e-02	4.1e-02	Processing concrete
Am-242m	8.0e+00	4.7e+00	7.9e+00	1.2e+01	3.0e-02	1.7e-02	2.9e-02	4.3e-02	Processing concrete
Am-243	2.0e+01	1.4e+01	2.0e+01	2.7e+01	7.4e-02	5.0e-02	7.3e-02	9.9e-02	Processing concrete
Cm-242	7.2e-01	4.2e-01	7.0e-01	1.1e+00	2.7e-03	1.6e-03	2.6e-03	4.1e-03	Processing concrete
Cm-243	1.3e+01	9.2e+00	1.3e+01	1.8e+01	4.9e-02	3.4e-02	4.9e-02	6.7e-02	Processing concrete
Cm-244	4.3e+00	2.3e+00	4.3e+00	6.5e+00	1.6e-02	8.7e-03	1.6e-02	2.4e-02	Processing concrete
Cm-245	1.2e+01	8.3e+00	1.2e+01	1.7e+01	4.6e-02	3.1e-02	4.5e-02	6.2e-02	Processing concrete
Cm-246	7.1e+00	3.8e+00	7.0e+00	1.1e+01	2.6e-02	1.4e-02	2.6e-02	4.0e-02	Processing concrete
Cm-247	3.4e+01	1.7e+01	3.0e+01	6.5e+01	1.3e-01	6.4e-02	1.1e-01	2.4e-01	Road building
Cm-248	2.6e+01	1.3e+01	2.5e+01	3.9e+01	9.4e-02	5.0e-02	9.3e-02	1.4e-01	Processing concrete
Bk-249	3.1e-02	1.7e-02	3.1e-02	4.7e-02	1.2e-04	6.2e-05	1.1e-04	1.7e-04	Processing concrete
Cf-248	1.3e+00	7.6e-01	1.3e+00	2.0e+00	4.9e-03	2.8e-03	4.8e-03	7.4e-03	Processing concrete
Cf-249	3.9e+01	2.6e+01	3.8e+01	5.2e+01	1.4e-01	9.7e-02	1.4e-01	1.9e-01	Processing concrete
Cf-250	5.7e+00	3.0e+00	5.6e+00	8.6e+00	2.1e-02	1.1e-02	2.1e-02	3.2e-02	Processing concrete
Cf-251	1.9e+01	1.3e+01	1.9e+01	2.6e+01	7.1e-02	4.7e-02	7.0e-02	9.7e-02	Processing concrete
Cf-252	3.3e+00	1.8e+00	3.2e+00	4.9e+00	1.2e-02	6.6e-03	1.2e-02	1.8e-02	Processing concrete
Cf-254	1.4e+03	8.1e+02	1.3e+03	2.0e+03	5.1e+00	3.0e+00	5.0e+00	7.5e+00	Processing concrete
Es-254	8.6e+01	4.2e+01	7.5e+01	1.7e+02	3.2e-01	1.6e-01	2.8e-01	6.1e-01	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.8 Normalized surficial effective doses to critical groups for concrete

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5^{th}	50^{th}	95^{th}		5^{th}	50^{th}	95^{th}	
H-3	2.5e-04	0.0e+00	1.6e-07	1.1e-03	9.1e-07	0.0e+00	6.0e-10	4.0e-06	Leachate-industrial
C-14	4.2e-04	0.0e+00	0.0e+00	1.0e-03	1.6e-06	0.0e+00	0.0e+00	3.7e-06	Leachate-industrial
Na-22	8.0e-01	3.9e-01	7.0e-01	1.5e+00	3.0e-03	1.4e-03	2.6e-03	5.7e-03	Road building
P-32	3.8e-04	1.6e-04	3.4e-04	7.3e-04	1.4e-06	5.8e-07	1.3e-06	2.7e-06	Processing concrete
S-35	6.7e-06	1.7e-06	6.6e-06	1.2e-05	2.5e-08	6.3e-09	2.4e-08	4.5e-08	Processing concrete
Cl-36	5.3e-03	0.0e+00	0.0e+00	2.5e-02	2.0e-05	0.0e+00	0.0e+00	9.3e-05	Leachate-industrial
K-40	6.4e-02	3.1e-02	5.6e-02	1.2e-01	2.4e-04	1.2e-04	2.1e-04	4.5e-04	Road building
Ca-41	2.2e-03	0.0e+00	0.0e+00	1.1e-02	8.0e-06	0.0e+00	0.0e+00	4.1e-05	Leachate-industrial
Ca-45	3.6e-05	7.0e-06	3.5e-05	6.7e-05	1.3e-07	2.6e-08	1.3e-07	2.5e-07	Processing concrete
Sc-46	5.9e-01	3.5e-01	5.8e-01	8.8e-01	2.2e-03	1.3e-03	2.2e-03	3.3e-03	Processing concrete
Cr-51	6.3e-03	3.3e-03	6.0e-03	1.0e-02	2.3e-05	1.2e-05	2.2e-05	3.8e-05	Processing concrete
Mn-53	5.6e-06	0.0e+00	0.0e+00	0.0e+00	2.1e-08	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial
Mn-54	2.8e-01	1.4e-01	2.5e-01	5.5e-01	1.1e-03	5.1e-04	9.2e-04	2.0e-03	Road building
Fe-55	1.5e-05	1.8e-06	1.5e-05	2.9e-05	5.6e-08	6.8e-09	5.5e-08	1.1e-07	Processing concrete
Fe-59	3.2e-01	1.8e-01	3.1e-01	4.9e-01	1.2e-03	6.7e-04	1.1e-03	1.8e-03	Processing concrete
Co-56	1.1e+00	6.3e-01	1.0e+00	1.6e+00	4.0e-03	2.3e-03	3.9e-03	5.9e-03	Processing concrete
Co-57	2.6e-02	1.3e-02	2.3e-02	5.1e-02	9.7e-05	4.7e-05	8.5e-05	1.9e-04	Road building
Co-58	2.7e-01	1.6e-01	2.7e-01	4.0e-01	1.0e-03	5.9e-04	9.8e-04	1.5e-03	Processing concrete
Co-60	9.7e-01	4.7e-01	8.5e-01	1.9e+00	3.6e-03	1.8e-03	3.1e-03	6.9e-03	Road building
Ni-59	7.9e-06	4.4e-06	7.8e-06	1.2e-05	2.9e-08	1.6e-08	2.9e-08	4.4e-08	Processing concrete
Ni-63	7.0e-06	9.2e-07	6.8e-06	1.4e-05	2.6e-08	3.4e-09	2.5e-08	5.0e-08	Processing concrete
Zn-65	2.0e-01	9.7e-02	1.8e-01	3.9e-01	7.4e-04	3.6e-04	6.5e-04	1.4e-03	Road building
As-73	3.7e-04	1.7e-04	3.2e-04	7.3e-04	1.4e-06	6.1e-07	1.2e-06	2.7e-06	Road building
Se-75	9.4e-02	4.4e-02	8.2e-02	1.8e-01	3.5e-04	1.6e-04	3.0e-04	6.8e-04	Road building
Sr-85	1.3e-01	7.6e-02	1.3e-01	1.9e-01	4.8e-04	2.8e-04	4.7e-04	7.2e-04	Processing concrete
Sr-89	6.3e-04	2.5e-04	5.4e-04	1.3e-03	2.3e-06	9.3e-07	2.0e-06	4.9e-06	Road building
Sr-90	3.8e-03	0.0e+00	0.0e+00	7.0e-09	1.4e-05	0.0e+00	0.0e+00	2.6e-11	Leachate-industrial
Y-91	1.6e-03	6.7e-04	1.4e-03	3.3e-03	6.0e-06	2.5e-06	5.1e-06	1.2e-05	Road building
Zr-93	1.6e-05	5.0e-06	1.6e-05	2.9e-05	6.1e-08	1.8e-08	6.0e-08	1.1e-07	Processing concrete
Zr-95	2.9e-01	1.4e-01	2.5e-01	5.6e-01	1.1e-03	5.2e-04	9.3e-04	2.1e-03	Road building
Nb-93m	9.9e-06	4.6e-06	9.8e-06	1.6e-05	3.7e-08	1.7e-08	3.6e-08	5.8e-08	Processing concrete
Nb-94	5.8e-01	2.8e-01	5.1e-01	1.1e+00	2.2e-03	1.1e-03	1.9e-03	4.1e-03	Road building
Nb-95	1.8e-01	1.0e-01	1.8e-01	2.9e-01	6.8e-04	3.8e-04	6.6e-04	1.1e-03	Processing concrete
Mo-93	3.2e-03	0.0e+00	0.0e+00	4.4e-03	1.2e-05	0.0e+00	0.0e+00	1.6e-05	Leachate-industrial
Tc-97	4.6e-03	0.0e+00	0.0e+00	2.1e-02	1.7e-05	0.0e+00	0.0e+00	7.9e-05	Leachate-industrial
Tc-97m	9.9e-05	5.8e-05	9.7e-05	1.5e-04	3.7e-07	2.1e-07	3.6e-07	5.4e-07	Processing concrete
Tc-99	4.3e-02	0.0e+00	0.0e+00	2.0e-01	1.6e-04	0.0e+00	0.0e+00	7.4e-04	Leachate-industrial
Ru-103	1.2e-01	6.6e-02	1.1e-01	1.8e-01	4.3e-04	2.4e-04	4.2e-04	6.7e-04	Processing concrete
Ru-106	7.4e-02	3.6e-02	6.5e-02	1.4e-01	2.7e-04	1.3e-04	2.4e-04	5.3e-04	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.8 Normalized surficial effective doses to critical groups for concrete

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ag-108m	5.8e-01	2.8e-01	5.0e-01	1.1e+00	2.1e-03	1.0e-03	1.9e-03	4.1e-03	Road building
Ag-110m	9.3e-01	4.5e-01	8.1e-01	1.8e+00	3.4e-03	1.7e-03	3.0e-03	6.6e-03	Road building
Cd-109	1.4e-03	6.9e-04	1.2e-03	2.7e-03	5.2e-06	2.6e-06	4.6e-06	1.0e-05	Road building
Sn-113	7.0e-02	4.2e-02	6.9e-02	1.0e-01	2.6e-04	1.5e-04	2.5e-04	3.8e-04	Processing concrete
Sb-124	5.2e-01	3.1e-01	5.1e-01	7.9e-01	1.9e-03	1.1e-03	1.9e-03	2.9e-03	Processing concrete
Sb-125	1.4e-01	6.9e-02	1.2e-01	2.7e-01	5.2e-04	2.6e-04	4.6e-04	1.0e-03	Road building
Te-123m	2.9e-02	1.4e-02	2.6e-02	5.7e-02	1.1e-04	5.1e-05	9.5e-05	2.1e-04	Road building
Te-127m	1.6e-03	1.0e-03	1.6e-03	2.4e-03	6.0e-06	3.7e-06	6.0e-06	8.8e-06	Processing concrete
I-125	1.1e-03	5.1e-04	1.1e-03	1.8e-03	4.0e-06	1.9e-06	3.9e-06	6.6e-06	Processing concrete
I-129	1.5e+00	0.0e+00	0.0e+00	6.8e+00	5.7e-03	0.0e+00	0.0e+00	2.5e-02	Leachate-industrial
I-131	3.6e-02	8.3e-03	2.8e-02	9.2e-02	1.3e-04	3.1e-05	1.0e-04	3.4e-04	Processing concrete
Cs-134	5.5e-01	2.7e-01	4.8e-01	1.1e+00	2.0e-03	9.9e-04	1.8e-03	3.9e-03	Road building
Cs-135	9.8e-05	0.0e+00	0.0e+00	0.0e+00	3.6e-07	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
Cs-137	2.0e-01	1.0e-01	1.8e-01	3.9e-01	7.5e-04	3.7e-04	6.6e-04	1.4e-03	Road building
Ba-133	1.2e-01	5.6e-02	1.0e-01	2.2e-01	4.3e-04	2.1e-04	3.7e-04	8.2e-04	Road building
Ce-139	3.1e-02	1.5e-02	2.7e-02	5.9e-02	1.1e-04	5.4e-05	9.9e-05	2.2e-04	Road building
Ce-141	1.1e-02	6.3e-03	1.1e-02	1.8e-02	4.2e-05	2.3e-05	4.1e-05	6.8e-05	Processing concrete
Ce-144	1.9e-02	9.3e-03	1.7e-02	3.7e-02	7.1e-05	3.4e-05	6.2e-05	1.4e-04	Road building
Pm-147	1.6e-05	5.3e-06	1.6e-05	2.7e-05	5.8e-08	2.0e-08	5.7e-08	1.0e-07	Processing concrete
Sm-151	6.0e-06	1.9e-06	5.9e-06	1.0e-05	2.2e-08	7.1e-09	2.2e-08	3.8e-08	Processing concrete
Eu-152	4.2e-01	2.1e-01	3.7e-01	8.1e-01	1.6e-03	7.6e-04	1.4e-03	3.0e-03	Road building
Eu-154	4.6e-01	2.2e-01	4.0e-01	8.9e-01	1.7e-03	8.3e-04	1.5e-03	3.3e-03	Road building
Eu-155	1.0e-02	5.0e-03	8.9e-03	2.0e-02	3.8e-05	1.8e-05	3.3e-05	7.3e-05	Road building
Gd-153	1.2e-02	5.9e-03	1.1e-02	2.4e-02	4.5e-05	2.2e-05	3.9e-05	8.7e-05	Road building
Tb-160	3.2e-01	1.9e-01	3.1e-01	4.7e-01	1.2e-03	6.9e-04	1.1e-03	1.7e-03	Processing concrete
Tm-170	7.6e-04	3.6e-04	6.7e-04	1.5e-03	2.8e-06	1.3e-06	2.5e-06	5.5e-06	Road building
Tm-171	6.1e-05	3.0e-05	5.3e-05	1.2e-04	2.3e-07	1.1e-07	2.0e-07	4.3e-07	Road building
Ta-182	3.8e-01	1.8e-01	3.3e-01	7.5e-01	1.4e-03	6.6e-04	1.2e-03	2.8e-03	Road building
W-181	3.3e-03	1.6e-03	2.9e-03	6.5e-03	1.2e-05	5.8e-06	1.1e-05	2.4e-05	Road building
W-185	3.5e-05	1.7e-05	3.4e-05	5.6e-05	1.3e-07	6.3e-08	1.3e-07	2.1e-07	Processing concrete
Os-185	1.9e-01	8.6e-02	1.6e-01	3.7e-01	7.0e-04	3.2e-04	6.1e-04	1.4e-03	Road building
Ir-192	2.1e-01	1.2e-01	2.0e-01	3.1e-01	7.7e-04	4.6e-04	7.5e-04	1.1e-03	Processing concrete
Tl-204	2.8e-04	1.4e-04	2.4e-04	5.3e-04	1.0e-06	5.1e-07	9.0e-07	2.0e-06	Road building
Pb-210	4.3e-02	6.0e-03	4.2e-02	8.4e-02	1.6e-04	2.2e-05	1.6e-04	3.1e-04	Processing concrete
Bi-207	5.6e-01	2.7e-01	4.9e-01	1.1e+00	2.1e-03	1.0e-03	1.8e-03	4.0e-03	Road building
Po-210	1.1e-02	2.1e-03	1.1e-02	2.1e-02	4.1e-05	7.8e-06	4.0e-05	7.7e-05	Processing concrete
Ra-226	6.8e-01	3.3e-01	6.0e-01	1.3e+00	2.5e-03	1.2e-03	2.2e-03	4.9e-03	Road building
Ra-228	4.0e-01	2.0e-01	3.5e-01	7.6e-01	1.5e-03	7.3e-04	1.3e-03	2.8e-03	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

Table 6.8 Normalized surficial effective doses to critical groups for concrete

Radionuclide	:Sv/y per Bq/cm^2				mrem/y per pCi/cm^2				Scenario
	Mean	Percentile[a]			Mean	Percentile[a]			
		5th	50th	95th		5th	50th	95th	
Ac-227	2.0e-01	1.3e-01	2.0e-01	2.8e-01	7.4e-04	4.6e-04	7.3e-04	1.0e-03	Processing concrete
Th-228	6.0e-01	3.0e-01	5.3e-01	1.2e+00	2.2e-03	1.1e-03	2.0e-03	4.3e-03	Road building
Th-229	1.5e-01	1.0e-01	1.5e-01	2.1e-01	5.7e-04	3.8e-04	5.6e-04	7.7e-04	Processing concrete
Th-230	2.6e-02	1.4e-02	2.6e-02	4.0e-02	9.7e-05	5.1e-05	9.5e-05	1.5e-04	Processing concrete
Th-232	1.2e-01	2.0e-02	1.1e-01	2.7e-01	4.4e-04	7.4e-05	3.9e-04	1.0e-03	Driving on road
Pa-231	9.4e-02	5.3e-02	9.3e-02	1.4e-01	3.5e-04	2.0e-04	3.4e-04	5.1e-04	Processing concrete
U-232	1.0e-01	0.0e+00	0.0e+00	0.0e+00	3.8e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-233	6.9e-02	0.0e+00	0.0e+00	0.0e+00	2.6e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-234	5.2e-02	0.0e+00	0.0e+00	0.0e+00	1.9e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-235	6.0e-02	0.0e+00	0.0e+00	0.0e+00	2.2e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-236	4.8e-02	0.0e+00	0.0e+00	0.0e+00	1.8e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
U-238	4.9e-02	0.0e+00	0.0e+00	0.0e+00	1.8e-04	0.0e+00	0.0e+00	0.0e+00	Leachate-MSW
Np-237	3.5e-01	0.0e+00	0.0e+00	7.9e-01	1.3e-03	0.0e+00	0.0e+00	2.9e-03	Leachate-industrial
Pu-236	1.2e-02	6.2e-03	1.1e-02	1.7e-02	4.3e-05	2.3e-05	4.2e-05	6.4e-05	Processing concrete
Pu-238	2.8e-02	1.5e-02	2.8e-02	4.3e-02	1.0e-04	5.5e-05	1.0e-04	1.6e-04	Processing concrete
Pu-239	3.0e-02	1.6e-02	3.0e-02	4.6e-02	1.1e-04	5.9e-05	1.1e-04	1.7e-04	Processing concrete
Pu-240	3.0e-02	1.6e-02	3.0e-02	4.6e-02	1.1e-04	5.9e-05	1.1e-04	1.7e-04	Processing concrete
Pu-241	5.6e-04	2.9e-04	5.5e-04	8.5e-04	2.1e-06	1.1e-06	2.0e-06	3.1e-06	Processing concrete
Pu-242	2.9e-02	1.5e-02	2.9e-02	4.4e-02	1.1e-04	5.7e-05	1.1e-04	1.6e-04	Processing concrete
Pu-244	1.4e-01	6.9e-02	1.2e-01	2.6e-01	5.1e-04	2.6e-04	4.4e-04	9.6e-04	Road building
Am-241	2.7e-02	1.5e-02	2.7e-02	4.0e-02	1.0e-04	5.6e-05	9.8e-05	1.5e-04	Processing concrete
Am-242m	2.8e-02	1.7e-02	2.8e-02	4.2e-02	1.1e-04	6.2e-05	1.0e-04	1.5e-04	Processing concrete
Am-243	7.1e-02	4.8e-02	7.0e-02	9.7e-02	2.6e-04	1.8e-04	2.6e-04	3.6e-04	Processing concrete
Cm-242	2.6e-03	1.5e-03	2.5e-03	4.0e-03	9.6e-06	5.5e-06	9.3e-06	1.5e-05	Processing concrete
Cm-243	4.8e-02	3.2e-02	4.7e-02	6.5e-02	1.8e-04	1.2e-04	1.7e-04	2.4e-04	Processing concrete
Cm-244	1.5e-02	8.3e-03	1.5e-02	2.3e-02	5.7e-05	3.1e-05	5.6e-05	8.7e-05	Processing concrete
Cm-245	4.4e-02	2.9e-02	4.3e-02	6.0e-02	1.6e-04	1.1e-04	1.6e-04	2.2e-04	Processing concrete
Cm-246	2.5e-02	1.3e-02	2.5e-02	3.9e-02	9.4e-05	5.0e-05	9.3e-05	1.4e-04	Processing concrete
Cm-247	1.2e-01	6.2e-02	1.1e-01	2.3e-01	4.6e-04	2.3e-04	4.0e-04	8.6e-04	Road building
Cm-248	9.1e-02	4.8e-02	9.0e-02	1.4e-01	3.4e-04	1.8e-04	3.3e-04	5.1e-04	Processing concrete
Bk-249	1.1e-04	5.9e-05	1.1e-04	1.7e-04	4.1e-07	2.2e-07	4.1e-07	6.2e-07	Processing concrete
Cf-248	4.8e-03	2.7e-03	4.7e-03	7.2e-03	1.8e-05	1.0e-05	1.7e-05	2.7e-05	Processing concrete
Cf-249	1.4e-01	9.2e-02	1.4e-01	1.9e-01	5.1e-04	3.4e-04	5.0e-04	7.0e-04	Processing concrete
Cf-250	2.0e-02	1.1e-02	2.0e-02	3.1e-02	7.5e-05	4.0e-05	7.4e-05	1.1e-04	Processing concrete
Cf-251	6.8e-02	4.5e-02	6.8e-02	9.5e-02	2.5e-04	1.7e-04	2.5e-04	3.5e-04	Processing concrete
Cf-252	1.2e-02	6.3e-03	1.1e-02	1.8e-02	4.3e-05	2.3e-05	4.3e-05	6.5e-05	Processing concrete
Cf-254	4.9e+00	2.9e+00	4.8e+00	7.3e+00	1.8e-02	1.1e-02	1.8e-02	2.7e-02	Processing concrete
Es-254	3.1e-01	1.5e-01	2.7e-01	5.9e-01	1.1e-03	5.5e-04	9.9e-04	2.2e-03	Road building

[a] 5th percentile to 95th percentile = 90% confidence interval

References

Associated General Contractors of America (AGC). 2002. "Concrete Recycling Facts." http://www.agc.org/Environmental_info/concrete_facts.asp (July 9, 2002).

American Nuclear Society. 1987. "Calculation and Measurement of Direct and Scattered Gamma Radiation from LWR Nuclear Power Plants,"ANSI/ANS 6.6.1-1987. Author.

Bureau of the Census (U.S.). 1999. "1997 Economic Census: Transportation—1997 Commodity Flow Survey." U.S. Department of Transportation, Bureau of Transportation Statistics; U.S. Department of Commerce, Economics and Statistics Administration. http://199.79.179.77/ntda/cfs/97tcf-us.pdf (March 4, 2002).

Code of Federal Regulations, *Title 29, Labor*, Part 1910, "Occupational Safety and Health Standards," Subpart Z, "Toxic and Hazardous Substances," 1910.1000, "Air Contaminants"(29 CFR 1910.1000). http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9991&p_text_version=FALSE (December 5, 2002).

Code of Federal Regulations, *Title 29, Labor*, Part 1910, "Occupational Safety and Health Standards," Subpart Z, "Toxic and Hazardous Substances," 1910.1000, "Air Contaminants," Table Z-3, "Mineral Dusts." http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9994&p_text_version=FALSE (December 5, 2002).

Code of Federal Regulations, *Title 29, Labor*, Part 1926, "Safety and Health Regulations for Construction," Subpart D, "Occupational Health and Environmental Controls," 1926.55, "Gases, Vapors, Fumes, Dusts, and Mists" (29 CFR 1926.55). http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10628&p_text_version=FALSE (December 4, 2002).

Eckerman, K. F., and J. C. Ryman. 1993. "External Exposure to Radionuclides in Air, Water, and Soil," Federal Guidance Report No. 12, EPA 402-R-93-081. Washington, DC: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air.

Franklin Associates. 1998. "Characterization of Building-Related Construction and Demolition Debris in the United States." Prepared for U.S. Environmental Protection Agency, Municipal and Solid Waste Division. http://www.epa.gov/epaoswer/hazwaste/sqg/c&d-rpt.pdf (December 6, 2002).

Parker, S. P. (Ed.) 1994. *McGraw-Hill Dictionary of Scientific and Technical Terms* (5th ed.) New York: McGraw Hill, Inc.

Riala, R. (n/d). "Good Practices in Controlling Quartz Dust Exposure." http://www.ufa.org.se/OSH&D/OSH&D4/4good.html (March 29, 2003).

Texas Department of Transportation (TxDOT). 1999. "January: Crushed Concrete." In "Year of Recycled Roadway Materials." ftp://ftp.dot.state.tx.us/pub/txdot-info/gsd/pdf/yrr_jan.pdf (December 9, 2002).

Turner-Fairbank Highway Research Center (TFHRC). 1997. "User Guidelines for Waste and Byproduct Materials in Pavement Construction," FHWA-RD-97-148. http://www.tfhrc.gov/hnr20/recycle/waste/begin.htm (December 13, 2002).

U.S. Geological Survey (USGS). 2000. "Recycled Aggregates—Profitable Resource Conservation," USGS Fact Sheet FS-181-99. http://pubs.usgs.gov/fs/fs-0181-99/fs-0181-99po.pdf (April 8, 2003).

7 QUALITY CONTROL PROGRAM

In order to ensure that the radiological assessments of the recycling and/or disposal of cleared materials are defensible, accurate, and verifiable, a Quality Management Plan (QMP) was prepared and followed during the conduct of this analysis. The QMP includes specification of procedures and conventions adopted to implement quality control for the present analysis. The QMP also describes requirements for model development, mathematical analyses, and software implementation, and also specifically addresses requirements for the preparation, review, verification, documentation, and record keeping of technical information. The QMP therefore provides a documented system for ensuring accuracy of results, as well as a basis for tracing calculations. The QMP incorporated quality assurance guidelines provided by the NRC and other recognized authorities.

The pathway models developed for this analysis serve as the design descriptions for software development. A Project Quality Assurance (QA) Manager ensures that appropriate steps are taken to implement the quality control, documentation and configuration management requirements of the analyses. The Project Manager acts as a central hub for the review process; all material passes through the Project Manager at each step of the review and final documentation of technical information. All technical information developed for the project is independently verified. This includes conceptual models, equations, and computer software. Specific items to be reviewed are indicated on the review checklist that accompanied all review packets. In addition to in-house review, the analysis of each of the four types of cleared material is peer reviewed by two or more outside consultants, including specialists in probabilistic radiological assessments and experts on the recycling practices for each material. This peer review ensure the technical adequacy and reasonableness of the analysis, the interpretation of the results, and that the assumptions reflect current U.S. industrial practices.

In order to meet the documentation requirements in an organized, retrievable manner, a formal system of document review and filing has been implemented. The Project Manager is responsible for maintaining the organization and contents of the Project Engineering Cabinet, which serve as a repository for the master versions of all controlled project documents.

As described in Chapter 1, the purpose of the present analysis is to assess the radiological impacts of the clearance of materials from NRC- and Agreement State-licensed facilities on members of the public. A defensible assessment must be accurate and verifiable. It must be supported by a quality assurance record of checks for errors in documentation, calculation, and transcription. In order to ensure that these elements are incorporated, a Quality Management Plan (QMP) has been prepared and is followed while conducting this analysis. The QMP is found in Appendix O.

The purpose of the QMP is to define responsibilities and to prescribe a process of controls to ensure the adequacy, completeness, and correctness of technical information and analyses. The QMP for this project addresses the preparation, review, approval, and revision of conceptual and mathematical models, computer software, and other technical information.

As a result of implementing the QMP, the following qualitites of the work products—deliverables and files—are ensured. A primary objective is to enable an independent review of all work performed.

- **Transparency.** Mathematical formulations and rationales for assumptions and parameter selections are explicit and complete.

- **Traceability**. Citations of references are complete enough to enable independent retrieval or copies of cited material are included in the Engineering Design Files.

- **Accuracy**. Results of calculations are checked for accuracy and consistency with the design objectives.

- **Organization**. Records in the Engineering Design Files are logically organized and indexed to facilitate data retrieval.

- **Archives**. Sufficient backup of files and work in progress are maintained to guard against loss due to unexpected events, such as fire or theft.

The QMP incorporates quality assurance guidelines provided by ASME (1997). Since this project is *not* "safety-related" as defined in 10 CFR 50.2, ASME 1997 does not strictly apply, but is still used to provide general guidance.

Computer software developed as part of this project was developed utilizing the quality assurance guidance provided by the American Nuclear Society (ANS 1987) and the NRC (1993).

References

American Nuclear Society (ANS). 1987. "Guidelines for the Validation and Verification of Scientific and Engineering Computer Programs for the Nuclear Industry," ANSI/ANS-10.4-1987 (R1998) Lagrange Park, IL: Author.

American Society of Mechanical Engineers (ASME). 1997. "Quality Assurance Program Requirements for Nuclear Facility Applications," ANSI/ASME NQA-1-1997. New York: Author.

Code of Federal Regulations, *Title 10, Energy*, Part 50, "Domestic Licensing of Production and Utilization Facilities,""General Provisions," 50.2 "Definitions." (10 CFR 50.2)

Nuclear Regulatory Commission (U.S.) (NRC). 1993. "Software Quality Assurance Program and Guidelines," NUREG/BR-0167. Washington, DC: Author.

8 GLOSSARY

Several references were consulted in preparing this glossary. Standard dictionaries are not cited as references. Citations are included in the text only for references that provide a unique definition of the listed term. Definitions not otherwise attributed are based on one or more of the listed references or on standard dictionaries. The discipline from which the usage arises is in italics within square brackets, where it may not be readily apparent, for example, [*radiation protection*]. Terms that appear in the body of the definition and are defined elsewhere in this glossary are in italics.

activity [*radiation protection*]: The rate of disintegration (transformation) or decay of radioactive material. The unit of activity is the *becquerel* (*Bq*) (10 CFR 20.1003).

activation [*radiation protection*]: The process of making a radioisotope by bombarding a stable element with neutrons or protons.

anode: The positive terminal of an electrolytic cell. In the electrolytic refining of copper, the anode is cast from copper produced by a *reverberatory furnace*.

areal activity concentration: (Also surficial *activity* concentration). The total residual *activity* of a component of *cleared material*, divided by the exposed surface area of the component, and expressed in *Bq*/cm^2.

baghouse [*metallurgical industry*]: An air pollution control device employed by *electric arc furnaces* and many other metal melting and refining furnaces. The baghouse contains rows of filters, suspended from the ceiling, that trap the particulate emissions from the melting and refining process. These bag-like filters are shaken at frequent intervals; the dust settles into collecting hoppers and is fed by a screw mechanism into a tanker trailer.

basic oxygen furnace (BOF): A pear-shaped furnace, lined with *refractory bricks*, that refines molten iron from the *blast furnace* and scrap into steel. Up to 30% of the *charge* into the BOF can be scrap, with *hot metal* accounting for the rest. BOFs, which can refine a *heat* (batch) of steel in less than 45 minutes, replaced open-hearth furnaces in the 1950s—the latter required five to six hours to process the metal. The BOF's rapid operation, lower cost, and ease of control give it a distinct advantage over previous methods. Scrap is dumped into the furnace vessel, followed by the *hot metal* from the *blast furnace*. A lance is lowered from above, through which blows a high-pressure stream of oxygen to cause chemical reactions that separate impurities as *offgas* or *slag*. Once refined, the liquid steel and *slag* are poured into separate containers.

becquerel (Bq): The unit of radioactive decay, equal to 1 disintegration per second.

blast furnace: A towering cylinder lined with heat-resistant (refractory) bricks, used by integrated steel mills to smelt iron from its ore. Its name comes from the "blast" of hot air and gases forced up through the iron ore, coke, and limestone that load the furnace.

brass: Copper base alloys in which zinc is the principal alloying element. Brass is harder and mechanically stronger than either of its alloying elements: copper and zinc. It is formable and ductile, develops high tensile strength with cold-working, but is not heat treatable.

bremsstrahlung: Secondary photon *radiation* produced by decelaration of electrically charged particles passing through matter.

bronze: Primarily an alloy of copper and tin, but additionally, the name is used when referring to other alloys not containing tin, for example, aluminum bronze, manganese bronze, and beryllium bronze.

busheling [*metallurgical industry*]: Steel scrap consisting of sheet clips and stampings from metal production. This term arose from the practice of collecting the material in bushel baskets through World War II.

capacity [*metallurgical industry*]: Normal ability to produce an amount metal in a given time period. This rating should include maintenance requirements, but because such service is scheduled to match the needs of the machinery (not those of the calendar), a mill, foundry, or smelter might run at more than 100% of capacity one month and then fall well below rated capacity as maintenance is performed.

carbon steel: Steel containing carbon as its principal alloying element. Most of the steel produced in the world is carbon steel.

cast iron: A hard, brittle non-malleable iron-carbon alloy containing 2.0% to 4.5% carbon, 0.5% to 3% silicon, lesser amounts of sulfur, manganese, and phosphorus.

cast steel: Steel in the form of *castings*, usually containing less than 2% carbon.

casting [*metallurgical industry*]: Pouring molten metal into a mold to produce an object of desired shape.

charge [*metallurgical industry*]: 1. The act of loading material into a vessel. For example, iron ore, coke, and limestone are charged into a *blast furnace*; a *basic oxygen furnace* is charged with scrap and *hot metal*. 2. The material introduced into a furnace for melting.

clear [*regulation*]: To implement *clearance.*

clearance [*regulation*]: The removal of radiological controls by the licensing authority–in this case the U.S. Nuclear Regulatory Commission.

cleared material [*regulation*]: Material that has been removed from radiological regulatory control.

coefficient of variability: (Also "coefficient of variation.") The ratio of the *standard deviation* of a distribution to its arithmetic *mean*.

confidence interval: The lower and upper end points of an interval from a distribution. For example, the interval from the 5th-percentile value to the 95th-percentile value is a "90% confidence interval" because it contains 90% of the estimated values in the distribution (95% minus 5%).

continuous casting [*metallurgical industry*]: A method of pouring steel directly from the furnace into a billet, bloom, or slab directly from its molten form. Continuous casting avoids the need for large, expensive mills for rolling *ingots* into slabs. Continuous cast slabs also solidify in a few minutes versus several hours for an ingot. Because of this, the chemical composition and mechanical properties are more uniform. Steel from the *BOF* or electric furnace is poured into a *tundish* atop the continuous caster. As steel is carefully allowed to flow from the *tundish* down into the water-cooled copper mold of the caster, it solidifies into a ribbon of red-hot steel. At the bottom of the caster, torches cut the continuously flowing steel to form slabs or blooms.

critical group: The group of individuals reasonably expected to receive the greatest *exposure* to *residual radioactivity* for any applicable set of circumstances (10 CFR 20.1003).

deterministic: A *model* whose output is predetermined by the mathematical form of its equations and the selection of a single value for each input parameter (NCRP 1984).

direct reduced iron (DRI): Processed iron ore that is iron-rich enough to be used as a scrap substitute in electric furnace steelmaking. As *mini-mills* expand their product abilities to *sheet steel*, they require much higher grades of scrap to approach integrated mill quality. Enabling the *mini-mills* to use iron ore without the *blast furnace*, DRI can serve as a low residual raw material and alleviate the *mini-mills*' dependence on cleaner, higher-priced scrap. The impurities in the crushed iron ore are driven off through the use of massive amounts of natural gas. While the result is 97% pure iron (compared with *blast furnace hot metal*, which, because it is saturated with carbon, is only 93% iron), DRI is only economically feasible in regions where natural gas is attractively priced.

dose [*radiation protection*]: A generic term that means absorbed dose, *dose equivalent*, *effective dose*, or *effective dose equivalent*.

dose coefficient (external): A set of coefficients that relate the *exposure* of an individual standing on soil contaminated with a given *radionuclide* to either the *effective dose* or *effective dose equivalent* (EDE). The *EDE*-external *exposure* dose coefficients used in the present analysis were taken from Federal Guidance Report No. 12 (Eckerman and Ryman 1993), while the *effective dose* coefficients were from EPA 2000.

dose coefficient (intake): A set of coefficients that relate the intake of a unit *activity* of a given *radionuclide* in a given chemical form to the 50-year committed *effective dose*. In the present report, the terms "committed effective dose" and *effective dose* are synonymous**.** The dose coefficients in the present analysis are based on the values tabulated in "ICRP Publication 68" (ICRP 1994). Separate dose coefficients are tabulated for the inhalation and ingestion pathways. In addition, there are separate coefficients for the inhalation of 1 :m and 5 :m particles.

dose conversion factor (DCF): More accurately "exposure-to-dose conversion factor." A set of factors that relate the intake of a unit *activity* of a given *radionuclide* in a given chemical form to the 50-year committed effective dose equivalent. In the present report, the terms "committed effective dose equivalent" and *effective dose equivalent* are synonymous. The DCFs in the present analysis are based on the values tabulated in Federal Guidance Report No. 11 (Eckerman et al. 1988). Separate DCFs are tabulated for the inhalation and ingestion pathways.

dose equivalent (H_T): The product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest. The units of dose equivalent are the rem and sievert (Sv) (10 CFR 20.1003)

dross [*metallurgical industry*]: An impurity, usually an oxide, formed on the surface of a molten metal; especially in melt-refining of secondary aluminum. Aluminum dross contains aluminum oxide, halide salts, and metallic aluminum.

effective dose: $E = \sum_T w_T H_T$, where w_T is a weighting factor and H_T is the mean *dose equivalent* to organ or tissue *T*. The factor w_T, normalized so that $\sum_T w_T = 1$, corresponds to the fractional contribution of organ or tissue *T* to the total risk of stochastic effects when the body is uniformly irradiated. For the purposes of radiological protection calculations, the human body is defined in "ICRP Publication 60" (ICRP 1991) by 12 designated tissues and organs, and the "remainder," which consists of 10 additional tissues and organs. Recommended weighting factors, which apply to a human adult population for these tissues and organs, are given in "ICRP Publication 60." (ICRP 1996)

effective dose equivalent (EDE): $H_E = \sum_T w_T^{/} H_T$, where wN_T represents the set of weighting factors specified in "ICRP Publication 26" (ICRP 1977). These weighting factors are specified for six organs and a composite set of five remaining organs, designated as the "remainder." Except for the difference in the weighting factors, the definitions of *effective dose* and *effective dose equivalent* are quite similar.

electric arc furnace (EAF): Steelmaking furnace where scrap constitutes up to 100% of the *charge*. Heat is supplied from electricity that arcs from the graphite electrodes to the metal bath. Furnaces may be either an alternating current or direct current. Direct current units consume less energy and fewer electrodes, but they are more expensive.

exposure [*radiation protection*]: Being exposed to ionizing *radiation* or to radioactive material (10 CFR 20.1003).

exposure scenario: The set of circumstances that define a potential situation that could result in a radiation *exposure* of an individual or a group of individuals. Exposure scenarios are used to *model* potential *doses* resulting from the recycling and disposal of *cleared material*.

extrusion [*metallurgical industry*]: Shaping metal into a chosen continuous form by forcing it through a die of appropriate shape.

ferrous: Related to iron (derived from the Latin *ferrum*). Ferrous alloys are iron base alloys.

flux [*metallurgical industry*]: An iron cleaning agent. Limestone and lime react with impurities within the metallic pool to form a *slag* that floats to the top of the relatively heavier (and now purer) liquid iron.

free-machining steel [*metallurgical industry*]: Steel to which impurities have been added to improve machinability.

galvanized steel [*metallurgical industry*]: Steel coated with zinc to provide corrosion resistance for a wide range of products, including automobiles, bridges, storage tanks, structural steel, fasteners, duct work, light poles, pipe, sign supports, reinforcing steel and wire.

heat [*metallurgical industry*]: A single heating, melting, or smelting operation, as in working iron or steel; also, the material heated, melted, etc., at one time.

home scrap [*metallurgical industry*]: Scrap generated during processing and consumed in the same plant where generated.

hot metal [*metallurgical industry*]: The molten iron produced in a *blast furnace*. It proceeds to the *basic oxygen furnace* in molten form or is cast as *pig iron.*

induction furnace [*metallurgical industry*]: An electric furnace in which heat is produced in a metal *charge* by electromagnetic induction.

ingot [*metallurgical industry*]: A solid metal *casting* suitable for remelting or working.

integrated mills [*metallurgical industry*]: Facilities that make steel by processing iron ore and other raw materials in *blast furnaces*. Technically, only the hot end differentiates integrated mills from *mini-mills*. However, the differing technological approaches to molten steel imply different scale efficiencies and, therefore, separate management styles, labor relations and product markets. Nearly all domestic integrated mills specialize in flat-rolled steel or plate.

mean (arithmetic): The arithmetic average of a population—i.e., the sum of all of the values in the population divided by the number in the population.

median: The value in a distribution such that half of the values are bigger, and half of the values are smaller.

mini-mills [*metallurgical industry*]: Normally defined as steel mills that melt scrap metal to produce commodity products. Although the mini-mills are subject to the same steel processing requirements after the caster as the integrated steel companies, they differ greatly in regard to their minimum efficient size, labor relations, product markets, and management style.

model: A mathematical abstraction of an ecological or biological system, sometimes including specific numerical values for the parameters of the system (NCRP 1984).

new scrap [*metallurgical industry*]: Scrap produced during the manufacture of metals and articles for immediate and ultimate consumption; this includes all defective finished and semifinished articles that must be reworked. Examples of new scrap are borings, *castings*, clippings, *drosses*, skims and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap – scarp obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is *home scrap* that is generated as process scrap and used at the same plant.

No. 1 heavy melt [*metallurgical industry*]: Obsolete steel scrap grade, at least one-quarter inch (~0.6 cm) in thickness and in sections no larger than five feet by two feet (~1.5 m × 0.6 m). Much of the metal comes from demolished buildings, truck frames and heavy duty springs. *Mini-mills* are primary consumers of No. 1 heavy scrap.

nuclide: A species of atom characterized by the number of protons, neutrons, and energy level of the nucleus. A nuclide can be stable or radioactive (see *radionuclide*).

offgas [*metallurgical industry*]: The gases, vapors, and particulates that evolve from a furnace during the melting and refining of metals.

old scrap [*metallurgical industry*]: Scrap that includes, but is not limited to, articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, metals from shredded cars and appliances, silver from photographic materials, spent catalysts, tool bits, and aluminum beverage cans. This is also referred to as "postconsumer scrap" and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paint and fertilizer, are not included.

oxygen lance [*metallurgical industry*]: A length of pipe used to convey oxygen onto a bath of molten metal.

parameter: Any one of a set of variables in a *model* whose values determine *model* predictions. (Till and Meyer 1983).

particulates: Fine solid particles which remain individually dispersed in gases or stack emissions.

partitioning [*metallurgical industry*]: The redistribution of impurities in the furnace *charge* among furnace products during melting. The impurities are distributed among molten metal, *slag* or *dross*, dust, and volatile vapors or gases.

partitioning factor [*metallurgical industry*]: The ratio of the total amount of a given element or compound in one of the furnace products to the amount in the scrap metal *charged* to the furnace.

percentile: The value in a distribution such that the given fraction (percentage) of values are less than that value. For example, 95% of the values in a distribution are less than the 95th-percentile value.

pig iron [*metallurgical industry*]: The name for the melted iron produced in a *blast furnace*, containing a large quantity of carbon (above 1.5%). Named long ago when molten iron was poured through a trench in the ground to flow into shallow earthen holes, the arrangement looked like newborn pigs suckling. The central channel became known as the "sow," and the molds were "pigs."

poling [*metallurgical industry*]: Insertion of wood poles into a molten metal bath [of copper], producing a reducing atmosphere by destructive distillation.

progeny [*radiation protection*]: The *nuclide* or *nuclides* resulting from the radioactive disintegration of a *radionuclide*, formed either directly or as the result of successive transformations in a radioactive series. Progeny may be either radioactive or stable.

Q-BOP [*metallurgical industry*]: Modified *basic oxygen furnace* in which the oxygen and other gases are blown in from the bottom, rather than from the top. While the Q-BOP stirs the metal bath more vigorously, allowing for faster processing, the design produces essentially the same steel grades as the top-blowing basic oxygen furnace. Today's state-of-the-art furnace design combines the previous technologies: 60% of the oxygen is blown from above, with the rest blown through the bottom of the vessel.

radiation [*radiation protection*]: Alpha particles, beta particles, gamma rays, x-rays, neutrons, high-speed electrons, high-speed protons, and other particles capable of producing ions. Radiation, as used in this report, does not include non-ionizing radiation, such as radio or microwaves, or visible, infrared, or ultraviolet light.

radionuclide: An atom that, due to its atomic instability, undergoes spontaneous nuclear disintegration. Nuclear disintegration is accompanied by the emission of electrically charged particles or photons, and results in the formation of another, distinct atom (see *progeny*).

radionuclide-dependent parameter: A parameter whose value is specific to a given *radionuclide*, and therefore may be different for different *radionuclides*.

radionuclide-independent parameter: A parameter whose value is not specific to any *radionuclide*.

realistic: Typical of a real-life situation, and therefore likely to be observed in real life. An accurate representation of a reasonably foreseeable, real-life situation.

refractory brick: Heat-resistant brick. Because its melting point is well above the operating temperatures of the process, refractory bricks line most steelmaking vessels that come in contact with molten metal, like the walls of the *blast furnace*, sides of the ladles, and inside of the *BOF*.

residual radioactivity: Radioactivity in structures, materials, soils, groundwater, and other media at a site resulting from activities under the control of an NRC-licensee. This includes radioactivity from all licensed and unlicensed sources used by the licensee, but excludes background *radiation* (10 CFR 20.1003).

reverberatory furnace [*metallurgical industry*]: A furnace in which heat is supplied by burning of fuel between the *charge* and the low roof.

scale [*metallurgical industry*]: A layer of oxidation products formed on a metal at high temperature.

secondary ingestion: Accidental or unintentional ingestion of material (also sometimes referred to as "inadvertent ingestion"). In this analysis, secondary ingestion applies to the unintentional ingestion of soil, dust, or other particulate matter.

sensitivity: The mathematical sensitivity of the *model* predictions to selected perturbations of *model* parameters (NCRP 1984).

sensitivity analysis: Identification of the relative contribution of the *uncertainty* in a given *model* component to the total uncertainty in the *model* result (NCRP 1996).

shaft furnace [*metallurgical industry*]: A vertical, refractory-lined cylinder in which a fixed bed (or descending column) of solids is maintained and through which an ascending stream of hot gases is forced.

sheet steel [*metallurgical industry*]: Thin, flat-rolled steel. Coiled sheet steel accounts for nearly one-half of all steel shipped domestically and is created in a hot-strip mill by rolling a cast slab flat while maintaining the side dimensions. The malleable steel lengthens to several hundred feet (100s of meters) as it is squeezed by the rolling mill. The most common differences among steel bars, strip, plate, and sheet are merely their physical dimensions of width and gauge (thickness).

sinter [*metallurgical industry*]: Baked particles that stick together in roughly one-inch (~2.5 cm) chunks. Normally used for iron ore dust collected from the *blast furnace*s.

slab [*metallurgical industry*]: A piece of metal, intermediate between *ingot* and plate, at least twice as wide as it is thick.

slag [*metallurgical industry*]: A nonmetallic product resulting from the mutual dissolution of *flux* and nonmetallic impurities in smelting and refining operations; the impurities in a molten pool of iron. *Flux* such as limestone may be added to foster the congregation of undesired elements into a slag. Because slag is lighter than iron, it will float on top of the pool, where it can be skimmed.

specialty steel [*metallurgical industry*]: Category of steel that includes electrical, alloy, stainless (see *stainless steel*) and tool steels.

specific activity: (Also mass *activity* concentration). The total *residual radioactivity* of a component of *cleared material*, divided by the mass of the component, and expressed in *Bq*/g.

stainless steel: The term for grades of steel that contain more than 10% chromium, with or without other alloying elements. Stainless steel resists corrosion, maintains its strength at high temperatures, and is easily maintained. For these reasons, it is used widely in items such as automotive and food processing products, as well as medical and health equipment.

standard deviation: The positive square root of the expected value of the square of the differences between a random variable and its *mean*.

tapping [*metallurgical industry*]: Transferring molten metal from melting furnace to ladle.

tundish [*metallurgical industry*]: The shallow refractory-lined basin on top of the continuous caster. It receives the liquid steel from the ladle, prior to the cast, allowing the operator to precisely regulate the flow of metal into the mold.

uncertainty: The lack of sureness or confidence in the predictions of *models* (NCRP 1984).

uniform distribution: A distribution of values such that all values are equally likely to occur, or alternatively, equally likely to be sampled during conduct of an *uncertainty* analysis.

vadose zone (unsaturated zone): The portion of porous media in the ground where the interconnecting interstices are only partially filled with fluid (NCRP 1984)

wirebar [*metallurgical industry*]: Cast copper *ingots* used in the manufacture of wire.

References

Code of Federal Regulations, *Title 10, Energy*, Part 20, "Standards for Protection Against Radiation," Subpart A, "General Provisions," 20.1003 "Definitions," (10 CFR 20.1003). http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/full-text.html (May 2, 2003).

Eckerman, K. F., A. B. Wolbarst, and A. C. B. Richardson. 1988. "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. Washington, DC: U.S. Environmental Protection Agency, Office of Radiation Programs.

Eckerman, K. F., and J. C. Ryman. 1993. "External Exposure to Radionuclides in Air, Water, and Soil," Federal Guidance Report No. 12, EPA 402-R-93-081. Washington, DC: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air.

Environmental Protection Agency (U.S.) (EPA). 1977. "Emission Factors and Emission Source Information for Primary and Secondary Copper Smelters," EPA-450/3-77-051. Research Triangle Park, NC: Author.

Environmental Protection Agency (U.S.) (EPA). 2000. "Federal Guidance Report 13: Cancer Risk Coefficients for Environmental Exposures to Radionuclides." CD Supplement, EPA-402-C-99-001. Washington DC: Author.

Fenton, M. D. 2001. "Iron and Steel Recycling in the United States in 1998," Open File Report 01-224. U.S. Geological Survey. http://pubs.usgs.gov/of/of01-224/of01-224.pdf (June 11, 2003).

International Commission on Radiological Protection (ICRP). 1977. "Recommendations of the ICRP," ICRP Publication 26. *Annals of the ICRP, 1*(3). Oxford: Pergamon Press.

International Commission on Radiological Protection (ICRP). 1991. "1990 Recommendations of the ICRP," ICRP Publication 60. *Annals of the ICRP, 21*(1-3). Oxford: Pergamon Press.

International Commission on Radiological Protection (ICRP). 1994. "Dose Coefficients for Intakes of Radionuclides by Workers," ICRP Publication 68. *Annals of the ICRP*, *24*(4). Tarrytown, NY: Elsevier Science, Inc.

International Commission on Radiological Protection (ICRP). 1996. "Conversion Coefficients for Use in Radiological Protection Against External Radiation," ICRP Publication 74. *Annals of the ICRP*, *26*(3/4). Tarrytown, NY: Elsevier Science, Inc.

National Council on Radiation Protection and Measurements (NCRP). 1984. "Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment," NCRP Report No. 76. Bethesda, MD: Author.

National Council on Radiation Protection and Measurements (NCRP). 1996. "NCRP Commentary 14: Guide for Uncertainty Analysis in Dose and Risk Assessments Related to Environmental Contamination." Bethesda, MD: Author.

Nuclear Regulatory Commission (U.S.) (NRC). (n/d). "Glossary of Nuclear Terms." http://www.nrc.gov/reading-rm/basic-ref/glossary/full-text.html (June 8, 2003).

Parker, S. P. (Ed.) 1994. *McGraw-Hill Dictionary of Scientific and Technical Terms* (5th Ed.) New York: McGraw Hill, Inc.

Principal Metals Online. (n/d). "Terms Glossary." http://www.principalmetals.com/glossary/step1.asp (June 11, 2003).

"The Steel Glossary." 2000. Salomon Smith Barney Inc. http://www.steel.org/learning/glossary/glossary.htm (May 20, 2003).

Till, J. E., and H. R. Meyer. 1983. "Radiological Assessment: A Textbook on Environmental Dose Analysis," NUREG/CR-3332. Washington, DC: U.S. Nuclear Regulatory Commission.