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RADIOLOGICAL ASSESSMENTS FOR CLEARANCE OF EQUIPMENT AND MATERIALS FROM NUCLEAR FACILITIES

Main Report

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Prepared by
M.A. McKenzie-Carter, M.D. Otis, M.E. Anderson, J.A. Roberts, R.L. Gotchy, R.A. Meck

Science Applications International Corporation
545 Shoup Avenue
Idaho Falls, ID 83402

Prepared for
Division of Regulatory Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington D.C. 20555-0001

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ABSTRACT

This report documents the technical basis for the Nuclear Regulatory Commission to use in developing regulatory standards for clearing equipment and materials with residual radioactivity from nuclear facilities. In addition to equipment reuse, the analysis identifies material flow models, based on U.S. industry practices, for recycle of steel, copper, aluminum, and concrete. Using information from the material flow models, likely potential exposure scenarios were realistically modeled for the recycle of these materials. Scenarios for copper, aluminum, and concrete were based on the steel scenarios, but were modified to reflect differences in each industry, and additional exposure scenarios unique to each material were included. The modeling includes all significant exposure pathways, and scenarios include handling and processing, storage, transportation, product use, and disposal. The results of the analyses are expressed in both mass and surficial units. Using Monte Carlo techniques, distributions of radionuclide concentrations were estimated in the material flow model, and concentrations at selected points in the process were used as inputs to the dose assessment model for each scenario. Probability distributions for dose factors (along with the mean, median, 5th and 95th percentile values) were estimated for each radionuclide and each scenario. For each material (e.g. steel), a critical group was identified for each radionuclide, which represents the scenario with the highest mean dose factor. Appendices containing details of the analysis and tabulations of results are included.

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EXECUTIVE SUMMARY

This report provides the technical basis for the Nuclear Regulatory Commission (NRC) to base regulatory standards for clearance of equipment and materials with residual radioactivity from regulatory control. The goal of the analyses is to identify realistic critical groups resulting from clearance of equipment and materials from NRC licensed facilities and to calculate dose factors for the average member of each critical group. The methods described in this report address both surficially contaminated equipment and volumetrically contaminated scrap materials.

In order to ensure that the reuse and recycle assessments are defensible, accurate, and verifiable, a Quality Control Plan (QCP) was prepared for and followed during this evaluation. The QCP specifies procedures and conventions for developing the reuse and recycle models, defining equations and definitions, and implementing spreadsheets. Also included in the QCP are requirements for preparing and reviewing calculations and recording and documenting technical information. The QCP provides a documented system for ensuring accurate results, as well as a method for tracing the bases of assumptions. The QCP incorporates quality assurance guidelines provided by the NRC and other recognized authoritative references.

Dose factors for both surficial and volumetric residual radioactivity were calculated in this analysis. The dose factors, as well as derived clearance levels, are compared to values from other documented sources. The dose factors used for deriving clearance levels for each radionuclide are the critical-group dose factors (the mean value of the distribution calculated from the model for each critical group). These dose factors represent the total effective dose equivalent (TEDE) for an average individual in the critical group for each radionuclide. The dose factors are normalized and are expressed in units of annual dose per unit of residual radioactivity. The recycle clearance levels for each radionuclide are based on the highest critical-group dose factors across the materials that are appropriate for comparison (steel, copper, aluminum, and concrete). The recycle scenario critical group is not the same for each radionuclide, due to the complex nature of the recycle analyses (e.g., differential behavior during melting, wide range of scenario categories, and different types of scrap material). The majority of clearance levels are based on critical groups that involve either commercial truck drivers or workers at processing facilities. With only two exceptions, the recycle (volumetric) critical-group dose factors are more restrictive than the equipment reuse (surficial) clearance levels, primarily because of the much smaller amount of radioactivity involved in the equipment reuse scenario analyses.

The wide range of radionuclide-specific clearance levels derived from the dose factors in this report compare inconsistently with those contained in Regulatory Guide 1.86. Using a clearance criterion of 10 μSv/y, approximately half of the derived radionuclide-specific clearance levels in this report are within a factor of 10 of the acceptable surface contamination levels in Regulatory Guide 1.86. Most of the remaining are greater than a factor of 10 higher than the Regulatory Guide values, indicating that the derived clearance levels in this report are less restrictive than Regulatory Guide 1.86.

Critical group dose factors from this analysis are similar to the draft dose factors published by the EPA. For 36 of the 40 radionuclides in common, the dose factors are within a factor of 10, indicating that the two sets of dose factors are in general agreement. Derived clearance levels do not compare as well to clearance levels from international sources. Using a common clearance criterion of 10 μSv/y, between 50% and 75% of the derived clearance levels for radionuclides in common are within a factor of 10 of the clearance levels published by the European Commission and International Atomic Energy Agency. For those derived clearance levels that are greater than a factor of 10 different in these two sources, the derived clearance levels in this report are more restrictive for all but one radionuclide in each comparison.

Reuse of equipment and recycle of materials were both evaluated and are described in this report. Equipment reuse scenarios differ from recycle scenarios in three ways: (1) only surficial contamination is modeled, (2) the cleared equipment is not processed, and (3) different material types are not considered. A generic equipment reuse scenario was selected for detailed evaluation based on a qualitative screening evaluation of potential equipment reuse exposure scenarios. Modeling the reuse of a large piece of contaminated equipment resulted in dose factors for each radionuclide that bound all other equipment reuse scenarios considered. Thus, it was not necessary to model other equipment reuse scenarios. Exposure pathways included in the dose evaluation are external, inhalation, and secondary ingestion. The mathematical equations and parameter values used to evaluate the scenario are presented, as well as a discussion of key parameter values. The exposure pathways analyzed produce reasonable estimates of the potential TEDE that a member of the critical group could receive.

Recycled material was evaluated using material flow models and dose assessment models. Both models are based on probabilistic methods. Input parameters are modeled as distributions instead of point values (because of uncertainty in the values) resulting in distributions for the output values (i.e., radionuclide concentrations and dose factors).

The material flow model is material-specific and describes the flow of cleared material beginning with the refining process (for metals) or the processing steps (for concrete) through the generation of consumer products. In the material flow model, the original concentration of radionuclides in the cleared material is redistributed to all the products of the process, such as baghouse dust and off-gas, as well as consumer products. The radionuclide concentrations calculated from the material flow model are used as input to the models that estimates potential dose factors for the various scenarios.

The material flow models were also used to identify all the reasonably possible exposure scenarios within the context of the current recycle industries. Approximately 50 potential scenarios were screened and consolidated to form set of 31 exposure scenarios (generic and specific) that were analyzed for the recycle of cleared steel. The scenarios comprise five general categories of potential exposure: handling and processing, storage, transportation, product use, and disposal. Within these categories, five source materials were examined: scrap metal, refinery slag, baghouse dust, refined metal, and atmospheric emissions from refineries.

Radionuclide-specific dose factors were calculated for all scenarios using the dose assessment models.

Exposure scenarios developed for clearance of steel served as the basis for the evaluation of three other materials (copper, aluminum, and concrete). Scenarios unique to each of the other materials were also analyzed. These unique scenarios involve the use of refined copper in household plumbing, use of refined aluminum in cookware, and a resident on the site of a closed landfill containing recycled concrete. Twenty-three scenarios were analyzed for copper recycle and 17 for aluminum recycle. Because of the lack of refining coproducts, there are fewer potential scenarios for concrete recycle (7 scenarios). Using the same methodology used for the steel evaluation, radionuclide-specific dose factors were calculated for all scenarios for these three additional materials.

The analyses were conducted using Monte Carlo techniques to develop probability distributions of the radionuclide concentrations given by the material flow model and of the scenario dose factors. Specific values tabulated from the output distributions consist of the mean dose factors for each exposed group, the median of each distribution, and upper (95^{th} percentile) and lower (5^{th} percentile) values from the distributions. The upper and lower values represent the range of a 90% confidence interval for each radionuclide-specific dose factor. The ratio between the upper and lower bounds of the confidence interval indicates the width of the distribution and is a measure of the uncertainty associated with each dose factor.

Calculated dose factors for an average member of the critical group in the reuse scenario are based on a unit level of residual surficial contamination and are expressed in normalized units of μSv/y per Bq/cm^2 (mrem/y per pCi/cm^2). Dose factors range from a high of 170 μSv/y per Bq/cm^2 (0.6 mrem/y per pCi/cm^2) for Th-229 to a low of 1E-05 μSv/y per Bq/cm^2. Most of the eighty-five radionuclide-specific dose factors (approximately two-thirds) are less than 10 μSv/y per Bq/cm^2 (0.04 mrem/y per pCi/cm^2). The size of the confidence intervals (i.e., the range from the 5^{th} percentile value to the 95^{th} percentile value) for dose factors in the equipment reuse scenario fall into two groups. For about half the nuclides, the confidence interval ratio is close to 5 (ratio of 95^{th} percentile to 5^{th} percentile values). The remaining nuclides have confidence interval ratios that range from about 10 to about 40. The unique radiological characteristics of each group are responsible for the wide range of ratios. Calculated dose factors that are dominated by inhalation and ingestion exposure pathways have wider confidence intervals (greater uncertainty) than dose factors dominated by the external exposure pathway.

Dose factors for the steel recycle analysis range from a high of 2,000 μSv/y per Bq/g (7 mrem/y per pCi/g) for Np-237 to a low of 4E-04 μSv/y per Bq/g. The derived surficial mean critical group dose factors for steel recycle range from 1,400 μSv/y per Bq/cm^2 (Np-237) to a low of 3E-04 μSv/y per Bq/cm^2. The Np-237 dose factor results from the drinking water exposure pathway in a refinery slag storage scenario. Only 6 of the 85 radionuclide-specific dose factors are greater than 270 μSv/y per Bq/g (1 mrem/y per pCi/g). Occupational doses associated with transportation and refinery facilities most commonly produce the critical groups for steel recycle.

Results for recycle of copper and aluminum generally yield similar—although lower—dose factors. Copper recycle dose factors range from a high of 300 µSv/y per Bq/g (1 mrem/y per pCi/g) for Th-229 to a low of 4E-04 µSv/y per Bq/g. The derived surficial mean critical group dose factors for copper recycle are numerically the same, range from 300 µSv/y per Bq/cm^2 (Th-229) to a low of 4E-04 µSv/y per Bq/cm^2. Aluminum recycle dose factors range from a high of 6 µSv/y per Bq/g (.02 mrem/y per pCi/g) for Ag-110m to a low of 2E-06 µSv/y per Bq/g. The derived surficial mean critical group dose factors for aluminum recycle range from 23 µSv/y per Bq/cm^2 (Ag-110m) to a low of 7E-06 µSv/y per Bq/cm^2. As in the steel evaluation, most of the 85 radionuclide-specific dose factors for both copper and aluminum are less than 270 µSv/y per Bq/g (1 mrem/y per pCi/g). Also similar to the steel evaluation, occupational doses associated with transportation and refinery facilities most commonly result in critical groups for copper and aluminum. One copper product-use scenario results in a critical group for copper recycle (use of a generic small copper object), and use of aluminum products accounts for several critical groups in the aluminum recycle analysis.

The mass-based concrete recycle dose factors are generally higher than those calculated for metals recycle, ranging from a high of 7E+04 µSv/y per Bq/g (300 mrem/y per pCi/g) for Np-237 to a low of 3E-03 µSv/y per Bq/g. The derived surficial mean critical group dose factors for concrete recycle range from 1,400 µSv/y per Bq/cm^2 (Np-237) to a low of 5E-05 µSv/y per Bq/cm^2. Approximately 90% of the 85 radionuclide-specific dose factors are less than 270 µSv/y per Bq/g (1 mrem/y per pCi/g). Unlike the metals, a scenario involving a resident on a closed landfill was analyzed and included in the critical group determination. This scenario accounts for one-third of the critical groups for concrete recycle.

Examining the distributions associated with the calculated dose factors for each recycle exposure scenario provides some additional information. Simple scenarios, with only a few exposure pathways and relatively well-known parameters, have distributions that are fairly narrow. For example, the dose factors associated with the commercial truck driver scenarios have confidence interval ratios that range from 2 to about 15 (ratio of 95th percentile to 5th percentile values). Confidence intervals are much wider for complex scenarios with many parameters and uncertain pathways of exposure, such as food-chain intake, groundwater transport, and atmospheric dispersion. The scenarios describing residents on closed landfills containing concrete debris and individuals near large slag storage piles exhibit the greatest range. The confidence interval ratios for these scenarios range from about 150 to about 650.

Appendices included as Volume 2 of this report provide details of the extensive calculations used in this evaluation of reuse and recycle. Radionuclide-specific data such as dose conversion factors and environmental transport factors are included, as well as parameter values for all materials and scenarios.

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The help of many individuals from the secondary metals industries, recycling facilities, and trade groups also needs to be acknowledged. The information gathered from conversations and visits with these individuals provided essential details needed for the development and refinement of the models used in the analysis.

No analysis is complete without the documentation, and this analysis is no exception. Lisa Marko was essential in this regard, as she played a critical role keeping the internal documentation in order during conduct of the analysis, and also provided tremendous support in the final stages of assembling this document. Carolyn Einerson of TechWrite provided crucial technical editing support on a very tight schedule. Also, Martha Reisenauer and Linda Hellewell were extremely helpful in the final stages of preparing this document, and Rayleona Sanders of the NRC Publications Branch provided timely and useful advice.

ABBREVIATIONS

AEC	Atomic Energy Commission
AIHC	American Industrial Health Council
AISE	Association of Iron and Steel Engineers
AISI	American Iron and Steel Institute
ALARA	as low as is reasonably achievable
BOF	basic oxygen furnace
BWR	boiling water reactor
CRC	Chemical Rubber Company
D&D	decontamination and decommissioning
DCF	dose conversion factor
DF	dilution factor
DOD	Department of Defense
DOE	Department of Energy
DWL	derived working limits
EAF	electric arc furnace
EC	European Commission
EDE	effective dose equivalent
EDF	engineering design file
EPA	Environmental Protection Agency
EPF	elemental partitioning factor
EPRI	Electric Power Research Institute
EPS	east pile slag
FGR	Federal Guidance Report
GF	geometry factor
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LANL	Los Alamos National Laboratory
LLW	low-level radioactive waste
MCNP	Monte Carlo N-Particle
MPC	maximum permissible concentration
MPF	mass partitioning factor
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute of Safety and Health
NRC	Nuclear Regulatory Commission
OSHA	Occupational Safety and Health Administration
PWR	pressurized water reactor
QA	Quality Assurance
QCP	Quality Control Plan
RCRA	Resource Conservation and Recovery Act
SAIC	Science Applications International Corporation
SC&A	Sandy Cohen and Associates
TDS	total dissolved solids
TEDE	total effective dose equivalent
TSD	Technical Support Document
USBM	United States Bureau of Mines

Units Conversion Table

This analysis was conducted using conventional units [e.g., radioactivity units of curies (Ci), dose in units of rem]. In the interest of promoting the use of internationally accepted units, the results of the analysis have been converted to S.I. units [e.g., radioactivity units of becquerel (Bq), dose in units of sievert (Sv)]. Units in the text discussion are primary in units of S.I. units, followed by conventional units in parentheses. Because the analysis was conducted using conventional units, parameter units listed with equations are maintained in conventional units.

The following table gives conversion factors that can be used to convert from conventional units to S. I. units.

To Convert From	To	Multiply by
degrees Fahrenheit (°F)	degrees Celsius (°C)	subtract 32 °F, then multiply by 0.556
short ton (ton)	kilogram (kg)	907.2
short ton (ton)	metric ton (t)	0.9072
pounds per ton (lbs/ton)	kilogram per metric ton (kg/t)	0.5
cubic yard (yd^3)	cubic meter (m^3)	0.7646
cubic foot (ft^3)	cubic meter (m^3)	0.02832
curie (Ci)	Becquerel (Bq)	3.7E+10
picocurie (pCi)	Becquerel (Bq)	0.037
picocurie per square centimeter (pCi/cm^2)	Bequerel per square centimeter (Bq/cm^2)	0.037
picocurie per gram (pCi/g)	Bequerel per gram (Bq/g)	0.037
picocurie per gram of product per picocurie per gram of scrap (pCi/g product per pCi/g scrap)	Bequerel per gram of product per Bequerel per gram of scrap (Bq/g product per Bq/g scrap)	1.0
millirem per year (mrem/y)	microseivert per year (µSv/y)	10
millirem per year per picocurie per gram (mrem/y per pCi/g)	microseivert per year per becquerel per gram (µSv/y per Bq/g)	270.27
millirem per year per picocurie per square centimeter (mrem/y per pCi/cm^2)	microseivert per year per becquerel per square centimeter (µSv/y per Bq/cm^2)	270.27
mrem per year per disintegration per minute per 100 square centimeters (mrem/y per dpm/100 cm^2)	microseivert per year per becquerel per square centimeter (µSv/y per Bq/cm^2)	60,000

1 INTRODUCTION

This report documents the technical basis for establishing a potential U.S. Nuclear Regulatory Commission (NRC) rulemaking that addresses clearance of equipment and materials from nuclear facilities. The report contains descriptions of the analyses used to estimate the potential doses resulting from reuse of equipment and recycle of steel, copper, aluminum, and concrete material following clearance. The analyses were conducted to calculate realistic dose factors for the average member of a critical group for each radionuclide. The analyses were conducted on a probabilistic basis, using parameter value distributions as input, to determine distributions for specific model results (i.e., concentrations and dose factors). The mean value from a dose factor output distribution represents the average dose to the exposed population, while the highest mean dose factor across all exposure scenarios designates the critical group for each radionuclide. In addition to the mean values, the 5th, 50th, and 95th percentiles from the distributions are presented and discussed in subsequent sections of the report.

The U.S. Nuclear Regulatory Commission (NRC) is considering the possibility of revising the criteria for the clearance of material and equipment from nuclear facilities. NRC licensed facilities are currently allowed to release materials and equipment during normal facility operations. These releases are conducted consistent with the acceptable surface contamination levels contained in Regulatory Guide 1.86 and site-specific technical specifications and license conditions. The current regulatory framework suffers from issues of consistency with current risk-based regulatory dose standards and lack of general applicability to a wide range of volumetrically contaminated equipment and material. Over the next few decades, large-scale decontamination and decommissioning (D&D) of NRC-licensed nuclear reactors and other facilities is expected to generate large quantities of potentially reusable equipment and recyclable material. The NRC has identified the need for a consistent and health protective regulatory basis to regulate the clearance of such material from regulatory control (NRC 1994a).

Clearance (unrestricted release from regulatory control) implies that there would be no restrictions on the fate of such equipment and materials based on radiological considerations. The many possible dispositions of material cleared from regulatory control can be grouped into the following three most likely categories: usable equipment could be reused directly after clearance (*direct reuse*); material could be immediately disposed in a landfill (*direct disposal*) and scrap material could be sold to a scrapyard for recycle (*recycle*). The potential radiological impacts associated with clearance of equipment and material from regulatory control with respect to each of these categories have been assessed and are presented in this document.

1.1 Purpose and Scope

This report documents analyses of potential radiation doses to members of the public from materials and equipment released by NRC licensed facilities. The analyses are designed to address two principal limitations of current regulatory standards: the lack of risk-based clearance levels and the lack of consistent guidelines for clearing material containing volumetrically distributed radioactivity. The results presented here are intended to support development of

generic clearance levels that are applicable to all NRC licensed facilities. The methodology developed for these analyses can be applied to case-by-case clearance decisions.

Clearance of iron/steel, aluminum, copper, and concrete is addressed in this report. These materials are the most likely to become available for clearance into the public sector and also represent the greatest volume of available material.

The results of these analyses are expressed as radionuclide-specific dose factors that relate the magnitude of radiation dose to the concentration of radioactivity in or on materials or equipment at the time of clearance. The dose factors provide estimates of the radiation dose received by an individual over 1 year for a given initial concentration of radioactivity and a specified set of circumstances that make up a hypothetical exposure scenario. The scenarios have been constructed to be as realistic as the quality of the underlying data allow. That is, rather than constructing each scenario as a conservative "worst case," the level of conservative bias has been limited to that required for generic application to the situations described in each scenario.

A wide range of exposure scenarios was evaluated to ensure that these dose factors are representative of likely dispositions of cleared material and equipment. The scenarios comprise a range of reasonably expected reuse, disposal, and recycle activities—from handling cleared scrap through activities during melting and processing, using refined metal products, to disposing materials in a sanitary or hazardous waste landfill. Impacts associated with residential use of a closed landfill are also assessed.

1.2 Technical Approach

The implications of clearing materials and equipment from licensed nuclear facilities to the public sector presents a complex assessment problem. Clearance from regulatory control implies that many possible groups in the general public could come in contact with these materials and equipment under a wide variety of circumstances. The approach taken in this report is designed to 1) identify a clear assessment endpoint to serve as a basis for clearance criteria that assures adequate protection of the public and 2) provide a comprehensive evaluation of the realistic situations that could result in exposure to groups of individuals in the general public.

The design objective for this analysis is to calculate a realistic estimate of the dose factor for the average member of the critical group for each radionuclide. The critical group is defined in 10CFR20.1003 as "the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances." For each material evaluated in this analysis, nuclide-specific dose factors are provided for both volumetrically (Bq/g or pCi/g) and surficially (Bq/cm^2 or pCi/cm^2) distributed radioactivity. The dose factors are annual individual doses that are normalized to the concentration of radioactivity in cleared material (μSv/y per Bq/g or mrem/y per pCi/g, and μSv/y per Bq/cm^2 or mrem/y per pCi/cm^2).

In order to assure adequate assessment of potential public doses, a wide range of possible scenarios were evaluated to identify the critical group for each radionuclide. The scenarios are

based on the flow of radioactivity associated with released material from the point of clearance to ultimate disposition and include likely industrial refining processes and use or disposal of refinery byproducts. This approach provides a basis for clearance criteria that bounds situations and behaviors that can be reasonably expected and avoids unnecessary conservative results.

Each exposure scenario was analyzed probabilistically using a unit activity concentration (1 pCi/g) for each radionuclide. Each exposure scenario analysis resulted in a distribution of dose factor estimates for each radionuclide. This was accomplished for a set of scenarios for each material analyzed (steel, copper, aluminum, and concrete) using material-specific assumptions.

The mean (average) dose factors from the dose factor distribution in each scenario were ranked to obtain the highest mean dose factor for each radionuclide within each set of material-specific scenarios. The exposed group described in the exposure scenario yielding the highest mean dose factor for each radionuclide was designated as the critical group for that radionuclide. The distribution of dose factors for each critical group is referred to as the critical-group dose factor distribution. Because the mean dose factors are representative of the average members of each critical group, the mean critical-group dose factor is sometimes simply referred to as the critical-group dose factor. In this analysis, there are four critical-group dose factors for each radionuclide—one for each material: steel, copper, aluminum, and concrete.

Figure 1.1 illustrates the relationship between dose factors for a range of exposed groups within the general public and the critical group. This figure displays hypothetical dose factor distributions (not based on calculated results) for a single radionuclide in various scenarios. Many members of the general public will not be in any exposed group, will not receive any dose, and will have dose factors of zero. The dose factors for each exposed group are comprised of a frequency distribution because of uncertainty in the estimated dose factor. The average member of the critical group is represented by the mean (average) value of the critical group frequency distribution, where the critical group is the exposed group with the highest average dose factor for each radionuclide.

As indicated in Figure 1.1, there are some hypothetical situations or behaviors that could result in dose factors higher than those of the average member of the critical population group. Dose factors higher than those of the critical group represent situations or behaviors that are not reasonably expected to occur. These situations are not considered in the analyses.

The process of estimating dose factors begins with the development of a set of exposure scenarios for reuse of equipment and recycle of steel, aluminum, copper, and concrete. The intent is to be comprehensive enough to include the situations and behaviors that might reasonably be expected to bring members of the public into contact with cleared material or equipment. Each scenario represents an exposed group with a potential for being designated the critical group. The individual scenarios are described in subsequent chapters for each material evaluated.

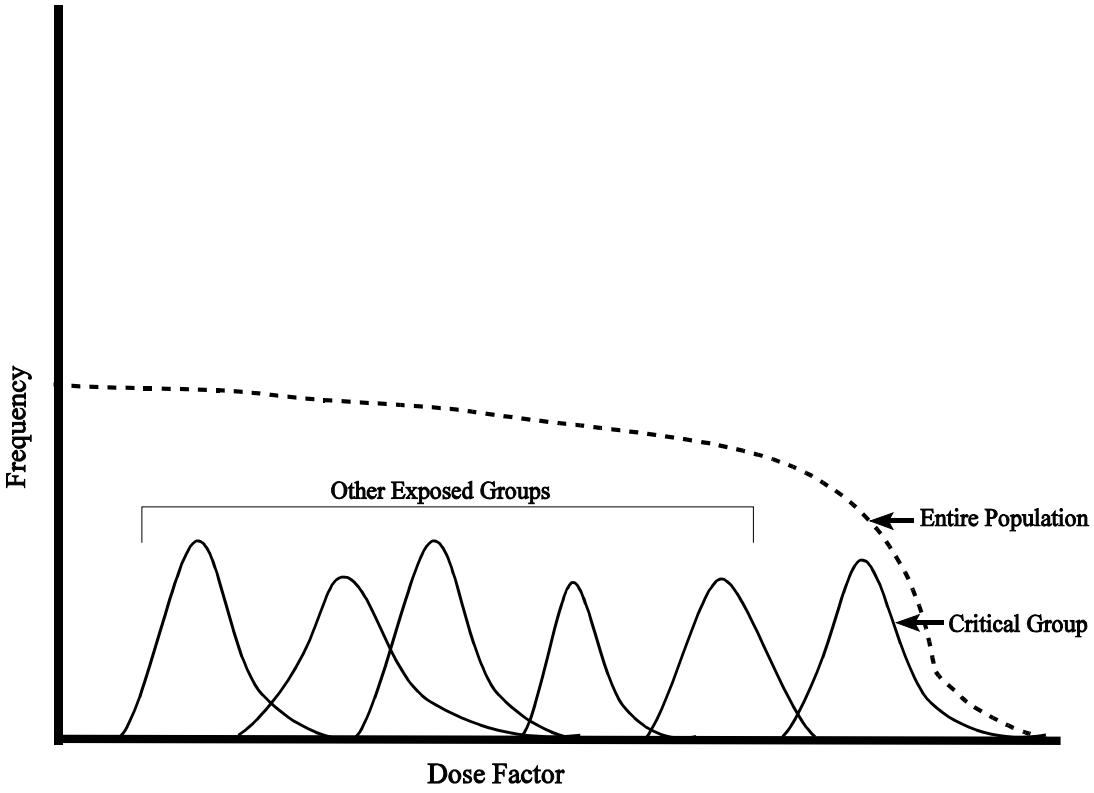

Figure 1.1 Relationship of the critical group to other exposed groups

A key input parameter for each exposure scenario is the concentration of radioactivity in or on the material that individuals may be exposed to. In the case of direct reuse of equipment, no processing takes place between clearance and the start of the exposure scenario. For recycle scenarios, however, a complex series of industrial processes can occur. Recycle of metal involves transportation to a scrap yard, cutting and sizing of scrap, transportation to a refinery, the refinery process itself, and subsequent use of the refined metal product. This process produces byproducts such as slag and baghouse dust, which may also contain residual radioactivity. Steel, copper, aluminum, and concrete each undergo a different set of industrial processes during recycle. These processing steps are addressed by a set of models, called material flow models, that calculate the concentration of residual radioactivity in each material and its byproducts at each step. These concentration estimates are input parameters to scenario models. The material flow models are described in subsequent chapters for each material evaluated.

Both the material flow models and the exposure scenario models are probabilistic. Both the input parameters and the results calculated by the models are represented by frequency distributions rather than point estimates. This approach follows the general guidance presented

in the Environmental Protection Agency's (EPA) Guiding Principles for Monte Carlo Analysis (EPA 1997b), NCRP Commentary Number 14 (NCRP 1996), and IAEA Safety Series Number 100 (IAEA 1989). These references contain recent guidance on the conduct of probabilistic analyses. They also provide a consistent set of technical terms for describing the various features of the analysis and its results.

All assessments based on model calculations are inherently uncertain. This uncertainty arises from several factors, including 1) our ability to adequately model the physical processes involved, 2) the degree to which exposure scenarios adequately represent individuals in the desired critical population groups, 3) the level of knowledge available to estimate appropriate values for parameters in the model, and 4) the natural variability in various quantities used to estimate parameter values.

Lack of knowledge about an input parameter typically contributes more to the uncertainty of the parameter value than does the natural variability of that parameter. Even in cases where the natural variability may be significant, quantifying the amount of uncertainty is difficult. This analysis does not attempt to quantify the relative contributions of natural variability and knowledge uncertainty in estimating parameter values.

The analysis presented here does not address uncertainty due to model structure. This has been the subject of other aspects of this dose assessment including external and internal technical reviews and benchmarking selected scenarios against alternative models proposed by other assessors (e.g., EPA 1997a).

The analysis uses Monte Carlo techniques to conduct a probabilistic analysis of the material flow and exposure scenario models. Monte Carlo methods produce a single model result (output) from a set of randomly selected parameter values (inputs). The distribution resulting from numerous iterations of this process are then statistically summarized and characterized. The required number of iterations depends on the complexity of the model and the statistical quantities to be used. For both the material flow model and the scenario spreadsheets 500 iterations were sufficient to produce stable estimates of the mean and the 5^{th}, 50^{th}, and 95^{th} percentiles of the output distribution. This analysis was conducted using models implemented on Excel spreadsheets (Microsoft 1997). Monte Carlo analysis of these spreadsheets was conducted using Crystal Ball® (Decisioneering 1996) software. Parameter values were sampled using a Latin Hypercube sampling scheme.

Key to the conduct of a probabilistic analysis is the development of frequency distributions for individual parameters in the model. In this analysis all parameters in both the material flow model and the exposure scenarios were characterized as either fixed constants or uncertain parameters with associated frequency distributions. Fixed constants are of three types: physical constants, such as radioactive decay rates; parameters fundamental to the definition of the individual addressed by the scenario; and parameters fundamental to the definition of the scenario itself.

The dose assessment addresses individuals representing members of the exposed groups. Some fundamental characteristics of these individuals are considered constants in the model and are not subject to variability or uncertainty. Examples of constants include the biological response to radiation or the dose equivalent due to radionuclide intake. Also, certain parameters within each scenario are considered constants because they are fundamental to the definition of the scenario. That is, because they are assumed for purposes of constructing the scenario, they are not subject to either natural variability or lack of knowledge. Examples include the placement of residences relative to the refinery stack or the location of a drinking-water well relative to a slag storage pile.

For the remaining parameters, frequency distributions have been developed that are appropriate to each scenario and reflect expert judgment regarding the degree to which each parameter is unknown. When available, data reflecting the measured variation of parameters was used in estimating parameter distributions. However, for many parameters, the only available data are not completely representative of the population being assessed. In the absence of acceptable representative data, subjective characterizations of parameter ranges and distributions have been developed based on physical plausibility arguments, the behavior of analogous parameters in other assessments, and expert judgment. The resulting frequency distributions are necessarily subjective and should not be considered to represent only natural variability. Conventions for the assignment of parameter distributions based on the quality of available data are presented in Appendix B.

In some cases, it is appropriate to combine the variability and uncertainty associated with more than one parameter into a single distribution which can be treated as a lumped parameter. Some complex pathways contain many nuclide-dependent parameters for which data on uncertainty are sparse. To avoid making the analysis overly complex and costly, the uncertainty in these pathways was estimated by choosing key parameters to represent the uncertainty in the entire pathway. For example, in scenarios containing a groundwater pathway, distributions on the absorption coefficient, K_d, contributed most to the total pathway uncertainty. Similarly, for the atmospheric release scenario, the uncertainty in the atmospheric dispersion model was precalculated and assigned to the average χ/Q parameter.

Uncertain parameters included in this analysis are assumed to vary independently; that is, covariance among parameters has not been incorporated into the modeling. The potential for strong covariances was evaluated during the parameter characterization process. No strong covariances were identified among the parameters explicitly treated in the analysis. In general, the effect of neglecting covariances is to estimate slightly wider confidence intervals on dose factors.

1.3 Results Presented

Results from the material flow models are included in the section for each material. These results consist of values from the calculated distribution of radioactivity concentrations in each medium of interest (material and industrial byproduct) normalized to unit concentration at the

time of clearance (Bq/g or pCi/g). The mean, median, and 90% confidence interval (5^{th} and 95^{th} percentiles) are presented.

The primary results from this analysis are radionuclide-specific dose factors for both volumetrically and surficially distributed residual radioactivity. The dose factors can be used to derive clearance levels (Bq/g or Bq/cm^2) from an appropriate individual dose criterion (μSv/y). The mean, median, and 90% confidence interval (5^{th} and 95^{th} percentiles) for these dose factors are presented and discussed. Critical-group dose factors are presented in Section 2 for each radionuclide from among all the materials evaluated. Subsequent sections present critical-group dose factors for each of the materials evaluated in this analysis: steel, copper, aluminum, and concrete.

The doses calculated are annual total effective dose equivalents (TEDE), which is the TEDE received during a year of exposure in a given scenario. The TEDE is defined (10CFR20) as the sum of the deep dose equivalent from external exposures and the committed effective dose equivalent (EDE) from internal exposures. Environmental Protection Agency (EPA) dose conversion factors were used for all internal dose calculations and for external exposures where appropriate. The committed EDE from internal exposures was calculated as the 50-year committed EDE from an intake.

As described above, the dose factors are radionuclide-specific. Each radionuclide dose factor is based on a unit radioactivity concentration of a single radionuclide at the time of clearance. Mixtures of radionuclides have not been addressed in this report, however, the radionuclide dose factors are additive in the case of a postulated mixture of radionuclides.

This report presents normalized dose factors (μSv/y per Bq/g or mrem/y per pCi/g, and μSv/y per Bq/cm^2 or mrem/y per pCi/cm^2) by which an assumed dose criterion can be divided to give clearance levels for each radionuclide. Comparisons of dose factors and derived clearance levels with several other sources are included in Section 2 (e.g., the International Atomic Energy Agency [IAEA]). An individual dose limit for clearance has not been established. Where needed, a dose criterion of 10 μSv/y (1 mrem/y) was used for purposes of comparison with other criteria. The clearance levels thus calculated are for comparative purposes only.

2 SUMMARY AND COMPARISON OF RESULTS

Dose factors for the average member of radionuclide-specific critical groups were calculated for equipment reuse and material recycle scenarios. The critical group for each radionuclide for each of the four materials analyzed (steel, copper, aluminum, and concrete) was identified by selecting the highest mean values from the distribution of dose factors generated for each exposure scenario. Dose factors for reuse are based on surficial residual radioactivity, and are independent of material type. Reuse dose factors are less restrictive than recycle dose factors, so they are not discussed further in this section. Dose factors for recycle are based on volumetric residual radioactivity; surficial dose factors were derived by multiplying the volumetric recycle dose factors by a surface-to-mass ratio.

Over half of the critical groups for recycle of steel, copper, and aluminum describe workers at scrap yards and steel refineries who transport, handle, and process scrap metal. This is due to a combination of characteristics of these scenarios: very little delay time following clearance, no mixing or melting, and involvement of large masses of material. There are also critical groups in scenarios involving handling refinery products such as slag and baghouse dust. These scenarios involve radionuclides that concentrate in certain refinery products, and they also involve internal dose pathways. Residual radioactivity in consumer products rarely yields any critical groups.

Transportation and handling of concrete debris are important for concrete for the same reasons that they are important for the metals. In addition, concrete is commonly used as landfill or disposed of in municipal landfills, so dose factors for a resident living above buried concrete in a closed landfill were explicitly evaluated and included in the concrete critical group determination. This scenario describes the critical group for about 25 radionuclides. In most cases, the critical-group dose factors for these radionuclides are higher for concrete than for the metals.

The results of this analysis were compared to other clearance criteria. The results compare inconsistently to the acceptable surface contamination levels of Regulatory Guide 1.86. This is probably due to the fact that the Regulatory Guide values are not based on a pathway analysis. The results of this analysis compare more favorably with Environmental Protection Agency (EPA) draft dose factors. In this comparison, the dose factors are almost all within an order of magnitude indicating that the two sets of results can be considered in general agreement. The results of this analysis were also compared with clearance levels published by the European Commission and the International Atomic Energy Agency. This comparison shows a general level of agreement that is closer than with Regulatory Guide 1.86 but not as close as with the EPA draft dose factors, and for those radionuclides where the difference is greater than a factor of 10, the derived clearance levels in this analysis are almost always more restrictive.

This section presents a summary, comparison, and brief interpretation of the results of the overall analysis for clearance of material from Nuclear Regulatory Commission (NRC) licensed facilities. It does not include a summary of the analysis methodology, but does provide a brief discussion of key aspects of the methodology where appropriate in order to explain the patterns of the results. This summary and comparison section contains information that will help interpretation of the results as well as help indicate the significance of them.

The following subsection presents tables containing the critical-group dose factors for all radionuclides, with a brief interpretation of those dose factors. This is followed by subsections containing comparisons of the results of this analysis with other available clearance criteria.

2.1 Dose Factors for Members of Critical Groups

The critical-group dose factors presented in this report represent the mean dose to the group of individuals exposed under the circumstances of the most restrictive scenario (highest calculated dose factor) for each material and radionuclide. The analysis addresses 85 radionuclides and four materials: steel, copper, aluminum, and concrete. Two types of dose factors are calculated: volumetric (mass-based) and derived surficial. The mass-based dose factors have units of μSv/y per Bq/g (mrem/y per pCi/g) and are calculated using a normalized concentration of 1 pCi/g distributed throughout the volume of material at the time of release. Derived surficial dose factors are calculated from the mass-based dose factors using a surface-to-mass ratio according to the discussion in Section 4.7. Together, these two sets of dose factors provide the technical basis for formulating a set of clearance levels for material and equipment to be released from NRC licensed facilities.

Both mass-based and derived surficial dose factors are based on scenarios related to the recycle or disposal of cleared scrap material. The related issue of equipment cleared for direct reuse is addressed in Section 3.

Table 2.1 lists the mass-based critical-group dose factors for each of the four materials analyzed in this report. Several scenarios were evaluated for each material. The values in Table 2.1 are the highest mean dose factors for each radionuclide from among all exposure scenarios for each material. Each critical-group dose factor is the mean of a distribution of values calculated for that scenario. Subsequent sections of this report for each material include tabulations of the 5^{th}, 50^{th} and 95^{th} percentiles of these distributions along with the mean values. Results for steel appear in Section 4.9. Those for copper are presented in Section 5.8. Results for aluminum are presented in Section 6.8 and those for concrete are in Section 7.7. A comprehensive tabulation of the results for all steel, copper, aluminum, and concrete scenarios is presented in Appendices F, G, H, and I, respectively.

Specific discussions of the scenarios and critical groups associated with the dose factors in Table 2.1 are presented in subsequent sections of this report. However, there are some general patterns in the results that are discussed in this summary presentation. Most critical groups for recycle of steel, copper, and aluminum describe workers at scrap yards and steel refineries who transport, handle, and process scrap metal or refinery products such as slag and baghouse dust. Two scenarios involving exposure to cleared scrap account for more than half of the 85 radionuclides for all metals (scrap transportation and scrap handling scenarios).

There are three reasons why the scrap transportation and handling scenarios are important for the largest number of radionuclides. First, there is minimal delay between clearance of scrap and transporting it to the scrap yard so no significant radioactive decay occurs before the scenario begins for most radionuclides. Consequently, this scenario describes the critical group for many short-lived radionuclides that decay before later scenarios can occur. Second, unprocessed scrap has not yet been subjected to mixing with other materials or chemical partitioning during

Table 2.1 Mass-based critical-group dose factors for recycle and disposal of cleared materials

	Mean dose factors (μSv/y per Bq/g)			
Radionuclide	Steel	Copper	Aluminum	Concrete
H-3	6.4E-04	5.6E-04	1.8E-06	8.8E-03
C-14	2.8E-03	1.6E-02	2.6E-04	1.6E+01
Na-22	4.1E+02	2.2E+02	4.4E+00	2.2E+02
P-32	1.3E-01	1.3E-01	2.6E-03	1.4E-01
S-35	7.6E-03	7.8E-04	8.6E-06	3.5E-03
Cl-36	2.7E+00	5.2E-02	6.8E-04	1.6E+02
K-40	5.2E+01	1.6E+01	3.2E-01	4.7E+01
Ca-41	1.3E-01	2.0E-03	1.0E-05	4.8E+00
Ca-45	8.2E-02	5.1E-03	3.0E-05	1.8E-02
Cr-51	2.5E+00	2.5E+00	4.9E-02	2.5E+00
Mn-54	8.5E+01	8.5E+01	1.7E+00	8.5E+01
Fe-55	1.0E-03	9.7E-04	7.3E-05	3.4E-03
Co-57	3.8E+00	3.8E+00	7.6E-02	6.6E+00
Co-58	9.5E+01	9.5E+01	1.9E+00	9.6E+01
Fe-59	1.1E+02	1.1E+02	2.3E+00	1.2E+02
Ni-59	4.5E-04	4.2E-04	2.9E-05	7.4E-03
Co-60	2.5E+02	2.5E+02	5.1E+00	2.5E+02
Ni-63	1.2E-03	1.1E-03	8.2E-05	1.0E-02
Zn-65	2.1E+02	7.8E+01	1.2E+00	6.0E+01
Cu-67	2.1E+00	2.1E+00	4.1E-02	2.9E+00
Se-75	3.6E+01	2.4E+01	4.9E-01	2.5E+01
Sr-85	4.7E+01	4.7E+01	9.4E-01	4.7E+01
Sr-89	1.2E-01	1.2E-01	2.3E-03	1.4E-01
Sr-90	1.0E+01	4.3E-01	1.0E-02	2.2E+00
Y-91	3.5E-01	3.5E-01	6.9E-03	4.3E-01
Mo-93	1.4E-02	1.1E-02	5.5E-04	3.8E+01
Nb-93m	8.4E-03	5.9E-03	8.7E-05	2.0E-02
Nb-94	1.6E+02	1.6E+02	3.3E+00	2.9E+02
Nb-95	7.2E+01	7.2E+01	1.4E+00	7.4E+01
Zr-95	7.2E+01	7.2E+01	1.4E+00	7.3E+01
Tc-99	1.9E-01	2.9E-03	1.8E-04	1.2E+02
Ru-103	4.6E+01	4.6E+01	9.3E-01	4.7E+01
Ru-106	2.1E+01	2.1E+01	4.1E-01	2.1E+01
Ag-108m	1.6E+02	1.6E+02	3.2E+00	1.7E+02
Cd-109	4.4E-01	2.6E-02	1.3E-03	2.5E-01
Ag-110m	2.8E+02	2.8E+02	5.7E+00	2.8E+02
Sb-124	1.8E+02	1.8E+02	3.6E+00	1.8E+02
I-125	2.7E+00	6.5E-02	1.3E-03	3.0E-01
Sb-125	4.1E+01	4.1E+01	8.1E-01	4.1E+01
I-129	6.1E+01	4.4E-01	1.9E-03	2.4E+03
I-131	2.5E+01	2.5E+01	5.0E-01	2.8E+01
Ba-133	2.8E+01	2.8E+01	5.6E-01	2.8E+01
Cs-134	6.6E+02	1.6E+02	3.2E+00	1.6E+02
Cs-137	2.6E+02	6.2E+01	1.2E+00	6.2E+01
Ce-141	2.7E+00	2.7E+00	5.4E-02	3.4E+00
Ce-144	3.3E+00	3.3E+00	6.6E-02	3.3E+00
Pm-147	1.1E-02	6.8E-03	5.5E-05	2.8E-02

Table 2.1 Mass-based critical-group dose factors for recycle and disposal of cleared materials

	Mean dose factors (μSv/y per Bq/g)			
Radionuclide	Steel	Copper	Aluminum	Concrete
Eu-152	1.1E+02	1.1E+02	2.2E+00	1.1E+02
Eu-154	1.2E+02	1.2E+02	2.4E+00	1.2E+02
Eu-155	1.1E+00	1.1E+00	2.1E-02	2.5E+00
Re-186	2.5E-01	2.5E-01	4.9E-03	3.1E-01
Ir-192	1.2E+02	7.1E+01	1.4E+00	7.2E+01
Pb-210	1.5E+02	3.8E+00	7.5E-01	3.1E+01
Po-210	6.0E+01	1.1E+00	7.4E-02	1.3E+01
Bi-210	3.3E-02	3.1E-02	6.2E-04	9.9E-02
Rn-222	8.6E+01	8.6E+01	1.7E+00	1.1E+02
Ra-223	1.8E+01	1.8E+01	3.6E-01	1.9E+01
Ra-224	6.1E+01	6.1E+01	1.2E+00	7.6E+01
Ac-225	1.4E+01	1.4E+01	2.8E-01	1.5E+01
Ra-225	1.8E+00	4.7E-01	9.6E-03	5.2E+00
Ra-226	1.7E+02	1.7E+02	3.5E+00	5.3E+02
Ac-227	3.4E+02	2.6E+02	1.9E+00	8.4E+02
Th-227	5.9E+00	5.9E+00	1.2E-01	1.1E+01
Th-228	1.3E+02	1.3E+02	2.5E+00	2.7E+02
Ra-228	8.4E+01	8.4E+01	1.7E+00	8.9E+01
Th-229	4.3E+02	3.3E+02	2.3E+00	1.4E+03
Th-230	6.5E+01	5.0E+01	3.4E-01	2.2E+02
Pa-231	2.3E+02	1.8E+02	1.5E+00	2.1E+03
Th-231	1.5E-02	1.5E-02	3.0E-04	3.9E-02
Th-232	2.9E+02	2.2E+02	1.5E+00	1.3E+03
Pa-233	1.3E+01	1.3E+01	2.6E-01	1.4E+01
U-233	3.4E+01	2.5E+01	1.8E-01	1.7E+02
Th-234	7.3E-01	7.3E-01	1.5E-02	7.5E-01
U-234	3.3E+01	2.5E+01	1.7E-01	1.7E+02
U-235	3.2E+01	2.5E+01	1.6E-01	1.4E+02
Np-237	2.0E+03	1.1E+02	7.2E-01	7.1E+04
Pu-238	7.1E+01	5.5E+01	3.8E-01	1.7E+02
U-238	2.9E+01	2.3E+01	1.5E-01	1.3E+02
Pu-239	7.6E+01	5.8E+01	4.0E-01	2.2E+02
Pu-240	7.6E+01	5.7E+01	4.0E-01	2.2E+02
Pu-241	1.2E+00	9.4E-01	6.5E-03	1.7E+01
Am-241	1.1E+02	9.0E+01	5.9E-01	3.3E+02
Cm-242	4.3E+00	3.0E+00	2.3E-02	1.1E+01
Pu-242	7.3E+01	5.4E+01	3.8E-01	2.1E+02
Cm-244	6.3E+01	4.9E+01	3.3E-01	1.6E+02

Note: to convert these values to conventional units (mrem/y per pCi/g) multiply by 3.70E-03

refining. This means that the initial radionuclide concentration is unchanged. Third, relatively large masses of scrap material are transported in each load so relatively larger amounts of radioactivity are present in this scenario than in most others. Because the scrap transportation scenario involves only the external dose pathway, the radionuclides for which this scenario describes the critical group are all gamma emitters.

Radionuclides with critical groups in slag, dust, and offgas scenarios are those which concentrate in these materials during the refining process. All of these scenarios include internal dose pathways: inhalation of dust, inadvertent ingestion, consumption of drinking water or ingestion of garden produce. The radionuclides for which these material-specific scenarios describe critical groups all have relatively long half-lives and are alpha or beta emitters that contribute to internal dose pathways.

Four radionuclides (H-3, C-14, Cl-36, and I-129) have a critical group consisting of members of the general public living in the vicinity of metal refineries exposed to refinery atmospheric releases. These are all volatile radionuclides with no external dose component.

Residual radioactivity in consumer products rarely yields any critical groups. There are four reasons for this. First, the passage of time between clearance and the use of consumer products allows many radionuclides to decay to very small concentrations. Second, the amount of all metals available from NRC licensed facilities is small compared to the total amounts that are recycled each year. Mixing cleared metals with other metals reduces concentrations of radioactivity in finished products. Third, many radionuclides are partitioned to slag or baghouse dust during refining and do not appear in finished metals. Finally, the relatively small size of consumer products (compared to the amounts of scrap metals encountered by refinery workers) limits the amount of radioactivity to which any individual could be exposed in these scenarios. In contrast, workers at scrap yards and steel refineries can be exposed to relatively large amounts of cleared steel before mixing, processing, or radioactive decay can take place.

For most radionuclides, the highest mass-based critical-group dose factor for the three metals are those for steel. Copper and aluminum critical-group dose factors for similar scenarios are smaller than those for steel due to the relatively smaller amounts of copper and aluminum available for clearance compared to the typical capacity of refineries for these metals.

Concrete presents a somewhat different case from the metals. Transportation and handling of concrete debris are important for the same reasons that they are important for the metals. In addition, concrete is commonly used as landfill or disposed of in municipal landfills. Potential doses to a resident living above buried concrete in a closed landfill were explicitly evaluated and included in the concrete critical group determination. This scenario describes the critical group for 28 long-lived, water-soluble radionuclides that contribute to ingestion and drinking water pathway doses. In most cases, the critical-group dose factors for these radionuclides are higher for concrete than for the metals.

Table 2.2 lists the derived surficial critical-group dose factors for the four materials analyzed in this report. For all radionuclides, the critical group for the derived surficial dose factor is the same as for the corresponding mass-based dose factor. The derived surficial dose factors are calculated from the mass-based dose factors using a surface-to-mass ratio appropriate for each material. Like the rest of this analysis, the derivation of surficial dose factors is a probabilistic calculation that takes into account the uncertainty in surface-to-mass ratio. This calculation is discussed in Section 4.7.

Table 2.2 Surficial critical-group dose factors for recycle and disposal of cleared materials

	Mean dose factors (μSv/y per Bq/cm^2)			
Radionuclide	Steel	Copper	Aluminum	Concrete
H-3	4.8E-04	4.8E-04	6.8E-06	1.9E-04
C-14	2.1E-03	1.4E-02	1.0E-03	3.7E-01
Na-22	3.2E+02	1.9E+02	1.8E+01	5.2E+00
P-32	9.9E-02	1.1E-01	1.1E-02	3.2E-03
S-35	5.6E-03	6.6E-04	3.5E-05	5.3E-05
Cl-36	2.1E+00	4.4E-02	2.8E-03	3.2E+00
K-40	4.0E+01	1.4E+01	1.3E+00	1.1E+00
Ca-41	9.8E-02	1.7E-03	4.1E-05	1.2E-01
Ca-45	6.1E-02	4.3E-03	1.2E-04	4.2E-04
Cr-51	1.9E+00	2.1E+00	2.0E-01	6.0E-02
Mn-54	6.4E+01	7.3E+01	6.9E+00	2.0E+00
Fe-55	7.6E-04	8.3E-04	2.9E-04	8.0E-05
Co-57	2.9E+00	3.3E+00	3.1E-01	1.5E-01
Co-58	7.2E+01	8.1E+01	7.7E+00	2.3E+00
Fe-59	8.7E+01	9.8E+01	9.3E+00	2.7E+00
Ni-59	3.4E-04	3.6E-04	1.2E-04	1.8E-04
Co-60	1.9E+02	2.2E+02	2.1E+01	6.0E+00
Ni-63	9.1E-04	9.7E-04	3.2E-04	2.4E-04
Zn-65	1.6E+02	6.7E+01	4.8E+00	1.4E+00
Cu-67	1.6E+00	1.8E+00	1.7E-01	6.8E-02
Se-75	2.7E+01	2.1E+01	2.0E+00	5.9E-01
Sr-85	3.6E+01	4.0E+01	3.8E+00	1.1E+00
Sr-89	8.8E-02	9.9E-02	9.4E-03	3.3E-03
Sr-90	7.5E+00	3.7E-01	4.0E-02	5.5E-02
Y-91	2.6E-01	3.0E-01	2.8E-02	1.0E-02
Mo-93	1.1E-02	9.5E-03	2.2E-03	8.5E-01
Nb-93m	6.4E-03	5.0E-03	3.4E-04	4.7E-04
Nb-94	1.2E+02	1.4E+02	1.3E+01	7.3E+00
Nb-95	5.5E+01	6.2E+01	5.8E+00	1.7E+00
Zr-95	5.4E+01	6.2E+01	5.8E+00	1.7E+00
Tc-99	1.4E-01	2.5E-03	7.2E-04	2.6E+00
Ru-103	3.5E+01	4.0E+01	3.7E+00	1.1E+00
Ru-106	1.6E+01	1.8E+01	1.7E+00	4.9E-01
Ag-108m	1.2E+02	1.4E+02	1.3E+01	4.3E+00
Cd-109	3.3E-01	2.2E-02	5.1E-03	5.8E-03
Ag-110m	2.1E+02	2.4E+02	2.3E+01	6.7E+00
Sb-124	1.4E+02	1.5E+02	1.5E+01	4.3E+00
I-125	2.1E+00	5.6E-02	5.3E-03	7.1E-03
Sb-125	3.1E+01	3.5E+01	3.3E+00	9.6E-01
I-129	4.6E+01	3.7E-01	7.5E-03	5.1E+01
I-131	1.9E+01	2.1E+01	2.0E+00	6.5E-01
Ba-133	2.1E+01	2.4E+01	2.3E+00	6.6E-01
Cs-134	4.9E+02	1.4E+02	1.3E+01	3.8E+00
Cs-137	2.0E+02	5.3E+01	5.0E+00	1.5E+00
Ce-141	2.1E+00	2.3E+00	2.2E-01	8.0E-02
Ce-144	2.5E+00	2.8E+00	2.7E-01	7.8E-02
Pm-147	8.4E-03	5.8E-03	2.2E-04	4.4E-04

Table 2.2 Surficial critical-group dose factors for recycle and disposal of cleared materials

	Mean dose factors (μSv/y per Bq/cm^2)			
Radionuclide	Steel	Copper	Aluminum	Concrete
Eu-152	8.4E+01	9.5E+01	9.0E+00	2.6E+00
Eu-154	9.2E+01	1.0E+02	9.8E+00	2.9E+00
Eu-155	8.0E-01	9.1E-01	8.6E-02	5.8E-02
Re-186	1.9E-01	2.1E-01	2.0E-02	7.2E-03
Ir-192	8.9E+01	6.1E+01	5.7E+00	1.7E+00
Pb-210	1.2E+02	3.3E+00	3.0E+00	7.4E-01
Po-210	4.4E+01	9.0E-01	2.9E-01	3.1E-01
Bi-210	2.5E-02	2.7E-02	2.5E-03	2.3E-03
Rn-222	6.5E+01	7.3E+01	6.9E+00	2.5E+00
Ra-223	1.4E+01	1.5E+01	1.5E+00	4.5E-01
Ra-224	4.6E+01	5.2E+01	4.9E+00	1.8E+00
Ac-225	1.1E+01	1.2E+01	1.1E+00	3.6E-01
Ra-225	1.4E+00	4.0E-01	3.9E-02	1.2E-01
Ra-226	1.3E+02	1.5E+02	1.4E+01	1.3E+01
Ac-227	2.5E+02	2.3E+02	7.6E+00	2.0E+01
Th-227	4.4E+00	5.0E+00	4.7E-01	2.6E-01
Th-228	9.6E+01	1.1E+02	1.0E+01	6.3E+00
Ra-228	6.3E+01	7.2E+01	6.8E+00	2.1E+00
Th-229	3.3E+02	2.9E+02	9.2E+00	3.3E+01
Th-230	4.9E+01	4.3E+01	1.4E+00	5.3E+00
Pa-231	1.7E+02	1.6E+02	5.9E+00	5.0E+01
Th-231	1.1E-02	1.3E-02	1.2E-03	9.2E-04
Th-232	2.2E+02	1.9E+02	6.1E+00	3.2E+01
Pa-233	1.0E+01	1.1E+01	1.1E+00	3.2E-01
U-233	2.5E+01	2.1E+01	7.2E-01	3.8E+00
Th-234	5.5E-01	6.2E-01	5.9E-02	1.8E-02
U-234	2.5E+01	2.1E+01	7.0E-01	3.8E+00
U-235	2.4E+01	2.1E+01	6.6E-01	3.2E+00
Np-237	1.4E+03	9.4E+01	2.9E+00	1.4E+03
Pu-238	5.4E+01	4.8E+01	1.5E+00	4.0E+00
U-238	2.2E+01	2.0E+01	6.3E-01	3.1E+00
Pu-239	5.8E+01	5.0E+01	1.6E+00	5.4E+00
Pu-240	5.8E+01	4.9E+01	1.6E+00	5.4E+00
Pu-241	9.3E-01	8.1E-01	2.6E-02	4.0E-01
Am-241	8.5E+01	7.8E+01	2.4E+00	8.0E+00
Cm-242	3.2E+00	2.5E+00	9.1E-02	2.5E-01
Pu-242	5.5E+01	4.6E+01	1.5E+00	5.1E+00
Cm-244	4.8E+01	4.2E+01	1.3E+00	3.7E+00

Note: to convert these values to conventional units (mrem/y per pCi/cm^2) multiply by 3.70E-03

The derived surficial critical-group dose factors for steel and copper in Table 2.2 are slightly smaller than the corresponding mass-based dose factors in Table 2.1. This is because the average surface-to-mass ratio for typical steel and copper objects are slightly less than 1 cm^2/g. The derived surficial dose factors for aluminum in Table 2.2 are larger than the corresponding mass-based dose factors because the average surface-to-mass ratio for typical aluminum objects is about 4 cm^2/g. This is largely a consequence of the lower density of aluminum rather than the

size and shape of typical aluminum objects. The surface-to-mass ratio for cleared concrete is significantly smaller, averaging about 0.02 cm^2/g. This reflects the surface-to-mass ratios of large concrete objects such as walls and floor slabs.

2.2 Comparison of Results with Other Clearance Criteria

In order to establish a context for interpreting the results of this analysis, they can be compared to other clearance criteria. The four available sets of criteria are the existing Regulatory Guide 1.86 surface contamination levels, the draft dose factors of the Environmental Protection Agency (EPA), and the draft clearance levels of the European Commission (EC) and the International Atomic Energy Agency (IAEA). Each of these sets of criteria are intended for slightly different purposes and are formulated differently. In particular, they are presented in different sets of units. The results of this analysis are comprehensive enough that they can be modified to allow direct comparison with each of the four sets of criteria using the units of each criterion.

2.2.1 Comparison with Regulatory Guide 1.86

Table 2.3 compares the results of this analysis with the average surface contamination levels of Regulatory Guide 1.86 (AEC 1974). The criteria in Regulatory Guide 1.86 are not dose-based and are stated in terms of surficial contamination levels ($dpm/100cm^2$). They do not address volumetric contamination levels and they do not specify the materials to which they apply.

The dose factors developed for this report do not, by themselves, specify surficial contamination levels for clearance. In order to compare the results of this analysis to the Regulatory Guide 1.86 acceptable contamination levels, it is necessary to assume some annual individual dose criterion. No annual individual dose level for clearance has been established by the NRC, but for purposes of this comparison a value of 10 µSv/y (1 mrem/y) has been used. While this dose criterion has not been established by regulation for clearance, it is the proposed criterion for the EC and the IAEA. Use of this value allows comparison across all sets of criteria.

The NRC clearance levels in the second column of Table 2.3 represent the results of this analysis expressed in units of $dpm/100cm^2$. They were calculated from the surficial dose factors in Table 2.2 using Equation 2.1. Consistent with the intended use of Regulatory Guide 1.86, the highest surficial critical-group dose factor from the four materials was used for each radionuclide.

$$\text{Clearance level} = (\text{dose criterion} \div \text{Dose Factor}_{\text{surficial}}) * 60{,}000 \qquad 2.1$$

where

Clearance level = derived clearance level expressed in Reg. Guide 1.86 units ($dpm/100cm^2$)

and

dose criterion = assumed annual individual dose criterion for clearance (10 µSv/y)
$\text{Dose Factor}_{\text{surficial}}$ = highest derived surficial dose factor from Table 2.2 (µSv/y per Bq/cm^2)
60,000 = constant for unit conversions

Table 2.3 Comparison of derived NRC surficial clearance levels with Regulatory Guide 1.86 acceptable contamination levels (across all materials)

Radionuclide	NRC (dpm/100 cm^2)	Reg. Guide 1.86 (dpm/100 cm^2)	Ratio NRC / Reg. Guide 1.86
H-3	1.3E+08	5000	3.E+04
C-14	1.6E+05	5000	3.E+01
Na-22	1.9E+02	5000	4.E-02
P-32	5.4E+05	5000	1.E+02
S-35	1.1E+07	5000	2.E+03
Cl-36	1.9E+04	5000	4.E+00
K-40	1.5E+03	5000	3.E-01
Ca-41	5.1E+05	5000	1.E+02
Ca-45	9.9E+05	5000	2.E+02
Cr-51	2.8E+04	5000	6.E+00
Mn-54	8.2E+02	5000	2.E-01
Fe-55	7.3E+07	5000	1.E+04
Co-57	1.8E+04	5000	4.E+00
Co-58	7.4E+02	5000	1.E-01
Fe-59	6.1E+02	5000	1.E-01
Ni-59	1.7E+08	5000	3.E+04
Co-60	2.8E+02	5000	6.E-02
Ni-63	6.2E+07	5000	1.E+04
Zn-65	3.7E+02	5000	7.E-02
Cu-67	3.4E+04	5000	7.E+00
Se-75	2.3E+03	5000	5.E-01
Sr-85	1.5E+03	5000	3.E-01
Sr-89	6.0E+05	5000	1.E+02
Sr-90	8.0E+03	1000	8.E+00
Y-91	2.0E+05	5000	4.E+01
Mo-93	7.0E+04	5000	1.E+01
Nb-93m	9.3E+06	5000	2.E+03
Nb-94	4.3E+02	5000	9.E-02
Nb-95	9.7E+02	5000	2.E-01
Zr-95	9.7E+02	5000	2.E-01
Tc-99	2.3E+04	5000	5.E+00
Ru-103	1.5E+03	5000	3.E-01
Ru-106	3.4E+03	5000	7.E-01
Ag-108m	4.3E+02	5000	9.E-02
Cd-109	1.8E+05	5000	4.E+01
Ag-110m	2.5E+02	5000	5.E-02
Sb-124	3.9E+02	5000	8.E-02
I-125	2.8E+04	100	3.E+02
Sb-125	1.7E+03	5000	3.E-01
I-129	1.2E+03	100	1.E+01
I-131	2.8E+03	1000	3.E+00
Ba-133	2.5E+03	5000	5.E-01
Cs-134	1.2E+02	5000	2.E-02
Cs-137	3.0E+02	5000	6.E-02
Ce-141	2.6E+04	5000	5.E+00
Ce-144	2.1E+04	5000	4.E+00
Pm-147	7.1E+06	5000	1.E+03

Table 2.3 Comparison of derived NRC surficial clearance levels with Regulatory Guide 1.86 acceptable contamination levels (across all materials)

Radionuclide	NRC (dpm/100 cm^2)	Reg. Guide 1.86 (dpm/100 cm^2)	Ratio NRC / Reg. Guide 1.86
Eu-152	6.3E+02	5000	1.E-01
Eu-154	5.8E+02	5000	1.E-01
Eu-155	6.6E+04	5000	1.E+01
Re-186	2.9E+05	5000	6.E+01
Ir-192	6.8E+02	5000	1.E-01
Pb-210	5.2E+02	5000	1.E-01
Po-210	1.4E+03	5000	3.E-01
Bi-210	2.3E+06	5000	5.E+02
Rn-222	8.2E+02	5000	2.E-01
Ra-223	3.9E+03	1000	4.E+00
Ra-224	1.2E+03	1000	1.E+00
Ac-225	5.0E+03	5000	1.E+00
Ra-225	4.4E+04	5000	9.E+00
Ra-226	4.0E+02	100	4.E+00
Ac-227	2.4E+02	100	2.E+00
Th-227	1.2E+04	5000	2.E+00
Th-228	5.5E+02	100	6.E+00
Ra-228	8.4E+02	100	8.E+00
Th-229	1.8E+02	5000	4.E-02
Th-230	1.2E+03	100	1.E+01
Pa-231	3.5E+02	100	4.E+00
Th-231	4.8E+06	5000	1.E+03
Th-232	2.8E+02	1000	3.E-01
Pa-233	5.3E+03	100	5.E+01
U-233	2.4E+03	5000	5.E-01
Th-234	9.6E+04	5000	2.E+01
U-234	2.4E+03	5000	5.E-01
U-235	2.5E+03	5000	5.E-01
Np-237	4.2E+01	100	4.E-01
Pu-238	1.1E+03	100	1.E+01
U-238	2.7E+03	5000	5.E-01
Pu-239	1.0E+03	100	1.E+01
Pu-240	1.0E+03	100	1.E+01
Pu-241	6.4E+04	100	6.E+02
Am-241	7.0E+02	100	7.E+00
Cm-242	1.8E+04	100	2.E+02
Pu-242	1.1E+03	100	1.E+01
Cm-244	1.3E+03	100	1.E+01

The Regulatory Guide 1.86 surface contamination levels are taken from Table 1 of Regulatory Guide 1.86. The ratios of the results of this analysis to the values in Regulatory Guide 1.86 vary over a wide range. Where this ratio is plus-or-minus an order of magnitude (0.1 to 10) the two sets of criteria can be considered in general agreement. The ratio is greater than 1.0 for 50 out of the 85 radionuclides listed in Table 2.3., indicating that the current analysis produces clearance levels less restrictive than Regulatory Guide 1.86 for these radionuclides. Radionuclides in this

group include all the low-energy beta emitters and most of the transuranic radionuclides. For the remaining 35 radionuclides the ratio is less than 1.0, indicating that the results of this analysis produce clearance levels more restrictive than Regulatory Guide 1.86. Radionuclides in this group include all the highest energy gamma-emitting radionuclides (e.g., Co-60). There are 10 radionuclides for which this analysis produces clearance levels that are more than a factor of 10 more restrictive than Regulatory Guide 1.86.

2.2.2 Comparison with the Environmental Protection Agency

The EPA has sponsored an analysis of doses from clearance and recycle of scrap steel (EPA 1997a). The results of this analysis are currently available only in draft form. No clearance levels have yet been established as regulations by the EPA.

The draft EPA dose factors were developed using an approach that is similar to the one presented in this report. They are based on estimating annual doses to individuals under a variety of scenarios formulated to represent standard industry practices in the United States. Dose factors address only recycle of volumetrically distributed contamination, and results are expressed as normalized annual individual dose factors in units of mrem/year per pCi/g. No annual dose level is specified. The draft published results are limited to clearance of iron and steel.

The EPA results are expressed as normalized annual dose factors, so they can be directly compared to the results in this report. No unit conversions or assumptions regarding an annual individual dose criterion are required. Table 2.4 presents this comparison for the 40 radionuclides in common between the two analyses. The NRC dose factors in the second column of Table 2.4 are mass-based critical-group dose factors for steel recycle taken from Table 2.1 of this report, expressed in conventional units. The EPA dose factors are taken from Table 7-1 of EPA (1997a). Both sets of values are expressed as dose factors, which are inversely proportional to the clearance levels that would likely be embodied in a clearance rule.

The ratio of EPA values to NRC values in the fourth column of Table 2.4 shows a much narrower range than the comparison with Regulatory Guide 1.86 clearance levels. For 36 of the 40 radionuclides in common, this ratio is plus-or-minus an order of magnitude (0.1 to 10) indicating that the two sets of criteria can be considered in general agreement. Where the ratio is greater than 10 (e.g., C-14, Sr-90), the NRC dose factors from this analysis would indicate a clearance level that is less restrictive than the EPA values. Where the ratio is less than 0.1 (Tc-99, Cs-137), the NRC values would be more restrictive.

2.2.3 Comparison with the European Commission

The EC has sponsored an analysis of doses from clearance and recycle of scrap steel, copper, and aluminum (EC 1998). The results of this analysis are currently available as recommended clearance levels for member states of the European Union for recycling of metals originating from the dismantling of nuclear facilities.

Table 2.4 Comparison of NRC mass-based steel recycle critical-group dose factors with EPA values

Radionuclide	NRC (mrem/y per pCi/g)	EPA (mrem/y per pCi/g)	Ratio EPA / NRC
H-3	2.4E-06	-	-
C-14	1.0E-05	8.7.E-04	8.E+01
Na-22	1.5E+00	-	-
P-32	4.8E-04	-	-
S-35	2.8E-05	-	-
Cl-36	1.0E-02	-	-
K-40	1.9E-01	-	-
Ca-41	4.9E-04	-	-
Ca-45	3.0E-04	-	-
Cr-51	9.1E-03	-	-
Mn-54	3.2E-01	2.0E-01	6.E-01
Fe-55	3.8E-06	6.7E-06	2.E+00
Co-57	1.4E-02	-	-
Co-58	3.5E-01	-	-
Fe-59	4.2E-01	-	-
Ni-59	1.6E-06	4.4E-06	3.E+00
Co-60	9.4E-01	9.0E-01	1.E+00
Ni-63	4.5E-06	1.1E-05	2.E+00
Zn-65	7.9E-01	9.6E-02	1.E-01
Cu-67	7.7E-03	-	-
Se-75	1.3E-01	-	-
Sr-85	1.7E-01	-	-
Sr-89	4.3E-04	-	-
Sr-90	3.8E-02	1.5E+00	4.E+01
Y-91	1.3E-03	-	-
Mo-93	5.2E-05	5.6E-05	1.E+00
Nb-93m	3.1E-05	-	-
Nb-94	6.1E-01	4.7E-01	8.E-01
Nb-95	2.7E-01	-	-
Zr-95	2.7E-01	-	-
Tc-99	7.0E-04	2.1E-05	3.E-02
Ru-103	1.7E-01	-	-
Ru-106	7.6E-02	5.2E-02	7.E-01
Ag-108m	6.0E-01	-	-
Cd-109	1.6E-03	-	-
Ag-110m	1.0E+00	6.3E-01	6.E-01
Sb-124	6.7E-01	-	-
I-125	1.0E-02	-	-
Sb-125	1.5E-01	6.4E-02	4.E-01
I-129	2.3E-01	7.9E-01	4.E+00
I-131	9.3E-02	-	-
Ba-133	1.0E-01	-	-
Cs-134	2.4E+00	2.5E-01	1.E-01
Cs-137	9.5E-01	8.9E-02	9.E-02
Ce-141	1.0E-02	-	-
Ce-144	1.2E-02	1.8E-02	1.E+00
Pm-147	4.2E-05	1.4E-04	3.E+00
Eu-152	4.1E-01	3.4E-01	8.E-01
Eu-154	4.5E-01	-	-

Table 2.4 Comparison of NRC mass-based steel recycle critical-group dose factors with EPA values

Radionuclide	NRC (mrem/y per pCi/g)	EPA (mrem/y per pCi/g)	Ratio EPA / NRC
Eu-155	3.9E-03	-	-
Re-186	9.1E-04	-	-
Ir-192	4.4E-01	-	-
Pb-210	5.7E-01	3.1E+00	5.E+00
Po-210	2.2E-01	-	-
Bi-210	1.2E-04	-	-
Rn-222	3.2E-01	-	-
Ra-223	6.7E-02	-	-
Ra-224	2.3E-01	-	-
Ac-225	5.3E-02	-	-
Ra-225	6.7E-03	-	-
Ra-226	6.4E-01	6.3E-01	1.E+00
Ac-227	1.3E+00	8.0E+00	6.E+00
Th-227	2.2E-02	-	-
Th-228	4.7E-01	1.4E+00	3.E+00
Ra-228	3.1E-01	3.7E-01	1.E+00
Th-229	1.6E+00	4.4E+00	3.E+00
Th-230	2.4E-01	6.4E-01	3.E+00
Pa-231	8.3E-01	2.5E+00	3.E+00
Th-231	5.5E-05	-	-
Th-232	1.1E+00	2.8E+00	3.E+00
Pa-233	4.9E-02	-	-
U-233	1.2E-01	-	-
Th-234	2.7E-03	-	-
U-234	1.2E-01	3.1E-01	3.E+00
U-235	1.2E-01	3.3E-01	3.E+00
Np-237	7.4E+00	1.5E+00	2.E-01
Pu-238	2.6E-01	6.8E-01	3.E+00
U-238	1.1E-01	2.9E-01	3.E+00
Pu-239	2.8E-01	7.3E-01	3.E+00
Pu-240	2.8E-01	7.3E-01	3.E+00
Pu-241	4.5E-03	1.2E-02	3.E+00
Am-241	4.2E-01	1.2E+00	3.E+00
Cm-242	1.6E-02	-	-
Pu-242	2.7E-01	6.9E-01	3.E+00
Cm-244	2.3E-01	6.8E-01	3.E+00

The EC recommended clearance levels were developed using an approach that is similar to the one presented in this report in that they are based on estimating annual doses to individuals under a variety of scenarios formulated to represent standard industry practices. However, they are based on European industry practices rather than the industry in the United States. Clearance levels address both volumetrically and surficially distributed contamination. The clearance levels are based on an annual individual dose level of 10 μSv/y, and are expressed in units of Bq/g or Bq/cm^2, as appropriate.

Table 2.5 compares the results in this report to the recommended EC clearance levels for the 62 radionuclides they have in common. The EC clearance levels in Table 2.5 were taken from Table 3-1 of EC (1998), and represent the most restrictive clearance level for each radionuclide among the three metals analyzed by the EC (steel, copper, and aluminum).

The NRC clearance levels in the Table 2.5 represent the results of this analysis expressed in units of Bq/g or Bq/cm^2, as appropriate for comparison. Mass-based clearance levels were calculated from the dose factors in Table 2.1 and surficial clearance levels were calculated from the dose factors in Table 2.2 of this report. In each case, the most restrictive dose factor among the three metals was used for each radionuclide. Equation 2.2 was used to calculate a clearance level for comparison with the EC values.

$$\text{Clearance level} = \text{Dose criterion} \div \text{Dose Factor} \qquad 2.2$$

where

Clearance level = derived clearance level expressed in EC units (Bq/g or Bq/cm^2)

and

Dose criterion = annual individual dose criterion (10 µSv/y)
Dose Factor = dose factor from Table 2.1 or 2.2 (µSv/y per Bq/gor µSv/y per Bq/cm^2)

The ratio of the results of this analysis to the EC clearance levels shows a general level of agreement that is closer than with Regulatory Guide 1.86 but not as close as with the draft EPA dose factors. Where this ratio is plus-or-minus an order of magnitude (0.1 to 10) the two sets of criteria can be considered in general agreement. For each radionuclide, the ratio differs between the mass-based and the surficial clearance level. This is because the derived surficial dose factors in this report are calculated from the mass-based dose factors using a surface-to-mass ratio appropriate to each material. The EC surficial clearance levels are based on a set of scenarios different from those used for their mass-based clearance level. A surface-to-mass ratio was not explicitly addressed in the EC analysis. For both mass-based and surficial clearance levels, where the ratio is greater than 1.0 the NRC values would indicate a clearance level that is less restrictive than the EC values. Where the ratio is less than 1.0 the NRC values would be more restrictive. For those radionuclides where the ratio is greater than a factor of 10 different, the derived clearance levels in this analysis are more restrictive for all radionuclides except one (H-3).

2.2.4 Comparison with the International Atomic Energy Agency

The IAEA has sponsored development of draft clearance levels intended for application to all solid materials irrespective of the disposition of the materials (IAEA 1996). The results of the analysis are currently available only in draft form. Final recommended clearance levels have not yet been established by the IAEA.

Table 2.5 Comparison of derived NRC clearance levels with European Commission values (all metals)

	Mass clearance levels				Surficial clearance levels		
Radionuclide	NRC (Bq/g)	EC (Bq/g)	Ratio NRC / EC	Radionuclide	NRC (Bq/cm^2)	EC (Bq/cm^2)	Ratio NRC / EC
H-3	2.E+04	1000	2.E+01	H-3	2.E+04	100000	2.E-01
C-14	6.E+02	100	6.E+00	C-14	7.E+02	1000	7.E-01
Na-22	2.E-02	1	2.E-02	Na-22	3.E-02	10	3.E-03
P-32	8.E+01	-	-	P-32	9.E+01	-	-
S-35	1.E+03	1000	1.E+00	S-35	2.E+03	1000	2.E+00
Cl-36	4.E+00	10	4.E-01	Cl-36	5.E+00	100	5.E-02
K-40	2.E-01	1	2.E-01	K-40	3.E-01	100	3.E-03
Ca-41	8.E+01	-	-	Ca-41	1.E+02	-	-
Ca-45	1.E+02	1000	1.E-01	Ca-45	2.E+02	100	2.E+00
Cr-51	4.E+00	-	-	Cr-51	5.E+00	-	-
Mn-54	1.E-01	1	1.E-01	Mn-54	1.E-01	10	1.E-02
Fe-55	1.E+04	10000	1.E+00	Fe-55	1.E+04	10000	1.E+00
Co-57	3.E+00	10	3.E-01	Co-57	3.E+00	100	3.E-02
Co-58	1.E-01	1	1.E-01	Co-58	1.E-01	10	1.E-02
Fe-59	9.E-02	-	-	Fe-59	1.E-01	-	-
Ni-59	2.E+04	10000	2.E+00	Ni-59	3.E+04	10000	3.E+00
Co-60	4.E-02	1	4.E-02	Co-60	5.E-02	10	5.E-03
Ni-63	8.E+03	10000	8.E-01	Ni-63	1.E+04	10000	1.E+00
Zn-65	5.E-02	1	5.E-02	Zn-65	6.E-02	100	6.E-04
Cu-67	5.E+00	-	-	Cu-67	6.E+00	-	-
Se-75	3.E-01	1	3.E-01	Se-75	4.E-01	100	4.E-03
Sr-85	2.E-01	1	2.E-01	Sr-85	2.E-01	100	2.E-03
Sr-89	9.E+01	-	-	Sr-89	1.E+02	-	-
Sr-90	1.E+00	10	1.E-01	Sr-90	1.E+00	10	1.E-01
Y-91	3.E+01	10	3.E+00	Y-91	3.E+01	100	3.E-01
Mo-93	7.E+02	100	7.E+00	Mo-93	9.E+02	1000	9.E-01
Nb-93m	1.E+03	1000	1.E+00	Nb-93m	2.E+03	10000	2.E-01
Nb-94	6.E-02	1	6.E-02	Nb-94	7.E-02	10	7.E-03
Nb-95	1.E-01	-	-	Nb-95	2.E-01	-	-
Zr-95	1.E-01	1	1.E-01	Zr-95	2.E-01	10	2.E-02
Tc-99	5.E+01	100	5.E-01	Tc-99	7.E+01	1000	7.E-02
Ru-103	2.E-01	-	-	Ru-103	3.E-01	-	-
Ru-106	5.E-01	1	5.E-01	Ru-106	6.E-01	10	6.E-02
Ag-108m	6.E-02	1	6.E-02	Ag-108m	7.E-02	10	7.E-03
Cd-109	2.E+01	10	2.E+00	Cd-109	3.E+01	100	3.E-01
Ag-110m	4.E-02	1	4.E-02	Ag-110m	4.E-02	10	4.E-03
Sb-124	6.E-02	1	6.E-02	Sb-124	6.E-02	10	6.E-03
I-125	4.E+00	1	4.E+00	I-125	5.E+00	100	5.E-02
Sb-125	2.E-01	10	2.E-02	Sb-125	3.E-01	100	3.E-03
I-129	2.E-01	1	2.E-01	I-129	2.E-01	10	2.E-02
I-131	4.E-01	-	-	I-131	5.E-01	-	-
Ba-133	4.E-01	-	-	Ba-133	4.E-01	-	-
Cs-134	2.E-02	1	2.E-02	Cs-134	2.E-02	10	2.E-03
Cs-137	4.E-02	1	4.E-02	Cs-137	5.E-02	100	5.E-04
Ce-141	4.E+00	-	-	Ce-141	4.E+00	-	-
Ce-144	3.E+00	10	3.E-01	Ce-144	4.E+00	10	4.E-01
Pm-147	9.E+02	10000	9.E-02	Pm-147	1.E+03	1000	1.E+00

Table 2.5 Comparison of derived NRC clearance levels with European Commission values (all metals)

Mass clearance levels				Surficial clearance levels			
Radionuclide	NRC (Bq/g)	EC (Bq/g)	Ratio NRC / EC	Radionuclide	NRC (Bq/cm^2)	EC (Bq/cm^2)	Ratio NRC / EC
Eu-152	9.E-02	1	9.E-02	Eu-152	1.E-01	10	1.E-02
Eu-154	8.E-02	1	8.E-02	Eu-154	1.E-01	10	1.E-02
Eu-155	9.E+00	10	9.E-01	Eu-155	1.E+01	1000	1.E-02
Re-186	4.E+01	-	-	Re-186	5.E+01	-	-
Ir-192	8.E-02	1	8.E-02	Ir-192	1.E-01	10	1.E-02
Pb-210	7.E-02	1	7.E-02	Pb-210	9.E-02	1	9.E-02
Po-210	2.E-01	1	2.E-01	Po-210	2.E-01	0.1	2.E+00
Bi-210	3.E+02	-	-	Bi-210	4.E+02	-	-
Rn-222	1.E-01	-	-	Rn-222	1.E-01	-	-
Ra-223	6.E-01	-	-	Ra-223	6.E-01	-	-
Ra-224	2.E-01	-	-	Ra-224	2.E-01	-	-
Ac-225	7.E-01	-	-	Ac-225	8.E-01	-	-
Ra-225	6.E+00	-	-	Ra-225	7.E+00	-	-
Ra-226	6.E-02	1	6.E-02	Ra-226	7.E-02	0.1	7.E-01
Ac-227	3.E-02	-	-	Ac-227	4.E-02	-	-
Th-227	2.E+00	-	-	Th-227	2.E+00	-	-
Th-228	8.E-02	1	8.E-02	Th-228	9.E-02	0.1	9.E-01
Ra-228	1.E-01	1	1.E-01	Ra-228	1.E-01	1	1.E-01
Th-229	2.E-02	1	2.E-02	Th-229	3.E-02	0.1	3.E-01
Th-230	2.E-01	1	2.E-01	Th-230	2.E-01	0.1	2.E+00
Pa-231	4.E-02	1	4.E-02	Pa-231	6.E-02	0.1	6.E-01
Th-231	7.E+02	-	-	Th-231	8.E+02	-	-
Th-232	3.E-02	1	3.E-02	Th-232	5.E-02	0.1	5.E-01
Pa-233	8.E-01	-	-	Pa-233	9.E-01	-	
U-233	3.E-01	1	3.E-01	U-233	4.E-01	1	4.E-01
Th-234	1.E+01	-	-	Th-234	2.E+01	-	-
U-234	3.E-01	1	3.E-01	U-234	4.E-01	1	4.E-01
U-235	3.E-01	1	3.E-01	U-235	4.E-01	1	4.E-01
Np-237	5.E-03	1	5.E-03	Np-237	7.E-03	0.1	7.E-02
Pu-238	1.E-01	1	1.E-01	Pu-238	2.E-01	0.1	2.E+00
U-238	3.E-01	1	3.E-01	U-238	4.E-01	1	4.E-01
Pu-239	1.E-01	1	1.E-01	Pu-239	2.E-01	0.1	2.E+00
Pu-240	1.E-01	1	1.E-01	Pu-240	2.E-01	0.1	2.E+00
Pu-241	8.E+00	10	8.E-01	Pu-241	1.E+01	10	1.E+00
Am-241	9.E-02	1	9.E-02	Am-241	1.E-01	0.1	1.E+00
Cm-242	2.E+00	10	2.E-01	Cm-242	3.E+00	1	3.E+00
Pu-242	1.E-01	1	1.E-01	Pu-242	2.E-01	0.1	2.E+00
Cm-244	2.E-01	1	2.E-01	Cm-244	2.E-01	0.1	2.E+00

The draft IAEA clearance levels were developed using an approach that is different from the one presented in this report. Rather than evaluate a set of scenarios representing specific industry practices, the IAEA reviewed several IAEA and other studies that included a variety of scenarios, materials, and radionuclides. In the IAEA approach, radionuclides were sorted into bins

representing orders of magnitude of the clearance levels. The logarithmic midpoint of each bin is treated as the single value of the clearance level for all radionuclides in each bin.

The IAEA clearance levels address both volumetrically and surficially distributed contamination. The surficial clearance levels are based on a comparative review of mass contamination and surface contamination studies. Based on this review, the IAEA chose to set surficial clearance levels in units of Bq/cm^2 at the same numerical value as the mass-based clearance levels in Bq/g. This is equivalent to assuming that all materials have a surface-to-mass ratio of 1 cm^2/g. As with the EC, clearance levels are based on an annual individual dose criterion of 10 μSv/y.

Table 2.6 compares the results in this analysis to the draft IAEA clearance levels for the 48 radionuclides they have in common. The IAEA clearance levels were taken from Table I of IAEA (1996).

The NRC clearance levels in Table 2.6 are the results of this analysis expressed in units of Bq/g or Bq/cm^2, as appropriate. Mass-based clearance levels were calculated from the dose factors in Table 2.1 and surficial clearance levels were calculated form the dose factors in Table 2.2 of this report. In each case, the most restrictive dose factor among the four materials analyzed was used for each radionuclide, because the IAEA clearance levels are intended to be applied to all solid materials. Equation 2.2 was used to calculate a clearance level for comparison with the IAEA values.

The ratio of NRC derived clearance levels to IAEA clearance levels shows a degree of agreement that is similar to that for the EC values. Where this ratio is plus-or-minus an order of magnitude (0.1 to 10) the two sets of criteria can be considered in general agreement. For both mass-based and surficial clearance levels, where the ratio is greater than 1.0 the NRC values indicate a clearance level that is less restrictive than the EC values. Where the ratio is less than 1.0 the NRC values are more restrictive. Similar to the EC comparison, for those radionuclides where the ratio is greater than a factor of 10 different, the derived clearance levels in this analysis are more restrictive for all radionuclides except one (Fe-55).

Table 2.6 Comparison of derived NRC clearance levels with IAEA values (all materials)

Mass clearance levels				Surficial clearance levels			
Radionuclide	NRC (Bq/g)	IAEA (Bq/g)	Ratio NRC / IAEA	Radionuclide	NRC (Bq/cm^2)	IAEA (Bq/cm^2)	Ratio NRC / IAEA
H-3	1.1E+03	3000	4.E-01	H-3	2.1E+04	3000	7.E+00
C-14	6.3E-01	300	2.E-03	C-14	2.7E+01	300	9.E-02
Na-22	2.4E-02	-	-	Na-22	3.2E-02	-	-
P-32	7.3E+01	300	2.E-01	P-32	9.0E+01	300	3.E-01
S-35	1.3E+03	3000	4.E-01	S-35	1.8E+03	3000	6.E-01
Cl-36	6.3E-02	300	2.E-04	Cl-36	3.1E+00	300	1.E-02
K-40	1.9E-01	-	-	K-40	2.5E-01	-	-
Ca-41	2.1E+00	-	-	Ca-41	8.5E+01	-	-
Ca-45	1.2E+02	3000	4.E-02	Ca-45	1.6E+02	3000	5.E-02
Cr-51	4.0E+00	30	1.E-01	Cr-51	4.7E+00	30	2.E-01
Mn-54	1.2E-01	0.3	4.E-01	Mn-54	1.4E-01	0.3	5.E-01
Fe-55	2.9E+03	300	1.E+01	Fe-55	1.2E+04	300	4.E+01
Co-57	1.5E+00	30	5.E-02	Co-57	3.1E+00	30	1.E-01
Co-58	1.0E-01	3	3.E-02	Co-58	1.2E-01	3	4.E-02
Fe-59	8.6E-02	3	3.E-02	Fe-59	1.0E-01	3	3.E-02
Ni-59	1.4E+03	-	-	Ni-59	2.8E+04	-	-
Co-60	3.9E-02	0.3	1.E-01	Co-60	4.6E-02	0.3	2.E-01
Ni-63	1.0E+03	3000	3.E-01	Ni-63	1.0E+04	3000	3.E+00
Zn-65	4.7E-02	0.3	2.E-01	Zn-65	6.2E-02	0.3	2.E-01
Cu-67	3.5E+00	-	-	Cu-67	5.7E+00	-	-
Se-75	2.8E-01	-	-	Se-75	3.8E-01	-	-
Sr-85	2.1E-01	-	-	Sr-85	2.5E-01	-	-
Sr-89	7.0E+01	300	2.E-01	Sr-89	1.0E+02	300	3.E-01
Sr-90	9.8E-01	3	3.E-01	Sr-90	1.3E+00	3	4.E-01
Y-91	2.3E+01	-	-	Y-91	3.4E+01	-	-
Mo-93	2.6E-01	-	-	Mo-93	1.2E+01	-	-
Nb-93m	4.9E+02	-	-	Nb-93m	1.6E+03	-	-
Nb-94	3.4E-02	0.3	1.E-01	Nb-94	7.2E-02	0.3	2.E-01
Nb-95	1.4E-01	-	-	Nb-95	1.6E-01	-	-
Zr-95	1.4E-01	-	-	Zr-95	1.6E-01	-	-
Tc-99	8.4E-02	300	3.E-04	Tc-99	3.9E+00	300	1.E-02
Ru-103	2.1E-01	-	-	Ru-103	2.5E-01	-	-
Ru-106	4.8E-01	3	2.E-01	Ru-106	5.7E-01	3	2.E-01
Ag-108m	5.8E-02	-	-	Ag-108m	7.2E-02	-	-
Cd-109	2.3E+01	300	8.E-02	Cd-109	3.1E+01	300	1.E-01
Ag-110m	3.5E-02	0.3	1.E-01	Ag-110m	4.1E-02	0.3	1.E-01
Sb-124	5.5E-02	0.3	2.E-01	Sb-124	6.5E-02	0.3	2.E-01
I-125	3.7E+00	30	1.E-01	I-125	4.7E+00	30	2.E-01
Sb-125	2.5E-01	-	-	Sb-125	2.9E-01	-	-
I-129	4.2E-03	30	1.E-04	I-129	2.0E-01	30	7.E-03
I-131	3.6E-01	3	1.E-01	I-131	4.7E-01	3	2.E-01
Ba-133	3.6E-01	-	-	Ba-133	4.2E-01	-	-
Cs-134	1.5E-02	0.3	5.E-02	Cs-134	2.0E-02	0.3	7.E-02
Cs-137	3.9E-02	0.3	1.E-01	Cs-137	5.1E-02	0.3	2.E-01
Ce-141	2.9E+00	-	-	Ce-141	4.3E+00	-	-
Ce-144	3.0E+00	30	1.E-01	Ce-144	3.6E+00	30	1.E-01
Pm-147	3.6E+02	3000	1.E-01	Pm-147	1.2E+03	3000	4.E-01
Eu-152	9.0E-02	0.3	3.E-01	Eu-152	1.1E-01	0.3	4.E-01

Table 2.6 Comparison of derived NRC clearance levels with IAEA values (all materials)

Mass clearance levels				Surficial clearance levels			
Radionuclide	NRC (Bq/g)	IAEA (Bq/g)	Ratio NRC / IAEA	Radionuclide	NRC (Bq/cm^2)	IAEA (Bq/cm^2)	Ratio NRC / IAEA
Eu-154	8.2E-02	-	-	Eu-154	9.6E-02	-	-
Eu-155	4.1E+00	-	-	Eu-155	1.1E+01	-	-
Re-186	3.3E+01	-	-	Re-186	4.8E+01	-	-
Ir-192	8.4E-02	3	3.E-02	Ir-192	1.1E-01	3	4.E-02
Pb-210	6.5E-02	0.3	2.E-01	Pb-210	8.7E-02	0.3	3.E-01
Po-210	1.7E-01	3	6.E-02	Po-210	2.3E-01	3	8.E-02
Bi-210	1.0E+02	-	-	Bi-210	3.8E+02	-	-
Rn-222	9.5E-02	-	-	Rn-222	1.4E-01	-	-
Ra-223	5.2E-01	-	-	Ra-223	6.5E-01	-	-
Ra-224	1.3E-01	-	-	Ra-224	1.9E-01	-	-
Ac-225	6.5E-01	-	-	Ac-225	8.3E-01	-	-
Ra-225	1.9E+00	-	-	Ra-225	7.3E+00	-	-
Ra-226	1.9E-02	0.3	6.E-02	Ra-226	6.7E-02	0.3	2.E-01
Ac-227	1.2E-02	-	-	Ac-227	3.9E-02	-	-
Th-227	9.0E-01	-	-	Th-227	2.0E+00	-	-
Th-228	3.7E-02	0.3	1.E-01	Th-228	9.2E-02	0.3	3.E-01
Ra-228	1.1E-01	0.3	4.E-01	Ra-228	1.4E-01	0.3	5.E-01
Th-229	7.4E-03	-	-	Th-229	3.1E-02	-	-
Th-230	4.5E-02	0.3	2.E-01	Th-230	2.0E-01	0.3	7.E-01
Pa-231	4.8E-03	-	-	Pa-231	5.9E-02	-	-
Th-231	2.5E+02	-	-	Th-231	7.9E+02	-	-
Th-232	7.6E-03	0.3	3.E-02	Th-232	4.6E-02	0.3	2.E-01
Pa-233	7.4E-01	-	-	Pa-233	8.9E-01	-	-
U-233	6.0E-02	-	-	U-233	3.9E-01	-	-
Th-234	1.3E+01	-	-	Th-234	1.6E+01	-	-
U-234	6.0E-02	0.3	2.E-01	U-234	4.0E-01	0.3	1.E+00
U-235	7.1E-02	0.3	2.E-01	U-235	4.1E-01	0.3	1.E+00
Np-237	1.4E-04	0.3	5.E-04	Np-237	7.0E-03	0.3	2.E-02
Pu-238	5.8E-02	-	-	Pu-238	1.8E-01	-	-
U-238	7.7E-02	0.3	3.E-01	U-238	4.5E-01	0.3	1.E+00
Pu-239	4.5E-02	0.3	1.E-01	Pu-239	1.7E-01	0.3	6.E-01
Pu-240	4.5E-02	0.3	2.E-01	Pu-240	1.7E-01	0.3	6.E-01
Pu-241	5.8E-01	30	2.E-02	Pu-241	1.1E+01	30	4.E-01
Am-241	3.0E-02	0.3	1.E-01	Am-241	1.2E-01	0.3	4.E-01
Cm-242	9.4E-01	-	-	Cm-242	3.1E+00	-	-
Pu-242	4.7E-02	-	-	Pu-242	1.8E-01	-	-
Cm-244	6.4E-02	0.3	2.E-01	Cm-244	2.1E-01	0.3	7.E-01

3 EVALUATION OF DIRECT REUSE OF EQUIPMENT

An analysis of the direct reuse of cleared equipment is presented. This analysis differs from recycle scenarios in three ways: (1) surficial contamination is assumed, rather than volumetric, (2) there is no processing of the equipment prior to use, and (3) the analysis is independent of equipment material.

A single scenario involving the driver of a cleared truck was analyzed, as this scenario was determined to bound all other equipment reuse scenarios. The evaluation resulted in realistic estimates of radionuclide-specific dose factors for an average member of the exposed group. The analysis was conducted on a probabilistic basis, and the mean of the dose factor distribution was selected to represent the dose to an average member of the exposed group.

Mean dose factors range from a high of 1.7E+02 µSv/y per Bq/cm^2 (0.6 mrem/y per pCi/cm^2) for Th-229 to a low of 1E-05 µSv/y per Bq/cm^2 (4E-08 mrem/y per pCi/cm^2) for H-3. The high mean dose factor of Th-229 (and also Ac-227 and Th-232) is attributed to the inhalation exposure pathway and a relatively high inhalation dose conversion factor. Other high reuse scenario mean dose factors (e.g., for Co-60 and Ag-110m) result from the external exposure pathway. Approximately one-third of the mean dose factors are greater than 10 µSv/y per Bq/cm^2 (0.04 mrem/y per pCi/cm^2), one-third are between 0.01–10 µSv/y per Bq/cm^2 (4E-05–0.04 mrem/y per pCi/cm^2), and the remaining one-third are less than 0.01 µSv/y per Bq/cm^2 (4E-05 mrem/y per pCi/cm^2). These equipment reuse dose factors are less restrictive than comparable recycle dose factors described later in the report.

The purpose of this section is to present an evaluation of the limiting dose consequences of immediate reuse of cleared equipment with residual radioactivity on its surface (*direct reuse of equipment*). As with recycle, direct reuse of equipment could result in an infinite number of exposure scenarios, from the reuse of items as small as hand tools, to very large items such as trucks or other vehicles. Reuse could also involve the one-time use of a piece of equipment for a very short duration, or long-term use for a year or more. Scenarios involving reuse of land or a building are outside the scope of this evaluation, as they are addressed elsewhere (i.e., NUREG/CR-5512 [Kennedy and Strenge 1992] or NUREG-1500 [NRC 1994b]).

The analysis of equipment reuse differs from the analysis of recycle (Section 4) primarily in three respects: surficial contamination is assumed, rather than volumetric; there is no processing of the equipment after clearance from the licensed facility; and the analysis is independent of equipment material. Also, the goal of the equipment reuse scenario analysis is different than that of the recycle analyses described in later sections of this report. The goal of the reuse scenario analysis is to realistically analyze a bounding scenario for reuse of cleared equipment. Thus the conceptual setting of the reuse exposure situation represents conditions of reuse that are judged to be bounding for all equipment reuse scenarios, however the parameter values used to analyze the scenario are realistically chosen.

The following sections contain a description of equipment reuse scenarios, including the bounding scenario analyzed. This includes a description of the exposure pathways included in the bounding scenario evaluation and the equations used to analyze the doses for the scenario. Finally, a discussion of the probabilistic parameter values used in the evaluation, a listing of

selected results from the distribution of dose factors from the equipment reuse scenario analysis, and a comparison of those results to the recycle analysis results are included.

3.1 Direct Reuse Scenario Description

In order to address the possible range of unrestricted reuse scenarios, the types of items likely to be reused were identified. These items fall into the following categories:

- small hand tools and other hand-held items such as drills, saws, and buffers
- electrical items such as motors, pumps, and generators
- office equipment (although these items should not be contaminated)
- construction equipment such as scaffolding, noise or dust-control barriers, wheelbarrows
- large equipment such as trucks and other vehicles.

An initial qualitative screening resulted in the judgment that work related use of a reused item would result in much longer potential durations of exposure, with other factors being the same, as for home or residential reuse. Home use of an item from the laboratory or industrial setting of a Nuclear Regulatory Commission (NRC) licensee would likely be for an intermittent or short duration, as opposed to the possible full-day, work-related reuse of an item, over a period of time equivalent to a full workyear. Therefore, work-related settings were emphasized.

It is likely that equipment that is cleared for direct reuse will contain surficial contamination rather than volumetric contamination, thus, only surficial contamination reuse scenarios were analyzed. In screening analyses conducted for this assessment, two scenarios involving reuse of equipment containing surficial contamination were analyzed in detail. Of these two scenarios, only the scenario resulting in consistently higher dose factors for all radionuclides is included in this report. This scenario was developed to represent the critical group scenario for all potential scenarios involving surficial contamination, including hand tools and other equipment. The critical group scenario consists of the reuse of a large piece of equipment (a truck). This bounding scenario is the reuse scenario discussed in the remainder of this section.

The critical group in this scenario is the group of individuals that drive trucks that have been cleared from NRC licensed facilities. The individual receptor in the reuse scenario is a truck driver. This individual is exposed externally to radiation from residual radioactivity on the inside of the truck cab, as well as internally to contamination resuspended from the surface and to inadvertent ingestion of surface radioactivity. The dose measure is the total effective dose equivalent (TEDE), which is defined in 10CFR20.1003 as the sum of the (external) deep-dose equivalent and the (internal) committed effective dose equivalent (EDE).

Based on assumed good health physics practices at NRC licensed facilities, removable surface contamination has been removed during decontamination procedures prior to final survey and clearance. Furthermore, to simplify the analysis, it is assumed that the residual surface radioactivity is uniformly distributed on the interior surface of the truck cab.

There are three exposure pathways included in the evaluation of the reuse scenario: external radiation exposure, inhalation exposure, and secondary ingestion exposure. External exposure to penetrating radiation would result from radionuclides on the inside surface of the truck cab. The inhalation pathway is included because a worker inside the truck cab could inhale contamination that has been resuspended into the air. This resuspension could either be caused by air flowing through the cab of the truck or other mechanical disturbance of residual surface radioactivity. The third exposure pathway is secondary ingestion. Secondary ingestion refers to the ingestion of removable residual surface radioactivity inside the truck cab after transfer to hands, food, or other items entering the mouth. Even more than inhalation of resuspended contamination, secondary ingestion is a poorly defined pathway that is not easily calculated by a detailed description of the mechanisms involved. The dose from this exposure pathway is calculated using an approach similar to the inhalation pathway, where the residual surface radioactivity is related to intake by means of a lumped parameter that accounts for the combined effects of several poorly understood processes. The lumped parameter represents the effective transfer rate, which is a parameter that estimates the area of contamination that is ingested per hour (in units of area/time).

3.2 Exposure Pathways

The modeled concentration of radioactive material on the surface of the truck cab is a unit concentration (1 pCi/cm^2) at the time of clearance from the nuclear facility. The following equations were evaluated separately for each radionuclide in the analysis. Therefore, parameters such as concentration, decay factors, decay constants, and dose conversion factors are not explicitly subscripted for each radionuclide.

The surface concentration at the time the reuse begins is calculated by Equation 3.1. This concentration is slightly less than the unit concentration assumed at the time of clearance.

$$C_{0,sc} = C_{x,sc}\, e^{-\lambda_r t_s} \qquad 3.1$$

where

$C_{0,sc}$ = surface concentration on the reused item at the time the scenario begins (pCi/cm^2)

and

$C_{x,sc}$ = surface concentration on the reused item at the time of clearance (pCi/cm^2)

λ_r = radioactive decay constant (d^{-1})

t_s = delay time from clearance of item from nuclear facility to time scenario begins (d)

The annual dose for the reuse scenario is calculated for the 1-year period immediately following clearance and the short delay time, t_s. The bounding reuse scenario involves the use of a single truck over an entire 1-year period, so radioactive decay over that period is appropriate to incorporate. This is done by the use of a decay factor that consists of the integrated decay over the time from beginning to end of use, as shown in Equation 3.2.

$$DK = \frac{1 - e^{-\lambda_r t_u}}{\lambda_r t_u} \quad 3.2$$

where

DK = decay factor for radioactive decay over period of reuse (unitless)

and

λ_r = radioactive decay constant (d^{-1})

t_u = duration of use of item (d)

The decay factor is applied to each pathway dose in Equations 3.3, 3.4, and 3.5; each pathway dose is multiplied by the decay factor. The TEDE for the scenario is then calculated by the addition of the decay-corrected doses from the external, inhalation, and secondary ingestion exposure pathways. The mathematical equations for calculating the doses for each of the three exposure pathways in this scenario are discussed in the following three subsections.

3.2.1 External Exposure

The dose from external exposure to penetrating radiation from residual surface radioactivity is calculated using Equation 3.3.

$$D_{ext} = C_{0,sc} * GF * t_{xs} * t_{ys} * DK \quad 3.3$$

where

D_{ext} = EDE due to external exposure (mrem/y)

and

$C_{0,sc}$ = surface concentration on the reused item at the time the scenario begins (pCi/cm^2)

GF = geometry factor for the scenario (mrem/h per pCi/cm^2)

t_{xs} = daily number of hours of exposure for the scenario (h/d)

t_{ys} = annual number of days of exposure for the scenario (d/y)

DK = decay factor for radioactive decay over period of reuse (unitless)

3.2.2 Inhalation Exposure

The dose due to the inhalation of resuspended residual surface radioactivity is calculated using Equation 3.4.

$$D_{inh} = C_{0,sc} * RF_{sc} * BR * DF_{inh} * t_{xs} * t_{ys} * DK * 1E+06 \quad 3.4$$

where

D_{inh} = EDE due to inhalation (mrem/y)

and

$C_{0,sc}$ = surface concentration on the reused item at the time the scenario begins (pCi/cm^2)

RF_{sc} = resuspension factor for residual surface radioactivity (cm^{-1})

BR = breathing rate for moderate physical activity (m^3/h)

DF_{inh} = inhalation dose factor (mrem/pCi intake)

t_{xs} = daily number of hours of exposure for the scenario (h/d)

t_{ys}	=	annual number of days of exposure for the scenario (d/y)
DK	=	decay factor for radioactive decay over period of reuse (unitless)
1E+06	=	unit conversion factor (cm^3/m^3)

3.2.3 Secondary Ingestion Exposure

The dose due to secondary ingestion of removable residual surface radioactivity inside the truck cab after transfer to hands, food, or other items entering the mouth is calculated using Equation 3.5

$$D_{ing} = C_{0,sc} * IR_{sc} * DF_{ing} * t_{xs} * t_{ys} * DK \quad 3.5$$

where

D_{ing}	=	EDE due to secondary ingestion (mrem/y)

and

$C_{0,sc}$	=	surface concentration on the reused item at the time the scenario begins (pCi/cm^2)
IR_{sc}	=	effective transfer rate for ingestion of residual surface radioactivity (cm^2/h)
DF_{ing}	=	ingestion dose factor (mrem/pCi intake)
t_{xs}	=	daily number of hours of exposure for the scenario (h/d)
t_{ys}	=	annual number of days of exposure for the scenario (d/y)
DK	=	decay factor for radioactive decay over period of reuse (unitless)

3.2.4 Total Dose from Equipment Reuse

The total dose from the reuse scenario is the sum of the three exposure pathway doses (external, inhalation, and secondary ingestion). This is calculated using Equation 3.6

$$D_T = D_{ext} + D_{inh} + D_{ing} \quad 3.6$$

Where

	D_T	=	TEDE for the Scenario
and	D_{ext}	=	EDE due to external exposure (mrem/y)
	D_{inh}	=	EDE due to inhalation (mrem/y)
	D_{ing}	=	EDE due to secondary ingestion (mrem/y)

3.3 Discussion of Models and Parameter Values

This section provides a basis for choosing values for key parameter values and distributions used in this analysis. The equipment reuse scenario was analyzed probabilistically, resulting in a distribution of dose factors for each radionuclide.

Values for the decay factor, DK, were calculated by integrating the radioactive decay over a period of 1 year, which is the duration of use of the reused item, t_u. Values for each radioactive decay constant, λ_r, used in the calculation were taken from Federal Guidance Report 11 (EPA 1988). All equipment that is cleared and reused is assumed to be initially taken to a distribution

center (e.g., surplus equipment broker). A time period of 4 days for handling and transport of the material prior to reuse is assumed, as well as an additional 7 day storage period at the distribution center (see Section 4). Thus, a value of 11 d (I 50%) is used for t_s. Finally, a range of 1 h/d to 8 h/d was used for t_{xs}, a fixed value of 250 d/y is used for t_{ys}, for both the external and internal exposure pathways.

The other parameters used are each unique to a given exposure pathway, so the remainder of the discussion is arranged by exposure pathway.

3.3.1 External Pathway

External dose models typically use generic geometrical shapes (e.g., discs, cylinders, and spheres) to represent a variety of potential items (e.g., O'Donnell et al. 1978, IAEA 1992, Chen 1993). Radionuclide-specific values for the geometry factor (GF) used for the external exposure pathway evaluation are based on shielding calculations using the computer code MCNP. Values are listed in Appendix C (GF #12). The GF values were calculated assuming the residual surface radioactivity is on the inside surface of a hollow sphere, with the receptor at the center of the sphere. External geometry factors include the dose contributions of progeny as described in Appendix E.

This analysis uses a hollow sphere to represent a vehicle. In this geometry, the receptor is inside the sphere and all the residual radioactivity is assumed to be on the inside surface of the sphere. The external geometry factors used in this evaluation do not include potential dose contributions from beta particles. This could be a nonconservative aspect of the external dose for some radionuclides, as it is conceivable that the driver of a truck with interior residual surface radioactivity could receive a skin dose from beta particles emitted from some radionuclides. However, this dose contribution would likely be insignificant for most radionuclides and very small, even for the radionuclides with the most energetic beta emissions. This is largely because in order to receive a significant skin dose to the most likely exposed part of the body (hands), the hands of the driver in this scenario would have to be in contact with the contaminated surface for a significant length of time. The steering wheel of the truck is the only potentially contaminated surface of the truck cab that a driver's hands would be in contact with for more than a very brief time.

3.3.2 Inhalation Pathway

The inhalation dose model used in this study is essentially the same as that used in several other similar studies (IAEA 1970, IAEA 1992, Kennedy and Strenge 1992, Chen 1993). An exception is one of the earliest recycle assessments (O'Donnell et al. 1978), which did not include resuspension of residual surface radioactivity as an exposure pathway.

Table 3.1 Representative reported indoor resuspension data and recommended values

Reference	Resuspension factor or range	Comments
Barnes (1959)	4E-5 m^{-1} (confined space) 2E-6 m^{-1} (open air)	Reported for "dusty operations"; 10^{-5} m^{-1} recommended for most laboratory work.
Stewart (1964)	1E-6 m^{-1} (quiescent conditions) 1E-5–1E-4 m^{-1} ("operational" conditions)	Notes that excessively high particulate resuspension values indoors are likely to indicate some degree of inefficiency in the ventilation system.
Brunskill (1964)	2E-4–4E-3 m^{-1}	Measured in small rooms with various types of personnel movement, including introduction of loose contamination on coveralls. Lower recommended values were measured for a large area of "loose" contamination on concrete; "much smaller" values were found for linoleum floor.
Jones and Pond (1964)	2E-8–5E-5 m^{-1} 5E-5 m^{-1} (recommended for worst practical conditions)	Estimated that 10–20% of total airborne radioactivity was respirable. Suggested that recommended value could be an order of magnitude lower for average conditions.
Dunster (1964)	2E-6–4E-5 m^{-1} 2E-6 m^{-1} (recommended safe value for long-term use)	Highest values from digging through dusty building rubble and in an enclosed and unventilated space.
Spangler and Willis (1964)	4E-5 m^{-1} (derived)	This value is calculated using equation for equilibrium airborne concentration in a small room from a surface concentration and recommended values appropriate for calculating 40 hr maximum permissible concentration (MPC) levels.
Healy (1971)	2.1 E-7–1.0 E-3 m^{-1}(derived)	This value is calculated using the equation for airborne concentration, assuming ventilation rate for a reasonably tight 28 m^2×2.4 m room.
Gibson and Wrixom (1979)	2E-6–4E-5 m^{-1}	The lower value was used in original calculation of derived working limits (DWL) for active area surfaces and might be inappropriate for widespread contamination on dusty surfaces. The higher value was obtained from measurements in a confined space and is suggested for general use.
IAEA (1970)	2E-6–3E-3 m^{-1} 5E-5 m^{-1} (recommended)	Recommended value is suggested as appropriate for general conditions of contamination on surfaces. Because of confounding factors, this effectively reduces the recommended value by 2.5× for use in calculating DWL values.
Kennedy et al. (1981)	2.5E-5 m^{-1} (derived)	This value is calculated using the equation for airborne concentration, assuming ventilation rate of an open transport truck and resuspension rate for a 28 m^2 room.
Kennedy and Strenge (1992)	1E-6 m^{-1} (recommended)	Based on a review of resuspension literature. Recommended as a reasonably conservative default value to be applied to total surface concentration.
IAEA (1992)	1E-6 m^{-1} (recommended)	This value is recommended for use in assessing reuse of tools and equipment. Used a transfer factor of 0.01 to account for the fraction of the residual surface radioactivity that is available for resuspension.
Chen (1993)	1 E-6 m^{-1}	No justification given (based on use in Kennedy and Strenge 1992)

Values for the inhalation dose conversion factors, DF_{inh}, are taken from Federal Guidance Report 11 (EPA 1988). Where more than one inhalation dose conversion factor is listed for a radionuclide in Federal Guidance Report 11, the largest value was selected. Inhalation dose conversion factors shown in Appendix B have been modified to include the dose contributions of progeny as described in Appendix E.

The resuspension factor, RF_{sc}, is the most poorly known parameter in the inhalation pathway analysis. Based on a literature review, information presented in previous evaluations, and the following discussion, a lognormal distribution with a geometric mean of 1E-10 cm^{-1} (1E-08 m^{-1}) is used for the resuspension factor for residual surface radioactivity. This value is at the low end of measured values. The low value is appropriate for this scenario, which includes the assumption that surfaces have been cleaned of easily removable, and most readily resuspendable, contamination at the time of clearance from regulatory control.

The resuspension of radioactive material from surfaces is typically modeled by the use of an equilibrium resuspension factor (in units of $length^{-1}$) or a fractional resuspension rate (in units of $time^{-1}$). The resuspension factor is simply a ratio of the air concentration of radioactive material above a surface (pCi/cm^3) to the concentration on the surface (pCi/cm^2). Although the theoretical inadequacies of both the resuspension factor and the resuspension rate have been discussed in the literature (e.g., Healy 1971, Horst 1982), both are commonly used in modeling assessments because more technically defensible approaches are lacking. The resuspension factor and the resuspension rate can be related by Equation 3.7

$$RF_{sc} = \frac{\chi}{\Omega} = \frac{f A}{V n} \qquad 3.7$$

Where

RF_{sc}	=	resuspension factor (cm^{-1})
χ	=	air concentration (pCi/cm^3)
Ω	=	residual surface radioactivity level (pCi/cm^2)
f	=	resuspension rate (h^{-1})
A	=	area of the source of residual surface radioactivity (cm^2)
V	=	volume of air in the room (cm^3)
n	=	rate of room air exchange (h^{-1})

Measured resuspension factors and rates can vary over very wide ranges (resuspension factors from approximately 1E-11 to 1E-2 m^{-1} [Kennedy and Strenge 1992] and resuspension rates from approximately 1E-7 to 1E-2 hr^{-1} [Healy 1971]), which suggests that resuspension is a complex process of several parameters, and that the specific conditions present at the time of measurement are critical. For modeling purposes, a resuspension factor or rate is a lumped parameter that is used to account for a complex combination of mechanisms that are poorly understood, but whose net effect is observed in the real world.

A resuspension *factor* rather than a resuspension *rate* is used in this evaluation, although neither is better known than the other, and neither is obviously more appropriate to the reuse scenario. The use of a resuspension rate would require additional parameters in Equation 3.4, and would, in turn introduce additional values and their associated uncertainties. The resuspension factor

value used in this study 1E-10 cm^{-1} (1E -8 m^{-1}) is based on a review of relevant literature data, combined with professional judgement and taking into account the application in this specific scenario. Unfortunately, there are no experimental data that specifically address resuspension from tools or equipment. The experimental data and recommendations summarized in Table 3.1 are felt to be the most appropriate available information. The range of resuspension factors cited in Table 3.1 is 2 E-8 m^{-1} to 4 E-3 m^{-1}. The reported data are generally from experiments that examined resuspension of liquid or powder contaminated material that had been uniformly applied to clean surfaces in a laboratory-like setting. The highest values are typically associated with inefficient ventilation, excessive mechanical disturbance, or dusty conditions. Typically, the purpose of these studies was to help determine radiation protection safety guidelines for loose residual, surface radioactivity. Although this situation is not the same as assumed for the reuse scenario, it is reasonable to use the lowest value of the resuspension factors cited in the studies, rounded to the nearest order of magnitude.

Using the lowest value as a geometric mean for this assessment is appropriate because of two key assumptions inherent in the scenario definition: (1) readily removable contamination has been removed from the surface of the truck cab prior to clearance, and (2) contamination that is not readily removable is the least susceptible to resuspension. This situation represents a key difference between this scenario and the conditions for which resuspension measurements have typically been taken.

The use of a mean resuspension factor near the lowest measured value is also justified based on consideration of the respirable fraction of resuspended contamination. In one of the few studies where particle size has been measured, Jones and Pond (1964) reported that measurements of air concentration were often biased by a few highly active large particles. In their study on resuspension of plutonium, they concluded that only 10%–20% of the total airborne radioactivity would be respirable. Rather than include a respirable fraction parameter and attempt to define it without a sound basis, the reuse scenario analysis assumes that all resuspended contamination is respirable. Although this assumption would result in overestimating the dose from inhalation, the effect is offset by using the lowest cited value for the parameter RF_{sc}. The resulting D_{inh} value is still considered conservative.

Another complicating factor is that the residual surface radioactivity is probably not uniform. Several studies (Dunster 1964, IAEA 1970, Healy 1971) discuss how this issue relates to resuspension values. Healy (1971) points out that in most cases, resuspension has been measured for uniformly contaminated surfaces and uniformly applied resuspension forces. Healy suggests that air concentrations are more strongly related to the total amount of surface contamination present, rather than the amount on any one limited area, and that basing allowable surface contamination limits on the highest surface levels may be too conservative.

The influence of ventilation is also a key factor that would likely result in a resuspension factor at the low end of measured values. The potential for excessive ventilation in a truck cab from open windows, air conditioning, and repeatedly opening doors would tend to reduce airborne concentrations of resuspended material via dilution and air exchange. Although increased airflow may also act to increase resuspension, this is likely a second-order effect when compared to dilution and resulting lower air concentrations (Healy 1971).

There are many other factors that contribute to the uncertainty in resuspension that are not addressed here because of lack of information. These include temperature, humidity, type and roughness of surface material, degree and effectiveness of mechanical disturbance, weathering processes, and chemical state of the contamination. The effect of changes in many of these factors on resuspended air concentration is intuitive (e.g., an increase in the size of the contaminated area would likely result in an increase in the resuspended air concentration), however, the degree and direction of the effect of other factors (e.g., specific surface conditions) is not so clear. Combining all these factors to define a "generic" resuspension factor or rate for modeling purposes is difficult. Based on a consideration of these factors and good engineering judgement, however, it is reasonable to use a lognormal distribution with geometric mean of the lowest reported resuspension factor in the model.

In an interesting review of measured resuspension factors, Brodsky (1980) concluded that the fractional amount of contamination on 1 m^2 of floor or ground that would enter 1 m^3 of air and be respirable by an individual over an extended period of time would be less than 10^{-6} and usually would be much lower. As a check of the methodology of this analysis against Brodsky's conclusion, an annual inhaled fraction of 2 E-6 can be derived for this reuse scenario, using parameters from Equation 3.4 and the appropriate mean parameter values. This fraction is consistent with Brodsky's estimate, which adds a degree of confidence that the model and parameter values used do not substantially underestimate or overestimate the resuspension factor.

Finally, the resuspension factor has not been consistently applied in previous evaluations. The resuspension factor in Kennedy et al. (1981) and Chen (1993) was applied to contamination that was assumed to be removable, whereas the rate in Kennedy and Strenge (1992) is intended to be applied to the total residual surface radioactivity present. The IAEA (1992) also intended for the resuspension factor to be applied to the total contamination present, however, the removability of the contamination was addressed by incorporating a transfer factor of 0.01. The resuspension factor in this evaluation of the reuse of a large piece of equipment is intended to be applied to the total contamination present at the time of clearance for reuse, because for a generic application, the full range of removable fraction must be assumed to be encountered. In addition, measurement of removable residual surface radioactivity is highly variable and uncertain (Royster and Fish 1964, IAEA 1970).

3.3.3 Secondary Ingestion

Values for the ingestion dose conversion factor, DF_{ing}, are taken from Federal Guidance Report 11 (EPA 1988). Where more than one ingestion dose conversion factor is listed for a radionuclide in Federal Guidance Report 11, the largest value was selected. Ingestion dose conversion factors shown in Appendix B have been modified to include the dose contributions of progeny as described in Appendix E.

A lognormal distribution is used for the effective transfer rate for ingestion with a geometric mean of 1E-4 cm^2/h. This value was estimated for this scenario using the alternative methods described below. It is lower than the value used in previous reuse evaluations (1 cm^2/hr) (e.g., Kennedy and Strenge 1992, and IAEA 1992), however it is judged to be appropriate for this reuse scenario.

The secondary ingestion model used in this study is essentially the same as that used in previous similar evaluations (Kennedy and Strenge 1992, IAEA 1992). As a review of the literature reveals, there are no data available on secondary ingestion of radioactive material from residual surface radioactivity. Consequently, most relevant evaluations over the past 30 years have made basically the same assumption: the amount of loose contamination on approximately 1 cm^2 of surface area would be ingested per hour (Dunster 1964, IAEA 1970, Healy 1971, Gibson and Wrixon 1979, Kennedy and Strenge 1992, IAEA 1992). Kennedy et al. (1981) modified the ingestion value to account for the specific scenario being addressed, and the IAEA (1992) applied a transfer factor of 0.01 to the ingestion value, although there was no basis provided for the value used.

Using a value of 1 cm^2/hr as a best estimate for the effective transfer rate for ingestion of residual surface radioactivity in this scenario has no sound, technical basis, and, as suggested by the modifications of Kennedy et al. (1981) and IAEA (1970), this value is extremely conservative. In fact, it is envisioned that the dose from this exposure pathway in this scenario would be very small, because there would be only a very small fraction of the total surface area that would come into contact with hands (e.g., steering wheel, seat belts, various knobs and handles). Also, the value of 1 cm^2/hr was originally applicable to loose contamination on smooth work surfaces (e.g., Barnes 1959, IAEA 1970), not a decontaminated, non-uniform surface such as the interior of a truck cab. The value of 1 cm^2/hr was also originally applied to the skin as often as other surfaces (Dunster 1964, IAEA 1970), which would then require a modeling parameter to account for transfer to the skin from the contaminated surface. Finally, using a value of 1 cm^2/hr would yield results that are not credible and are counter-intuitive in this analysis. For example, the use of 1 cm^2/hr would result in a secondary ingestion dose for this scenario that is much greater than doses from other exposure pathways for many radionuclides (i.e., > 95% of the total dose). Also, for radionuclides with energetic gamma-ray emissions, such as Co-60, an unreasonable amount of the total dose (10%–15%) would be due to secondary ingestion. The other exposure pathways have been reasonably evaluated, and it is unexpected and unreasonable that secondary ingestion would represent such a large fraction of the total dose for so many radionuclides in this scenario.

Because a realistic (not overly conservative) analysis was desired for this scenario, alternative methods of estimating the secondary ingestion rate were explored. A "face validity" check can be made using the evaluation of Brodsky (1980), who reviewed residual surface radioactivity data and concluded that a fraction of 10^{-6} is a reasonably conservative estimate of the maximum fractional amount of "plant throughput" that a single individual could intake via inhalation and that intake via ingestion would be lower. "Plant throughput" is the material in process at a facility and is judged to be analogous to the total amount of residual surface radioactivity initially present in this scenario. In order to obtain an annual fractional intake via ingestion of 10^{-6} in this scenario, an ingestion rate of 7E-5 cm^2/hr would have to be used in equation 3.5. A second alternative method of estimating the secondary ingestion rate is to base it on the intake of contamination via inhalation. These exposure pathways are linked in that they both rely on the removability of contamination from the same surfaces plus a mechanism of intake to the body (i.e., breathing or hand-to-mouth habits). It seems reasonable that intake via secondary ingestion could be bounded by the estimated intake via inhalation because resuspension potentially comes from all exposed surfaces and secondary ingestion comes only from the fraction of exposed surfaces that is touched. Thus, a second estimate of ingestion rate is based on the inhalation pathway as follows:

$$IR_{sc} = RF_{sc} * BR * 1E+06 \qquad 3.8$$

where

IR_{sc} = effective transfer rate for ingestion of residual surface radioactivity (cm^2/h)

and

RF_{sc} = resuspension factor for residual surface radioactivity (cm^{-1})

BR = breathing rate for moderate physical activity (m^3/h)

1E+06 = unit conversion factor (cm^3/m^3)

Using mean values of 1E-10 cm^{-1} for RF_{SC} and 1.2 m^3/h for BR, an IR_{SC} value of 1E-4 cm^2/h is calculated with Equation 3.8.

Based on the arguments and the alternative methods discussed above, a value of 1 cm^2/hr is clearly an unreasonably conservative value for IR_{SC} in this scenario. Further, use of the 1 cm^2/hr value and the modified International Atomic Energy Agency (IAEA) value (.01 cm^2/hr) in previous studies appears to have been somewhat arbitrary. Taking this into consideration, along with the other values derived with alternate methods and discussed above (1E-4, 7E-5), a value of 1E-4 cm^2/hr is reasonable to use as a geometric mean in this analysis. In the absence of any empirical data, this value is thought to be reasonable for this scenario.

3.4 Reuse Scenario Evaluation Results

The results of the analysis for the equipment reuse critical group scenario are listed in Table 3.2. The mean dose factor and the 90% confidence interval for the critical group are reported for each radionuclide. These results represent dose factors for reuse of equipment cleared from NRC licensed facilities, based on the bounding scenario that involves the truck driver of a cleared

truck. The dose factors range from a high of 170 μSv/y per Bq/cm^2 (0.62 mrem/y per pCi/cm^2) for Th-229 to a low of less than 0.01 μSv/y per Bq/cm^2 (4E-05 mrem/y per pCi/cm^2). Roughly one-third of the dose factors are greater than 10 μSv/y per Bq/cm^2 (0.04 mrem/y per pCi/cm^2), roughly one-third are between 0.01–10 μSv/y per Bq/cm^2 (4E-05–0.04 mrem/y per pCi/cm^2), and the remaining one-third are less than: 0.01 μSv/y per Bq/cm^2 (4E-05 mrem/y per pCi/cm^2).

The surficial dose factors from the bounding equipment reuse scenario can be compared to the derived surficial results of the recycle analyses, in order to help interpret the equipment reuse analysis results. As described in Section 4.7, the mass-based recycle dose factors were converted to a surficial basis using a surface-to-mass ratio. This yields dose factors in surficial units (i.e., μSv/y per Bq/cm^2).

For comparison to the equipment reuse dose factors, the highest recycle analysis critical-group dose factor for each radionuclide, across the three metals analyzed in this report, was used (from Table 2.2). After comparison, it can be seen that the surficial metals recycle dose factors are larger than the equipment reuse dose factors for all radionuclides except Mo-93, Nb-93m, and Cd-109. This means that for almost all radionuclides, the recycle analyses surficial critical-group dose factors are more restrictive than the equipment reuse critical-group dose factors. Thus, the equipment reuse dose factors may not need to be considered when setting clearance dose criteria, and no individual is likely to exceed the clearance criteria under conditions of any equipment reuse scenario.

As described above, the radionuclides Mo-93, Nb-93m, and Cd-109 are unique in this comparison. The dose factors for Mo-93 yield the largest difference between equipment reuse and recycle, with the equipment reuse dose factor a factor of approximately 30 higher than the highest metals surficial recycle dose factor. For these three radionuclides, there is some possibility that a clearance dose criterion could be exceeded under the conditions described by the equipment reuse scenario in this analysis.

Table 3.2 Dose factors for reuse of a large piece of equipment

	Mean dose factor		90% Confidence interval, μSv/y per Bq/cm^2		
	μSv/y per Bq/cm^2	mrem/y per pCi/cm^2	5th	50th	95th
H-3	1.1E-05	4.1E-08	2.2E-06	7.5E-06	3.1E-05
C-14	3.1E-04	1.1E-06	1.3E-04	2.5E-04	6.4E-04
Na-22	2.6E+01	9.6E-02	1.2E+01	2.5E+01	4.4E+01
P-32	1.7E-03	6.4E-06	7.6E-04	1.6E-03	2.9E-03
S-35	1.2E-04	4.5E-07	4.2E-05	8.7E-05	3.3E-04
Cl-36	1.3E-02	4.9E-05	6.1E-03	1.2E-02	2.2E-02
K-40	1.9E+00	7.1E-03	8.7E-01	1.9E+00	3.2E+00
Ca-41	2.3E-04	8.6E-07	4.5E-05	1.6E-04	6.6E-04
Ca-45	6.7E-04	2.5E-06	2.6E-04	5.2E-04	1.6E-03
Cr-51	4.1E-02	1.5E-04	1.9E-02	3.9E-02	6.9E-02
Mn-54	7.8E+00	2.9E-02	3.6E+00	7.6E+00	1.3E+01
Fe-55	1.5E-04	5.7E-07	2.5E-05	9.4E-05	5.1E-04
Co-57	9.5E-01	3.5E-03	4.4E-01	9.4E-01	1.6E+00
Co-58	3.4E+00	1.2E-02	1.6E+00	3.3E+00	5.8E+00
Fe-59	2.3E+00	8.4E-03	1.0E+00	2.2E+00	3.8E+00
Ni-59	1.0E-04	3.8E-07	1.4E-05	5.6E-05	3.6E-04
Co-60	3.0E+01	1.1E-01	1.4E+01	2.9E+01	5.0E+01
Ni-63	2.6E-04	9.8E-07	3.7E-05	1.5E-04	9.0E-04
Zn-65	4.6E+00	1.7E-02	2.1E+00	4.5E+00	7.8E+00
Cu-67	1.1E-03	4.1E-06	1.7E-04	7.8E-04	3.3E-03
Se-75	2.2E+00	8.0E-03	1.0E+00	2.1E+00	3.7E+00
Sr-85	1.7E+00	6.4E-03	8.0E-01	1.7E+00	3.0E+00
Sr-89	7.4E-03	2.7E-05	3.5E-03	7.1E-03	1.3E-02
Sr-90	1.4E-01	5.0E-04	2.0E-02	6.7E-02	4.7E-01
Y-91	1.0E-02	3.8E-05	4.9E-03	9.9E-03	1.8E-02
Mo-93	3.6E-01	1.3E-03	1.7E-01	3.5E-01	6.1E-01
Nb-93m	6.1E-02	2.3E-04	2.9E-02	5.9E-02	1.0E-01
Nb-94	2.2E+01	8.2E-02	1.0E+01	2.2E+01	3.8E+01
Nb-95	1.2E+00	4.5E-03	5.6E-01	1.2E+00	2.0E+00
Zr-95	2.3E+00	8.5E-03	1.1E+00	2.2E+00	3.9E+00
Tc-99	1.8E-03	6.7E-06	7.2E-04	1.4E-03	4.2E-03
Ru-103	9.6E-01	3.6E-03	4.4E-01	9.2E-01	1.6E+00
Ru-106	2.1E+00	7.8E-03	9.8E-01	2.0E+00	3.5E+00
Ag-108m	2.4E+01	8.9E-02	1.1E+01	2.4E+01	4.1E+01
Cd-109	4.2E-01	1.6E-03	1.9E-01	4.1E-01	7.2E-01
Ag-110m	2.3E+01	8.5E-02	1.1E+01	2.2E+01	3.9E+01
Sb-124	4.9E+00	1.8E-02	2.3E+00	4.8E+00	8.4E+00
I-125	2.6E-01	9.7E-04	1.2E-01	2.6E-01	4.5E-01
Sb-125	5.9E+00	2.2E-02	2.7E+00	5.7E+00	9.9E+00
I-129	7.2E-01	2.7E-03	3.5E-01	7.0E-01	1.2E+00
I-131	7.4E-02	2.7E-04	2.9E-02	6.6E-02	1.3E-01
Ba-133	6.3E+00	2.3E-02	2.9E+00	6.2E+00	1.1E+01
Cs-134	1.9E+01	7.0E-02	8.7E+00	1.8E+01	3.2E+01
Cs-137	8.6E+00	3.2E-02	4.0E+00	8.4E+00	1.5E+01
Ce-141	1.1E-01	3.9E-04	4.8E-02	1.0E-01	1.8E-01

Table 3.2 Dose factors for reuse of a large piece of equipment

	Mean dose factor		90% Confidence interval, μSv/y per Bq/cm^2		
	μSv/y per Bq/cm^2	mrem/y per pCi/cm^2	5th	50th	95th
Ce-144	4.2E-01	1.6E-03	2.0E-01	4.1E-01	7.1E-01
Pm-147	3.3E-03	1.2E-05	3.7E-04	1.5E-03	1.2E-02
Eu-152	1.5E+01	5.6E-02	6.9E+00	1.5E+01	2.5E+01
Eu-154	1.6E+01	5.9E-02	7.3E+00	1.5E+01	2.7E+01
Eu-155	7.5E-01	2.8E-03	3.4E-01	7.3E-01	1.3E+00
Re-186	5.3E-04	2.0E-06	1.4E-04	4.3E-04	1.3E-03
Ir-192	3.2E+00	1.2E-02	1.5E+00	3.1E+00	5.4E+00
Pb-210	1.8E+00	6.7E-03	3.8E-01	1.1E+00	5.9E+00
Po-210	4.2E-01	1.5E-03	5.6E-02	2.2E-01	1.4E+00
Bi-210	1.6E-04	6.0E-07	4.5E-05	1.2E-04	4.6E-04
Rn-222	5.3E-02	2.0E-04	1.4E-02	4.3E-02	1.3E-01
Ra-223	1.2E-01	4.4E-04	5.0E-02	1.1E-01	2.1E-01
Ra-224	3.7E-02	1.4E-04	9.7E-03	3.0E-02	9.2E-02
Ac-225	7.2E-02	2.7E-04	2.9E-02	6.7E-02	1.4E-01
Ra-225	3.7E-02	1.4E-04	1.1E-02	2.4E-02	1.1E-01
Ra-226	2.3E+01	8.6E-02	1.1E+01	2.3E+01	3.9E+01
Ac-227	1.3E+02	4.7E-01	1.6E+01	5.8E+01	4.5E+02
Th-227	1.6E-01	5.8E-04	6.1E-02	1.2E-01	3.6E-01
Th-228	4.1E+01	1.5E-01	1.2E+01	2.7E+01	1.2E+02
Ra-228	1.7E+01	6.4E-02	7.0E+00	1.4E+01	3.6E+01
Th-229	1.7E+02	6.2E-01	1.8E+01	7.5E+01	6.1E+02
Th-230	2.5E+01	9.1E-02	2.0E+00	1.1E+01	9.1E+01
Pa-231	8.2E+01	3.0E-01	8.2E+00	3.7E+01	3.0E+02
Th-231	1.2E-05	4.3E-08	8.7E-08	2.4E-06	5.5E-05
Th-232	1.1E+02	4.1E-01	1.0E+01	4.9E+01	4.0E+02
Pa-233	2.7E-01	1.0E-03	1.2E-01	2.6E-01	4.5E-01
U-233	1.3E+01	4.7E-02	1.0E+00	5.6E+00	4.7E+01
Th-234	1.8E-02	6.7E-05	8.3E-03	1.7E-02	3.0E-02
U-234	1.2E+01	4.6E-02	1.0E+00	5.5E+00	4.6E+01
U-235	1.4E+01	5.1E-02	2.9E+00	7.2E+00	4.5E+01
Np-237	5.5E+01	2.0E-01	8.2E+00	2.6E+01	1.9E+02
Pu-238	2.7E+01	1.0E-01	2.2E+00	1.2E+01	1.0E+02
U-238	1.1E+01	4.2E-02	1.2E+00	5.2E+00	4.2E+01
Pu-239	2.9E+01	1.1E-01	2.3E+00	1.3E+01	1.1E+02
Pu-240	2.9E+01	1.1E-01	2.3E+00	1.3E+01	1.1E+02
Pu-241	4.6E-01	1.7E-03	3.6E-02	2.0E-01	1.7E+00
Am-241	4.2E+01	1.6E-01	4.1E+00	1.9E+01	1.6E+02
Cm-242	8.3E-01	3.1E-03	1.0E-01	3.8E-01	3.0E+00
Pu-242	2.8E+01	1.0E-01	2.2E+00	1.2E+01	1.0E+02
Cm-244	2.3E+01	8.5E-02	2.0E+00	1.0E+01	8.5E+01

4 EVALUATION OF RECYCLE AND DISPOSAL OF STEEL SCRAP

Twenty-seven exposure scenarios for cleared steel scrap that are based on current American industries are evaluated in this section. Scenario categories include handling and processing, storage, transportation, product use, and disposal. Four landfill resident scenarios were also analyzed. A radionuclide-specific, probabilistic dose factor distribution was calculated for the members of the exposed group in each scenario. The highest mean dose factor among the 27 scenarios on a radionuclide-by-radionuclide basis for 85 radionuclides is the critical-group dose factor i.e., for an average member of the critical group. This critical-group dose factors are reported in normalized units of µSv/y per Bq/g scrap (mrem/y per pCi/g) and µSy/y per Bq/cm^2 scrap (mrem/y per pCi/cm^2 scrap) for each radionuclide. Dose factors at the 5th , 50th , and 95th percentiles are also reported.

The most common critical groups are commercial truck drivers carrying cleared steel scrap and workers at steel refineries. Scenarios involving transport of scrap material resulted in critical group designation for almost half (39) of the 85 radionuclides in the analysis. Other scenarios identifying critical groups for many radionuclides involve exposure while handling scrap (14 radionuclides), to refinery slag and slag leachate (12 radionuclides), and exposure to refinery baghouse dust (11 radionuclides). Only one critical group involves the use of steel consumer products.

Critical group mean dose factors range from a high of 2.0E+03 µSv/y per Bq/g (7 mrem/y per pCi/g) for Np-237 to a low of 4.5E-04 µSv/y per Bq/g (1.6E-06 mrem/y per pCi/g) for Ni-59. The derived surficial mean dose factors range from a high of 1.4E+3 µSv/y per Bq/cm^2 (5.3 mrem/y per pCi/cm^2) to a low of 3E-4 µSv/y per Bq/cm^2 (1E-6 mrem/y per pCi/cm^2). The high critical-group mean dose factors of Np-237 are attributed to the drinking water exposure pathway in the refinery slag storage scenario. Seventy-nine of the radionuclide-specific, critical group mean dose factors for steel are 270 µSv/y per Bq/g or lower (1 mrem/y per pCi/g).

This section describes the technical evaluation of the recycle of steel scrap metal that could be cleared from Nuclear Regulatory Commission (NRC) licensed facilities. The flow of cleared steel scrap was modeled using the likely sequence of steps recycled and disposed steel would be subjected to following clearance. Radioactivity concentrations in recycle byproducts and disposed materials were calculated, and potential dose factors to members of exposed population groups were estimated using reasonable formulations of potential situations where individuals could be exposed to radioactivity in cleared material and recycle byproducts.

This evaluation is based on mass radioactivity concentration (i.e., Bq/g or pCi/g) because material likely to be cleared is inventoried on a mass basis. Therefore, all calculated dose factors are initially in units of annual dose per unit mass (i.e., µSv/y per Bq/g or mrem/y per pCi/g). This normalization allows the NRC to scale doses according to concentration of a radionuclide in scrap to be cleared. The mass dose factors have been converted to surficial dose factors by the use of a surface-to-mass ratio, which is the ratio of the surface area to the mass of a piece of scrap or other cleared material. This differs from the dose factors calculated for reuse of equipment, which are based exclusively on surficial contamination as described in Section 3. This surface to mass relationship and its use in converting mass dose factors to surficial dose

factors is discussed later in Section 4. Therefore, all dose factors are also in units of annual dose per unit surface area (i.e., μSv/y per Bq/cm^2 or mrem/y per pCi/cm^2).

4.1 Introduction to Analysis

The overall evaluation of the potential dose impacts of recycling and disposal of scrap iron and steel was conducted in two general steps. First, a probabilistic material flow model specific to iron and steel scrap was developed, and distributions of material radionuclide concentrations in recycle products and disposed material were calculated. This step provided the basic radioactivity for the second step, which was the development and probabilistic evaluation of potential situations of individual exposure to radioactivity in cleared material and recycle byproducts. The development of the iron and steel material flow model is discussed in Sections 4.2 and 4.3, and the calculations used to implement the material flow model are presented in Section 4.4.

The dose assessment step of the overall evaluation is described in detail in Section 4.6. The exposure scenarios developed and analyzed are key parts of the assessment. The exposure scenarios define the exposure situation, so they play an extremely important role in the analyses. They define the conditions surrounding the potential exposure of individuals and populations and, in the modeling of potential exposure, they relate the radionuclide concentration in recycled and disposed material to the potential dose of an individual. Before developing exposure scenarios and the approach to be used to model scenarios for this study, several general objectives were defined. The desired approach was intended to:

- Simplify the evaluation of numerous possible exposure scenarios
- Identify scenarios that adequately represent critical groups
- Calculate potential dose factors as realistically as possible.

The material flow model was used to identify general scenarios that would represent a comprehensive range of potential exposure situations. Simple mathematical models of those non-specific scenarios were developed to streamline evaluation and analysis. The simplicity of the mathematical models makes them potentially applicable to a wide range of scenarios, providing flexibility for analyzing potential doses associated with whole categories of scenarios.

4.1.1 Approach to Scenario Development

The majority of previous analyses of recycled material did not present a clear rationale for scenario selection and evaluation. This section of the report documents the philosophy and technical approach that were used for this project to select, evaluate, and analyze potential exposures to recycled materials.

A number of previous assessments have been conducted to quantify the potential radiation exposures to workers and the general public from recycle of contaminated materials. In general, these assessments have been based on the formulation and evaluation of fairly specific scenarios

that describe hypothetical situations in which workers or members of the general public might be exposed to radioactivity in reused or recycled materials. In order to be comprehensive, this approach requires identifying the entire range of potential scenarios and using professional judgement to select a final set for detailed analysis.

A review of the literature on radiological assessment indicates that there are two general approaches to scenario-based assessments. The "specific" approach attempts to model, as accurately as possible, the actual physical circumstances surrounding a selected set of very detailed scenarios. Among the assessments addressing recycle of radioactive materials, this approach is exemplified by the work of O'Donnell et al. (1978) in which an iron frying pan was used as the reference consumer product. The analysis included calculations based on extensive details of frying pan manufacture and use.

For the purposes of the assessment proposed here, the "specific" approach suffers from several weaknesses. First, it restricts the number of scenarios that can be treated to those for which extensive, detailed descriptions can be formulated. Second, it is open to the criticism that the chosen scenarios are too limited because they do not specifically represent other situations of interest. Third, many individual parameters are required to describe the scenario details. Each of the parameter values in the scenario must be defended as technically sound even when only the grossest estimates are used. Finally, the data requirements of the "realistic" approach introduce serious demands on available resources. Each value must be researched, documented, and subjected to quality assurance procedures.

In contrast, a "generic" approach uses broadly defined scenarios that can be taken as representative of a wide range of possible exposure circumstances and does not attempt to model the details of any specific, real-world situation. Several recent studies illustrate the main features of this approach. Charles and Smith (1992), for example, modeled a wide range of consumer products using a generic geometry factor based on a cylinder of specified height, diameter, and thickness without attempting to mimic the manufacture and use of actual objects. Deckert et al. (1992) evaluated two generic geometries, one defined as "a 1 kg object" and the other as "a 1000 kg" object to represent different categories of consumer products.

The "generic" approach addresses each of the objections to the "specific" scenario approach. Since each generic scenario is representative of a wide range of situations, the number of situations addressed is not so severely restricted. By representing a range of situations, carefully chosen generic scenarios can address any situation of interest that falls into the generic category. Finally, the number of detailed parameters can be minimized, along with the need to estimate and defend values for each parameter.

The approach taken in this analysis is a combination of the “specific” and “generic” approaches. Several specific scenarios have been modeled, as realistically as available data allow. In addition, several generic scenarios have been modeled to represent a range of potential exposure situations that are similar.

4.1.2 Scenarios for Recycle and Disposal of Cleared Steel Scrap Metal

An infinite number of potential exposure scenarios for recycle and disposal of steel scrap could be postulated. The goal-based criteria set for this study required that the scenarios selected be comprehensive, appropriate, and practical. *Comprehensive* means that the scenarios must address all potential critical group exposure situations. The scenarios must be *appropriate* to actual practices in the recycle industry and conditions of product use. Finally from a modeling viewpoint, the scenarios had to be *practical*, in that a relatively small number of scenarios needed to include an extremely large pool of potential exposure scenarios. Selected scenarios had to account for all potential significant recycle scenarios. The very unlikely cases that could result in higher doses were excluded on the basis of not addressing the design objective of the analysis.

The approach for this evaluation is similar to that taken by Charles and Smith (1992), who evaluated the feasibility of different options for managing large volumes of very low level waste. The management options included scenarios similar to those selected for this report, including clearance followed by recycling and disposal of steel and concrete in landfills. The exposure scenarios used in their models were derived from adopting the various management options. The methodology used generic exposure scenarios that are similar to the scenarios used in this evaluation in terms of their generic nature. Scenarios used in previous studies, including scenarios reported by Charles and Smith (1992), are shown in Table 4.1.

Table 4.1 Scenarios discussed in previous studies

Work-related	Non-worker
• Decontamination and dismantling of concrete and steel structures and handling scrap during the process • Transport of scrap to smelter or disposal facility • Exposure to scrap piles before smelting • Repair of contaminated machinery • Operation of smelter and subsequent processing • Building renovation or demolition • Landfill disposal (operation of facility or waste fires) • Reuse of large concrete masses (building renovation) • Reuse of contaminated slag in concrete manufacture production/manufacture of end products	• End product use (i.e. frying pan, steel furniture, steel car, steel reinforcement in houses, large and small products) • Smelting process (airborne effluents) • Slag in roadbeds, foundations of houses, reuse of contaminated slag in concrete • Landfill and sanitary disposal of waste products or contaminated scrap (leachate, inadvertent intrusion) • Incineration of contaminated scrap • Building occupancy by the public • Drinking water—drinking water that contains radionuclides leached from surface soils • Residential (contaminated soil) • Shallow repository disposal • Reuse of large concrete masses (building occupancy)

Rather than attempting to initially define a specific "bounding" scenario, in which potential exposure is maximized even though the combination of circumstances is very improbable, broad scenario categories and a combination of general and specific scenarios within the categories were identified and evaluated. Scenarios were then evaluated so that dose factors calculated in the model would be realistic estimates for potential real-life situations.

The material flow model provides a basis for developing exposure scenarios. Junctures in the material flow that provide opportunities for exposure to radionuclides in recycled iron or steel define the broad scenario categories, such as handling or product use. Scenarios within those categories describe the conditions surrounding the potential exposure of individuals and populations. For example, several scenarios within the handling category evaluate potential exposure of workers to a variety of material (e.g., scrap metal, baghouse dust, refined metal product) and locations (scrap yard, refinery, baghouse). The exposure scenarios were selected to comprise a reasonable set of potential exposures to the estimated concentrations of radioactivity in scrap metal or refinery co-products.

The combination of a "specific" and "generic" approach used to develop exposure scenarios provided flexibility in defining a set of reasonable scenarios for identifying critical groups. This approach addresses a wide range of potential exposure situations and also lends itself to future evaluation of additional scenarios of interest.

4.2 Flow of Recycled and Disposed Steel Scrap

4.2.1 Conceptual Description

This section presents the conceptual model that describes the flow of cleared steel scrap through the normal refining process, beginning with the generation of scrap, through refining, manufacturing, product use, and finally disposal. Figure 4.1 presents a schematic diagram of the overall material flow conceptual model for steel scrap. Both the mass and radioactivity of steel scrap follow this flow model. As seen in Figure 4.1, there are several distinct steps in the refining process. Each of these is discussed in the following subsections. Direct reuse of equipment is discussed in Section 3.

4.2.2 Sources of Material

There are two sources of materials for the steel refining process: the primary and secondary metals pools. The primary metals pool consists of pig iron smelted from ore. The material from this pool would not be contaminated at any point by the recycling of scrap cleared by NRC licensed facilities because scrap is not used during the smelting of ore. Approximately 5.2E+7 t (5.7E+7 tons) of pig iron was consumed in 1995 in the U.S. (Fenton 1996).

The secondary metals pool is comprised of scrap metal. A total of 7.2E+7 t (7.9E+7 tons) of iron and steel scrap was consumed in the U.S. in 1995 (Fenton 1996). There are three types of scrap metal used in the steel-making industry: home, new, and old. *Home scrap* consists of unusable metal produced during the processing or fabrication of steel into a form usable for manufacturing. Home scrap is usually high-grade metal with very few impurities. Even though home scrap is produced at the refinery, it is still considered a secondary metal because it is not the processed raw material, pig iron. *New scrap* is produced during manufacture of end products. New scrap is also high-grade metal with very few impurities. *Old scrap* includes obsolete, worn-out or broken products that have been used by the general public or industry. Old scrap is usually

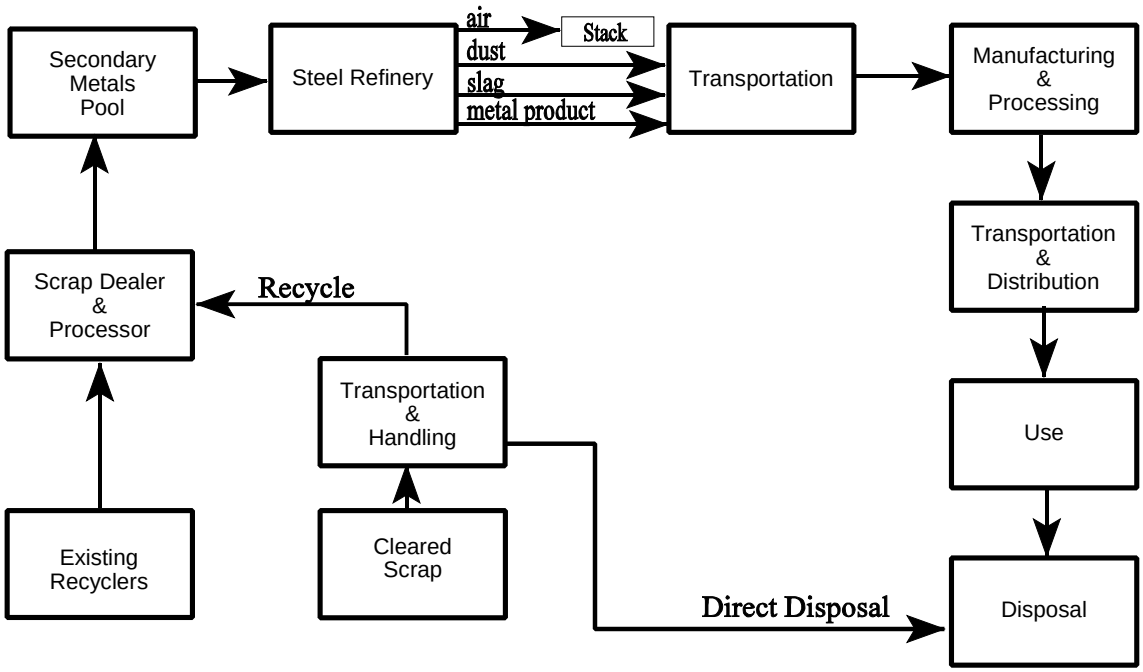

Figure 4.1 Flow of steel scrap

low-grade metal, and the chemical composition is not well-known. Therefore, it must first be sorted, sized, and classified. Cleared scrap metal from the nuclear industry would be considered old scrap.

The modeling for this analysis does not distinguish between the different types of scrap. Cleared materials are assumed to be mixed with a single source of uncontaminated scrap—roughly the total of old, new, and home scrap sources.

The two sources of secondary metals considered in this evaluation are conventional recyclers, and potential, cleared scrap metal. Recyclers are the current producers of scrap metal and consist of the general public (e.g., recycling steel cans), industry (e.g., recycle automobiles), or manufacturers (e.g., scrap produced during manufacture of end products).

The main source of the cleared scrap for this study is the nuclear industry (decommissioned material from nuclear facilities), which consists mainly of commercial power plants, test and research reactors, and industrial nuclear facilities. Other producers of such scrap include the Department of Energy (DOE) weapons complex and the Department of Defense (DOD), which could contribute slightly contaminated scrap primarily from conventional weapons testing and army and navy test reactors. Approximately 3.0E+3 t/y (3.3E+3 ton/y) of potentially cleared material is generated each year from NRC licensed facilities; increased dismantling and

decommissioning activities by DOE could increase the mass of steel to about 7.1E+4 t/y (7.8E+4 ton/y) (NUREG/CR-5610[1]) for a limited number of years.

Following entry of cleared material into the steel pool, a continuing buildup of residual radioactivity levels in steel products to significant levels is not likely. Especially unlikely is any significant increase in potential individual doses (compared to collective doses). This is because 1) ongoing radioactive decay occurs; 2) virgin, raw materials are continually added to the metals production processes, and 3) cleared material will comprise only a small fraction of the total recycled amount of any material. Therefore, the radioactivity concentrations in any subsequent recycling will likely be lower than that resulting from the initial recycle. Therefore, any individual doses from secondary recycle would likely be lower than those calculated for initial recycle in this analysis. The potential, long-term buildup of radioactivity in the steel pool may be a collective dose issue, but it is not considered an individual dose issue, and is therefore outside the scope of this analysis.

4.2.3 Transportation and Processing of Scrap

Scrap cleared by a NRC licensed facility must be commercially transported to a scrap dealer or processor. Not all cleared scrap is likely to be suitable for recycle, so some would be transported directly to a disposal site. In all cases, transportation could occur either by truck or rail.

After scrap is processed at a scrap dealer, it is transported by rail or truck to a refinery, where it is usually off-loaded directly for melting in a furnace. Two types of processes are involved in steel making: smelting and refining. Smelting treats the raw material (ore), to separate the metal portion (pig iron), from the waste slag. Because the smelting process does not accept scrap, it is not discussed further in this report.

Scrap cleared from NRC licensed facilities would become part of the generic refining process represented by Figure 4.2. Refining takes pig iron produced at a smelter and refines it to a specified impurity level by adding differing types and amounts of scrap metal. Refining is also commonly done by using only scrap with no pig iron. The two types of steel refineries currently in use (*integrated* and *non-integrated*) differ primarily in characteristics of the charge (i.e., the material that is melted in the furnace per cycle). The integrated process accepts small amounts of scrap per charge and, therefore, produces a product of higher purity. The non-integrated process, on the other hand, can use up to 100% scrap metal in a charge. This results in a product with lower purity but with greater strength.

[1]Recycle/Reuse Literature Search Report, SAIC, 1994 scheduled to be published as NUREG/CR-5610

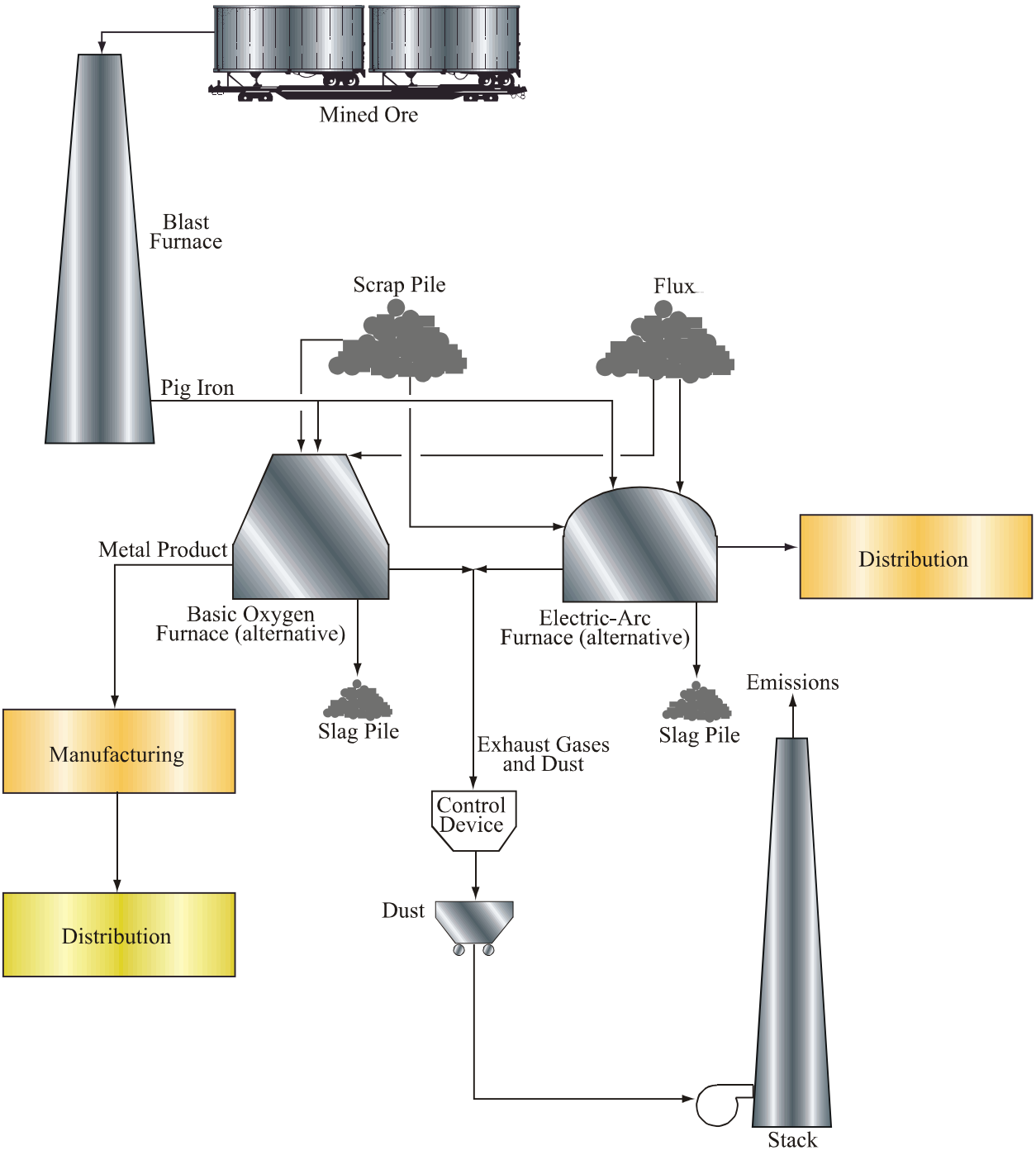

Figure 4.2 Generic refining process

Together, integrated and non-integrated mills consumed a total of approximately 6.2E+7 t (6.8E+7 ton) of steel scrap, and produced a total of 9.52E+7 t (1.0E+08 ton) of raw steel in 1995 (Fenton 1996). A small amount of scrap and pig iron is consumed by foundries and other types of refineries [9.78E+6 t (1.1E+7 tons)] of scrap. However, because these facilities contribute only a small percentage (<1%) of the total steel production, they are not included in this analysis (Brown 1993). Refinery worker activities at the two types of steel refineries are similar, and on average, it takes 3.5 man-hours to produce 0.907 t (1 ton) of steel (NUREG/CR-5610[1]).

4.2.3.1 Integrated Steel Mills

The integrated steel mills use mainly basic oxygen furnaces (BOF). The input material for this type of furnace consists of molten pig iron, scrap, and flux materials (mostly lime and silica or limestone). (Flux materials are added to achieve a desired composition.) The exothermic reaction of oxygen (added during the process), with the molten pig iron, oxidizes and removes impurities in the iron while providing heat for melting the scrap. The amount of oxygen added varies depending on the quality of the scrap and the desired final steel chemistry. Furnace capacities of BOFs range up to 300 t (330 ton) per charge, and the required time per melting cycle typically ranges from 25 to 45 minutes (EPA 1986). The average size of a charge in a BOF refinery is estimated to be 58 t (64 ton) with an average of 5580 charges per year for one refinery.

The fumes that are generated when oxygen is added to a BOF are captured by the primary exhaust hood and cleaned by high pressure venturi scrubbers or electrostatic precipitators. The fumes generated during melting, tapping (pouring molten steel), and slagging (decanting slag) are captured by local or canopy hoods and transported via a duct system to a baghouse. (For this report the fume collection system is generalized and referred to as a baghouse.) The BOF baghouse is assumed to be 99.9% efficient because of the cleaning efficiency of the primary collection system in conjunction with the baghouse (Mody and Jaknet 1988).

Scrap used in the BOF refining process is largely home scrap. Because of the small percent of old scrap used, the concentrations of Environmental Protection Agency (EPA)-listed hazardous metals (i.e., lead, cadmium, and chromium) in the dust are below regulatory limits. Therefore, BOF dust is not listed as a hazardous waste (EPRI 1993).

The integrated mills produce "flat" products (e.g., sheets and strips) and supply the consumer goods market, mainly automotive and appliance. In 1995, BOFs consumed about 22% and 96% of the total scrap and pig iron, respectively used in the U.S., while producing approximately 60% of the total raw steel for that year (Fenton 1996).

4.2.3.2 Non-Integrated Steel Mills

The non-integrated steel mills employ mostly electric arc furnaces (EAF), and primarily produce carbon steel. The input material to an EAF is usually 100% scrap, with a very small amount of

[1]Recycle/Reuse Literature Search Report, SAIC, 1994 scheduled to be published as NUREG/CR-5610

flux. Capacities of EAFs vary, ranging from a diameter of 2 m (6.6 ft) and a product capacity of 3 t (3.3 tons), to 12 m (39 ft) with a capacity of 360 t (397 tons) (EPA 1986). Melting cycles range from about 1½ to 5 hours to produce carbon steel. Based on information presented in the 1993 Directory of Iron and Steel Plants (AISE 1993), the average size of a charge in an EAF refinery is 88 t (97 ton) with an average of 5,580 charges per year for one refinery.

The fumes generated during the meltdown and refining period of an EAF are evacuated directly off the furnace (direct shell evacuation) and transported via a duct system to the collection system. The fumes produced during melting, tapping, and slagging are evacuated through a fume collection hood on the roof of the building, then transported through a duct to the collection system. The most efficient, cost-effective, and typical collection system used to control the EAF fume dust is the fabric filter baghouse system. Discussions with industry indicate that these systems typically have a collection efficiency greater than 99% when running optimally.

However, Cass and Langley (1977) provide data from a controlled experiment that measured dust characteristics from an EAF refining carbon steel. Measurements included particle size and mass at both the inlet and outlet of a baghouse. Ten separate experiments were run. The mass fraction penetrating the filters was reported to have a mean of 1.904 % with a standard deviation of 0.3862 % (Cass and Langley 1977). The mean value corresponds to a filter efficiency of 98.1 %. The mass penetration value that is two standard deviations above the mean is 2.68 %, corresponding to a filter efficiency of 97.3 %. The mass penetration value two standard deviations below the mean is 1.13 %, corresponding to a filter efficiency of 98.9 %.

Cuscino (1979) reports the results of emission measurements at a variety of steel refineries. The data are difficult to interpret because of variations between facilities and variations between sampling procedures. Two pairs of values are given which provide measures of dust entering and leaving a baghouse. These measurements provide two direct estimates of filter efficiencies at 97.3% and 95.0%. In addition, four values related to dust production are reported for emissions measured downstream from a baghouse at an EAF refinery making carbon steel from scrap. These are 0.02 kg dust per metric ton of steel produced and 0.072, 0.16, and 0.85 kg/t of scrap input. If one assumes 15 kg of dust enters the baghouse per metric ton of steel produced and 90 t of steel is produced per 100 t of scrap (see Section 4.3), these values correspond to mass penetration fractions of 0.15%, 0.54%, 1.2%, and 6.3% with a mean of 2.0%. The corresponding filter efficiencies range from 99.8% to 93.7% and average 98%. Although these values are questionable because of the quality of the original data and the assumptions required to interpret them, they are consistent with values from controlled experiments. They are used here to justify a wider range of uncertainty in real baghouse efficiencies than in the controlled experiments. Cuscino (1979) reports that, depending on refinery configuration, significant fractions of refinery dust may not be ducted to the baghouse and may be emitted unfiltered to the atmosphere. Therefore, a value of 98% is a reasonable most likely value for the baghouse filter efficiency, BH_{eff}, for an EAF refinery.

Because a large percentage of an EAF charge is comprised of old scrap, the concentrations of hazardous metals (i.e., lead, cadmium, and chromium) in the baghouse dust, which are regulated

under the Resource Conservation and Recovery Act (RCRA), are above regulatory limits (EPRI 1993). Therefore, the EAF baghouse dust is listed by the EPA as a hazardous waste and is handled differently than BOF dust.

The non-integrated mills produce high-strength, low alloy steel, supplying mainly the construction industry. In 1995, EAFs consumed about 64% and 3% of the total scrap and pig iron used in the U.S., while producing about 40% of the total raw steel made in that year (Fenton 1996). The remaining 14% scrap and 1% pig iron were consumed by other facilities (e.g., blast furnace, cupola furnace, etc). It is common practice for an EAF to operate using only scrap metal as feed.

The amount of oxygen used in the EAF process is assumed to be about the same as the amount used for the BOF process. For the purpose of this analysis, a BOF and an EAF are treated the same for determining the elemental partitioning factors, but are modeled differently for other factors, including scrap dilutions, baghouse efficiency, end products, and EPA regulation of the dust. Table 4.2 lists the differences that are relevant to the modeling in this analysis.

Table 4.2 Key assumptions for the steel material flow model

Assumptions	Basic oxygen furnace	Electric arc furnace
End product and use	flat products and used mainly in the consumer goods market	high-strength, low alloy steel and used mainly in the construction industry
End use of baghouse dust	disposed of in a sanitary landfill on site	sent to metals recovery, fertilizer, or disposal in a hazardous (RCRA) landfill
Temperature inside furnace	1600°C	1600°C
Temperature inside the baghouse	190°C	190°C
Chemical form of elements entering baghouse	oxides	oxides
Efficiency of baghouse	99.9%	98%
Type of slagging agent used in furnace	basic	basic
Average size of a charge	58 t	88 t
Average number of charges per year for a single refinery	5,580	5580

4.2.3.3 Output of Refinery Processes

During the refining process (using either the EAF or BOF), the furnace contents separate into four different end products: off-gas, dust, slag, and metal (Figure 4.2). Both the mass and radioactivity are redistributed (partitioned) into the different end products. To account for this in the material flow modeling, partitioning factors for both mass and radioactivity were developed and are discussed in detail in Section 4.3.

Each of the end products undergoes a different process, use, and final disposal. The off-gas includes elements that are completely volatilized into stable gases or very fine particles during refining and exit the refinery stack. Furnace fume dust includes elements that are volatilized from the furnace, form particulates when cooled, and are collected in baghouse filters. Neither EAF or BOF air pollution control systems are 100% efficient, and a small percentage of the dust exiting the baghouse is released to the atmosphere with the off-gas. After collection, BOF dust is placed in a sanitary landfill.

The baghouse dust from EAF facilities is classified as a RCRA hazardous waste because of the metal content (EPA Waste No. K061), and refineries have two options for disposition of the dust: treatment and disposal, or delisting. Both of these options are addressed in the material flow modeling. At the time this issue was investigated, the two most common treatment and disposal methods in use were 1) immobilization treatment, followed by disposal, and 2) high-temperature metals recovery. Immobilization and disposal is explicitly addressed in the modeling for this analysis, as described in subsequent sections of this report. Metals recovery was also investigated, including calculation of radionuclide concentrations in recovered metal products. However, the calculated radioactivity concentrations have a very large degree of uncertainty associated with them (due primarily to the lack of specific information about the proprietary metals recovery processes) and were judged to be inadequate to support development of new scenarios associated with metals recovery. Therefore, the radionuclide concentrations of recovered metal are not used further in this analysis, but their uncertainty suggests areas for future investigation, and also to address the types of questions that can arise during rulemaking and related activities. Electric arc furnace dust is transported by truck to either a hazardous landfill facility or to a processor. At either type facility, it is typically unloaded in an enclosed building, where it is immediately placed in a bin and moistened with water for dust control.

Steel-making slag is not considered a hazardous waste, therefore, it can be reprocessed for use or directly disposed of. Typical uses of slag are railroad bases, aggregate, and railroad ballast. After slag is removed from the furnace and cooled, it is stored in piles outdoors at the refinery until it is either used by the refinery or transported to a slag processor. Approximately 10% of the total slag produced in 1992 was used at the plant where it was originally produced (Solomon 1993). Slag is transported from the refinery to manufacturers or processors by either truck, rail, or waterway. Of the slag produced and transported in 1992, 82.9% traveled by truck with an average range of 45 km (72 mi), 3.6% traveled by waterway with an average range of 400 km (250 mi), and 3.5% traveled by rail with an average range of 400 km (250 mi)

(Solomon 1993). As those figures indicate, most slag is used within a 50 km (80 mi) radius of its source.

Basic oxygen furnaces and EAFs yield different types of metal products. Electric arc furnaces manufacture mainly bar products for use in the construction industry. These products have a lower purity and a greater strength than BOF products and do not require additional manufacturing or processing prior to use. The metal produced at mills using BOFs is usually in sheet form and will undergo additional manufacturing or processing for use in items such as appliances or automobiles. Both product types follow the flow model presented in Figure 4.1. Basic oxygen furnace metal products are transported from the mill to manufacturers or processors by either truck, rail, or waterway.

Manufacturing and processing converts slag and BOF metal products created at the refineries into finished products. Manufacturing involves activities such as cutting and shaping the metal. Electric arc furnace refined metal products are not processed after leaving the refinery.

After a metal product or slag is manufactured into a finished product, it must be transported and distributed to the general public (i.e., end user). Facilities involved in the distribution of finished metal products, produced at both EAFs and BOFs, include stores, warehouses, and car lots. Slag is usually distributed and transported directly from the refinery where it is produced or from the manufacturer where it is processed. EAF dust is usually processed (immobilized) at the same facility where it is disposed of and requires no additional transportation. EAF dust that is processed into fertilizer is containerized and shipped by truck to distributors.

There are other refinery byproducts in addition to refined metal, slag, and baghouse dust. However, these represent comparatively small material flow pathways, and have not been evaluated in this analysis. One such byproduct is mill scale, which is the oxidized surface of refined steel that is produced, for example, during the hot rolling of steel slabs. Scale consists of a mixture of iron oxides, and therefore has a high iron content (e.g., 55%). Scale production can be as high as 1% of refined steel output at a refinery, but is more typically between 0.5% and 0.75%. Scale must be removed from refined steel because it results in unwanted characteristics of the finished steel. Because of its high iron content and other characteristics, mill scale is a commodity and can be used in the steel industry as well as the cement industry. Partitioning of radionuclides to scale has not been evaluated for this analysis, but it would be dependent on the partitioning to refined steel, and it is likely that radionuclide concentrations in scale would be roughly the same as in refined steel. Radionuclides in any mill scale that is returned to the steel industry would likely end up in refined steel at some point, at lower concentrations than initially in the scale. The fate of radionuclides in scale that is used in the cement industry is unknown, however the evaluation of slag use in concrete in this analysis may be an adequate substitute analysis for this potential flow pathway.

4.2.4 Disposition of EAF Baghouse Dust

Between 450,000 and 590,000 t (500,000 and 650,000 tons) of EAF baghouse dust is generated each year in the U.S. This dust is classified as a RCRA hazardous waste because of the metal content (EPA Waste No. K061). For many years, the majority of the dust was thermally treated for metals extraction or disposal. Data available at the time this was formally investigated (for calendar year 1992) indicated processes that an estimated 86.5% of the EAF dust generated was treated by high-temperature metals recovery (EPRI 1993). Therefore, the high-temperature metals recovery process was evaluated for this analysis. However, because of a high degree of uncertainty in the modeled radionuclide concentrations of byproducts, plus evolving industry practices, these concentrations were not used for scenario evaluation.

Also in 1992, approximately 11.2% of all EAF dust collected by baghouse filters was treated and disposed of as hazardous waste (EPRI 1993). The standard treatment prior to disposal is immobilization. Electric arc furnace dust is immobilized by mixing it with hydraulic cement, the most common of which is Portland cement. Cement hydration reactions require that the waste-cement mixture have an alkaline pH. While cement—a highly alkaline medium—is quite effective itself in raising the pH of most wastes, its effectiveness is limited, particularly with highly acidic wastes. Such wastes are typically pretreated to raise the pH before solidification.

At the disposal facility, EAF dust is treated to obtain a waste form that meets RCRA immobilization requirements. Typically about 100 g of EAF dust is mixed with about 30 g of two additives (liquid reagent and dry cement), which results in a dilution factor of 0.77; the density of the solidified product is typically 1.36 g/cm^3 (Logan 1993). It is then loaded into steel roll-off boxes or drums, which are temporarily stored in the yard. When laboratory tests confirm that the waste meets EPA treatment standards, the containers are placed in the disposal trench.

The remaining 2.3% of EAF dust collected by baghouse filters was used for the manufacture of fertilizer in 1992 (EPRI 1993). According to 40CFR266.20, which details use of EAF dust in fertilizer, EAF dust used in fertilizer is no longer regulated under RCRA; however, this classification is subject to change. In this application, fertilizer manufacturers treat the dust with sulfuric acid to form soluble zinc compounds and insoluble lead sulfates. Fertilizer manufacturers require high zinc content (preferably above 20%) in the dust (EPRI 1993) to achieve a reasonable maximum concentration of zinc in fertilizer of 3%.[1] Assuming that the initial concentration of zinc is 20% in the EAF dust and that the final zinc concentration is 3% in enriched fertilizer, 1.36E+5 g of EAF dust would be added to 7.71E+5 g of non-enriched fertilizer (additives).[1] This results in a dilution factor of 0.15. All EAF dust shipped for use in fertilizer manufacturing is consumed during the process. The enriched fertilizer is loaded into packing loaders, boxed, and shipped out on trucks.

The disposition of EAF dust has been an issue for the steel industry for several years; as a result of this, the regulatory situation is evolving. Because of the regulatory and liability issues,

[1]Personal communication between Mary Anderson (SAIC) and J. Wyett (Frit Fertilizer), February 1995.

industry has responded rapidly with new practices for the disposition of EAF dust: these changing practices, however, make the process difficult to analyze. New recycle processes are being developed to remove heavy metals and zinc oxide, producing various byproducts such as building bricks, roofing granules, and abrasives. Also, several approaches to minimize the amount of dust requiring disposition are being investigated by the steel industry. This includes efforts to minimize the generation of dust and various on-site recycling programs. There is sufficient economic motivation and environmental liability to pursue such efforts, so practices for the disposition of EAF dust will likely continue to evolve.

4.2.5 Product Use

Slag or finished metal products are used by the public for many applications. Examples of finished metal products from BOFs are small appliances (e.g., toasters), automobiles, public transportation vehicles, furniture, and small objects that would be in contact with the body, such as jewelry. Types of finished EAF metal products include large items (reinforcements for houses, rebar, fence posts) and smaller objects (tools and belt buckles). Slag can be used in commercial applications for construction (various types of concrete aggregates and products), road-building (road bases), glass manufacture, mineral wool, railroad ballast, and soil conditioning (Solomon 1993). Fertilizer containing EAF dust is used by the agricultural industry to fertilize produce that is meant for human consumption. However, because of the concerns discussed above, EAF dust fertilizer is not included in this analysis.

4.2.6 Disposal

The ultimate endpoint for finished metal products, slag, and BOF dust is disposal in a public sanitary landfill (RCRA Subtitle D). The types of objects that could end up in a public sanitary landfill include discarded end products, waste from manufacturing, slag directly from the refinery, products made from slag, scrap not suitable for reuse or recycle, and BOF dust. The ultimate endpoint for immobilized EAF dust is a hazardous landfill (RCRA Subtitle C).

4.3 Mass and Elemental Partitioning Factors for Refinery Operations

Redistribution (partitioning) of the radioactivity and mass present in cleared steel scrap entering the refinery furnace must be followed to estimate concentrations of radionuclides in various recycle end products. Partitioning factors are defined as the fraction of original radioactivity or mass of scrap entering the refinery furnace that would be present in various end products.

For this analysis, the mass of scrap metal entering a furnace during the refining process is redistributed into the three immediate products of the refining process: metal product, slag, and dust. Radioactivity in incoming scrap metal is also redistributed among those products, as well as in the off-gas leaving the refinery stack. Assumptions and data used to develop the partitioning factors, as well as calculated partitioning factors used in the material flow modeling for both mass and radioactivity, are discussed in the following sections.

4.3.1 Mass Partitioning Factors

Mass partitioning factors are calculated and used for the metal product, slag, and dust. Partitioning factors for the metal product and dust are based on literature, while those for slag are calculated by approximating conservation of mass.

The partition factor distributions are not sampled to ensure that they add up to 1.0 for any single run within a Monte Carlo simulation. This is not necessary since each exposure scenario calculates dose factors from radioactivity in only one material at a time (i.e., refined metal, slag, or baghouse dust).

4.3.1.1 Metal Product

Industry data indicates that EAFs typically produce 90 t (99 tons) of steel for every 100 t (110 tons) of scrap used (Lankford et al. 1985). Data reported by the American Iron and Steel Institute for the period 1988 through 1992 yield an average mass partitioning factor for metal product (f_{p1}) of 90% with a range from 85% to 95% (AISI 1993). These estimates are supported by three industry contacts (Border Steel, TX , Bayou Steel, LA, and Arkansas Steel, AR). Each of these three refineries indicated that they controlled their process toward a target yield of 90% with a range from 88% to 92%.

4.3.1.2 Baghouse Dust

All available references give dust generation rates in terms of mass of dust *per mass of steel produced* not per mass of scrap used. In order to estimate a mass partitioning factor, some assumptions must be made regarding the mass of steel produced per mass of scrap used. The equation for the mass partitioning factor for dust, f_{d1}, is as follows:

$$\begin{aligned} f_{d1} &= Mass_{dust} / Mass_{scrap\ used} \\ &= (Mass_{dust} / Mass_{steel\ produced}) * (Mass_{steel\ produced} / Mass_{scrap\ used}) \\ &= (Mass_{dust} / Mass_{steel\ produced}) * f_{p1} \end{aligned}$$

The value used here for f_{p1} (mass partitioning factor for metal product) is 90 t (99 tons) of carbon steel produced per 100 t (110 tons)of scrap used (see Section 4.3.1.1).

There is remarkable consensus in the literature for a best estimate value of 15 kg of dust per metric ton of carbon steel produced at EAF facilities. Brough and Carter (1972) and Venturini (1970) give 15 kg/t a “measured operating value.” This value is supported by two industry contacts (Border Steel, TX and Arkansas Steel, AR). EPRI (1993) presents 15 kg/t of capacity as an industry average of 52 plants responding to their survey. A dust production rate of 15 kg/t of steel produced corresponds to an f_{d1} of 0.014.

Estimates of the range of dust production are also fairly consistent. Brough and Carter (1972) cites a range of 7.5 to 20 kg/t as a specification for baghouse design. Elert and Wiborgh (1992)

cites a range of 10 to 15 kg/t for Swedish EAF steel mills. Szabo and Gerstle (1978) gives a range of 12 to 29 kg/t. The range used for this evaluation is from 10 to 25 kg/t which corresponds to a range in f_{d1} of 0.009 to 0.023.

4.3.1.3 Slag

Steel yield is well-known because it is of significant economic importance, and baghouse dust production is well-known because it is a regulated material. However, the mass of slag produced per mass of scrap is not well-documented in the literature and has not been readily available from industry contacts. Estimates for slag production can be calculated based on a mass balance for a typical carbon steel recipe. In addition to scrap, the typical EAF uses fluxing agents (mostly lime and silica or limestone) at a rate of about 38 kg/t of scrap (AISI 1993). Small amounts of other materials are included in the melt (carbon, consumed electrodes, and refractory brick). In addition, oxygen is consumed in the oxidation of materials that are incorporated into slag. Slag consists primarily of iron oxide, calcium, and silicon oxides from oxidation of fluxes, along with oxides of various metals appearing as impurities in scrap. Slag is about 20% oxygen by weight (Lankford 1985).

Table 4.3 provides estimates for slag production using a mass balance approach. Sufficient oxygen has been included to account for oxidation of the fluxing material and the difference in mass between the scrap and the steel produced. The masses of steel and dust produced are taken from preceding sections of this report. Dust production is assumed to be inversely proportional to steel production. That is, the maximum dust production of 2.0% occurs when steel production is 85%, the minimum dust production of 0.9% occurs when steel production is 95%, and the average dust production of 1.4% occurs when steel production is 90%. Using this method, a value of 0.16 is chosen for the most likely estimate for the mass partitioning factor for slag, f_{s1}.

Table 4.3 Values used for calculation of EAF mass partitioning factors (metric tons per charge)

		Nominal	High*	Low*
Furnace Input				
	Scrap	100	100	100
	Flux	4	4	4
	Oxygen	3.15	2	4.3
	Total	107.15	106	108.3
Furnace Output				
	Steel	90	95	85
	Baghouse Dust	1.4	0.9	2.0
	Slag	15.75	10.1	21.3
	Total	107.15	106	108.3

* High = Highest yield of steel (lowest production of baghouse dust and slag)
Low = Lowest yield of steel (highest production of baghouse dust and slag)

4.3.1.4 Basic Oxygen Furnace

As cleared steel scrap is processed in a refinery, new refined metal, dust, slag, and off-gas is produced. A mass partition factor is used in the model to simulate the quantity of each of the four media produced during refining. The uncertainty in the mass partition factors is related to a number of factors including composition of the scrap, the refining method used, fluxing, charging, and other factors. The mass partition factors are different for EAF and BOF refinery processes because of different furnace charging procedures.

The efficiency for an EAF has a most likely value of 90% with a range of 85% to 95%. According to Lankford (1985) a typical basic oxygen furnace (BOF) has a yield of about 88%. (i.e., 88 t of metal product produced for every 100 t charge). However, a charge in a BOF can consist of 20–35% scrap with a typical value of about 32.2% (Lankford 1985). A value of 32 t of scrap for every 100 t of metal charge is used for the amount of scrap in each charge.

Because no information was found to indicate that a typical BOF is less efficient than an EAF, the same efficiency range for the BOF metal-product mass partitioning factor is used.

The only available reference gives dust generation rates in terms of mass of dust *per mass of steel produced* not per mass of scrap used. According to EPA (1986), about 14 kg of dust is produced for every metric ton of metal product produced in a BOF. In order to estimate a mass partitioning factor for dust, some assumptions must be made regarding the mass of steel produced per mass of scrap used. The equation for f_{d1} is as follows:

$$\begin{aligned} f_{d1} &= M_{dust} / M_{scrap\ used} \\ &= (M_{dust} / M_{steel\ produced}) * (M_{steel\ produced} / M_{scrap\ used}) \\ &= (M_{dust} / M_{steel\ produced}) * f_{p1} \end{aligned}$$

The mass of slag produced per mass of scrap is not well documented in the literature and has not been readily available from industry contacts. Steel yield is well known because it is of economic importance. Estimates for slag production can be calculated based on a mass balance for a typical carbon steel recipe. In addition to scrap and pig iron, the typical BOF takes fluxing agents (mostly burnt lime and dolomitic lime) at a rate of about 90 kg/t (180 lb/ton) of metal product produced (Lankford 1985). Small amounts of other materials are included in the melt (carbon, consumed electrodes, refractory brick, and fluorspar). In addition, oxygen is consumed in the oxidation of materials that are incorporated into the slag. Oxygen is added at a rate of about 2 m^3 per minute per metric ton for a period of 16 to 25 minutes (Lankford 1985). Assuming an average period (20.5) for the oxygen blow and density of 1.43 g/L for oxygen at standard temperature and pressure (CRC 1992), approximately 5.9 t of oxygen is used for a 100 t (scrap + pig iron) charge.

Table 4.4 provides input and yield estimates used for calculating mass partitioning factors for the metal product, dust, and slag.

Table 4.4 Values used for calculation of BOF mass partition factors (metric tons per charge)

	Nominal	High*	Low*
Furnace Input			
Pig Iron	68	68	68
Scrap	32	32	32
Flux	7.8	7.8	7.8
Oxygen	5.9	5.9	5.9
Total, t	113.7	113.7	113.7
Furnace Output			
Steel	88	95	85
Baghouse Dust	1.2	1.3	1.2
Slag	24.5	17.4	27.5
Total, t	113.7	113.7	113.7

* High = Highest yield of steel (lowest production of baghouse dust and slag)
Low = Lowest yield of steel (highest production of baghouse dust and slag)

4.3.2 Elemental Partitioning Factors

This section presents the basic assumptions and methodology used in developing the elemental partitioning factors. Section 4.3.2.3 summarizes a comparison of the estimated partitioning factors used in this analysis against data available in the literature.

4.3.2.1 Basic Assumptions

All the elements included in the material flow model, with the exception of the actinides and noble gases, are typically found in steel-making as components of steel scrap, alloying additions, or unwanted impurities. Sulfur, for example, is usually an unwanted impurity in steel. However, sulfur and other chalcogenides are sometimes added to alloys to produce free-machining steels. In general, steel making processes and operating conditions have been developed that, depending on the desired result, can maximize the retention of a particular element in the molten steel or, conversely, maximize its removal. The elemental partitioning factors determined for the material flow model are intended to be representative of the expected behavior during melting in a typical domestic EAF or BOF.

It is recognized that there will be variability in the behavior of elements during the refining of steel. For example, cesium may almost completely volatilize to the dust if a basic slag is used, but would tend to partition to both the slag and dust if a neutral or acidic slag is used (Harvey 1990). Other factors that could affect elemental partitioning factors are gas sparging, mixing, or the type of desired melt (e.g., carbon steel or stainless steel). Thus, any single partitioning value used in the material flow modeling has some associated uncertainty. In order to address this uncertainty, the partitioning values are included as variables in the uncertainty analysis of the material flow modeling.

The primary components of a typical steel refining facility that are important to the material flow model are the primary melting chamber (the furnace) and the air pollution control system. As

stated previously, the air pollution control system consists of a fabric baghouse filter. Other components of the refinery, such as ladles, tun dishes, and reheating ovens, are not important to the material flow model because no phase changes occur and there is no dilution or concentration of elements. The most common type of furnace uses a basic process with a basic slag (Lankford et al. 1985). Other processes, such as the use of different slagging agents, gas sparging, and mixing, can affect the partitioning of elements. However, for this study, these will not be included because their use in refineries is extremely variable and their effects are difficult to predict.

During refining, elements can partition to one or both of the main melt components (i.e., the slag and metal phases), or discharge from the furnace in the volatilized gas. Some of the elements that leave the furnace in the volatilized gas will remain in the vapor phase (off-gas) and some will condense or coalesce into particulates (dust). Elements found in coarse particulates are captured by the baghouse filter. Some of the fine particles and species in the vapor phase will escape in the off-gas exiting the stack. A small fraction of metals and oxides that are refractory or ferrous in nature will be carried over to the dust. Based on general knowledge of these elements in baghouse dust and actual experience with EAF baghouse dust, a fraction of 1% was assumed to be carried over to the dust for this flow model. For example, even though iron is a ferrous element and would be expected to partition completely to the steel product, data from baghouse filter dust analyses show that iron is present in baghouse dust (EPRI 1993).

The refinery furnace is assumed to be using a basic process, i.e., basic slag, with an average temperature of about 1600°C. The average temperature of the baghouse is assumed to be 190°C. For purposes of determining partitioning, it is assumed that the air flowing through the baghouse is cooled to this temperature. Other assumptions include those listed in Table 4.2.

4.3.2.2 General Methodology for Determining Elemental Partitioning

In order to simplify the material flow modeling, elements of concern were grouped according to their elemental partitioning factors. It was assumed that all isotopes of a given element would behave identically (no isotope effects).

First, the likely chemical form of the element in question after charging the furnace was determined. For example, iron, cobalt, and nickel will remain in the metallic state as part of a solid solution in the steel. Elements that are more reactive than iron will readily form oxides (e.g., Pu, Ac, Th). The physical properties of that form, particularly boiling point, were then examined. If the boiling point of the element of interest is less than 1600°C, then it is assumed to volatilize from the melt or the slag. However, if the boiling point of the element of interest is greater than 1600°C, it is assumed to remain in the original form. Most volatilized from the furnace will form oxides before they reach the baghouse, no matter what their form at the time of volatilization. To determine if the element that volatilizes from the furnace will stay in the vapor phase or form particulates, the boiling points of the oxide of these elements were compared to the temperature of the baghouse (190°C). If the boiling point of an element is greater than 190°C, it will tend to form particulates as it cools, with a small fraction remaining in the vapor phase. If

the boiling point is less than 190°C the element will remain in the vapor phase with a small fraction forming particulates. For example, zinc, which is found as a metal, boils at a temperature well below the expected temperature in the furnace. Thus, zinc is expected to partition primarily to the off-gas components. However, the boiling point of zinc oxide is well above 190°C, and it is expected to form particulates (dust). On the other hand H, I, and Rn are assumed to remain in the vapor phase.

In some cases, it is inappropriate to assume elements will appear as oxides in the baghouse. For example, the partitioning of chlorine depends on the presence of alkali metals. Even though the elemental characteristics indicate that chlorine would form a stable gas, it would likely tend to form particulates if alkali metals are present. Based on this information, it is determined that a small fraction of chlorine would most likely form particulates.

There are some elements that were treated as special cases because certain chemical reactions occur in the furnace that do not follow the methodology presented above. These special case elements and their expected behavior are presented below.

P - oxidized by a basic slag and volatilizes as an oxide
C - alloys with steel (with more oxygen it will tend to volatilize)
Se - generally difficult to remove from steel
Sb - readily alloys with steel and is difficult to remove
Mn - used extensively in the steel industry for desulfurization and reacts with sulfur to form MnS_2 which forms as inclusions in the steel melt.
Na - very reactive and readily forms oxides. Because of the temperature at which Na_2O sublimes it will only partially volatilize from the slag.[1]
Tc - alloys with steel and is difficult to remove.[2]
Ru - alloys with steel and is difficult to remove.[2]
Bi - reactive and readily forms oxides. Because of the temperature at which Bi_2O_5 decomposes it will only partially volatilize from the slag.
K - very reactive and readily forms oxides but decomposes at a low temperature and will volatilize in the elemental form.
Pb - normally less reactive than iron. With the addition of oxygen it will form oxides and volatilize.

Table 4.5 lists elemental partitioning factors for each element in the anlaysis. For many elements there is sufficient data to identify a most likely value within this range. In probabilistic calculations, these are described using a triangular distribution with the mode equal to the most likely value. For some elements, the data do not allow a best estimate to be chosen from the ranges in the table. Partitioning of these elements is described by a uniform distribution of values across the ranges with maxima and minima, as shown in the table. Information on the uncertainty distributions for this parameter appears in Appendix B, Table B.3.

[1]Personal communication, G. L. Leatherman, Science Applications International Corporation, 1995.

[2]Personal communication, A. Murray, Science Applications International Corporation, 1995.

Table 4.5 Elemental partitioning factors (EPF) for steel

Elements	Elemental partitioning factors (%)			
	Metal product	Baghouse dust	Slag	Volatile
Ag, C, Co, Cu, Mo, Ni, Ru, Tc	95–100	0–2	0–1	0
Sb	80–100	0–1	0–20	0
Se	0–80	0–80	20–77	0
Fe	95–100	0–2	0–5	0
Pb	0–5	95–100	0–5	0
Zn	0–20	80–100	0–1	0
Cd, Cs, Po	0–1	95–100	0–5	0
S	0–20	4–97	0–3	0
Re	0–99	1–97	3–87	0
P	0–10	4–97	3–77	0
K	0–1	50–100	3–50	0
Ir	0–100	0–100	0–3	0
Bi	0–25	45–100	0–25	0–5
Mn	24–50	0–4	50–75	0
Cr	49–99	0–1	0–50	0
Na	0–10	40–50	45–55	0–5
Ra	0–5	0–5	95–100	0
Ac, Am, Ba, Ca, Ce, Cm, Eu, Nb, Np, Pa, Pm, Pu, Sr, Sm, Th, U, Y, Zr	0–1	0–5	95–100	0
Cl	0–1	8–50	0–50	0–90
I, Rn	0	0	0	100
H	0–10	0	0	90–100

EPF = [element concentration in product/element concentration in scrap]×100

Partitioning factors are not sampled to ensure that they add up to 1.0 for any single run within a probabilistic calculation. This is not necessary for the purpose of this anlaysis because each scenario calculates dose from exposure to only one material at a time.

4.3.2.3 Comparison of Partitioning Factors with Published Studies

A comparison of the partitioning factors presented above to experimental information on partitioning was done in order to help establish their validity. The comparison was limited to those studies that presented results from actual experimental meltings of radioactively contaminated metal. One exception to this was Copeland (Copeland et al. 1978) who used a non-experimental thermodynamic approach similar to this study. However, dust was not included in the Copeland study, and elements were partitioned between slag and the metal product only. Articles that did not present enough data to determine partitioning were not included. The literature reviewed had information on only a limited number of elements—most commonly cobalt and cesium— probably because these are most likely to be involved in accidental melting of sealed sources.

In general, the results presented in previous studies support the grouping and partitioning factors developed herein. Even though partitioning values do not agree exactly, the overall grouping is supported. The differences between the previous studies and partitioning factors and groupings developed for this study are mainly due to the different assumptions used (e.g., type of furnace used, purpose of refining). The purpose of some experiments was to decontaminate the metal

and force the radionuclides to the slag. This is different than the assumption used in this report (normal refining operations and no decontamination). In some cases the assumptions used were not stated in the study, so an accurate interpretation and comparison of the partitioning data was impossible.

4.4 Mathematical Model for Flow of Recycled Steel Scrap

This section presents the equations that comprise the mathematical model of the information presented previously in Sections 4.2 and 4.3. The equations are used to estimate radionuclide concentrations in refined steel and other co-products of refining. For calculation, the equations are entered in spreadsheets that have been organized and structured specifically for this analysis. The calculated radionuclide concentrations in refined steel, refinery slag, refinery baghouse dust, and the activity released out the refinery stack are used as input to the scenario analyses described in Section 4.6.

4.4.1 Scrap Mixing

There are two processes by which the original concentration of each radionuclide in steel scrap is potentially changed. The first can occur upon mixing with other scrap metal prior to refining. This mixing is a radionuclide-independent process, so the radioactivity concentration of all radionuclides is affected the same when mixing with a given mass of non-contaminated scrap steel. The second process is the refining process itself, which generally consists of the melting of steel scrap metal and the resulting redistribution (partitioning) of mass and radioactivity. Partitioning of mass during refining is radionuclide-independent, however partitioning of radioactivity during refining is element-dependent. The following equations are used to calculate the radionuclide concentrations in refinery co-products at those points in the material flow which correspond to potential exposure scenarios.

The first change in radioactivity concentration occurs if the cleared scrap from the nuclear facility is mixed with other metal prior to melting. There are actually two potential places that mixing can occur: at the scrap dealer (i.e., secondary metal pool) and in the primary metal pool at the refinery furnace. For simplicity, these two mixings were treated as a single potential dilution. This mixing is modeled using appropriate ranges for the masses of cleared and other scrap entering a refinery furnace. These masses were derived for both EAFs and BOFs and are listed in Appendix B. The total mass of scrap entering the furnace in a year was calculated using Equation 4.1.

$$M_1 = M_0 + M_{NC} \qquad 4.1$$

where

M_1 = total mass of scrap metal entering the furnace per charge (g/charge)

and

M_0 = mass of cleared material entering the furnace per charge (g/charge)

M_{NC} = mass of non-contaminated scrap metal entering the furnace per charge (g/charge)

The radionuclide concentration in the metal entering the furnace was calculated using Equation 4.2. The original radioactivity concentration, C_0, is reduced by the ratio of the mass of cleared scrap entering the furnace to the total mass of material entering the furnace. The following equations are intended to be evaluated separately for each radionuclide in the analysis. However, parameters such as concentration and other radionuclide-specific parameters are not explicitly subscripted in the equations.

$$C_1 = \frac{M_0}{M_1} * C_0 \qquad 4.2$$

Where

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)

and

M_0 = mass of cleared material entering the furnace per charge (g/charge)

M_1 = total mass of scrap metal entering the furnace per charge (g/charge)

C_0 = original radionuclide concentration in cleared material (pCi/g)

For slag, baghouse dust, and off-gas, Equations 4.1 and 4.2 were evaluated using annual average values for the masses of scrap input to the furnaces, because all of the exposure scenarios for these materials depend on annual average radionuclide concentrations. For metal, both an annual average and a single charge evaluation of Equations 4.1 and 4.2 were conducted. This was done for metal because there are metal products that could easily be manufactured from a single refinery charge. The single charge radionuclide concentrations were used in metal product use exposure scenarios except where noted. (See Appendix D for additional details.)

4.4.2 Refinery Process

To accurately account for the changes in radionuclide concentration in the different products, the mass of each refinery product must be calculated independent of radionuclide activity. Equations 4.3, 4.4, and 4.5 were used to calculate the masses of slag, dust, and metal product, respectively.

$$M_s = M_1 * f_{s1} * CPY \qquad 4.3$$

$$M_d = M_1 * f_{d1} * CPY \qquad 4.4$$

$$M_p = M_1 * f_{p1} * CPY \qquad 4.5$$

where

M_s = mass of slag produced from a refinery per year (g)
M_d = mass of dust produced from a refinery per year (g)
M_p = mass of metal product produced from a refinery per year (g)

and

M_1 = total mass of scrap entering the furnace per charge (g/charge)
f_{s1} = mass partitioning factor for slag during the refining process (dimensionless)
f_{d1} = mass partitioning factor for dust during the refining process (dimensionless)
f_{p1} = mass partitioning factor for metal product during the refining process (dimensionless)
CPY = number of charges per refinery per year (charge)

The radioactivity in the original scrap metal entering the furnace during the refining process is partitioned into four products. Equation 4.6 shows the calculation of the concentration of radionuclides in slag, taking into account both the mass and elemental partitioning factors.

$$C_s = \frac{C_1 * f_s * M_1}{M_1 * f_{s1}} = \frac{C_1 * f_s}{f_{s1}} \quad 4.6$$

where

C_s = radionuclide concentration in slag after the refining process (pCi/g)

and

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
f_s = slag elemental partitioning factor during the refining process (dimensionless)
M_1 = total mass of scrap entering the furnace per charge (g/charge)
f_{s1} = mass partitioning factor for slag during the refining process (dimensionless)

The concentration of radionuclides in the dust and metal product are calculated using Equations 4.7 and 4.8, respectively.

$$C_d = \frac{C_1 * f_d}{f_{d1}} \quad 4.7$$

where

C_d = radionuclide concentration in dust after the refining process (pCi/g)

and

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
f_d = dust elemental partitioning factor during the refining process(dimensionless)
f_{d1} = mass partitioning factor for dust during the refining process (dimensionless)

$$C_p = \frac{C_1 * f_p}{f_{p1}} \quad 4.8$$

where

C_p = radionuclide concentration in metal product after the refining process (pCi/g)

and

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
f_p = metal product elemental partitioning factor during the refining process (dimensionless)
f_{p1} = mass partitioning factor for metal product during the refining process (dimensionless)

Because there is no mass associated with the refinery off-gas, the total quantity of radioactivity was calculated instead of a concentration. The off-gas radioactivity was calculated using Equation 4.9 using only the elemental partitioning factor (i.e., no mass partitioning factor). This radioactivity is calculated on an annual basis.

$$A_g = C_1 * M_1 * f_g * CPY \quad 4.9$$

where

A_g = radioactivity in the off-gases leaving the refinery stack in a year (pCi)

and

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
M_1 = total mass of scrap entering the furnace per charge (g/charge)
f_g = off-gas elemental partitioning factor during the refining process (dimensionless)
CPY = number of charges per refinery per year (charge)

Equations 4.10 and 4.11 were used to calculate the mass of dust that escapes the baghouse filters, and that which is captured in the baghouse, respectively.

$$M_{ra} = M_d * (1 - BH_{eff}) \quad 4.10$$

where

M_{ra} = total mass of dust that escapes the baghouse in a year (g)

and

M_d = mass of dust produced from the refining process in a year (g)
BH_{eff} = baghouse efficiency (dimensionless)

$$M_{db} = M_d - M_{ra} \quad 4.11$$

where

M_{db} = total mass of dust captured in the refinery baghouse in a year (g)

and

M_d = mass of dust produced from the refining process in a year (g)
M_{ra} = total mass of dust that escapes the baghouse in a year (g)

4.4.3 EAF Dust Hazardous Landfill

A certain percentage of the EAF dust produced by the steel industry each year is treated for direct disposal in a hazardous landfill. During this immobilization treatment, dilution of the EAF dust is the only process modeled. The mass of EAF dust that is sent to hazardous landfills in a year is represented by Equation 4.12. The total mass of material entering the immobilization process in a year is calculated using Equation 4.13. The radioactivity concentration in the treated dust when it is placed in a hazardous landfill is calculated using Equation 4.14.

$$M_H = M_{db} * f_H \quad 4.12$$

$$M_{tH} = M_{H,add} + M_H \quad 4.13$$

$$C_H = C_d * df_H \quad 4.14$$

Where

M_H	=	mass of contaminated EAF dust sent to a hazardous landfill in a year (g)
M_{tH}	=	total mass of material entering the immobilization process in a year (g)
C_H	=	radionuclide concentration in immobilized dust (pCi/g)

and

M_{db}	=	total mass of dust captured in the refinery baghouse in a year (g)
f_H	=	annual fraction of total EAF dust that is sent to hazardous landfills (dimensionless)
$M_{H,add}$	=	mass of additives used in the immobilization process in a year (g)
C_d	=	radionuclide concentration in dust after the refining process (pCi/g)
df_H	=	dilution factor for immobilization process (dimensionless)

4.5 Radioactivity Concentrations in Steel Refining Co-products

The values listed in Table 4.6 are calculated radioactivity concentrations at an EAF refinery and Table 4.7 for a BOF refinery. The values are normalized to a unit radioactivity concentration in scrap, and are listed in S.I. units. The values are numerically identical if expressed in conventional units (e.g., pCi/g product per pCi/g scrap).

4.6 Dose Assessment for Steel Recycle and Disposal

4.6.1 General Description of Recycle Scenarios

General categories of scenarios were established to organize and simplify the evaluation and analysis of potential exposure scenarios. Because of the logical link between material flow models and potential exposure scenarios, the categories were derived from the steel scrap material flow model (Figure 4.1). Analysis of material characteristics and human behavior at certain points in the flow model identified six logical scenario categories for the evaluation: handling and processing (individual atmospheric releases), storage, product use, transportation, disposal activities, and resident on closed landfill scenarios.

Exposure conditions for scenarios not in these identified categories would be similar to those in the selected categories, and can be reasonably approximated by the evaluation of the categories chosen for evaluation. Consistent with the goals of the analysis, the exposure categories were selected to simplify the evaluation without limiting its comprehensiveness.

The following sections briefly describe the exposure pathways included in the recycle scenario analyses, followed by a description of the six general categories that the exposure scenarios fall into. Starting with handling at a scrap yard, through processing and use, to disposal and post-closure of a landfill, the categories encompass a "cradle to grave" picture of recycle of steel cleared from a NRC licensed facility. The scenarios can be divided into two broad categories work related and non-work related. Work related exposure scenarios, obviously, would be limited to workers exposed to recycled material during the course of their workday. Non-work related exposure scenarios describe situations where the general public might come in contact with recycled material as consumers or as part of daily activities not directly associated with employment. Some scenario categories contain both worker and non-worker exposure scenarios.

There are 31 exposure scenarios listed in Table 4.8. Of these, only 27 were used for the determination of critical groups. The four landfill resident scenarios were judged to be too unlikely to use in the critical group determination, but were analyzed for completeness. A summary of the highest mean dose factors for the landfill resident scenarios is included in Appendix J.

Table 4.6 Results of material flow model—steel electric arc furnace

	Mean radionuclide concentrations in refinery products (Bq/g per Bq/g scrap)				
	Refined metal				Off-gas
Nuclide	Single charge	Annual	Slag	Dust	(Bq per Bq/g)
H-3	3.1E-02	2.3E-03	0.0E+00	0.0E+00	3.4E+10
C-14	9.2E-01	7.0E-02	1.5E-03	4.3E-02	0.0E+00
Na-22	3.1E-03	2.3E-04	2.1E-01	1.9E+00	1.2E+09
P-32	3.2E-02	2.4E-03	1.9E-01	2.1E+00	0.0E+00
S-35	9.4E-02	7.0E-03	1.6E-01	2.2E+00	0.0E+00
Cl-36	6.2E-03	4.7E-04	1.0E-01	1.3E+00	1.6E+10
K-40	3.1E-03	2.4E-04	1.1E-01	3.2E+00	0.0E+00
Ca-41	3.1E-03	2.4E-04	4.1E-01	8.6E-02	0.0E+00

Table 4.6 Results of material flow model—steel electric arc furnace

	Mean radionuclide concentrations in refinery products (Bq/g per Bq/g scrap)				
	Refined metal				Off-gas
Nuclide	Single charge	Annual	Slag	Dust	(Bq per Bq/g)
Ca-45	3.2E-03	2.4E-04	4.1E-01	8.3E-02	0.0E+00
Cr-51	7.0E-01	5.2E-02	1.1E-01	2.9E-02	0.0E+00
Mn-54	3.5E-01	2.6E-02	2.6E-01	7.1E-02	0.0E+00
Fe-55	9.1E-01	6.9E-02	9.7E-03	4.3E-02	0.0E+00
Co-57	9.2E-01	7.0E-02	1.4E-03	4.3E-02	0.0E+00
Co-58	9.2E-01	7.0E-02	1.4E-03	4.3E-02	0.0E+00
Fe-59	9.1E-01	6.9E-02	9.6E-03	4.3E-02	0.0E+00
Ni-59	9.2E-01	7.0E-02	1.4E-03	4.3E-02	0.0E+00
Co-60	9.2E-01	7.0E-02	1.3E-03	4.3E-02	0.0E+00
Ni-63	9.2E-01	7.0E-02	1.4E-03	4.2E-02	0.0E+00
Zn-65	9.4E-02	7.0E-03	1.4E-03	3.9E+00	0.0E+00
Cu-67	9.2E-01	7.0E-02	1.4E-03	4.4E-02	0.0E+00
Se-75	3.8E-01	2.9E-02	2.0E-01	1.7E+00	0.0E+00
Sr-85	3.1E-03	2.4E-04	4.1E-01	8.5E-02	0.0E+00
Sr-89	3.1E-03	2.4E-04	4.1E-01	8.8E-02	0.0E+p0
Sr-90	3.1E-03	2.4E-04	4.1E-01	8.6E-02	0.0E+00
Y-91	3.2E-03	2.5E-04	4.1E-01	8.5E-02	0.0E+00
Mo-93	9.2E-01	7.0E-02	1.4E-03	4.3E-02	0.0E+00
Nb-93m	3.1E-03	2.3E-04	4.1E-01	8.7E-02	0.0E+00
Nb-94	3.1E-03	2.4E-04	4.1E-01	8.6E-02	0.0E+00
Nb-95	3.1E-03	2.4E-04	4.1E-01	8.6E-02	0.0E+00
Zr-95	3.1E-03	2.4E-04	4.1E-01	8.6E-02	0.0E+00
Tc-99	9.2E-01	7.0E-02	1.4E-03	4.3E-02	0.0E+00
Ru-103	9.2E-01	7.0E-02	1.4E-03	4.3E-02	0.0E+00
Ru-106	9.2E-01	7.0E-02	1.4E-03	4.3E-02	0.0E+00
Ag-108m	9.2E-01	7.0E-02	1.3E-03	4.3E-02	0.0E+00
Cd-109	3.1E-03	2.3E-04	1.1E-02	4.2E+00	0.0E+00
Ag-110m	9.2E-01	7.0E-02	1.4E-03	4.4E-02	0.0E+00
Sb-124	8.5E-01	6.4E-02	4.1E-02	1.4E-02	0.0E+00
I-125	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.6E+10
Sb-125	8.5E-01	6.4E-02	4.2E-02	1.4E-02	0.0E+00
I-129	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.6E+10
I-131	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.6E+10
Ba-133	3.2E-03	2.4E-04	4.1E-01	8.5E-02	0.0E+00
Cs-134	3.1E-03	2.3E-04	1.1E-02	4.2E+00	0.0E+00
Cs-137	3.2E-03	2.3E-04	1.1E-02	4.2E+00	0.0E+00
Ce-141	3.1E-03	2.4E-04	4.1E-01	8.7E-02	0.0E+00
Ce-144	3.1E-03	2.4E-04	4.1E-01	8.4E-02	0.0E+00
Pm-147	3.2E-03	2.5E-04	4.1E-01	8.7E-02	0.0E+00
Eu-152	3.1E-03	2.4E-04	4.1E-01	8.4E-02	0.0E+00
Eu-154	3.1E-03	2.4E-04	4.1E-01	8.7E-02	0.0E+00
Eu-155	3.2E-03	2.4E-04	4.1E-01	8.7E-02	0.0E+00
Re-186	4.6E-01	3.5E-02	8.3E-03	2.1E+00	0.0E+00
Ir-192	4.7E-01	3.7E-02	8.4E-03	2.2E+00	0.0E+00

Table 4.6 Results of material flow model—steel electric arc furnace

	Mean radionuclide concentrations in refinery products (Bq/g per Bq/g scrap)				
	Refined metal				Off-gas
Nuclide	Single charge	Annual	Slag	Dust	(Bq per Bq/g)
Pb-210	2.2E-02	1.7E-03	9.6E-03	4.2E+00	0.0E+00
Po-210	3.1E-03	2.3E-04	1.1E-02	4.2E+00	0.0E+00
Bi-210	1.2E-01	8.8E-03	5.2E-02	3.2E+00	1.2E+09
Rn-222	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.6E+10
Ra-223	1.9E-02	1.5E-03	4.1E-01	8.6E-02	0.0E+00
Ra-224	1.9E-02	1.4E-03	4.1E-01	8.6E-02	0.0E+00

Table 4.6 Results of material flow model—steel electric arc furnace

	Mean radionuclide concentrations in refinery products (Bq/g per Bq/g scrap)				
	Refined metal				Off-gas
Nuclide	Single charge	Annual	Slag	Dust	(Bq per Bq/g)
Ac-225	3.1E-03	2.4E-04	4.1E-01	8.6E-02	0.0E+00
Ra-225	1.9E-02	1.5E-03	4.1E-01	8.6E-02	0.0E+00
Ra-226	1.9E-02	1.4E-03	4.1E-01	8.8E-02	0.0E+00
Ac-227	3.1E-03	2.3E-04	4.1E-01	8.7E-02	0.0E+00
Th-227	3.1E-03	2.4E-04	4.1E-01	8.7E-02	0.0E+00
Th-228	3.1E-03	2.3E-04	4.1E-01	9.0E-02	0.0E+00
Ra-228	1.9E-02	1.4E-03	4.1E-01	8.4E-02	0.0E+00
Th-229	3.1E-03	2.4E-04	4.1E-01	8.5E-02	0.0E+00
Th-230	3.1E-03	2.4E-04	4.1E-01	8.6E-02	0.0E+00
Pa-231	3.2E-03	2.3E-04	4.1E-01	8.5E-02	0.0E+00
Th-231	3.2E-03	2.4E-04	4.1E-01	8.8E-02	0.0E+00
Th-232	3.1E-03	2.3E-04	4.1E-01	8.7E-02	0.0E+00
Pa-233	3.1E-03	2.3E-04	4.1E-01	8.6E-02	0.0E+00
U-233	3.2E-03	2.4E-04	4.1E-01	8.8E-02	0.0E+00
Th-234	3.1E-03	2.4E-04	4.1E-01	8.5E-02	0.0E+00
U-234	3.2E-03	2.4E-04	4.1E-01	8.6E-02	0.0E+00
U-235	3.2E-03	2.4E-04	4.1E-01	8.7E-02	0.0E+00
Np-237	3.1E-03	2.4E-04	4.1E-01	8.4E-02	0.0E+00
Pu-238	3.1E-03	2.4E-04	4.1E-01	8.5E-02	0.0E+00
U-238	3.1E-03	2.4E-04	4.1E-01	8.6E-02	0.0E+00
Pu-239	3.1E-03	2.4E-04	4.1E-01	8.5E-02	0.0E+00
Pu-240	3.1E-03	2.4E-04	4.1E-01	8.5E-02	0.0E+00
Pu-241	3.2E-03	2.3E-04	4.1E-01	8.5E-02	0.0E+00
Am-241	3.2E-03	2.3E-04	4.1E-01	8.3E-02	0.0E+00
Cm-242	3.1E-03	2.4E-04	4.1E-01	8.5E-02	0.0E+00
Pu-242	3.2E-03	2.3E-04	4.1E-01	8.5E-02	0.0E+00
Cm-244	3.2E-03	2.4E-04	4.1E-01	8.8E-02	0.0E+00

Table 4.7 Results of material flow model—for steel basic oxygen furnace

	Mean radionuclide concentrations in refinery products (Bq/g per Bq/g scrap)				
	Refined metal				Off-gas
Nuclide	Single charge	Annual	Slag	Dust	(Bq per Bq/g)
H-3	1.0E-02	6.9E-03	0.0E+00	0.0E+00	2.2E+10
C-14	3.0E-01	2.0E-01	2.6E-03	1.5E-01	0.0E+00
Na-22	1.0E-03	6.7E-04	4.0E-01	6.6E+00	7.7E+08
P-32	1.0E-02	6.7E-03	3.7E-01	7.2E+00	0.0E+00
S-35	3.0E-02	2.0E-02	3.3E-01	7.3E+00	0.0E+00
Cl-36	2.0E-03	1.4E-03	2.0E-01	4.3E+00	1.1E+10
K-40	1.0E-03	6.8E-04	2.1E-01	1.1E+01	0.0E+00
Ca-41	1.0E-03	6.8E-04	7.9E-01	3.0E-01	0.0E+00
Ca-45	1.0E-03	6.7E-04	7.9E-01	3.0E-01	0.0E+00
Cr-51	2.2E-01	1.5E-01	2.0E-01	9.7E-02	0.0E+00
Mn-54	1.1E-01	7.7E-02	5.0E-01	2.4E-01	0.0E+00
Fe-55	2.9E-01	2.0E-01	1.9E-02	1.5E+00	0.0E+00
Co-57	3.0E-01	2.0E-01	2.7E-03	1.5E-01	0.0E+00
Co-58	3.0E-01	2.0E-01	2.7E-03	1.4E-01	0.0E+00
Fe-59	2.9E-01	2.0E-01	1.9E-02	1.4E+00	0.0E+00
Ni-59	3.0E-01	2.0E-01	2.6E-03	1.5E-01	0.0E+00
Co-60	3.0E-01	2.0E-01	2.7E-03	1.5E-01	0.0E+00
Ni-63	3.0E-01	2.0E-01	2.7E-03	1.5E-01	0.0E+00
Zn-65	3.0E-02	2.0E-02	2.7E-03	1.3E+01	0.0E+00
Cu-67	3.0E-01	2.0E-01	2.7E-03	1.4E-01	0.0E+00
Se-75	1.2E-01	8.2E-02	3.9E-01	5.8E+00	0.0E+00
Sr-85	1.0E-03	6.8E-04	7.9E-01	3.0E-01	0.0E+00
Sr-89	1.0E-03	6.8E-04	7.9E-01	2.9E-01	0.0E+00
Sr-90	1.0E-03	7.1E-04	7.9E-01	2.9E-01	0.0E+00
Y-91	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
Mo-93	3.0E-01	2.0E-01	2.7E-03	1.5E-01	0.0E+00
Nb-93m	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
Nb-94	1.0E-03	6.9E-04	7.9E-01	3.0E-01	0.0E+00
Nb-95	1.0E-03	7.0E-04	7.9E-01	3.0E-01	0.0E+00
Zr-95	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
Tc-99	3.0E-01	2.0E-01	2.6E-03	1.4E-01	0.0E+00
Ru-103	3.0E-01	2.0E-01	2.6E-03	1.5E-01	0.0E+00
Ru-106	3.0E-01	2.0E-01	2.7E-03	1.4E-01	0.0E+00
Ag-108m	3.0E-01	2.0E-01	2.7E-03	1.5E-01	0.0E+00
Cd-109	1.0E-03	6.9E-04	2.1E-02	1.4E+01	0.0E+00
Ag-110m	3.0E-01	2.0E-01	2.7E-03	1.5E-01	0.0E+00
Sb-124	2.7E-01	1.9E-01	8.2E-02	4.7E-02	0.0E+00
I-125	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.3E+10
Sb-125	2.7E-01	1.9E-01	7.9E-02	4.8E-02	0.0E+00
I-129	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.3E+10
I-131	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.3E+10
Ba-133	1.0E-03	6.8E-04	7.9E-01	2.9E-01	0.0E+00
Cs-134	1.0E-03	6.9E-04	2.1E-02	1.4E+01	0.0E+00
Cs-137	1.0E-03	6.9E-04	2.2E-02	1.4E+01	0.0E+00

Table 4.7 Results of material flow model—for steel basic oxygen furnace

	Mean radionuclide concentrations in refinery products (Bq/g per Bq/g scrap)				
	Refined metal				Off-gas
Nuclide	Single charge	Annual	Slag	Dust	(Bq per Bq/g)
Ce-141	1.0E-03	7.0E-04	7.9E-01	2.9E-01	0.0E+00
Ce-144	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
Pm-147	1.0E-03	7.0E-04	7.9E-01	3.0E-01	0.0E+00
Eu-152	1.0E-03	6.8E-04	7.9E-01	2.9E-01	0.0E+00
Eu-154	1.0E-03	7.0E-04	7.9E-01	2.9E-01	0.0E+00
Eu-155	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
Re-186	1.5E-01	1.0E-01	1.6E-02	7.3E+00	0.0E+00
Ir-192	1.5E-01	1.0E-01	1.6E-02	7.2E+00	0.0E+00
Pb-210	7.0E-03	4.8E-03	1.8E-02	1.4E+01	0.0E+00
Po-210	1.0E-03	6.9E-04	2.1E-02	1.4E+01	0.0E+00
Bi-210	3.8E-02	2.6E-02	1.0E-01	1.1E+01	7.6E+08
Rn-222	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.3E+10
Ra-223	6.0E-03	4.1E-03	7.9E-01	3.0E-01	0.0E+00
Ra-224	6.0E-03	4.1E-03	7.9E-01	3.0E-01	0.0E+00
Ac-225	1.0E-03	6.7E-04	7.9E-01	2.9E-01	0.0E+00
Ra-225	6.0E-03	4.1E-03	7.9E-01	2.9E-01	0.0E+00
Ra-226	6.1E-03	4.0E-03	7.9E-01	2.9E-01	0.0E+00
Ac-227	9.8E-04	6.7E-04	7.9E-01	2.9E-01	0.0E+00
Th-227	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
Th-228	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
Ra-228	6.1E-03	4.2E-03	7.9E-01	3.0E-01	0.0E+00
Th-229	1.0E-03	7.0E-04	7.9E-01	2.9E-01	0.0E+00
Th-230	1.0E-03	6.8E-04	7.9E-01	2.9E-01	0.0E+00
Pa-231	1.0E-03	6.8E-04	7.9E-01	3.0E-01	0.0E+00
Th-231	1.0E-03	7.0E-04	7.9E-01	3.0E-01	0.0E+00
Th-232	1.0E-03	6.9E-04	7.9E-01	3.0E-01	0.0E+00
Pa-233	1.0E-03	6.7E-04	7.9E-01	2.9E-01	0.0E+00
U-233	1.0E-03	6.7E-04	7.9E-01	2.9E-01	0.0E+00
Th-234	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
U-234	9.9E-04	6.9E-04	7.9E-01	2.9E-01	0.0E+00
U-235	1.0E-03	6.8E-04	7.9E-01	2.9E-01	0.0E+00
Np-237	1.0E-03	6.8E-04	7.9E-01	2.9E-01	0.0E+00
Pu-238	1.0E-03	6.8E-04	7.9E-01	2.9E-01	0.0E+00
U-238	1.0E-03	7.0E-04	7.9E-01	3.0E-01	0.0E+00
Pu-239	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
Pu-240	1.0E-03	7.1E-04	7.9E-01	2.9E-01	0.0E+00
Pu-241	1.0E-03	7.1E-04	7.9E-01	3.0E-01	0.0E+00
Am-241	1.0E-03	6.8E-04	7.9E-01	2.8E-01	0.0E+00
Cm-242	1.0E-03	6.9E-04	7.9E-01	2.9E-01	0.0E+00
Pu-242	1.0E-03	7.1E-04	7.9E-01	3.0E-01	0.0E+00
Cm-244	1.0E-03	6.7E-04	7.9E-01	2.9E-01	0.0E+00

Table 4.8 Scenario and exposure pathway matrix

Scenario title and abbreviation for steel	Exposure pathways[a]				
	Ext	Inh	Sec	DW	Ing
Handling and Processing Scenarios					
Handling scrap metal at the scrapyard, FE-SCRP-HANDLIN-W	1	●	●		
Handling slag at the refinery, FE-SLAG-HANDLIN-W	F1	●	●		
Refinery baghouse operations, FE-EAFD-BAGHOUS-W	8	●	●		
Handling EAF dust at the refinery, FE-EAFD-HANDLIN-W	9	●	●		
Handling refined metal product at the refinery, FE-METL-HANDREF-W	2	●	●		
Handling BOF refined metal during product manufacturing, FE-BOFM-HANDMAN-W	2	●	●		
Handling EAF refined metal product during distribution, FE-METL-HANDDIS-W	2				
Processing EAF dust for disposal, FE-EAFD-PROCESS-W	1	●	●		
Processing slag for use as aggregate or as roadbed, FE-SLAG-PROCESS-W	1	●	●		
Atmospheric release during refining, FE-ATMO-REFINER-N	F2	●		●	●
Storage Scenario					
Storage of slag at the refinery, FE-SLAG-STORAGE-N				●	
Transport Scenarios					
Transport of scrap metal, FE-SCRP-TRANSPO-W	4				
Transport of slag, FE-SLAG-TRANSPO-W	4				
Transport of untreated EAF dust, FE-EAFD-TRANSPO-W	4				
Transport of refined metal product, FE-METL-TRANSPO-W	4				
Disposal Scenarios					
Disposal of BOF dust in a sanitary landfill, FE-BOFD-DISPOSL-W	F1	●	●		
Disposal of refinery slag in a sanitary landfill, FE-SLAG-DISPOSL-W	F1	●	●		
Disposal of scrap metal in a sanitary landfill, FE-SCRP-DISPOSL-W	F1				
Disposal of EAF dust in a hazardous waste landfill, FE-EAFD-DISPOSL-W	F1				
Product Use Scenarios					
Road construction activities using refinery slag, FE-SLAG-ROADBED-W	F1	●	●		
In proximity of a large metal mass, FE-METL-LGMASS-N	2				
In proximity of a small metal mass, FE-METL-SMMASS-N	3				
Small steel mass close to the body, FE-METL-SMOBJCT-N	6				
Inside an automobile, FE-METL-VEHICLE-N	11				
Inside a building structure, FE-METL-BLDGSTR-N	10				
Use of slag as aggregate in basement construction, FE-SLAG-CONCBAS-N	7				
Use of slag in a roadbed, FE-SLAG-ROADBED-N	F1				

Table 4.8 Scenario and exposure pathway matrix

Scenario title and abbreviation for steel	Exposure pathways[a]				
	Ext	Inh	Sec	DW	Ing
Landfill Resident Scenarios					
Resident on a closed landfill after disposal of BOF dust, FE-BOFD-LANDFIL-N	F1	●		●	●
Resident on a closed landfill after disposal of refinery slag, FE-SLAG-LANDFIL-N	F1	●		●	●
Resident on a closed landfill after disposal of scrap metal, FE-SCRP-LANDFIL-N	F1	●		●	●
Resident on a closed landfill after disposal of EAF dust, FE-EAFD-LANDFIL-N	F1	●		●	●

a. Ext = external, Inh = inhalation, Sec = secondary ingestion, Ing = ingestion of food (plants), DW = drinking water ingestion.
b. These landfill resident scenarios were analyzed, but were not included in the determination of critical groups. A dose summary is included in Appendix J.
1 External dose based on geometry factor #1 (large pile)
2 External dose based on geometry factor #2 (large metal object)
3 External dose based on geometry factor #3 (small metal object)
4 External dose based on geometry factor #4 (driver of truck)
5 External dose based on geometry factor #5 (beside truck)
6 External dose based on geometry factor #6 (small metal object close to body)
7 External dose based on geometry factor #7 (inside a structure)
8 External dose based on geometry factor #8 (inside refinery baghouse)
9 External dose based on geometry factor #9 (on top of bag house dust truck)
10 External dose based on geometry factor #10 (steel-framed structure)
11 External dose based on geometry factor #11 (inside an automobile)
F1 External dose based on Federal Guidance Report # 12 values (soil contaminated to an infinite depth)
F2 External dose based on Federal Guidance Report # 12 values (contaminated ground surface)

Exposure Pathways

The characteristics and behavior of the radionuclides in recycled material will also determine the potential exposure pathways. For example, gamma-emitting radionuclides will present an external exposure potential, whereas alpha-emitting radionuclides will not. Three main exposure pathways have been identified for this study: external exposure, inhalation, and ingestion. Each pathway has been subdivided into more specific pathways for modeling purposes. Exposure scenarios were modeled by combinations of various exposure pathways. The exposure pathways that were included in each exposure scenario are shown in Table 4.8.

Each scenario description includes an identification of the pathways most likely to result in exposure to the individual(s) evaluated. Although other exposure pathways for many of the scenarios are theoretically possible, they were not included because the probability of them occurring to a significant extent is very low. For example, doses resulting from external exposure to resuspended dust would be insignificant compared to doses from external exposure to the volume source itself. Those pathways that are unlikely—or that represent comparatively insignificant exposure—are not included.

Of the many possible exposure pathways that could be identified for reuse and recycle exposure scenarios, a comprehensive set of five potentially important pathways has been used for this analysis. The five exposure pathways are described below.

External exposure to penetrating radiation—The source material containing radionuclides that emit penetrating radiation can include volume sources, such as piles of scrap metal or slag, refinery baghouse structures, large or small metal products made from refined steel, or transport containers. Plane sources, such as from disposed metal, baghouse dust, or slag are also included.

Inhalation exposure to airborne radionuclides—This pathway includes inhalation of material resuspended from surfaces during handling, processing, and disposal activities; atmospheric releases from refineries; and selected product use activities. Source material includes dust, soil slag, and fine particulates from metal-cutting operations.

Secondary ingestion of surface contamination—This exposure pathway addresses inadvertent ingestion of surface sources of material (dust, soil, slag, and metal shavings). Except for two exceptions, this pathway is included whenever the inhalation pathway is present and is based on the same source material as the inhalation pathway. (The scenarios addressing atmospheric releases from a refinery and resident on a closed landfill do not include secondary ingestion.)

Ingestion of food and soil—This exposure pathway is the conventional food consumption pathway (vegetables), plus direct ingestion of soil.

Drinking water ingestion—This exposure pathway addresses the consumption (ingestion) of drinking water extracted from a groundwater source (i.e., a well).

4.6.2 Work Related Scenarios

The exposure scenario categories that are work related are:

- handling
- processing
- storage
- product use
- transport
- disposal scenarios.

4.6.2.1 Handling Scenarios

After clearance from a NRC licensed facility, if the material is for recycle or disposal, scrap and refinery byproducts (slag, dust, metal product) must be handled in a number of work related settings. A variety of work related conditions and practices were analyzed to identify the most likely exposure scenarios. This included investigating the details of work-related settings to develop accurate and representative scenarios and to assign realistic values (and ranges) to

exposure parameters. During scenario development, details were periodically re-examined to ensure that appropriate scenarios were identified and completely described.

The handling scenarios analyzed for this report encompass a representative range of work related activities associated with handling scrap and refinery byproducts in a number of work related settings.

- Handling scrap metal at the scrapyard
- Handling slag at refinery
- Refinery baghouse operations
- Handling EAF dust at the mill
- Handling of refined metal product at the mill
- Handling BOF refined metal product during manufacturing
- Handling EAF refined metal product during distribution.

Handling Scrap Metal at the Scrapyard

Following clearance from a NRC licensed facility, scrap metal would be transported to a scrap yard, where it would be unloaded, processed, and prepared for shipment to a refinery. This scenario addresses activities that require scrap yard workers to be in proximity to the scrap metal. These activities include unloading, sorting, cutting (sizing), shredding, baling, and loading for shipment. The individual evaluated in this scenario is assumed to perform several of these activities.

Cutting and shredding processes used on scrap metal can generate airborne particulates. This is a result of the mechanical and chemical (torch) techniques used on the scrap. These airborne particulates can settle and be inadvertently ingested by workers. This is the basis for including inhalation and secondary ingestion exposure pathways.

Exposure pathways: Because of the variety of operations involved at the scrap yard, internal, as well as external exposure pathways are included in this scenario evaluation.

External: Proximity to incoming or piled scrap metal could result in external exposure to penetrating radiation from the volume source (scrap pile).

Inhalation: The various processing methods used (e.g., cutting and shredding) could result in resuspended metal particulates from the scrap metal, resulting in inhalation exposure.

Secondary Ingestion: Suspended metal particulates created from processing could be deposited on surfaces, causing inadvertent ingestion from contaminated hands and food.

Handling Slag at Refinery

Refinery slag is handled at the refinery in preparation for processing or use, potentially subjecting workers to exposure. In this scenario, the slag is in a very large pile and a front-end loader is used to move it. This would involve driving a loader around and on top of the pile. Since the driver is subject to the greatest potential exposure, this is the individual evaluated.

Exposure Pathways:

External: The worker would receive external exposure from the slag pile.

Inhalation: Exposure to suspended slag in the vicinity of the slag pile.

Secondary Ingestion: Inadvertent ingestion of surface contamination.

Refinery Baghouse Operations

Normal operations of a steel refinery require routine and non-routine maintenance of the baghouse and baghouse filters, requiring workers to spend time near the exterior of the baghouse and inside the baghouse that encloses the filters. Typical operations near the exterior of the baghouse include routine inspections of the baghouse structure, ductwork, fans, and other parts of the ventilation and filter system. Typical operations inside the baghouse include inspection, repair, and replacement of filter bags and inspection and maintenance of other components of the dust removal system, such as seals, valves, and shaker mechanisms. The individual evaluated in this scenario is the worker performing routine inspections and maintenance, as well as non-routine operations, in and around the refinery baghouse.

A larger percentage of the charge at an EAF refinery would be comprised of scrap metal than would be the case at a BOF refinery, and dust produced by an EAF would be higher in concentration for all radionuclides. Therefore, the baghouse at an EAF refinery is the case analyzed and it bounds the exposure at BOF refineries.

The inside of a baghouse represents a hazardous environment. The presence of airborne baghouse dust in a confined and congested area requires that precautions be taken, such as use of protective clothing and a respirator. This scenario assumes a respirator is used. Volatile and entrained particulate radionuclides in the effluent would be trapped on the filters, presenting a possible source of exposure to the individuals involved in baghouse operations.

Exposure Pathways:

External: Exposure to penetrating radiation from the dust on the baghouse filters.

Inhalation: Exposure to resuspended dust in the baghouse.

Secondary Ingestion: A baghouse worker would likely be dressed in anti-contamination clothing. However, because of the prevalence of dust in the general refinery environment it is still reasonable to include the secondary ingestion exposure pathway (inadvertent ingestion of surface contamination).

Handling EAF Dust at the Refinery

This work related scenario involves a refinery worker handling EAF dust at a refinery in preparation for shipment. Most EAF refineries do not process their dust before shipping, so this scenario assumes that there is no preparation of the dust for transport to a treatment and disposal facility or fertilizer manufacturer. The bulk dust is loaded directly from its storage container into a shipping container (e.g., an enclosed truck trailer) via a handling chute. The truck driver and the worker who disconnects the chute and caps the transportation container would be the only individuals in close proximity to the dust or the truck for a significant amount of time. This scenario addresses the potential exposure of the refinery worker; the potential dose to the truck driver is covered in another scenario. This scenario involves a worker that is located on top of the container while the dust is being loaded via an overhead chute or conveyor belt. Exposure to individuals other than the worker handling the chute are also possible. However, those people would not be in close proximity to the truck for more than a very short time, and any amount of dust that escaped the truck container would be small and would disperse before reaching any nearby occupied areas. The scenario does not include public exposures, because the dust is essentially contained at all times.

Exposure Pathways:

External: The worker would be exposed to penetrating radiation from the volume of dust inside the container.

Inhalation: This scenario assumes that while dust is being loaded into a truck container, a fraction escapes and could be inhaled by the worker.

Secondary Ingestion: The EAF dust that is resuspended during the loading of dust into the shipping container can be deposited as surface contamination, causing inadvertent ingestion of EAF dust from contaminated hands and food.

Handling Refined Metal Product at the Refinery

This work related scenario covers a variety of specific jobs involving working close to refined metal slabs, rods, sheets, and other forms at a refinery or mill. Even though just handling the metal products will not generate airborne dust, other processing activities ongoing at the refinery (melting, pouring molten steel, water-cooling steel, etc.) would cause metal dust to be resuspended in the air. Similar to the refinery baghouse operations scenario, EAF refined metal product is the case analyzed and bounds the exposure at BOF refineries.

Exposure Pathways:

External: The worker would be exposed to penetrating radiation from the metal forms.

Inhalation: Inhalation of the resuspended metal dust from the various processing activities mentioned is possible.

Secondary Ingestion: Suspended dust from other refinery operations could be deposited as surface contamination, causing inadvertent ingestion from contaminated hands and food.

Handling BOF Refined Metal During Product Manufacture

This work related scenario involves proximity to metal sheets in a metal-shop or factory and activities such as bending, cutting, or shaping metal, which could result in resuspended metal particles. Metal products from BOF refineries represent the analyzed scenario because EAF metal products are typically items such as rebar and metal tractor cleats, and they do not undergo further manufacturing.

Exposure Pathways:

External: The worker would be exposed to penetrating radiation from the metal forms.

Inhalation: Manufacturing activities would generate airborne metal particles.

Secondary Ingestion: Material deposited as surface contamination could be inadvertently ingested from contaminated hands and food.

Handling EAF Refined Metal Product During Distribution

This work related scenario involves activities for distributing products made of EAF metal for final use. Examples of potentially affected workers include delivery truck drivers, warehouse workers, and shipping and receiving personnel. Metal items include such things as industrial items, construction supplies, and general consumer products. Electric arc furnace metal product is the case analyzed for this scenario for two reasons: 1) a larger percentage of the charge at an EAF refinery would be scrap metal and 2) there is a shorter amount of time from production of the metal to distribution for the EAF than the BOF (therefore less radioactive decay).

Exposure Pathways:

External: Because distribution workers would not be in an environment where activities would result in airborne metal dust, they would only be exposed to penetrating radiation from the finished metal products.

4.6.2.2 Processing Scenarios

Refinery byproducts (dust and slag) must be processed before use or disposal, providing opportunity for worker exposure to radioactivity. For this study, a variety of work related conditions and practices were analyzed to identify the most likely exposure scenarios. This included investigating the details of work related settings to develop accurate and representative scenarios and to assign reasonable values (and ranges) to exposure parameters. During scenario development, details were re-examined to ensure that appropriate scenarios were identified and completely described.

Processing activities involve potential exposure to all radionuclides present in refinery byproducts by all three exposure pathways. Most processing activities involve worker proximity to large masses of volumetrically contaminated refinery byproduct and moving it by a front-end loader. The driver operating a front-end loader in close proximity to a large pile of material is the individual evaluated. Other possible exposures (e.g., to other workers in the facility) would be small. This scenario category includes two specific scenarios:

- Processing EAF dust for disposal
- Processing slag for use as aggregate or as roadbed

Processing EAF Dust for Disposal

This work related scenario addresses a worker at a processing facility moving dust with a front-end loader or working near a pile of EAF dust.

Exposure Pathways:

External: A worker in proximity to large masses of contaminated EAF dust would be exposed to penetrating radiation from the volume source.

Inhalation: While the EAF dust is being moved by the front-end loader, a fraction of it could be suspended into the air, where it could be inhaled by the worker.

Secondary Ingestion: The material that is suspended can be deposited as surface contamination, enabling secondary ingestion of radioactive material from contaminated hands and food.

Processing Slag for Use as Aggregate or as Roadbed

This work related scenario addresses a worker at a processing facility moving slag with a front-end loader or working near a slagpile. The same type of activities that occur at a facility processing EAF dust would occur here. Slag from an EAF refinery is the case analyzed, because a larger percentage of an EAF charge is comprised of scrap metal, therefore, potentially resulting in a higher concentration of radionuclides in slag.

Exposure Pathways:

External: Exposure to penetrating radiation from the material volume source (the slag pile).

Inhalation: A fraction of the slag could be suspended into the air, where it could be inhaled by the worker.

Secondary Ingestion: Suspended material could be deposited as surface contamination, allowing inadvertent secondary ingestion of radioactive material from contaminated hands and food.

4.6.2.3 Storage Scenarios

Prior to use or disposal, slag is stored in large piles at the refinery and EAF dust in a storage silo. This category evaluates one work related exposure scenario (any work related exposures from a slap pile would be bounded by the slag handling scenario).

Storage of EAF Dust at Refinery

This scenario evaluates potential exposure to a worker at a refinery performing activities near an EAF dust silo. This scenario assumes that a worker would be located near the silo where the EAF dust is stored, for a certain amount of time each day. Exposure to EAF dust is being analyzed instead of BOF dust because the concentration of radionuclides is higher in EAF dust, due to less mixing with non-contaminated material in each furnace charge.

Exposure Pathways:

External: Because EAF baghouse dust is typically contained within a silo, exposure to penetrating radiation from the material volume source (the silo) is the only pathway explored.

4.6.2.4 Product Use Scenarios—Workers

The product-use category includes an extremely large number of possible worker exposure situations. Because this category includes the use of products manufactured from recycled scrap metal as well as refinery byproducts, it represents the most diverse category of potential exposure scenarios—including both work related and public exposures. The size and diversity of potential exposure situations makes it difficult to identify, organize, screen, and evaluate all possible scenarios.

This analysis does not evaluate the wide variety of possible worker product-use scenarios. These exposure scenarios would be similar to the many potential non-worker product use scenarios, and are, therefore, implicitly addressed in the non-worker scenarios described in Section 4.6.3.3. Refinery slag is considered a product of the refining process and is used in the single worker product-use scenario: road construction activities using refinery slag.

Road Construction Activities Using Refinery Slag

This work related product-use scenario involves the use of refinery slag as construction material for a roadbed. It evaluates the potential exposures associated with activities necessary for handling and laying the slag as road construction material.

In this scenario, the slag is transported in a large dump truck to the construction site, where it is dumped onto the roadbed and spread evenly on the road. The majority of work-related exposure would occur as a result of being on the slag, to level it, after it is dumped on the roadbed. Therefore, the worker using the leveling equipment on the slag is the individual evaluated. The exposure to the worker loading the dump truck from the slag pile is bounded by the handling slag at the refinery scenario, and the exposure to the driver of the dump truck is bounded by the transport of slag scenario.

Exposure Pathways:

*External***:** This scenario assumes that a worker is on the surface of the roadbed leveling the slag and would be exposed to penetrating radiation from the slag volume source.

Inhalation: While the slag is being dumped and leveled, a fraction of it could be suspended into the air, making inhalation by the worker possible.

Secondary Ingestion: Redeposited surface contamination can be inadvertently ingested on contaminated hands and food.

4.6.2.5 Transportation Scenarios

One activity that occurs many times throughout the material flow for steel is transportation (see Figure 4.1). Scrap metal cleared from NRC licensed facilities must be transported from the nuclear facility to the refinery, and the refined metal product and refinery byproducts must be transported from the refinery or mill to manufacturers, processors, users, or disposal sites. Although these can occur by either truck, rail, air, or barge, truck transportation is most common. Truck transportation also presents the highest potential dose to individuals because of long exposure times and small distances from the source (truck) to the receptor (driver).

In general, those who handle packages directly are exposed to the highest dose rates, although these exposures are usually for relatively short periods of time. Bystanders and persons traveling or living along a travel route generally are subjected to lower dose rates. In most cases, exposures of persons along the transport route are for a relatively short duration, but the number of persons who can be exposed may become very large during a shipment of considerable distance. A worker (the truck driver) is analyzed for all transportation scenarios.

The transportation scenarios analyzed for this report include:

- Transport of scrap metal
- Transport of slag
- Transport of untreated EAF dust
- Transport of refined metal product.

Exposures of the general public during transportation are addressed in Section 4.6.3.4.

Exposure Pathways

External: The only exposure pathway included in the evaluation of all transportation scenarios is the external exposure pathway for penetrating radiation from the truck load of material (e.g., scrap metal, slag, EAF dust).

Transport of Scrap Metal

This scenario describes the transportation of scrap metal from the nuclear facility. As described in Section 4.2, the scrap metal can either be transported to a scrap dealer if it is suitable for recycling, to the user if it is suitable for direct reuse rather than recycling, or directly to a disposal facility if it is not suitable for either recycling or direct reuse.

Transport of Slag

This scenario describes the transportation of slag from the refinery to processors. The majority of refinery slag is transported by truck within a 50 km (80 mi) radius of its source, the refinery.

Transport of Untreated EAF Dust

This scenario describes the transportation of EAF dust from the refinery to manufacturers or processors (e.g., hazardous landfill or fertilizer manufacturer). As described in Section 4.2, EAF baghouse dust is transported to either a hazardous landfill for immobilization and disposal or to a fertilizer manufacturer for use as an additive.

Transport of Refined Metal Product

This scenario describes the transportation of refined metal product from the refinery or mill to the manufacturers or distributors. Electric arc furnace refined metal products are sent directly to the distributors with no additional manufacturing required, while BOF refined metal products are sent to manufacturers prior to distribution (see Section 4.2). Because EAF refineries typically use more scrap metal in a furnace charge than BOF refineries, and, therefore, have greater potential radionuclide concentrations in refined metal products, the case analyzed for this scenario is the transport of EAF refined metal products.

4.6.2.6 Disposal Activities Scenarios

When scrap metal or refinery byproducts have reached the end of their usefulness, they are disposed of in either a RCRA Subtitle C (hazardous) or D (sanitary) landfill. Material placed in a Subtitle C landfill is stabilized and, typically, placed in 55-gallon drums prior to disposal. Material placed in a Subtitle D sanitary landfill is not stabilized or placed in containers before disposal. Disposal of this material involves workers placing waste in the final location within the landfill unit, an activity that requires workers to spend time near the waste.

This category of scenarios evaluates the activities associated with the disposal of materials. The disposal activity scenarios include reasonable exposures to disposal facility workers. Some of the total potential exposure is likely to occur after disposal of cleared material, not during actual handling of the material (i.e., external exposure to disposed waste material).

Four work related disposal activities scenarios were examined for this study. These scenarios address those workers involved with the disposal of the material.

- Disposal of BOF dust in a sanitary landfill
- Disposal of refinery slag in a sanitary landfill
- Disposal of scrap metal in a sanitary landfill
- Disposal of EAF dust in a hazardous waste landfill.

No exposures of the general public would occur under any of the work related disposal scenarios presented here.

Disposal of BOF Dust in a Sanitary Landfill

This work related exposure scenario describes a worker disposing of BOF dust in a sanitary landfill. Such activities can include a worker moving the BOF dust with a front-end loader from a pile or truck to the landfill, or a worker on a piece of machinery, such as a bulldozer, compacting the material in the landfill. The BOF dust is assumed to be in a form similar to soil, with suspension of the material for inhalation and inadvertent ingestion by the worker. This scenario assumes that BOF dust is disposed of in a sanitary landfill directly after production at the refinery. Only the worker involved with the actual disposal activities is addressed.

Exposure Pathways*:*

External: Exposure to penetrating radiation from the BOF dust on the ground.

Inhalation: Exposure to suspended BOF dust.

Secondary Ingestion: Inadvertent ingestion of surface contamination.

Disposal of Refinery Slag in a Sanitary Landfill

This work related exposure scenario describes a worker disposing of slag in a sanitary landfill. Such activities can include a worker moving the slag with a front-end loader from a pile or truck to the landfill or a worker on a piece of machinery, such as a bulldozer, compacting the material in the landfill. The slag is assumed to be in a form similar to soil, with suspension of the material for inhalation and inadvertent ingestion by the worker. This scenario assumes that slag is disposed of in a sanitary landfill directly after production at the refinery. Only the worker involved with the actual disposal activities is addressed.

Exposure Pathways*:*

External: Exposure to penetrating radiation from the slag in the ground.

Inhalation: Exposure to suspended slag.

Secondary Ingestion: Inadvertent ingestion of surface contamination.

Disposal of Scrap Metal in a Sanitary Landfill

This work related exposure scenario describes a worker disposing of NRC licensed facility scrap metal in a sanitary landfill. Only the worker involved with the actual disposal activities is addressed. Disposal activities can include a worker at the landfill handling the metal manually or using machinery. Activities can also include a worker on a piece of machinery, such as a bulldozer, compacting the scrap metal.

Because no mechanical cutting or shredding of cleared scrap metal is assumed to occur prior to disposal, it is reasonable to assume that there would be no appreciable suspension of contamination, and therefore, no inhalation exposure to resuspended material. Likewise, there would be no mechanism that would result in appreciable amounts of contamination for inadvertent ingestion. Therefore, the only exposure pathway that is relevant is the external exposure to penetrating radiation from the volume source. This scenario assumes that scrap metal is disposed of in a sanitary landfill directly from the nuclear facility.

Exposure Pathways*:*

External: Exposure to penetrating radiation from the scrap metal in the ground.

Disposal of EAF Dust in a Hazardous Waste Landfill

This work related exposure scenario describes a worker disposing of EAF baghouse dust immobilized in 55-gallon drums in a hazardous landfill. Handling includes moving the 55-gallon drums with a fork lift, moving them from a vehicle to a storage facility, or placing them into the landfill unit. (NOTE: Processing the dust, immobilizing it, and placing it in 55-gallon drums is

covered in Section 4.6.2.2). Because the EAF dust is immobilized in the 55-gallon drums, it is reasonable to assume that there is no suspension of contamination and, therefore, no exposure due to inhalation of the resuspended material or inadvertent ingestion of surface contamination. Therefore, the only exposure pathway that is relevant is the external exposure to penetrating radiation from the volume source. Only the worker involved with the actual disposal activities is addressed. Exposures could also occur after initially handling the drums. These exposures are also included.

Exposure Pathways:

External: Exposure to penetrating radiation from the 55-gallon drums containing immobilized EAF dust.

4.6.3 Description of Non-worker Scenarios

The exposure scenario categories that include non-worker exposure are:

- atmospheric releases
- storage
- product use
- transportation
- resident on closed landfill.

4.6.3.1 Refinery Atmospheric Releases

When scrap metal is processed at a refinery, atmospheric effluents released from the stack potentially expose people living nearby to radioactivity contained in the release. A representative scenario was evaluated for this category:

Atmospheric Release During Refining

This public exposure scenario takes place near a refinery that is processing scrap metal from a nuclear facility. During the refining process, atmospheric effluents are released from the stack. The scenario assumes the exposed person lives in the area surrounding the refinery year round and has a home garden.

This scenario includes the exposure pathways listed below and illustrated in Figure 4.3.

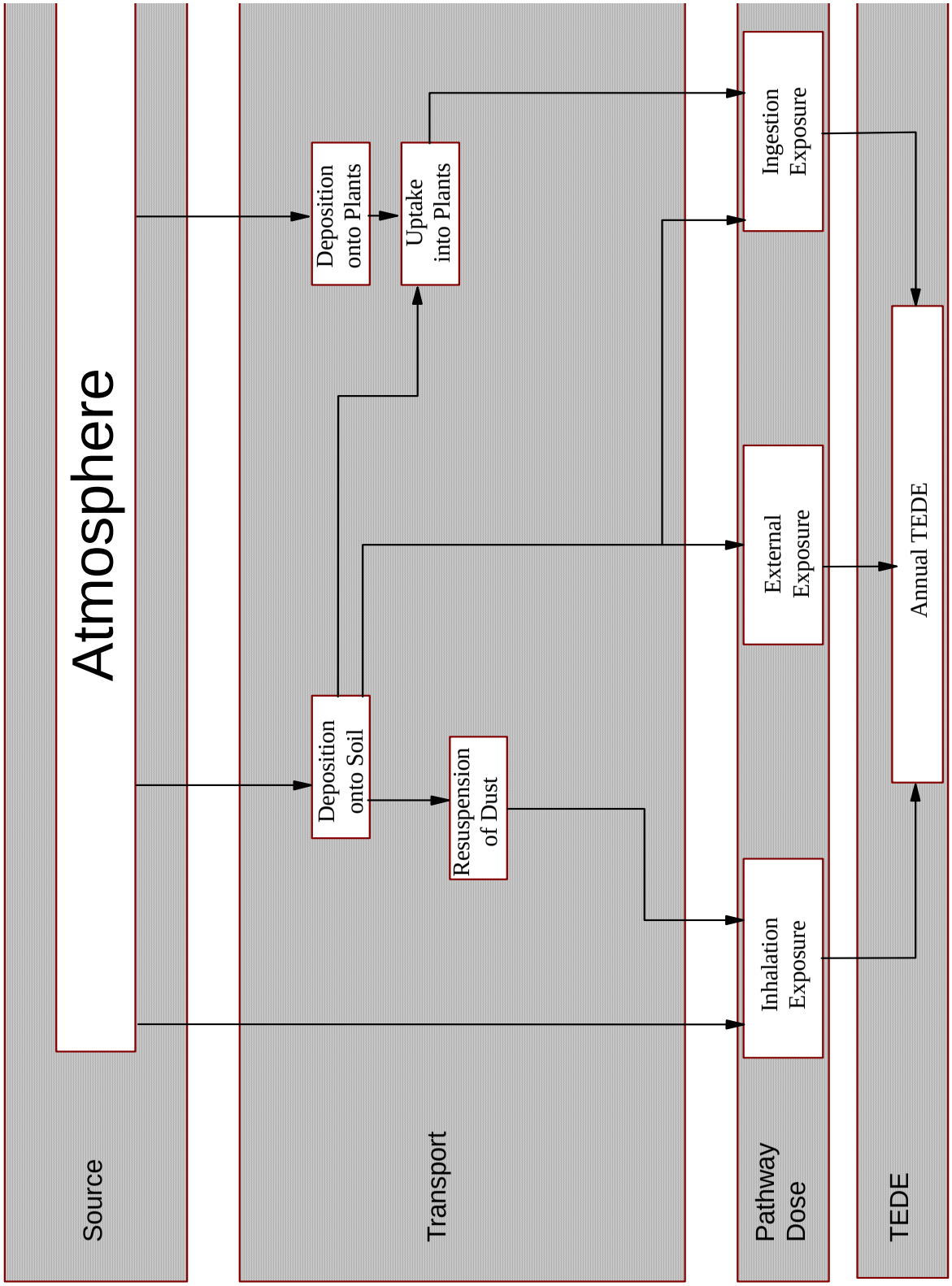

Figure 4.3 Modeling approach for the atmospheric releases from a refinery

Exposure Pathways:

External: Exposure to penetrating radiation from volume sources while indoors and/or outdoors.

Inhalation: Exposure to the passing plume while indoors and outdoors, to suspended soil while indoors and outdoors, and to suspended surface sources from soil tracked indoors.

Ingestion of Food and Soil: Ingestion of soil (secondary) from plant products grown in contaminated soil and soil tracked indoors (inadvertent).

This set of exposure pathways, along with the selection of reasonable parameter values, provides a comprehensive analysis for this scenario.

Other exposure pathways are possible, but were judged to have very small contributions in comparison to the ones selected. For instance, ingestion of drinking water from a contaminated surface water source in the vicinity of the refinery would be very small unless very large amounts of radioactivity were released. Similarly, a potential dose from ingestion of drinking water from a contaminated ground-water source would be insignificant unless the atmospheric deposition source was very large and the subsequent transport to groundwater was rapid and unretarded.

The material that is released from a refinery stack is in two forms; particulates and off-gases. The off-gases are either completely volatilized or are in the form of particulates too small to be captured in the air pollution control system at the refinery. Besides these off-gases, a small fraction of the larger particulates that are produced are also released into the atmosphere. This is because the baghouse filters that make up the air pollution control system are not 100% efficient. On average, these filters are about 99% efficient (see Sections 4.2 and 4.3).

Refinery emissions are the principal airborne effluents of concern during recycled steel processing. Other effluents could be postulated, such as fugitive atmospheric releases from scrap handling, however, these effluents are considered insignificant due to the small probability and small magnitude of any release.

Listed below are assumptions for the specific exposure pathways.

External: People that live near the refinery would spend their time indoors, outdoors, and offsite. The time spent offsite is the fraction of the year that no external exposure occurs. Therefore, the annual effective dose equivalent (EDE) for the external exposure pathway results from outdoor activities and indoor activities onsite. The radionuclide concentration on the soil as a result of deposition from the plume is used as the basis for calculating the external exposure.

Ingestion of Food and Soil: In general, an individual is assumed to live at a residence that has soil contaminated via atmospheric deposition. Ingestion pathways that are included are ingestion of plant products grown at the receptor location and secondary (inadvertent) ingestion of surface soil at the receptor location. Since the ingestion dose is based on the air concentration at the

specified receptor location, the calculated intake of radioactivity is based on concentrations of radionuclides in plant products grown at the same location.

The following assumptions were made for the ingestion pathway:

- The concentration of radionuclides in edible parts of the plant at the end of the first growing period is used as the harvest concentration. Multiple harvesting of plant crops is not included.
- The concentration of C-14 and H-3 in the edible parts of the plant due to atmospheric release was calculated separately using different equations.
- The resident consumes soil, leafy vegetables, and other vegetables grown on the contaminated soil.
- The harvested crops, v, for human consumption (i.e., leafy vegetables and other vegetables) are retained during a hold-up period before human consumption.
- The consumption period by an individual for plant food crops is 1 year. Radioactive decay during the consumption period is accounted for in the intake calculation.
- Instantaneous equilibrium occurs between the radionuclide concentration in the soil and in the concentration in the plants.

4.6.3.2 Storage Scenarios

Prior to use or disposal, slag is accumulated and stored in large piles at the refinery and EAF dust in a storage silo. This category evaluates one exposure scenario, storage of slag at refinery.

Storage of Slag at Refinery

This non-worker scenario takes place near a refinery that stores slag outside and does not include any work related exposures associated with handling the slag. This scenario does not include potential exposures associated with direct contact with the slag by the public (i.e., external, exposure inhalation, or inadvertent ingestion). These exposure pathways are addressed in the work related scenario which describes the worker near a slag pile (Section 4.6.2.1). Any public exposure that would occur near the pile, such as external or inhalation, would be very small because of the likely distance between the piles and any non-workers. Therefore, the only pathway analyzed in this scenario is the ingestion of drinking water from a groundwater source. The analysis models the transport of radionuclides from the slag pile to the groundwater and subsequent intake by a member of the public. The total effective dose equivalent (TEDE) due to the ingestion of drinking water is calculated for a period of 1 year.

Exposure Pathway:

Ingestion of drinking water: A member of the public would ingest contaminated drinking water from a well near a refinery.

Once the slag is placed outside on the unprotected ground there is a potential to contaminate groundwater in either the saturated or unsaturated zones. The primary mechanisms controlling potential groundwater contamination include infiltration and leaching, transport through the unsaturated zone, and transport through the saturated zone. Many additional characteristics of the site influence these mechanisms, including precipitation rates, the land's surface properties, soil properties, the chemical nature of the radioactive contamination, spatial distributions of the contamination, and advection/retardation in the aquifer.

For this scenario, the method used to estimate the concentration of radionuclides in a groundwater aquifer is a simple leach-rate model accounting for total water use. Leach rates are dependent on the chemical properties of the radionuclides and soil/slag and the rate of local water movement. For the water-use model used, it was assumed that radionuclides would be transferred to the groundwater because of contact with infiltrating water (i.e., as a function of the solubility of the material in water with no retardation in soils). To account for potential saturated and unsaturated conditions, a three-box compartmental model, similar to that used in NUREG/CR-5512 (Kennedy and Strenge 1992), is used to estimate the transfer of radioactivity from the surface to the groundwater aquifer over time. Figure 4.4 illustrates the three-box compartmental model.

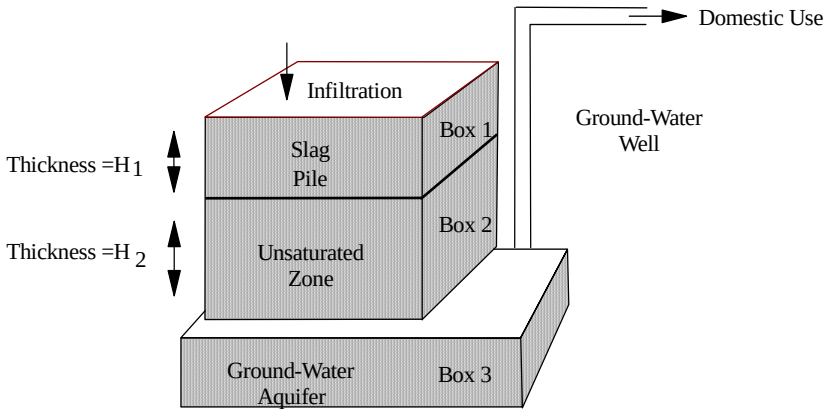

Figure 4.4 Three-box compartment model for the storage of slag scenario

The basic drinking water scenario from NUREG/CR-5512 is used for this scenario (Kennedy and Strenge 1992). Assumptions for the drinking water model are listed below (box numbers refer to Figure 4.4):

- Initial radioactivity is contained within box 1 (slag pile) and is assumed to be constant throughout the year.
- Box 2 (unsaturated zone) and box 3 (aquifer) are initially free of contamination.
- The unsaturated zone refers to the distance between the bottom of the slag pile to the top of the aquifer. For simplicity, the soil in this zone is treated as being homogeneous.
- Vertical, saturated, hydraulic conductivity is greater than the infiltration rate; water will move vertically downward at least as fast as the infiltration rate.
- Infiltration volume is the product of the infiltration rate and the area of land contaminated.
- No retardation in box 3 (aquifer).
- Activity in box 3 (aquifer) is diluted by the total volume of water in the aquifer
- Radionuclide concentrations in all parts of box 3 (aquifer) are the same. Radionuclides entering box 3 (aquifer) are immediately and uniformly mixed with the total volume of water in the aquifer.
- Water is removed from the aquifer at a constant rate during the year to meet the needs of irrigation and domestic water uses. The volume of water removed is immediately replaced with an equal volume of uncontaminated water.
- The volume of water used for domestic purposes is sufficient for ten people.
- Radioactivity not removed during a year remains in the aquifer and contributes to the initial radioactivity concentration for the next annual period.
- Water infiltration rate is a fraction of the total water application rate, which is equal to the annual precipitation rate.
- Evaporative losses remove only water from the system (i.e., surface soil); radioactivity is not lost by evaporation.

Steel slag is a very basic substance, and any water that leaches through a large pile of slag would become “hard” through the leaching of oxides of calcium and magnesium. Therefore, it is likely that in this scenario, an aquifer underlying a large slag pile would contain high concentrations of

dissolved solids. In order to incorporate the probable high dissolved solids content of the aquifer in this scenario, the total dissolved solids (TDS) in the aquifer were calculated over a period of time, and when a TDS level of 10,000 mg/L was reached, the aquifer was no longer considered drinkable. This TDS level is part of the EPA definition of an “underground source of drinking water” (e.g., 40CFR146) and is considered a reasonable natural limit on potability of drinking water, even without regulatory oversight.

4.6.3.3 Product Use Scenarios—Non-workers

The product-use category includes an extremely large number of possible exposure situations. Because this category includes the use of consumer products manufactured from recycled scrap metal, as well as refinery byproducts, it represents the most diverse category of potential exposure scenarios—including both work related and public exposures. The size and diversity of potential exposure situations makes it difficult to identify, organize, screen, and evaluate all possible scenarios. In line with the goals set for this study (the scenarios are required to be comprehensive, appropriate, and practical) exposure scenarios were represented generically instead of modeling a limited group of specific scenarios. The generic representations describe groups of similar exposure situations (e.g., individuals close to a large mass of metal or a small mass of metal close to tissue) rather than specific scenarios (e.g., person wearing a belt buckle or using a frying pan). The sub-category of "individuals close to a large mass of metal," for example, represents exposure situations such as individuals using office equipment (a desk) or large consumer products (a refrigerator) made from recycled steel.

The product-use exposure scenarios analyzed for this report include:

- In proximity of large metal mass
- In proximity of small steel mass
- Small steel mass close to body
- Inside an automobile
- Inside a steel-framed structure
- Use of slag as aggregate in basement construction
- Use of slag in a roadbed.

In Proximity of Large Metal Mass

Following clearance from a licensee, scrap metal would enter the scrap metal market, where it could be melted and made into sheets or large, more massive pieces of steel stock. These in turn can be manufactured into large metal items used by workers, consumers, or other members of the general public. These items could be used in homes, offices, warehouses, and other industrial settings.

This scenario description is intended to be generic, in the sense that no specific situation is described and is representative of any of the settings listed above. Among the numerous examples of objects this scenario is intended to cover are large home appliances (such as

refrigerators and washing machines), office furnishings (such as large filing cabinets and metal desks), and large industrial machines. An individual near such an object would be subject to external radiation from radionuclides contained in the metal. The geometry of the object can be represented generically by viewing it as an individual near a “large metal mass.” Other settings where this geometry is applicable include less frequented areas, such as near highway bridge supports, and certain work related settings, such as near scaffolding or other large items.

Items falling into the category of "large objects" could be the products of either a BOF refinery (e.g., appliance, large filing cabinets) or EAF refineries (e.g., large structures like bridge supports or scaffolding), based on the type of products from each refinery type (Section 4.2).

Activities conducted as part of this scenario could include short duration activities (e.g., occasional use of industrial items, such as scaffolding), medium duration (e.g., office work), and long duration (e.g., residential). The case analyzed was of an individual in a residential setting where a BOF product is used, because it is more likely that BOF products would result in the residential exposures described in this scenario.

Exposure Pathway:

External: The only exposure pathway included in the scenario evaluation is the external exposure pathway for penetrating radiation from the large object.

In Proximity of Small Steel Mass

This scenario addresses activities that take place in the vicinity of a small object that is constructed of metal made from recycled scrap metal. The scenario description is generic, in the sense that no specific situation is described. Rather, this scenario covers use of numerous small objects composed of metal from either a BOF refinery (e.g., small appliances such as a toaster) or EAF refineries (e.g., hand tools). Items could be used in homes, offices, warehouses, and other industrial settings. An individual near such an object would be subject to external radiation from radionuclides contained in the metal. The geometry of the object can be generically represented by categorizing it as an individual near a small steel mass.

Activities conducted as part of this scenario could include short duration activities (e.g., occasional use of industrial items such as small tools), medium duration (e.g., an office worker), and long duration (e.g., residential). The case analyzed is of an individual in a residential setting where a BOF product is used.

Exposure Pathways:

External: The only exposure pathway included in the scenario evaluation is the external exposure pathway for penetrating radiation from the small object. Other exposure pathways theoretically possible—such as inhalation of contaminated material from degraded metal—are not likely to be significant, compared to doses from external exposure.

Small Steel Mass Close to Body

This public-use scenario is similar to the scenario Proximity to Small Steel Mass, above, in that it addresses activities that take place close to a small object that is constructed of metal made from recycled scrap metal. The scenario description is generic and covers the use of numerous small items, such as tools or belt buckles, made of metal from an EAF refinery. An individual very near such an object would be subject to external radiation from radionuclides contained in the metal. The geometry can be represented generically by a small metal object essentially on an individual's body.

Exposure Pathways:

External: The only exposure pathway included in the scenario evaluation is the external exposure pathway for penetrating radiation from the small object.

Inside an Automobile

Following clearance from a NRC licensed facility, cleared scrap metal would enter the scrap metal market, where it could be melted and made into components for a vehicle. This is a likely occurrence, because approximately 70% of a typical U.S. automobile is made from steel and iron, and many of the steel components (e.g., undercarriage, engine block, axle, springs, and drive shaft) are made from recycled steel (SRI 1995). An individual inside such a vehicle would be subject to external radiation from radionuclides contained in the metal components. The geometry can be represented generically by a plane (the undercarriage, drive shaft, axle, etc.) and a block of metal (engine block).

The exposed group in this scenario consists of people who drive or ride in an automobile a significant part of each day (more than one hour). The scenario may be work related (i.e., a fleet driver) or non-work related (e.g., a commuter).

Exposure Pathways:

External: The only exposure pathway included in the scenario evaluation is the external exposure pathway for penetrating radiation from the steel vehicle components. Other exposure pathways theoretically possible—such as inhalation of contaminated material from degraded metal—are not likely to be significant, compared to doses from external exposure, because the residual radioactivity would be distributed throughout the volume of the recycled steel and hence would not be easily mobilized.

Although the metal could come from either an EAF or BOF, it is more likely that the types of structural components involved in the scenario are products of EAF refineries. Therefore, this scenario assumes EAF steel was used.

Inside a Steel-Framed Structure

Following clearance from a NRC licensed facility, cleared scrap metal would enter the scrap metal market, where it could be melted and made into steel-framing components. This is an increasingly likely occurrence, as the steel-framing industry uses recycled steel components, and this U.S. residential industry is growing. The American Iron and Steel Institute estimates that the number of full steel home starts in the U.S. has doubled from 40,000 in 1994 to 95,000 in 1997 and is projected to reach 325,000 by the year 2000 (AISI 1998).

An individual inside a steel-framed building would be subject to external radiation from radionuclides contained in the metal structural components. The geometry can be represented generically by an individual inside a cage.

The exposed group in this scenario consists of people who spend time inside a building containing structural members made of recycled scrap steel. They could be in a work related setting (e.g., an office building) or a residential setting (a home). Activities conducted as part of this scenario could include short duration activities (occasional entry into a warehouse), medium duration (office work), and long duration (residential). All of these were considered in determining the exposure duration time for this scenario, however, the office and residential settings were emphasized due to the longer times inside the building.

Although the metal could come from either an EAF or BOF, it is likely that the types of structural components involved in the scenario are products of EAF refineries. Therefore, this scenario assumes EAF steel was used.

Exposure Pathway:

External: The only exposure pathway included in the scenario evaluation is the external exposure pathway for penetrating radiation from the steel frame material (studs and joists). Other exposure pathways theoretically possible—such as inhalation of contaminated material from degraded metal—are not likely to be significant, compared to doses from external exposure, because the residual radioactivity would be distributed throughout the volume of the recycled steel and, hence, would not be easily mobilized.

Use of Slag as Aggregate in Basement Construction

This public residential scenario evaluates exposure from slag used as aggregate in concrete. Slag produced as a byproduct of refining can be used for construction of basements in homes, although this is a limited practice. Because of its unsuitability, steel slag would not constitute more than 3% of any concrete mixture. An individual living in a home with a basement built of concrete with steel slag would be subject to external radiation from radionuclides contained in the slag.

The individual evaluated in this scenario is a member of the public whose basement is constructed with concrete containing refinery slag, and who spends the maximum defined period inside the home.

Exposure Pathways:

External: The only exposure pathway included in the scenario evaluation is the external exposure pathway for penetrating radiation from the slag.

Use of Slag in a Roadbed

Refinery slag can be used as an aggregate in a roadbed. For this scenario, it is assumed that slag is used as a base and asphalt or concrete is placed over it. Since the slag is either contained within or under a solid mass, no resuspension of it can occur under normal conditions. It is recognized that slag is sometimes used as the entire roadway and is not contained in a solid mass. The potential dose from this type of use is bounded by the evaluation of the work related scenario addressed in Section 4.6.2, Road Construction Activities Using Refinery Slag.

Exposure would differ by type of use. The average driver may only be on the roadway a short time each day, whereas a truck driver can spend a full work day on the road. However, the length of time that a person is potentially exposed is balanced by proximity and shielding. The truck driver is much higher off the ground and is more heavily shielded than is the average driver in a car. This scenario analyzes the average person in a car.

Exposure Pathways:

External: Because there is no possibility for the suspension of the slag in this scenario, only external exposure to penetrating radiation from the volume source (the slag in the roadbed) is analyzed.

4.6.3.4 Transportation

One non-worker receptor was initially analyzed for all transportation scenarios, a maximally exposed individual along the transportation route. This person is either caught in traffic next to the truck or is driving next to the truck for a distance. The dose factors for this situation were found to be insignificant and are, therefore, not included in the final tabulation of dose factors.

4.6.3.5 Resident on Closed Landfill

This category of public exposure scenarios involves a resident on the site of a RCRA Subtitle C or D landfill unit after the completion of the post-closure monitoring period. These scenarios are of a different nature than the other scenarios analyzed, because they describe unlikely situations potentially occurring many years in the future. Therefore, the dose factors calculated for the four landfill-resident scenarios were not used in the critical group determination, but were analyzed

for completeness. The scenarios are described here and elsewhere in this section, and a summary of the highest landfill-resident dose factors is included in Appendix J.

Section 4.6.2 discussed exposure of workers involved with disposing various types of material in a either a RCRA Subtitle C or D landfill. This section introduces the scenarios describing potential exposures to the general public after closure of such a landfill. The four scenarios examined for this study are:

- Resident on closed landfill after disposal of BOF dust
- Resident on closed landfill after disposal of refinery slag
- Resident on closed landfill after disposal of scrap metal
- Resident on closed landfill after disposal of EAF dust

These scenarios are very similar to each other, with the disposed material representing the most significant difference. No scenarios involving more than one potentially contaminated byproduct of recycle have been evaluated, however, doses from more than one of the scenarios listed above could be added if appropriate.

This resident scenario category involves a person occupying a house with a basement and maintains a vegetable garden on the site of a closed landfill that contains material derived from cleared scrap steel. The exposure pathways modeled are listed and illustrated in Figure 4.5. The modeling approach and assumptions that each of the scenarios within this category have in common are presented below.

Exposure Pathways

Specific exposure pathways included in the evaluation of resident scenarios are listed below. General and exposure-specific assumptions for the scenarios are discussed following this listing.

External: The only exposure pathway consists of penetrating radiation from volume soil sources while indoors and/or outdoors.

Inhalation: The inhalation pathway includes exposure to suspended soil while indoors and/or outdoors and to suspended surface sources of soil tracked indoors.

Ingestion of Food and Soil: Ingestion exposure includes soil (secondary ingestion) and soil tracked indoors (inadvertent ingestion), plant products grown in contaminated soil, soil contaminated by irrigation (direct and inadvertent), and plant products irrigated with contaminated ground water only.

Ingestion of drinking water: This pathway is limited to ingestion of drinking water from a ground water source.

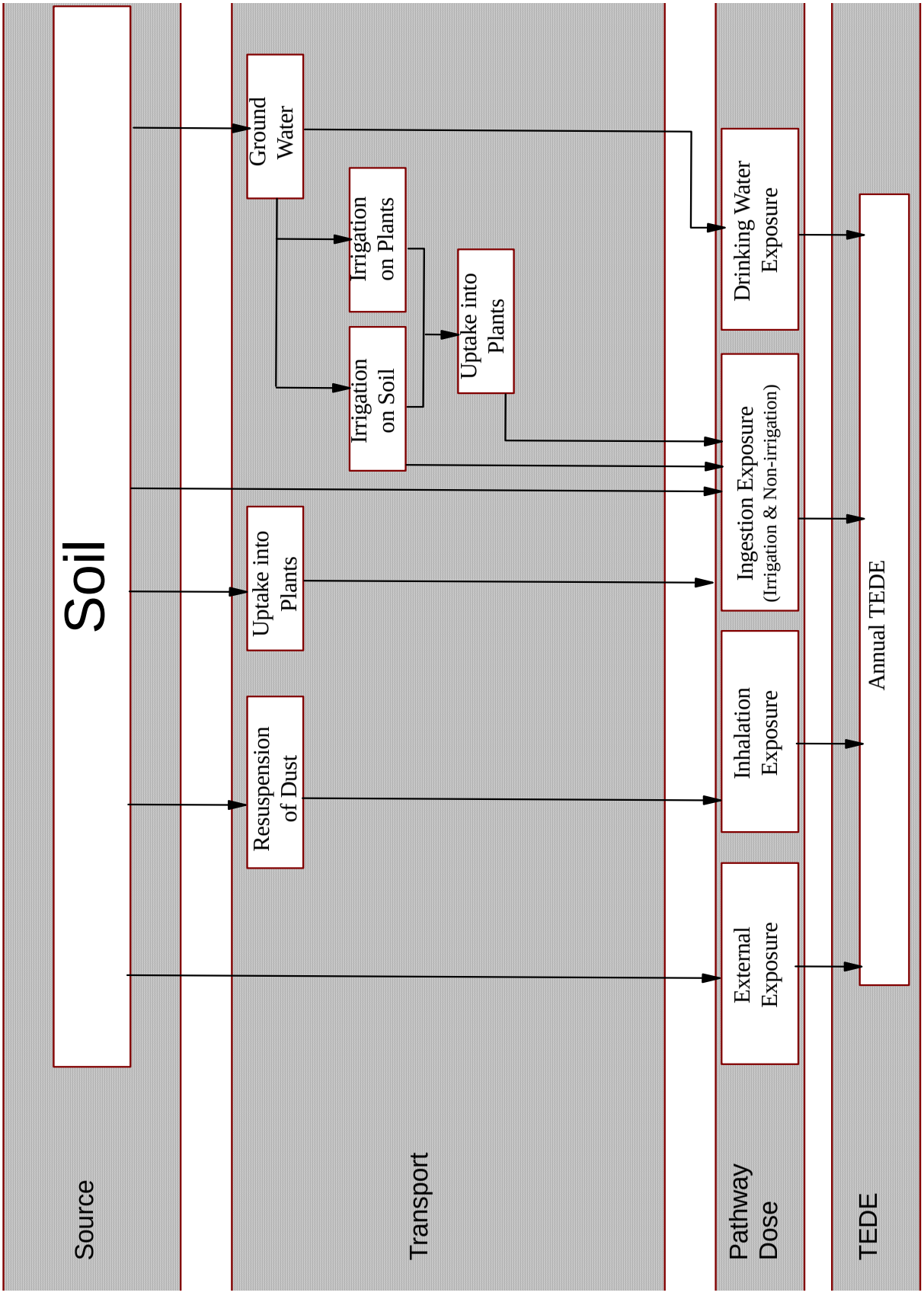

Figure 4.5 Modeling approach for the resident on a closed landfill scenario

Because these residential scenarios are not based on worst-case occurrences, several exposure pathways were not analyzed. For example, while air submersion may be an important pathway to consider when evaluating the potential consequences of airborne releases from some facilities, numerous studies of residual contamination in soil left after decommissioning a nuclear facility have concluded that external doses from air submersion are trivial compared with external doses from surface or volume sources (Schneider and Jenkins 1977; Smith et al. 1978; Oak et al. 1980). Since these residential scenarios are similar to residual contamination in soil, left after decommissioning a nuclear facility, air submersion doses are considered insignificant and are not evaluated.

Similarly, internal exposures from puncture wounds or from dermal absorption may be important when evaluating sources of exposure to workers in licensed nuclear facilities. But most dose assessments using these pathways are retrospective (after-the-fact) and rely on bioassay results to help establish the magnitude of internal deposition that occurred for specific situations. The frequency of occurrence of puncture wounds, although unpredictable, is assumed to be low. Dermal absorption may be important for only a few radionuclides, most notably H-3. To help account for dermal absorption of H-3, the International Commission on Radiological Protection (ICRP) increased the inhalation conversion by 50% (ICRP 1978). The dose that could result from dermal absorption is assumed to be low compared with inhalation and ingestion doses. Thus, internal doses from puncture wounds and dermal absorption are not included in this scenario.

Finally, some ingestion pathways often included in subsistence farmer scenarios have been omitted. Maintenance of a dairy cow, a cattle herd, a wheat field, or a fish pond were considered too unlikely to be appropriate for this exposed group. Therefore the milk, meat, grain, and fish ingestion pathways were not included in this scenario. Ingestion rates for home grown vegetables were chosen to represent a typical family garden rather than a subsistence farmer.

Six general assumptions for the residential scenarios are listed below. Assumptions specific to a particular exposure pathway are discussed following this listing of general assumptions.

- Waste is placed in the landfill in the middle of its lifetime, 15 years before closure of a hazardous landfill and 20 years before closure of a sanitary landfill.

- By a non-specific and unidentified means, the radionuclides in the waste are dispersed evenly throughout the soil to a depth equal to that of the original landfill. The time that leaching begins is different for each type of landfill. Waste disposed of in a sanitary landfill begins leaching immediately after emplacement; waste disposed of in a hazardous landfill begins leaching at the end of the post-closure monitoring period. Similarly, it is assumed that the total activity in the waste is dispersed throughout the total volume of material (soil and waste) in the landfill. This assumption simplifies the calculation by not attempting to model the complex and uncertain waste-leaching process.

- Contamination in the soil decays normally and continues to leach until the time activity is determined.

- Irrigation (watering with contaminated groundwater) contaminates crops, which are subsequently ingested by the resident. Recycling of radioactivity in irrigation water back to the groundwater is not included in order to simplify the models.

- A resident moves onto the landfill site after a post-closure monitoring period is concluded. The scenario TEDE is for a 1-year period.

- The scenario "begins" at the time leaching starts, although no resident moves onto the landfill until 50 to 150 years later.

Exposure Pathway-Specific Assumptions

External: The soil radioactivity concentration at the time a resident is assumed to move onto the landfill site consists of the radioactivity remaining in the contaminated layer after leaching and radioactive decay occurring during the post-closure monitoring period.

Residents on the contaminated soil would spend their time indoors, outdoors, and offsite. The time spent offsite is the fraction of the year that no external exposure occurs. Therefore, the annual dose for the external exposure pathway results from outdoor activities and indoors activities onsite. The radioactivity concentration in the soil, when the resident moves onto the landfill, is used as the basis for calculating the external exposure.

Inhalation: Similar to the external exposure pathway, the inhalation exposure pathway involves a person that spends their time indoors, outdoors, and offsite. However, for this exposure pathway, the outdoor exposure is separated into time spent on dusty activities (e.g., gardening) and time spent on non-dusty activities (e.g., sitting). Because the original contamination occurs as soil contamination, the inhalation dose only includes the suspension of contaminated soil from the ground. The resuspension of soil indoors has two sources; material blown into the house from outside and the suspension of soil that was tracked into the house.

Ingestion of Food and Soil: The landfill resident is assumed to consume plants grown in a home garden. This individual would also be exposed to secondary (inadvertent) ingestion of soil or house dust.

The ingestion exposure pathway is separated into two parts: non-irrigation and irrigation models. These two models can be used separately (e.g., growing plants in contaminated soil and irrigating with uncontaminated water or growing plants in clean soil offsite but irrigating with contaminated water), or they can be used together (e.g., growing plants in the contaminated soil and irrigating with contaminated water). Effective dose equivalents are calculated for each model separately, and the total ingestion (non-irrigation plus irrigation) dose assumes both occur simultaneously.

The following assumptions were made for the ingestion pathway dose modeling:

- The soil radionuclide concentration at the beginning of the crop-growing period is considered to be the same as the soil radionuclide concentration at the time the resident moves onto the landfill, $C_{s(t)}$.

- The concentration of radionuclides in edible parts of the plant at the end of the first growing period is used as the harvest concentration. Multiple harvesting of plant crops is not included.

- A resident consumes soil, and vegetables, grown on the contaminated soil.

- Harvested vegetables for human consumption are held for a hold-up period before human consumption.

- The consumption period by an individual for plant food crops is 1 year. Radioactive decay during the consumption period is accounted for in the intake calculation.

- Instantaneous equilibrium occurs between the radionuclide concentration in the soil and the concentration in the plants (for both human and animal consumption).

Irrigation vs Non-irrigation Ingestion Pathways

The irrigation ingestion pathway is similar to the non-irrigation pathway, except that the total dose results from the use of contaminated irrigation water to grow plants in a home garden instead of from surface soil contamination. In the non-irrigation ingestion model, the only contamination available to be transferred to the plants is due to the initial soil radioactivity concentration after the post closure monitoring period. In contrast, the irrigation model is used to calculate the dose to a person who consumes plants and soil irrigated with contaminated water.

The evaluation of resident doses can be made with both irrigation and non-irrigation models or just one model. For example, if an individual lives on contaminated soil and irrigates with contaminated water, use of both would be appropriate. Alternately, if the scenario involves an individual who lives on non-contaminated soil and irrigates with contaminated water, the irrigation model alone would be appropriate. For the evaluation of resident doses, the two models are assumed simultaneously.

To calculate the radionuclide concentration in foods grown with contaminated irrigation water and consumed by a person living on the contaminated area, the following additional assumptions have been made.

- The entire land surface area is irrigated and under cultivation.

- Radioactivity in the irrigation water is deposited in box 1 (surface layer).

- Initial radionuclide concentration in the soil is zero and the concentration in plants and soil is due only to the contamination from the irrigation water.

- Plants are contaminated from the irrigation water through deposition directly onto plants, deposition onto the soil, and subsequent root uptake into the plant.

- The concentration of radionuclides in irrigation water is constant over the year of irrigation (an average water concentration is used).

- Material deposited on plant surfaces is removed at a constant weathering half-life.

- Radionuclide concentrations in the soil from irrigation water are immediately in equilibrium with radionuclide concentrations in edible portions of the plants grown in the soil.

Ingestion of drinking water: Once the contamination from the waste is placed in the landfill, it has the potential to contaminate groundwater in either the saturated or unsaturated zones. The primary mechanisms controlling potential groundwater contamination include infiltration and leaching, transport through the unsaturated zone, and transport through the saturated zone. Many additional characteristics of the site influence these mechanisms, including precipitation rates, the land's surface properties, soil properties, the chemical nature of the radioactive contamination, spatial distributions of the contamination, and advection\retardation in the aquifer.

For the drinking-water pathway, the method used to estimate the concentration of radionuclides in a groundwater aquifer is a simple leach-rate model accounting for total water use. Leach rates are dependent on the chemical properties of the radionuclides and soil and the rate of local water movement. For the water-use model used, it was assumed that radionuclides would be transferred to the groundwater because of contact with infiltrating water (i.e., as a function of the solubility of material in water with no retardation in soils). To account for potential saturated and unsaturated conditions, a three-box compartmental model, similar to that used in NUREG/CR-5512 (Kennedy and Strenge 1992) is used to estimate the transfer of activity from the surface to the groundwater aquifer over time. Figure 4.6 illustrates the three-box compartmental model.

The basic drinking-water scenario from NUREG/CR-5512 was used instead of the residential drinking-water pathway. The basic drinking-water scenario does not include the recycling of contamination from the aquifer back to the surface. The pumping-rate constant for the residential scenario was used.

Assumptions for the drinking-water model are listed below (box numbers refer to Figure 4.6):

- Initial radioactivity is contained within box 1 (surface layer).

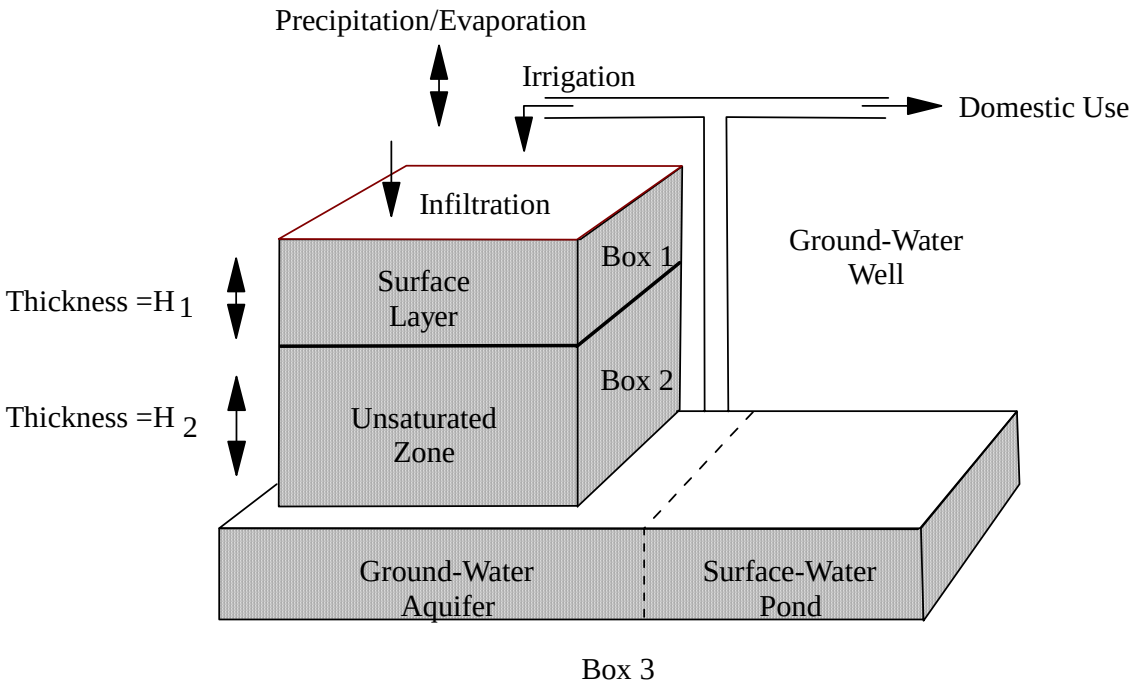

Figure 4.6 Three-box compartmental model for surface-to-groundwater transport for resident on closed landfill scenario

- Box 2 (unsaturated zone) and box 3 (aquifer) are initially free of contamination.

- Vertically saturated hydraulic conductivity is greater than the infiltration rate. Water will move vertically downward at least as fast as the infiltration rate.

- Infiltration volume is the product of the infiltration rate and the area of land contaminated.

- No retardation in box 3 (aquifer).

- Activity in box 3 (aquifer) is diluted by the total volume of water in the aquifer (including the volume of water in the surface water pond that is recharged from the aquifer).

- Radionuclide concentrations in all parts of box 3 (aquifer) are the same. Radionuclides entering box 3 (aquifer) are immediately and uniformly mixed with the total volume of water in the aquifer.

- Water is removed from the aquifer at a constant rate during the year to meet the needs of irrigation and domestic water uses. The volume of water removed is immediately replaced with an equal volume of uncontaminated water.

- The volume of water used for domestic purposes is sufficient for ten people.

- Water is removed from the aquifer at a constant rate during the year of interest in the analysis.

- Radioactivity not removed during a year remains in the aquifer and contributes to the initial concentration for the next annual period.

- Water infiltration rate is a fraction of the total water application rate, which is the sum of the irrigation application rate and the annual precipitation rate.

- Evaporative losses remove only water from the system (i.e., surface soil and surface-water pond). Radioactivity is not lost by evaporation.

The initial activity present in box 1 is defined as the total activity present in box 1 when leaching begins. Once leaching begins, the contamination is dispersed evenly throughout the soil to a depth equal to the original depth of the landfill. The total capacity of the landfill unit does not consist completely of cleared waste. Daily cover material is interspersed between the waste, as well as being placed over the entire landfill upon closure.

Landfill Resident Scenario Descriptions

The specific landfill resident scenarios are described below.

Resident on a Closed Landfill After Disposal of BOF Dust

This public exposure scenario describes exposure to a resident on the site of a closed sanitary landfill after the disposal of BOF dust from the refinery. This residence begins after the post-closure monitoring period is completed and does not include any work related exposures associated with operating the landfill. This scenario assumes that the BOF dust is immediately disposed of in a sanitary landfill in the middle of its lifetime, 20 years before closure. The waste is assumed to begin leaching immediately upon placement in the landfill. Because the BOF dust is able to physically mix throughout the soil, the radioactivity is assumed to be dispersed throughout the mass of waste, daily cover-soil (soil used to cover the waste on a daily basis) and final cover-soil. This scenario addresses the same exposure pathways that are addressed in the generic scenario: drinking water, external exposure, inhalation exposure, and ingestion exposure.

Resident on a Closed Landfill After Disposal of Refinery Slag

This public exposure scenario describes a resident on the site of a closed sanitary landfill after the disposal of refinery slag. This scenario assumes that slag is disposed of in a sanitary landfill directly from the refinery and allowed to immediately leach towards the groundwater. A resident then moves onto the closed landfill after the completion of the post-closure monitoring period. Because the slag is able to physically mix throughout the soil, the activity is assumed to be dispersed throughout the mass of waste, daily cover-soil, and final cover-soil.

Resident on a Closed Landfill After Disposal of Scrap Metal

This public exposure scenario describes a resident on the site of a closed sanitary landfill after the disposal of scrap metal from a nuclear facility (direct disposal of cleared scrap). In order to calculate the radionuclide concentration in the surface layer after leaching occurs, the total mass of material in which the radioactivity is dispersed must be determined. Because the scrap metal cannot physically mix throughout the soil, the activity is assumed to be dispersed throughout the daily cover soil and final cover soil only.

Radionuclides are modeled to begin leaching from the scrap immediately upon placement in the landfill. The radionuclides in the scrap metal leach to the unsaturated zone beneath the scrap as well as the cover soil surrounding the scrap metal. The radioactivity that is leached to the cover soil surrounding the scrap metal is then accumulated and not allowed to leach toward the groundwater. This is reasonable within the context of this scenario because the same leach-rate constant is used for the movement of radionuclides from the scrap metal to the unsaturated zone and the cover-soil. Therefore, twice the normal amount is allowed to leach from the scrap metal. A resident moves onto the closed landfill after completion of the post closure monitoring period, 50–100 years after the scrap metal is placed in the landfill.

Resident on a Closed Landfill After Disposal of EAF Dust

This public exposure scenario describes a resident on the site of a closed hazardous landfill after the disposal of EAF dust directly from the refinery. This scenario assumes that EAF dust is disposed of in a hazardous landfill directly from the refinery. Because EAF dust is placed in 55-gallon drums for disposal, leaching does not begin immediately upon disposal. At the end of the post-closure monitoring period, the integrity of the drum is assumed to be lost and the EAF dust is dispersed throughout the soil. The total mass of material in which the radioactivity is mixed includes the waste, daily cover-soil, and final cover-soil. At this point, modeling the radionuclides leaching toward the groundwater begins. A resident is assumed to move onto the landfill after the completion of the post-closure monitoring period, 95–145 years after the EAF dust is placed in the landfill.

4.6.4 Environmental Media Concentrations Resulting from Environmental Trans

4.6.4.1 Atmospheric Releases (Source Term, Dispersion, Media Concentration)

Before the TEDE from atmospheric releases can be calculated, the source term and atmospheric dispersion term, must be calculated.

As stated previously, the emissions from a refinery consist of two parts, the off-gases and the particulates that escape the air pollution control system. The volumetric release rate of air from the refinery stack over the time period of interest is not a critical value, as long as it is relatively constant, and it is assumed that all activity is released. The average radioactivity release rate from the refinery stack is the important parameter. This is represented in Equation 4.15.

$$Q = \frac{(A_g + A_{ra}) * e^{-\lambda_r t_s}}{RD} \quad 4.15$$

where

Q	=	radionuclide release rate from refinery stack (pCi/s)

and

A_g	=	activity in the off-gases leaving the refinery stack in a year (pCi)
A_{ra}	=	dust activity in refinery atmospheric effluent that passes through the baghouse filter (pCi)
RD	=	duration of release of refinery atmospheric effluent (s)
λ_r	=	radioactive decay constant (1/d)
t_s	=	time from clearance of material from nuclear facility to time scenario begins (d)

The dust radioactivity in the refinery atmospheric effluent that passes through the baghouse filter (A_{ra}) can be calculated from the mass of dust that passes through the filter and the radioactivity concentration in dust as follows. This is shown in Equation 4.16.

$$A_{ra} = M_{ra} * C_d \quad 4.16$$

where

A_{ra}	=	dust radioactivity in refinery atmospheric effluent that escapes the refinery baghouse in a year (pCi)

and

M_{ra}	=	total mass of dust that escapes the refinery baghouse in a year (g)
C_d	=	radionuclide concentration in dust after the refining process (pCi/g)

Atmospheric Dispersion Term

The effluent dispersion of radioactive materials released into the atmosphere from a refinery facility is a function of several physical and environmental variables. For routine airborne

releases, the concentration of radioactive material at a given downwind locus depends upon the effluent emission rate, the effective height of the release, the average windspeed, atmospheric stability, airflow patterns at the site, and various effluent removal mechanisms.

Of the different approaches to modeling atmospheric dispersion, the straight-line Gaussian plume model (Slade 1968) is the most widely used method. In this model, the windspeed and atmospheric stability at the release point are assumed to determine the atmospheric dispersion characteristics in the mean wind direction at all distances. For effluent releases that are continuous or intermittent over long periods of time and, thus, subject to variations in wind direction, horizontal dispersion can be treated as an average over the width of a user-defined sector. The sector-averaged form of the Gaussian model (NRC 1977) used for this scenario is based on a sector width of 22.5°. The frequency of occurrence for windspeed and stability class are based on national-average data. This model treats the exposed group as residing in the downwind direction throughout the year. Atmospheric dispersion is given by Equation 4.17.

$$\frac{\chi}{Q} = 2.032 \sum_j (FSC_j) * [x u_j \sigma_{zj}]^{-1} * \exp\left[-\frac{1}{2}\left(\frac{H_e}{\sigma_{zj}}\right)^2\right] \qquad 4.17$$

where

χ/Q	=	annual average atmospheric dispersion factor (s/m^3)

and

FSC_j	=	fraction of time that stability class j occurs (dimensionless)
x	=	distance from release point to receptor (m)
u_j	=	average windspeed for stability class j (m/s)
σ_{zj}	=	vertical dispersion coefficient for stability class j at distance x (m)
H_e	=	effective stack height (m)

The vertical dispersion coefficient, σ_z, is defined for each Pasquill atmospheric stability class A-G and is a function of downwind distance, x. The Jülich System, for an emission height of 50 m (164 ft) is used to define σ_z. According to Till and Meyer (1983), this system is applicable to sites with medium to high surface roughness, due to settlements, vegetation, and other ground obstacles. Equation 4.18 is used to calculate these coefficients for stability classes, SC, A-F and Equation 4.19 is used for stability class G.

$$\sigma_{z(j)} = SC * x^n \qquad 4.18$$

where

σ_{zj}	=	vertical dispersion coefficient for stability class j at distance x (m)
SC	=	stability class
x	=	distance from release to receptor (m)

SC = 0.2222 (j = A,B)
0.2149 (j = C)
0.2048 (j = D)
0.1616 (j = E)
0.3960 (j = F)

n = 0.9680 (j = A, B)
0.9438 (j = C)
0.9358 (j = D)
0.8094 (j = E)
0.6183 (j = F)

$$\sigma_{zG} = 0.6\ \sigma_{zF} \qquad 4.19$$

Equation 4.20 represents the air concentration of radionuclides at a distance x from the refinery.

$$\chi = \frac{\chi}{Q} * Q \qquad 4.20$$

where

χ = the average effluent concentration, averaged over a sector 22.5° wide (pCi/m^3)

and

χ/Q = annual average atmospheric dispersion factor (s/m^3)

Q = radionuclide release rate from refinery stack (pCi/s)

Ground-Surface Concentration Resulting from Atmospheric Releases

Doses were calculated for external irradiation from nuclides deposited on the ground surface. The ground-surface dose originates from a thin layer of radionuclides deposited on the ground surface from the passing plume. This concentration also includes the amount of radioactivity that is weathered off plants. Therefore, the total deposition velocity, $V_d(t)$, is used in Equation 4.21 to calculate the ground-surface radioactivity concentration.

$$C_{grnd} = \chi * V_d(T) * \frac{1 - e^{-(\lambda_r t_b)}}{\lambda_r} \qquad 4.21$$

where

C_{grnd} = ground-surface radioactivity concentration (pCi/m^2)

and

χ = the average effluent concentration, averaged over a sector 22.5° wide (pCi/m^3)

$V_d(T)$ = total deposition velocity (m/d)

t_b = the period of long-term buildup for activity in soil (d)

λ_r = radioactive decay constant (1/d)

The volumetric radionuclide concentration in the soil is represented by Equation 4.22.

$$C_{S(0)} = \frac{C_{grnd}}{H_1 * \rho_s} \quad 4.22$$

where

$C_{s(O)}$ = soil radionuclide concentration at time of scenario (pCi/g dry-weight soil)

and

C_{grnd} = ground surface radionuclide concentration (pCi/m^2)
H_1 = thickness of surface soil layer (m)
ρ_s = average density of soil in surface layer (g dry-weight soil/m^3)

Concentration in Edible Parts of Plants

The radionuclide concentration in the edible parts of plants at the time of harvest is described in Equation 4.23. This equation is used to calculate the concentration in leafy vegetables and vegetables (for human consumption) due to direct deposition and root uptake. The concentration of C-14 and H-3 in plants is calculated using Equations 4.24 and 4.25, respectively.

$$C_v = \chi * V_d(T)\left[\frac{r(1-e^{-\lambda_e t_{gv}})}{Y_v \lambda_e} + \frac{B_{iv} W_v (1-e^{-\lambda_r t_b})}{\lambda_r P}\right] \quad 4.23$$

where

C_v = radionuclide concentration in edible part of plant v for consumption (i.e., leafy vegetables and vegetables) due to root uptake and directly deposited material (pCi/kg wet-weight plant)

and

χ = average effluent radionuclide concentration, averaged over a sector 22.5° wide (pCi/m^3)
$V_d(T)$ = total deposition velocity (m/d)
r = the fraction of total material being deposited that is intercepted by crops (dimensionless)
λ_e = effective weathering and decay constant at harvest (1/d) ($\lambda_r + \lambda_w$)
t_{gv} = the time period that crops are exposed to contamination during the growing season (d)
Y_v = yield of plant v (kg wet-weight plant/m^2)
B_{iv} = root uptake factor for radionuclide i from soil to plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil)
W_v = dry-weight-to-wet-weight conversion factor for plant v (kg dry-weight plant/kg wet-weight plant)
λ_r = radioactive decay constant (1/d)
t_b = the period of long-term buildup for radioactivity in soil (d)
P = areal soil density (kg dry-weight soil/m^2)

The concentration of C-14 in plants due to deposition is calculated using Equation 4.24.

$$C_{v,C-14} = (1.0E+03) * p_{c-14} * \chi * \left(\frac{0.11}{0.16}\right) \quad 4.24$$

where

$C_{v,C-14}$ = concentration of C-14 in edible part of plant v for consumption (i.e., all plants) (pCi/kg wet-weight plant)

and

χ = average effluent radionuclide concentration, averaged over a sector 22.5° wide (pCi/m^3)

p_{c-14} = fractional equilibrium ratio (dimensionless)

0.11 = fraction of total plant mass that is natural carbon (dimensionless)

0.16 = radionuclide concentration of natural carbon in the atmosphere (g/m^3)

1.0E+3 = unit conversion factor (g/kg)

The concentration of H-3 in plants due to deposition is represented by Equation 4.25.

$$C_{v,H-3} = (1.0E+03) * (0.75) * \chi * \left(\frac{0.5}{H}\right) \quad 4.25$$

where

$C_{v,H-3}$ = concentration of H-3 in edible part of plant v for consumption (i.e., all plants) (pCi/kg wet-weight plant)

and

χ = average effluent radionuclide concentration, averaged over a sector 22.5° wide (pCi/m^3)

H = absolute humidity of the atmosphere at receptor (g/m^3)

0.5 = ratio of tritium concentration in plant water to tritium concentration in atmospheric water (dimensionless)

1.0E+3 = unit conversion factor (g/kg)

0.75 = fraction of total plant mass that is water (dimensionless)

Plants for direct human consumption are considered to have a hold-up period before being consumed. The radionuclide concentration in plants at the end of the hold-up period is calculated using Equation 4.26 for all radionuclides including C-14 and H-3.

$$C_{v,h} = C_v e^{-\lambda_r t_h} \quad 4.26$$

where

$C_{v,h}$ = radionuclide concentration in edible part of plant v for human consumption at the end of the hold-up period (pCi/kg wet-weight plant)

and

C_v = radionuclide concentration in edible part of plant v for consumption due to root uptake and directly deposited material (pCi/kg wet-weight plant)

λ_r = radioactive decay constant (1/d)

t_h = hold-up period between harvesting and consumption (d)

4.6.4.2 Drinking Water Concentrations

The drinking water pathway is included in residential scenarios and the slag storage scenario. Calculation of doses resulting from ingestion of drinking water requires calculating radioactivity concentrations in the aquifer, i.e., the assumed source of drinking water. This section contains the equations comprising the drinking-water model, starting with the surface layer. The total mass of waste in the surface layer, for landfill resident scenarios is calculated using Equation 4.27.

$$M_w = V_w * \rho_w * FW \qquad 4.27$$

where

M_w = total mass of waste that is from cleared material in box 1 (surface layer) (g waste)

and

V_w = volume of all waste in landfill (m^3)

ρ_w = density of waste that is from cleared material (g waste/m^3)

FW = fraction of total waste that is from cleared material

The total initial radioactivity is calculated by multiplying the radioactivity concentration in the waste for residential landfill scenarios, when leaching to the groundwater begins, by the total mass of waste in the contaminated surface layer as shown in Equation 4.28.

$$A_{1(0)} = C_{waste} * M_w \qquad 4.28$$

where

$A_{1(0)}$ = initial activity in box 1 (surface layer) (pCi)

and

C_{waste} = radionuclide concentration in waste when leaching to groundwater begins (pCi/g waste)

M_w = total mass of waste that is from cleared material in box 1 (surface layer) (g waste)

For the slag storage scenario, the total activity in the slag pile is represented by Equation 4.29.

$$A_{1(0)} = C_0 * M \qquad 4.29$$

where

$A_{1(0)}$ = initial radioactivity in box 1 (slag pile) (pCi)

and

C_0 = radionuclide concentration in the source material at the time the scenario begins (pCi/g)

M = total mass of material in box 1 (slag pile) (g)

Once the initial radioactivity in the surface layer is calculated, the activities in each of the other two boxes (layers) in the model can be calculated. These activities are calculated as a function of time because radionuclides move through the boxes according to leach rate constants, which have units of d^{-1}. Leaching is assumed to begin immediately after placement of slag or waste, prior to the beginning of the exposure scenario. The activity in box 1 (surface layer) as a function of time is expressed using Equation 4.30.

$$A_{1(t)} = A_{1(0)} e^{-(\lambda_r + L_{12})t} \quad 4.30$$

Box 1 in the groundwater model for scrap disposal scenarios consists of the scrap metal instead of the surface layer. Box 2 and box 3 still refer to the unsaturated zone and the aquifer, respectively. Therefore, $A_{1(0)}$, calculated by Equation 4.29, is defined as the initial activity in the scrap metal at the time leaching to the groundwater begins. Equation 4.31 is used for scrap disposal scenarios to calculate activity in the surrounding soil at time t.

$$A_{s(t)} = A_{1(0)} e^{-\lambda_r t} - A_{1(0)} e^{-(\lambda_r + L_{ws})t} \quad 4.31$$

where

$A_{s(t)}$ = activity in the surrounding cover soil at time t (pCi)

and

$A_{1(0)}$ = initial activity in box 1 (scrap metal) (pCi)
λ_r = radioactive decay constant (1/d)
t = time from beginning of leaching to time activity is determined (d)
L_{ws} = rate constant for movement of radionuclide from box 1 (scrap metal) to box 2 (unsaturated zone and cover soil) (1/d)

Equation 4.32 is used to calculate the activity in the unsaturated zone at time t. In scrap disposal scenarios, the rate constant L_{ws} is substituted for L_{12}. L_{ws} is also substituted for L_{12} in Equation 4.33.

$$A_{2(t)} = \frac{L_{12} A_{1(0)} e^{-(\lambda_r + L_{12})t}}{(\lambda_r + L_{23}) - (\lambda_r + L_{12})} + \left[A_{2(0)} - \frac{L_{12} A_{1(0)}}{(\lambda_r + L_{23}) - (\lambda_r + L_{12})} \right] e^{-(\lambda_r + L_{23})t} \quad 4.32$$

The activity of the radionuclide in box 3 (aquifer) as a function of time is calculated using Equation 4.33.

$$A_{3(t)} = \frac{L_{23}\, L_{12}\, A_{1(0)} e^{-(\lambda_r + L_{12})t}}{[(\lambda_r + L_{23}) - (\lambda_r + L_{12})][(\lambda_r + w_r) - (\lambda_r + L_{12})]}$$

$$\left\{\frac{L_{23}\, A_{2(0)}}{(\lambda_r + w_r) - (\lambda_r + L_{23})} - \frac{L_{23}\, L_{12}\, A_{1(0)}}{[(\lambda_r + L_{23}) - (\lambda_r + L_{12})][(\lambda_r + w_r) - (\lambda_r + L_{23})]}\right\} e^{-(\lambda_r + L_{23})t} \qquad 4.33$$

$$+\left\{A_{3(0)} - \frac{L_{23}\, A_{2(0)}}{(\lambda_r + w_r) - (\lambda_r + L_{23})} + \frac{L_{23} L_{12}\, A_{1(0)}}{[(\lambda_r + w_r) - (\lambda_r + L_{12})][(\lambda_r + w_r) - (\lambda_r + L_{23})]}\right\} e^{-(\lambda_r + w_r)t}$$

where

$A_{1(t)}$	=	activity in box 1 (surface layer) at time t (pCi)
$A_{2(t)}$	=	activity in box 2 (unsaturated zone) at time t (pCi)
$A_{3(t)}$	=	activity in box 3 (aquifer) at time t (pCi)

and

$A_{1(0)}$	=	initial activity in box 1 (surface layer) (pCi)
$A_{2(0)}$	=	initial activity in box 2 (unsaturated zone) (pCi)
$A_{3(0)}$	=	initial activity in box 3 (aquifer) (pCi)
λ_r	=	radioactive decay constant (1/d)
L_{12}	=	rate constant for movement of radionuclide from box 1 (surface layer) to box 2 (unsaturated zone) (1/d)
L_{23}	=	rate constant for movement of radionuclide from box 2 (unsaturated zone) to box 3 (aquifer) (1/d)
t	=	time from beginning of leaching to time activity is determined (d)
w_r	=	residential pumping rate constant from box 3 (aquifer) to box 2 (surface layer) (1/d)

As described for previous equations, Box 1 can represent a slag pile, the surface layer, or scrap metal. The rate constants for movement of radionuclides from box 1 to box 2 are calculated using Equations 4.35, 4.34, and 4.36. The rate constant for the movement of radionuclides from the scrap metal to the surrounding soil and to the unsaturated zone, L_{ws}, was not calculated by Equation 4.34. Instead this value was input as a radionuclide-independent parameter. Two different pumping rate constants are used in Equation 4.33 depending on the scenario being analyzed. The residential pumping rate constant, w_r, is used for the resident on closed landfill scenarios while w_d is used for the storage of slag scenario.

$$L_{12} = \frac{I}{H_1\, \theta_1\, R t_1\, (365.25)} \qquad 4.34$$

$$\theta_1 = n_1\, f_1 \qquad 4.35$$

$$Rt_1 = 1 + \frac{Kd_1 \rho_1}{n_1} \quad 4.36$$

where

L_{12} = rate constant for movement of radionuclide from box 1 (surface layer) to box 2 (unsaturated zone) (1/d)

and

I = infiltration rate (m/y)
H_1 = thickness of box 1 (surface layer) (m)
θ_1 = volumetric water content of box 1 (surface layer) (dimensionless)
Rt_1 = retardation factor for movement of radionuclide from box 1 (surface layer) to box 2 (unsaturated zone) (dimensionless)
365.25 = unit conversion factor (d/y)
n_1 = total porosity of box 1 (surface layer) (dimensionless)
f_1 = saturation ratio for box 1 (surface layer) (dimensionless)
Kd_1 = soil/water partition coefficient for radionuclide in box 1 (surface layer) (mL/g)
ρ_1 = bulk density of soil in box 1 (surface layer) (g/mL)

Equations used to calculate movement of radionuclides from box 2 to box 3 are shown below as Equations 4.37, 4.38, and 4.39.

$$L_{23} = \frac{I}{H_2 \theta_2 Rt_2 (365.25)} \quad 4.39$$

$$\theta_2 = n_2 f_2 \quad 4.37$$

$$Rt_2 = 1 + \frac{Kd_2 \rho_2}{n_2} \quad 4.38$$

where

L_{23} = rate constant for movement of radionuclide from box 2 (unsaturated zone) to box 3 (aquifer) (1/d)

and

I = infiltration rate (m/y)
H_2 = thickness of box 2 (unsaturated zone) (m)
θ_2 = volumetric water content of box 2 (unsaturated zone) (dimensionless)
Rt_2 = retardation factor for movement of radionuclide from box 2 (unsaturated zone) to box 3 (aquifer) (dimensionless)
365.25 = unit conversion factor (d/y)
n_2 = total porosity of box 2 (unsaturated zone) (dimensionless)
f_2 = saturation ratio for box 2 (unsaturated zone) (dimensionless)
Kd_2 = soil/water partition coefficient for radionuclide in box 2 (unsaturated zone) (mL/g)
ρ_2 = bulk density of soil in box 2 (unsaturated zone) (g/mL)

Pumping rate constants are calculated in order to estimate the amount of water pumped from the aquifer, using Equations 4.40 and 4.41.

$$w_d = \frac{V_{dd} / V_{Td}}{T_p} \quad 4.40$$

where

w_d	=	pumping rate constant from box 3 (aquifer) to surface (1/d)

and

V_{dd}	=	volume of water used for domestic purposes during a year (L)
V_{Td}	=	total water volume in box 3 (aquifer) (L)
T_p	=	time period for pumping (d)

$$w_r = \frac{\frac{V_{irr} + V_{dr}}{V_{Tr}}}{T_p} \quad 4.41$$

where

w_r	=	residential pumping rate constant from box 3 (aquifer) to box 1 (surface layer) (1/d)

and

V_{dr}	=	volume of water used for domestic purposes during a year (L)
V_{irr}	=	volume of water used for irrigation purposes during a year (L)
V_{Tr}	=	total water volume in box 3 (aquifer) (L)
T_p	=	time period for pumping (d)

The concentration of radioactivity in the groundwater is calculated by dividing the total activity in the aquifer at the time the scenario begins by the total volume of water in the aquifer, as shown in Equation 4.42.

$$C_w = \frac{A_{3(t)}}{V_{Tr}} \quad 4.42$$

where

C_w	=	radionuclide concentration in groundwater (pCi/L)

and

$A_{3(t)}$	=	activity in box 3 (aquifer) at time t (pCi)
V_{Tr}	=	total water volume in box 3 (aquifer) (L)

The value for the total volume of water in the aquifer is the greater of (1) the sum of the annual infiltration and annual irrigation volume or (2) the sum of the annual volume of water used for irrigation, the annual domestic water use, and the aquifer-fed surface-water pond volume. For some scenarios (e.g., storage of slag at the refinery), the total volume of water in the aquifer is

simply the greater of (1) the sum of the annual infiltration and the annual irrigation volume, or (2) the annual domestic water use.

The annual infiltration and irrigation volume is calculated using Equation 4.43.

$$V_{Ir} = I * A_c * 1000 * T_i \quad 4.43$$

where

V_{Ir} = annual infiltration and irrigation volume through the cultivated farmland area (L)

And

I = infiltration rate (m/y)
A_c = area of land under cultivation (m^2)
1000 = unit conversion factor (L/m^3)
T_i = time period for infiltration and irrigation (y)

For the slag storage scenario, the annual infiltration and irrigation volume is calculated using Equation 4.44, where the area of contaminated land has been substituted for the area of land under cultivation.

$$V_{Ir} = I * A_d * 1000 * T_i \quad 4.44$$

where

V_{Ir} = annual infiltration and irrigation volume through the cultivated farmland area (L)

and

I = infiltration rate (m/y)
A_d = area of contaminated land (m^2)
1000 = unit conversion factor (L/m^3)
T_i = time period for infiltration and irrigation (y)

The soil radionuclide concentration at the beginning of landfill resident scenarios, after leaching has taken place, is calculated using Equation 4.45. The total mass of material in the landfill, QT, refers to the waste, daily cover-soil, and final cover-soil.

$$C_{S(t)} = \frac{A_{1(t)}}{QT} \quad 4.45$$

where

$C_{s(t)}$ = soil radionuclide concentration at time resident moves onto landfill (pCi/g dry-weight soil)

and

$A_{1(t)}$ = activity in box 1 (surface layer) at time t (pCi)
QT = total mass of material in box 1 (surface layer) (g dry-weight soil)

For one scenario (resident on closed landfill after disposal of scrap metal) Equation 4.46 was used in place of Equation 4.45 to calculate soil radionuclide concentration where the total mass of material in the landfill is comprised of the daily cover-soil and final cover-soil.

$$C_{s(t)} = \frac{A_{s(t)}}{QT} \quad 4.46$$

where

$C_{s(t)}$ = soil radionuclide concentration at time resident moves onto landfill (pCi/g dry-weight soil)

and

$A_{s(t)}$ = activity in the surrounding cover soil at time t (pCi)

QT = total mass of material in box 1 (surface layer) (g dry-weight soil)

4.6.4.3 Food and Soil Concentrations

The ingestion exposure pathway is analyzed in two parts using non-irrigation and irrigation models. These two models can be used separately (i.e., growing plants in contaminated soil and irrigating with uncontaminated water or growing plants in clean soil offsite, but irrigating with contaminated water) or they can be used together (i.e., growing plants in contaminated soil and irrigating with contaminated water). Effective dose equivalents are calculated for each model separately; the total ingestion dose (non-irrigation plus irrigation) dose assumes both occur simultaneously.

Non-Irrigation Ingestion Model for Resident on Closed Landfill

Concentration in edible parts of plant. The radionuclide concentration in the edible part of the plant of interest at the time of harvest is described in Equation 4.47. This Equation is used to calculate the radionuclide concentration in vegetables for human consumption.

$$C_{v,n} = 1000 * (ML_v + B_{iv}) * W_v * C_{s(t)} e^{-\lambda_r t_{gv}} \quad 4.47$$

where

$C_{v,n}$ = radionuclide concentration in edible part of plant v for consumption due to root uptake and resuspended soil (non-irrigation model) (pCi/kg wet-weight plant)

and

B_{iv} = root uptake factor for radionuclide I from soil to plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

ML_v = plant soil mass-loading factor for resuspended soil to plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

W_v = dry-weight-to-wet-weight conversion factor for plant v (kg dry-weight plant/kg wet-weight plant)

$C_{s(t)}$ = soil radionuclide concentration at time resident moves onto landfill (pCi/g dry-weight soil)

λ_r = radioactive decay constant (1/d)

t_{gv} = growing period for plant v (d)

1000 = unit conversion factor (g/kg)

The soil radionuclide concentration at the time the resident moves onto the landfill, $C_{s(t)}$, is calculated using Equation 4.45; Equation 4.46 is used for disposal of metal. Plants for direct human consumption are considered to have a hold-up period before being consumed. The radionuclide concentration in plant v at the end of the hold-up period is calculated using Equation 4.48.

$$C_{v,nh} = C_{v,n} e^{-\lambda_r t_h} \quad 4.48$$

where

$C_{v,nh}$ = radionuclide concentration in edible part of plant v for human consumption at end of hold-up period (non-irrigation model) (pCi/kg wet-weight plant)

and

$C_{v,n}$ = radionuclide concentration in edible part of plant v for consumption due to root uptake and resuspended soil (non-irrigation model) (pCi/kg wet-weight plant)

λ_r = radioactive decay constant (1/d)

t_h = hold-up period between harvesting and consumption (d)

Irrigation Ingestion Model for Resident on Closed Landfill

Concentration in edible parts of plant. There are two ways for contamination to enter the plant, direct deposition of irrigation water on the plants and direct deposition of irrigation water on the soil, with subsequent root uptake into the plant. Each of these radionuclide concentrations are calculated separately.

The rate of direct deposition of irrigation water onto plants is calculated using Equation 4.49.

$$R_{v,p} = \frac{IR * r_v * T_v * C_w}{Y_v} \quad 4.49$$

where

$R_{v,p}$ = rate of deposition of irrigation water onto plant v (pCi translocated/kg-d)

and

IR = average annual application rate of irrigation water (L/m^2-d)

r_v = fraction of initial deposition of irrigation water retained on plant v (pCi retained/pCi deposited)

T_v = fraction of retained activity translocated to edible part of plant v (pCi translocated/pCi retained)

C_w = radionuclide concentration in groundwater (pCi/L)

Y_v = yield of plant v (kg wet-weight plant/m^2)

The radionuclide concentration in plants, due only to direct deposition of irrigation water at the time of harvest, is calculated using Equation 4.50.

$$C_{v,id} = R_{v,p}\left[\frac{1 - e^{-\lambda_e t_{gv}}}{\lambda_e}\right] \quad 4.50$$

where

$C_{v,id}$ = radionuclide concentration in edible part of plant v at time of harvest due to direct deposition of irrigation water (pCi/kg wet-weight plant)

and

$R_{v,p}$ = rate of deposition of irrigation water onto plant v (pCi translocated/kg-d)
λ_e = effective weathering and decay constant at harvest (1/d) ($\lambda_w + \lambda_r$)
λ_w = weathering constant at harvest (1/d)
λ_r = radioactive decay constant (1/d)
t_{gv} = growing period for plant v (d)

Deposition onto soil and subsequent root uptake is also modeled. The rate at which irrigation water is deposited onto the soil is calculated using Equation 4.51.

$$R_s = \frac{IR * C_w}{P} \quad 4.51$$

where

R_s = rate of deposition of irrigation water onto soil (pCi/kg dry-weight soil- d)

and

IR = average annual application rate of irrigation water (L/m^2-d)
C_w = radionuclide concentration in groundwater (pCi/L)
P = areal soil density (kg dry-weight soil/m^2)

The radionuclide concentration in the soil at the end of the growing season is calculated using Equation 4.52.

$$C_{sg} = R_s\left[\frac{1 - e^{-\lambda_r t_{gv}}}{\lambda_r}\right] \quad 4.52$$

where

C_{sg} = soil radionuclide concentration at end of growing season due to direct deposition of irrigation water (pCi/kg dry-weight soil)

and

R_s = rate of deposition of irrigation water onto soil (pCi/kg dry-weight soil - d)
λ_r = radioactive decay constant (1/d)
t_{gv} = growing period for plant v (d)

The radionuclide concentration in the edible part of the plant at the time of harvest (only from deposition onto the soil and root uptake) is calculated using Equation 4.53.

$$C_{v,psi} = (ML_v + B_{iv}) * W_v * C_{sg} \quad 4.53$$

where

$C_{v,psi}$ = radionuclide concentration in edible part of plant v at time of harvest due to root uptake (pCi/kg wet-weight plant)

and

ML_v = plant soil mass-loading factor for resuspended soil to plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

B_{iv} = root uptake factor for radionuclide i from soil to plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil)

W_v = dry-weight-to-wet-weight conversion factor for plant v (kg dry-weight plant/kg wet-weight plant)

C_{sg} = soil radionuclide concentration at end of growing season due to direct deposition of irrigation water (pCi/kg dry-weight soil)

Finally, the total radionuclide concentration in the edible parts of plants, following deposition via irrigation and after the hold-up period, is calculated using Equation 4.54.

$$C_{v,ih} = (C_{v,id} + C_{v,psi}) * e^{-\lambda_r t_h} \quad 4.54$$

where

$C_{v,ih}$ = total radionuclide concentration in plant v after hold-up period (irrigation model) (pCi/kg wet-weight plant)

and

$C_{v,id}$ = radionuclide concentration in edible part of plant v at time of harvest due to direct deposition of irrigation water (pCi/kg wet-weight plant)

$C_{v,psi}$ = radionuclide concentration in edible part of plant v at time of harvest due to root uptake (pCi/kg wet-weight plant)

λ_r = radioactive decay constant (1/d)

t_h = hold-up period between harvesting and consumption (d)

4.6.5 Exposure Pathway Doses

This section presents the equations used to calculate pathway doses, using the media radionuclide concentrations described in Section 4.6.4, as well as other parameters described in other sections.

4.6.5.1 External Exposure Pathway

When external exposure is due to penetrating radiation from an object such as a drum or pile, then it is calculated using Equation 4.55 which assumes that a worker is in close proximity to the object. The parameter GF is a nuclide- and scenario-specific dose rate factor. The values of GF incorporate information on the photon spectrum of each nuclide and the size, mass, shape, and elemental composition of objects such as drums or piles of material. For each nuclide and object, GF has a fixed value. Calculation of GF is discussed in Appendix C. The parameter U_{GF} is a multiplicative factor which carries the uncertainty information about each GF. The range and

mode of each U_{GF} are based on uncertainty in the mass of the object and the relative position of the exposed individual. This equation is used for scenario categories such as handling, processing, storage, transportation, and product use.

$$D_{ext} = C_0 * GF * U_{GF} * t_{xs} * t_{ys} \quad 4.55$$

where

D_{ext} = EDE due to external exposure (mrem/y)

and

C_0 = radionuclide concentration in the source material at the time scenario begins (pCi/g waste)
GF = geometry factor for the scenario (mrem/h per pCi/g)
t_{xs} = daily number of hours of exposure for scenario (h/d)
t_{ys} = annual number of days of exposure for scenario (d/y)
U_{GF} = uncertainty factor for GF (dimensionless)

Federal Guidance Report No. 12 (EPA 1993a) provides dose rate factors for certain simple geometries such as an infinite plane of soil contaminated to various depths. These values have been used for scenarios in which the geometry of the source is similar to one specified in Federal Guidance Report No. 12. Equation 4.56 is used for the disposal activities scenarios.

$$D_{ext} = C_0 * U_{GF} * DF_{ext} * SF * \rho_w * t_{xs} * t_{ys} * 3600 \quad 4.56$$

where

D_{ext} = EDE due to external exposure (mrem/y)

and

C_0 = radionuclide concentration in the source material at the time scenario begins (pCi/g waste)
DF_{ext} = external dose rate factor for contamination of infinite depth (mrem-m^3/pCi-s)
SF = vehicle shielding factor (dimensionless)
ρ_w = density of waste from cleared material (g waste/m^3)
t_{xs} = daily number of hours of exposure for scenario (h/d)
t_{ys} = annual number of days of exposure for scenario (d/y)
3600 = unit conversion factor (s/h)
U_{GF} = uncertainty factor for dose rate factor (dimensionless)

Equation 4.57 is used to calculate the dose to a resident on a closed landfill due to both outdoor and indoor external exposure, where contamination is distributed volumetrically in soil.

$$D_{ext} = (t_{od} * SFO * C_{s(t)} * \rho_s * U_{GF} * DF_{ext} * 86400) + (t_{id} * SFI * C_{s(t)} * \rho_s * U_{GF} * DF_{ext} * 86400) \quad 4.57$$

Where

D_{ext} = EDE due to external exposure (mrem/y)

and

SFO = shielding factor during outdoor activities (dimensionless)
SFI = shielding factor during indoor activities (dimensionless)
$C_{s(t)}$ = soil radionuclide concentration at time resident moves onto landfill (pCi/g dry-weight soil)
ρ_s = average density of soil in surface layer (g dry-weight soil/m^3)
DF_{ext} = external dose rate factor for contamination of soil of infinite depth (mrem-m^3 per pCi-s)
86400 = unit conversion factor (s/d)
t_{od} = annual number of days spent outdoors (d/y)
t_{id} = annual number of days spent indoors (d/y)
U_{GF} = uncertainty factor for dose rate factor (dimensionless)

Equation 4.58 is to calculate external exposure due to ground-surface radionuclide concentrations of radionuclides. This equation is used for external exposure due to atmospheric releases from a refinery.

$$D_{ext} = (t_{od} * SFO + t_{id} * SFI) * C_{grnd} * DF_{grnd} * U_{GF} * 86400 \quad 4.58$$

where

D_{ext} = EDE due to external exposure (mrem/y)

and

t_{od} = annual number of days spent outdoors (d/y)
SFO = shielding factor during outdoor activities (dimensionless)
t_{id} = annual number of days spent indoors (d/y)
SFI = shielding factor during indoor activities (dimensionless)
C_{grnd} = ground surface concentration of radionuclide at time of scenario (pCi/m^2)
DF_{grnd} = external dose rate factor for exposure to contaminated ground surface (mrem/s per pCi/m^2)
U_{GF} = uncertainty on geometry factor (dimensionless)
86400 = unit conversion factor (s/d)

For the transportation scenarios, the potential external doses for the truck driver are calculated using Equation 4.59.

$$D_{ext,} = (GF * C_O) * t_{xs} * t_{ys} * U_{GF} \quad 4.59$$

where:

$D_{ext,}$ = EDE due to external exposure for individual (mrem/y)
GF = geometry factor for the scenario (mrem/hr per pCi/g)
C_O = radionuclide concentration in the source material at the time the scenario begins (pCi/g)
t_{xs} = daily number of hours of exposure for the scenario (h/d)
t_{ys} = annual number of days of exposure for the scenario (d/y)

U_{GF} = uncertainty factor for dose rate factor (dimensionless)

4.6.5.2 Inhalation Exposure Pathway

Work related. In some worker scenarios, a fraction of the material (e.g., metal shavings, slag, and EAF dust) would be suspended into the air, making it available for inhalation by a worker at a steel refinery. The dose due to this exposure pathway is calculated using Equation 4.60.

$$D_{inh} = C_0 * ML * RF * BR * PF * DF_{inh} * (1E-03) * t_{xs} * t_{ys} \quad 4.60$$

where

D_{inh} = EDE due to inhalation (mrem/y)

and

C_0 = radionuclide concentration in the source material at the time the scenario begins (pCi/g)
ML = mass loading of the source material (mg/m^3)
RF = respirable fraction of resuspended source material (dimensionless)
BR = breathing rate for moderate physical activity (m^3/h)
DF_{inh} = inhalation dose factor (mrem/pCi intake)
PF = protection factor for respirator (dimensionless)
1E-3 = unit conversion factor (g/mg)
t_{xs} = daily number of hours of exposure for scenario (h/d)
t_{ys} = annual number of days of exposure for scenario (d/y)

Landfill resident. To estimate inhalation exposure for the scenarios involving a resident on a closed landfill, Equation 4.61 is used. This equation is used to calculate the total inhalation dose due to indoor, dusty, and non-dusty activities.

$$\begin{aligned} D_{inh} = {} & (BR_{dust} * t_{dd} * ML_{dust} * C_{s(t)} * DF_{inh} * 24) \\ & + (BR_{out} * (t_{od} - t_{dd}) * ML_{out} * C_{s(t)} * DF_{inh} * 24) \\ & + (BR_{in} * t_{id} * (ML_{in} + P_d * RF_r) * C_{s(t)} * DF_{inh} * 24) \end{aligned} \quad 4.61$$

where

D_{inh} = EDE due to inhalation (mrem/y)

and

$C_{s(t)}$ = soil radionuclide concentration at time resident moves onto landfill (pCi/g dry-weight soil)
ML_{dust} = mass loading factor for resuspended soil for dusty activities outdoors (g/m^3)
ML_{out} = mass loading factor for resuspended soil for normal activities outdoors(g/m^3)
ML_{in} = mass loading factor for resuspended soil blown indoors from outdoors (g/m^3)
P_d = indoor dust-loading on floors (g/m^2)
RF_r = indoor resuspension factor (1/m)

BR_{dust} = breathing rate for dusty activities outdoors (m^3/h)
BR_{out} = breathing rate for normal activities outdoors (m^3/h)
BR_{in} = breathing rate for indoor activities (m^3/h)
DF_{inh} = inhalation dose factor (mrem/pCi intake)
24 = conversion factor (h/d)
t_{dd} = annual number of days spent on dusty activities outdoors (d/y)
t_{od} = annual number of days spent outdoors (d/y)
t_{id} = annual number of days spent indoors (d/y)

Atmospheric Releases

Inhalation doses resulting from refinery releases are calculated for inhalation of airborne radionuclides at a residence (from the passing plume) and inhalation of suspended soil (dust). Like the external pathway, an individual's time is divided between offsite and onsite, and while onsite, indoors and outdoors. The EDE due to inhalation includes the radioactivity inhaled as a result of the passing plume and from suspension of the soil. This is represented by Equation 4.62.

$$D_{inh} = (A_{plm} + A_{res}) * DF_{inh} \quad 4.62$$

where
D_{inh} = EDE due to inhalation (mrem/y)
and
A_{plm} = activity inhaled directly from the passing plume in a year (pCi/y)
A_{res} = activity inhaled due to resuspension of soil in a year (pCi/y)
DF_{inh} = inhalation dose factor (mrem/pCi intake)

The activity inhaled directly from the passing plume is represented by Equation 4.63. The average effluent radionuclide concentration used in this equation is calculated using Equation 4.20.

$$A_{plm} = \left[(BR_{in} * RFI * t_{id}) + (BR_{out} * t_{od}) \right] * 24 * \chi \quad 4.63$$

where
A_{plm} = activity inhaled directly from the passing plume in a year (pCi/y)
and
BR_{in} = breathing rate for indoor activities (m^3/h)
RFI = indoor fraction of outdoor radionuclide concentration
t_{id} = annual number of days spent indoors (d/y)
BR_{out} = breathing rate for normal activities outdoors (m^3/h)
t_{od} = annual number of days spent outdoors (d/y)
χ = average effluent radionuclide concentration, averaged over a sector 22.5° wide (pCi/m^3)
24 = unit conversion factor (h/d)

Doses due to inhalation of radionuclides in resuspended soil (dust) at a residence will also be calculated. A fraction of an individual's time at the residence will be spent indoors, during which the individual will breathe dust blown in from outdoors as well as dust tracked inside then resuspended. During the fraction of the time spent outdoors onsite, the individual's time will be divided into time spent engaged in activities that could generate dust (such as sweeping, playing sports, and gardening) and time spent engaged in other outdoor activities (such as walking, sunbathing, and washing windows). Equation 4.64 represents the activity inhaled as a result of resuspension of the soil.

$$A_{res} = [\ (BR_{dust} * t_{dd} * ML_{dust}) + (BR_{out} * (t_{od} - t_{dd}) * ML_{out}) + (BR_{in} * t_{id} * \{ML_{in} + P_d * RF_r\})\ ] * [\frac{C_{grnd}}{\rho_s * RL} * 24] \quad 4.64$$

where

A_{res} = radioactivity inhaled due to resuspension of soil in a year (pCi/y)

and

BR_{dust} = breathing rate for dusty activities outdoors (m^3/h)
BR_{out} = breathing rate for normal activities outdoors (m^3/h)
BR_{in} = breathing rate for indoors activities (m^3/h)
t_{dd} = annual number of days spent on dusty activities outdoors (d/y)
t_{od} = annual number of days spent outdoors (d/y)
t_{id} = annual number of days spent indoors (d/y)
ML_{dust} = mass loading factor for resuspended soil for dusty activities outdoors (g/m^3)
ML_{out} = mass loading factor for resuspended soil for normal activities outdoors (g/m^3)
ML_{in} = mass loading factor for resuspended soil blown indoors from outdoors (g/m^3)
RF_r = indoor resuspension factor (1/m)
P_d = indoor dust-loading on floors (g/m^2)
C_{grnd} = ground surface radionuclide concentration (pCi/m^2)
ρ_s = average density of soil in surface layer (g/m^3)
RL = thickness of soil layer available for resuspension (resuspension layer) (m)
24 = unit conversion factor (h/d)

4.6.5.3 Inadvertent Secondary Ingestion Exposure Pathway

Material that is resuspended can be deposited as surface contamination. Secondary ingestion includes ingestion of radioactive material from contaminated hands and food. This is a relatively poorly defined pathway that is not easily calculated by a detailed description of the mechanisms involved. The dose from this exposure pathway is calculated using Equation 4.65.

$$D_{sec} = C_0 * IR * DF_{ing} * t_{xs} * t_{ys} \quad 4.65$$

where

D_{sec} = EDE due to secondary ingestion (mrem/y)

and

C_0 = radionuclide concentration in the source material at the time the scenario begins (pCi/g)
IR = secondary ingestion rate (g/h)
DF_{ing} = ingestion dose factor (mrem/pCi intake)
t_{xs} = daily number of hours of exposure for scenario (h/d)
t_{ys} = annual number of days of exposure for scenario (d/y)

4.6.5.4 Water Ingestion

The drinking-water dose (from ingesting contaminated groundwater) is calculated using Equation 4.66. The radionuclide concentration in groundwater, C_w, is calculated using Equation 4.42

$$D_{dw} = C_w * U_w * DF_{ing} * 365.25 \quad 4.66$$

where
D_{dw} = EDE due to ingestion of drinking water (mrem/y)
and
C_w = radionuclide concentration in groundwater (pCi/L)
U_w = human consumption rate of water (L/d)
DF_{ing} = ingestion dose factor (mrem/pCi intake)
365.25 = unit conversion factor (d/y)

4.6.5.5 Ingestion of Food

Effective Dose Equivalent Due to Ingestion of Non-Irrigated Foods—Resident on Closed Landfill

In the non-irrigation model, the dose from ingestion of contaminated plants is calculated using Equation 4.67.

$$D_{n,ing} = \left\{ DIET_n * \left(C_{lv,nh} * U_{lv} + C_{veg,nh} * U_{veg} \right) + \left(C_{s(t)} * U_{soil} * 1000 \right) \right\} * DF_{ing} \quad 4.67$$

where
$D_{n,ing}$ = EDE due to non-irrigation ingestion model of plants (i.e., leafy vegetables and vegetables) (mrem/y)
and
$DIET_n$ = fraction of annual diet from non-irrigated plants (dimensionless)
$C_{s(t)}$ = soil radionuclide concentration at time resident moves onto landfill (pCi/g dry-weight soil)
$C_{lv,nh}$ = radionuclide concentration in edible part of leafy vegetables after hold-up period (non-irrigation model) (pCi/kg wet-weight plant)
$C_{veg,nh}$ = radionuclide concentration in edible part of vegetables after hold-up period (non-irrigation model) (pCi/kg wet-weight plant)

U_{soil} = human consumption rate of soil (kg dry-weight soil/y)
U_{lv} = human consumption rate of leafy vegetables (kg wet-weight plant/y)
U_{veg} = human consumption rate of vegetables (kg wet-weight plant/y)
DF_{ing} = ingestion dose factor (mrem/pCi intake)
1000 = unit conversion (g/kg)

Effective Dose Equivalent Due to Irrigation Ingestion Model—for Resident on Closed Landfill

The EDE for the irrigation ingestion model is calculated using Equation 4.68. All plant radionuclide concentrations and human consumption rates of plants are in wet-weight while soil radionuclide concentrations and human consumption rates of soil are in dry-weight.

$$D_{i,ing} = \left\{ DIET_n * (C_{lv,ih} * U_{lv} + C_{veg,ih} * U_{veg}) + (C_{sg} * U_{soil}) \right\} * DF_{ing} \quad 4.68$$

where
$D_{i,ing}$ = EDE due to irrigation ingestion model of irrigated plants (mrem/y)
and
$DIET_i$ = fraction of annual diet from irrigated plants (dimensionless)
$C_{lv,ih}$ = radionuclide concentration in edible part of leafy vegetables after hold-up period (irrigation model) (pCi/kg wet-weight plant)
$C_{veg,ih}$ = radionuclide concentration in edible part of vegetables after hold-up period (irrigation model) (pCi/kg wet-weight plant)
C_{sg} = soil radionuclide concentration at end of growing season due to direct deposition of irrigation water (pCi/kg dry-weight soil)
U_{lv} = human consumption rate of leafy vegetables (kg wet-weight plant/y)
U_{veg} = human consumption rate of vegetables (kg wet-weight plant/y)
U_{soil} = human consumption rate of soil (kg dry-weight soil/y)
DF_{ing} = ingestion dose factor (mrem/pCi intake)

Effective Dose Equivalent for Total Ingestion Model

The TEDE for the ingestion model assumes that the vegetables are grown on contaminated soil and are spray irrigated with contaminated groundwater. The total dose, non-irrigation plus irrigation, is calculated using Equations 4.69, 4.70, and 4.71, below. All plant radionuclide concentrations and human consumption rates of plants are in wet-weight while soil radionuclide concentrations and human consumption rates of soil are in dry-weight.

$$PF_n = U_{lv} * C_{lv,nh} + U_{veg} * C_{veg,nh} \quad 4.69$$

$$PF_i = D_{ing} + U_{lv} \left[DIET * (C_{lv,ih} + C_{veg,ih}) \right] \quad 4.70$$

$$+ (C_{s(t)} * U_{soil} * 1000) + (C_{sg} * U_{soil}) \Big] * DF_{ing} \quad 4.71$$

where

PF_n	=	activity uptake from non-irrigation model (pCi/y)
PF_i	=	activity uptake from irrigation model (pCi/y)
D_{ing}	=	EDE due to ingestion (non-irrigation and irrigation models) (mrem/y)

and

U_{lv}	=	human consumption rate of leafy vegetables (kg wet-weight plant/y)
U_{veg}	=	human consumption rate of vegetables (kg wet-weight plant/y)
U_{soil}	=	human consumption rate of soil (kg dry-weight soil/y)
$C_{lv,nh}$	=	radionuclide concentration in edible part of leafy vegetables after hold-up period (non-irrigation model) (pCi/kg wet-weight plant)
$C_{veg,nh}$	=	radionuclide concentration in edible part of vegetables after hold-up period (non-irrigation model) (pCi/kg wet-weight plant)
$C_{lv,ih}$	=	radionuclide concentration in edible part of leafy vegetables after hold-up period (irrigation model) (pCi/kg wet-weight plant)
$C_{veg,ih}$	=	radionuclide concentration in edible part of vegetables after hold-up period (irrigation model) (pCi/kg wet-weight plant)
$C_{s(t)}$	=	soil radionuclide concentration at time resident moves onto landfill (from non-irrigation model) (pCi/g dry-weight soil)
C_{sg}	=	soil radionuclide concentration at end of growing season due to direct deposition of irrigation water (pCi/kg dry-weight soil)
1000	=	unit conversion factor (g/kg)
DF_{ing}	=	ingestion dose factor (mrem/pCi intake)

Effective Dose Equivalent Due to Ingestion of Foods and Soil—Refinery Stack Releases

The TEDE from ingestion of contaminated plants, and soil is calculated using Equation 4.72.

$$D_{ing} = \Big\{ DIET * (C_{lv,h} * U_{lv} + C_{veg,h} * U_{veg}) \quad 4.72$$

$$+ (C_{s(0)} * U_{soil} * 1000) \Big\} * DF_{ing}$$

where

DIET	=	fraction of annual diet derived from home-grown foods (dimensionless)
$C_{s(0)}$	=	soil radionuclide concentration at time of scenario (pCi/g dry-weight soil)
$C_{lv,h}$	=	radionuclide concentration in edible part of leafy vegetables after hold-up period (pCi/kg wet-weight plant)

$C_{veg,h}$ = radionuclide concentration in edible part of vegetables after hold-up period (pCi/kg wet-weight plant)
U_{soil} = human consumption rate of soil (kg dry-weight soil/y)
U_{lv} = human consumption rate of leafy vegetables (kg wet-weight plant/y)
U_{veg} = human consumption rate of vegetables (kg wet-weight plant/y)
DF_{ing} = ingestion dose factor (mrem/pCi intake)
1000 = unit conversion (g/kg)

4.7 Derived Surficial Dose Factors

At the time of clearance, residual radioactivity may initially be distributed on the surface or throughout the volume (mass) of the cleared material. All of the scenarios discussed in this section treat residual radioactivity as volumetrically distributed throughout the mass of scrap or refinery product such as slag or baghouse dust. This is because, once the material has been processed, radioactivity is redistributed throughout the entire volume regardless of its initial distribution. Even "unprocessed" scrap that has not yet been melted at a refinery can be treated as volumetrically contaminated. Consistent with industry practices, scrap that is ready for release would be sized and sorted for efficient loading onto trucks. The residual radioactivity associated with large piles or truck loads of such scrap would be effectively distributed throughout the volume even if it were present only on the surfaces of individual pieces of equipment or scrap metal.

The mass-based dose factors for each recycle scenario indicate the annual dose to an individual from residual radioactivity distributed throughout the mass of cleared material. The derived surficial dose factor indicates the annual dose to an individual exposed under the same conditions from radioactivity that was initially distributed over the surface of the cleared material. A derived surficial dose factor for each scenario is calculated using the surface-to-mass ratio of the cleared object or material according to Equation 4.73.

$$\text{Dose Factor}_{surficial} = SM * \text{Dose Factor}_{mass} \quad 4.73$$

where

$\text{Dose Factor}_{surficial}$ = derived surficial dose factor (mrem/y per pCi/cm^2)

and

SM = surface-to-mass ratio (cm^2/g)
$\text{Dose Factor}_{mass}$ = mass-based dose factor (mrem/y per pCi/g)

The surface-to-mass ratio of objects and materials available for clearance can vary over a wide range. This is due, in part to the different surface-to-volume ratios of various objects such as pipes, sheets, and bar stock. It is also the result of different densities among various materials. The parameter SM is represented by a distribution of values that incorporate the variability and uncertainty in the surface-to-mass ratio of objects available for clearance. The distributions used for the surface-to-mass ratios are chosen as appropriate for each material in the analysis (see Section 4.8.5).

4.8 Parameter Discussion

Calculation of potential impacts from reuse or recycle of cleared licensee scrap material depends on many parameter values. Parameter values are needed for both material flow and dose assessment models. The material flow parameter values rely on information from the U.S. secondary steel industry. The parameter values for the dose modeling rely on receptor behavior information, such as time on a specific job or breathing rate, as well as environmental transport of radionuclides. Parameter values used for the assessment of impacts are discussed in the following sections and are tabulated as appropriate in this section. Although not a parameter value, a description of the selection of radionuclides is also provided in this section.

To support the probabilistic nature of the dose calculations, a range and assumed distributional shape was used for most parameter values in the dose modeling. Parameter value distributions are intended to capture uncertainty and variability in the parameter values for the exposed groups described for each scenario. Each exposed group is relatively homogeneous in characteristics that are relevant to the calculated dose factors. Therefore, most of each parameter range is due to uncertainty rather than variability among individuals.

In some cases, only nominal parameter values are discussed, not the ranges. If only a nominal value is discussed, it is generally a "most likely value" (i.e., fixed value or the mode of a distribution), or an estimate of central tendency (e.g., a mean value). A complete listing of parameter distributions and their characteristics is provided in Appendix B.

The quality of underlying data varies among the parameters used in the analyses. In some cases, appropriate data were available and were used as a basis for a realistic parameter value range. In other cases, appropriate data were not readily available, and professional judgement was more heavily relied on to determine a parameter range. Appendix B describes the data quality conventions and levels used in this analysis.

4.8.1 Radionuclide Selection

Several recent sources were reviewed to identify those radionuclides that are most likely to be found in equipment and material cleared from a NRC licensed facility. Rather than use lists from previous similar assessments, developing the list independently of previous studies helped ensure that radionuclides of interest would not be overlooked—or included—because of convention. The list (presented in Table 4.9) was compiled from the following five sources:

NRC Correspondence with IAEA (Meck 1992). Radioactive contamination in recycled or re-used material is likely to be similar to that of low level waste currently disposed. Radionuclides listed in this reference constitute greater than 90 percent of the radioactivity disposed of by U.S. commercial sites during the three years 1988 through 1990.

1992 State-by-State Assessment of Low-Level Radioactive Wastes Received at Commercial Disposal Sites (Fuchs and McDonald 1993). This document lists those radionuclides that were

disposed of in 1992 at commercial low level disposal sites from various sources: nondirect (shipments from the generator to the disposal facility through an intermediary), reactors, academic, medical, industrial, and government.

Radionuclides in United States Commercial Nuclear Power Reactors (Dyer 1995)**.** This article presents data from several studies on the amounts and types of radionuclide activities found in nuclear power plant systems and materials (specifically stainless steel). The study considered only those radionuclides with half-lives longer than 50 days.

Special activation products in certain materials. Some radionuclides not listed in the previous three sources are activation products for certain materials. The materials considered for this study were steel, copper, aluminum, and concrete.

Radioactive progeny of radionuclides on the list. Potentially significant (half life greater than 1 day) radioactive progeny from parent radionuclides identified in the sources listed above were included explicitly on the list. Radioactive progeny with half-lives of less than 1 day are excluded from the list because their emissions would be insignificant by the time of the first exposure scenario, 4 days post-clearance. The effects of progeny radionuclides are included with the parent radionuclides listed in Table 4.9; these are described in Appendix E.

Radionuclides excluded. Radionuclides with half-lives longer than Th-232 (greater than 1.41E+10 years) were not included in the analysis. Emissions from these radionuclides (e.g., Sm-147) would be insignificant during the relatively short time periods that are assumed for the scenarios. Two radionuclides listed above (Y-90, Kr-85) meet the criteria for inclusion, however, these radionuclides are not included in final dose tables because it seems unlikely that they would be found in the equipment or material cleared from a NRC licensed facility addressed in this study. The short radioactive half-life of Y-90 (64 hours) makes it unlikely that is would be in any cleared material except in equilibrium with its parent Sr-90, and Kr-85 is a noble gas and would not exist as residual radioactivity in cleared material.

Table 4.9 Radionuclides of interest for recycle, disposal, and reuse of equipment and materials

H-3 [1]	Co-58 [1]	Y-91 [3]	I-125 [1]	Eu-155 [3]	Ac-227 [5]	U-234 [5]
C-14 [1]	Fe-59 [1]	Mo-93 [3]	Sb-125 [2]	Re-186 [2]	Th-227 [5]	U-235 [2]
Na-22 [1]	Ni-59 [2]	Nb-93m [3]	I-129 [1]	Ir-192 [2]	Th-228 [2]	Np-237 [5]
P-32 [1]	Co-60 [1]	Nb-94 [3]	I-131 [1]	Pb-210 [5]	Ra-228 [2]	Pu-238 [3]
S-35 [1]	Ni-63 [1]	Nb-95 [1]	Ba-133 [2]	Po-210 [1]	Th-229 [5]	U-238 [1]
Cl-36 [1]	Zn-65 [1]	Zr-95 [1]	Cs-134 [1]	Bi-210 [5]	Th-230 [5]	Pu-239 [3]
K-40 [2]	Cu-67 [2]	Tc-99 [1]	Cs-137 [1]	Rn-222 [2]	Pa-231 [5]	Pu-240 [3]
Ca-41 [4]	Se-75 [1]	Ru-103 [1]	Ce-141 [1]	Ra-223 [5]	Th-231 [5]	Pu-241 [1]
Ca-45 [1]	Kr-85 [1]	Ru-106 [1]	Ce-144 [1]	Ra-224 [5]	Th-232 [1]	Pu-242 [6]
Cr-51 [1]	Sr-85 [2]	Ag-108m [3]	Pm-147 [1]	Ac-225 [5]	Pa-233 [5]	Am-241 [2]
Mn-54 [1]	Sr-89 [3]	Cd-109 [2]	Eu-152 [2]	Ra-225 [5]	U-233 [5]	Cm-242 [3]
Fe-55 [1]	Sr-90 [1]	Ag-110m [1]	Eu-154 [2]	Ra-226 [1]	Th-234 [5]	Cm-244 [3]
Co-57 [1]	Y-90 [5]	Sb-124 [1]				

(1) Meck (1992); (2) Fuchs and McDonald (1993); (3) Dyer (1995); (4) Special activation product; (5) Radioactive progeny; (6) added in review process

4.8.2 Material Flow Model

The parameter values used in the material flow model are presented in Appendix B and are based on the information presented in Sections 4.2 and 4.3 of this report. The values are based on recycling material cleared from a NRC licensed facility for 1 year in the existing, commercial iron and steel industry.

4.8.3 Scenario Timing

This section presents the basic assumptions used in defining the nominal time periods for each of the recycle scenarios. All exposure scenarios were derived from the material flow conceptual modeling, and scenarios were assumed to occur at specific points in time following clearance. This basis was used to define the parameter t_s, the time from clearance of material to the time the scenario begins. Where a reference was used as a basis for the assumed time period, it is cited. If no citation is given, general knowledge of practices gained from talking with industry personnel combined with professional judgement was used as the basis. A uniform distribution was used with a range of ±50% of the nominal value. The following is a list of basic assumptions that were used in developing nominal values for the timing of the scenarios:

Scrap Handling:

- All scrap metal is assumed to be initially taken to a scrap dealer. It takes 4 days for the scrap metal to reach the scrap dealer.

- The scrap metal remains at the scrap dealer for a period of 7 days prior to reuse or disposal, and 25 days for scrap metal that is recycled.

Refining and Processing:

- For recycled scrap metal the refining process and associated product manufacture, final processing, and any onsite storage at the refinery is assumed to take a total of 11 days for an EAF (O'Donnell et al. 1978) and 15 days for BOF.

- Following initial processing, BOF products undergo further processing before use; this secondary processing, plus storage and handling, is assumed to take 22 days.

- EAF metal products are distributed to the public upon completion of the refinery process while BOF products are distributed for use upon completion of the secondary process. Distribution for both products is assumed to take 7 days.

- Releases of radionuclides in the atmospheric effluent from an EAF or BOF refinery occur at the time the scrap is refined, i.e., 29 days after clearance.

Use and Disposal:

- An EAF metal product is used for 30 years, based on an assumed use in the construction industry. Use of a BOF metal product is 10 years, based on an assumed general purpose use (IAEA 1992).

- EAF and BOF refinery slag and baghouse dust are produced at the time refining occurs, 29 days after clearance of scrap metal from the licensee.

- Refinery slag that is sold for subsequent use is processed at the refinery 3 days after production and leaves the refinery in another 2 days. Slag is assumed to be used within 2 days after distribution and is used for a period of 30 years. Once the period of use is completed, the products are disposed in a sanitary landfill. Slag that is to be directly disposed is held at the refinery for 7 days, at which time it is transported to a disposal facility. The slag is assumed to be disposed immediately following handling at a sanitary landfill.

- The two management options for EAF baghouse dust that are being analyzed in this report are direct disposal in a hazardous landfill and use as an additive in fertilizer. If the dust is to be disposed of, it is transported within 3 days after production. Handling and processing of the dust takes 4 days, at which time the dust is disposed in a hazardous waste landfill. Electric arc furnace dust that is to be processed as fertilizer is sent to the processor 3 days after production. Processing takes 3 days, and the fertilizer is distributed for use and is used within 1 day.

- BOF baghouse dust is disposed of onsite or sent to a sanitary disposal facility after 7 days. Storage and handling take 4 days, at which time disposal occurs.

Post Disposal:

- A sanitary landfill operates for 40 years.

- A hazardous landfill operates for 30 years.

- Disposed items are placed in the landfill at the midpoint of the landfill operating period.

- Post-closure monitoring of landfills is done for 30 years.

- A disposal site is available for potential residential use after post-closure monitoring ends.

4.8.4 Dose Evaluation

Values for radionuclide-dependent parameters (e.g., λ_r, DF_{ing}) are taken from Federal Guidance Report 11 (EPA 1988) and are tabulated in Appendix B. All other parameters are either radionuclide-independent or material-dependent, and are discussed below; values for these parameters are also listed in Appendix B.

4.8.4.1 Input Radionuclide Concentrations from the Material Flow

The undecayed radioactivity concentration in the source material, C_x, is used as the source material input as the source material input radioactivity concentration for scenario evaluations. This parameter is radionuclide dependent and is calculated in the material flow modeling. Table B.8 lists the sources for C_x as they appear in the mathematical modeling of the material flow (e.g., C_p, radioactivity concentration in metal product after the refining process).

4.8.4.2 Exposure Duration

The duration of exposure is the time that the individuals in the exposed group are assumed to spend in the scenario conditions that result in exposure to cleared material. The number of hours of exposure in each scenario is calculated as the product of the parameters t_{xs} (h/d) and t_{ys} (d/y). Values for both these parameters are tabulated in Appendix B. All scenarios incorporate uncertainty via the parameter for hours per day, t_{xs}, and the parameter t_{ys} (d/y) is fixed. The work-related scenarios use a fixed value of 250 d/y for t_{ys}, and all other scenarios use a fixed value of 350 d/y.

Work-related Scenarios

The maximum number of hours in a typical work year was limited to the fraction of time that a worker would reasonably spend performing the work that would result in exposure to cleared material during a calendar year. The fraction is based on the amount of time a worker would be working directly with cleared material plus the time working in the vicinity of the material.

Generic scenarios for industry workers (scrap handling, refinery workers, and manufacturing workers) use a range of values that reflects varying operational practices among scrap yards and refineries. Even though the members of the exposed groups in these scenarios are dedicated to handling scrap or refinery products, it is reasonable to assume that any individual would actually spend less than a full working day handling material with residual radioactivity. Other activities during a typical day would include checking out equipment, driving equipment back and forth between parking, storage, and handling areas, refueling equipment, waiting for vehicles to load or unload, receiving instructions or plans for work to be done, and performing other duties. Therefore a range that often does not include the maximum number of hours in a work day was determined to reflect the likelihood of these other activities.

The specific handling scenarios incorporate a range involving a much smaller number of hours in an average workday. This is reasonable because there is a much smaller volume of material being handled (EAF baghouse dust) as compared to the other worker scenarios.

The single product use scenario that involves workers ("Roadbed construction activities") would involve considerable variability in the daily number of hours spent using and in the vicinity of refinery slag. These workers would likely not spend an entire year constructing roads using refinery slag, because roads are also constructed using materials other than slag (e.g., gravel). Also, road construction is a seasonal activity in many northern areas of the U.S.

An exposure duration for scenarios involving disposal of material with residual radioactivity was determined using the capacity of typical landfills and the amount of material available to be disposed in a geographic area. These two values (capacity and amount of material available) were ratioed, and the material-specific ratio was multiplied by the number of hours in a working year to estimate values for each material of interest.

The basic assumption for the duration of exposure for commercial drivers of trucks carrying cleared material or any of the co-products of refining was that these individuals were employed full-time in a trucking job. Specific assumptions for the scenarios in this analysis were developed after talking with individuals in the steel transport industry. It is common for these drivers to work up to 50 hours per week; this is supported by statistics from the Bureau of Labor Statistics (BLS 1998), which indicate that local truck drivers frequently work 48 hours or more a week. It was also determined that it was reasonable to assume that there are sufficient amounts of scrap, slag, baghouse dust, and refined steel for some drivers to spend a majority of their time hauling this material (not necessarily all *cleared* material, however). These drivers would be hauling a single material a maximum of half of their workdays (i.e., full loads only one-way). Some drivers may haul one material (e.g., scrap) to a refinery and load their trucks at the refinery with another material (e.g., slag) for a "return" trip.

A most likely value was determined to be one-half of a 40-hour work week, with a reasonable minimum value incorporating the assumption of less time for the drivers that do not spend all of their time hauling steel industry material. A maximum value was used to represent one-half of a 50-hour work week.

Values for a driver of a vehicle were used to model a taxi driver or other commercial driver (e.g. small delivery van). A range from one-half to a full work day with no most likely value was used.

Non-worker scenarios

Similar to the worker scenarios, the non-worker scenarios incorporate uncertainty into exposure duration via the parameter for hours per day, while the value for days per year was held constant. Most of the non-worker scenarios involve use of refinery co-products, most commonly refined steel products. Duration times for the generic small object and large object scenarios were

developed to include those individuals who spend a large fraction of their work day or residential time near these objects (e.g., machine tools, office furniture, and household appliances or furniture). The most likely value for these scenarios is one-half of a typical work day. A range of 2–8 hours per day would cover a variety of potential exposure situations in both residential and occupational settings.

The scenario involving a small object close to the body involves a wide range of exposure duration because of the variety of potential exposure scenarios (e.g., belt buckles, tools). The scenario involving individuals inside a basement (or other concrete structure) could involve occupational or residential settings, and a range was chosen to incorporate both of these settings. A most likely value was chosen to represent a residential setting; this was also used as the maximum value in the parameter range. Use of a roadway containing refinery slag was assumed to involve regular, short-term use. Values were for a range to represent a commuter using the same route every work day.

For those exposure scenarios that occur in a residential setting (e.g., person inside a basement made with slag) a year's duration consisting of 5600 hours is assumed. For residential landfill scenarios and the atmospheric release scenarios where an individual spends time indoors as well as outdoors, additional exposure duration parameters are needed. The number of hours spent on indoor, outdoor, and dusty activities are represented by t_{id}, t_{od}, and t_{dd}, respectively, and are listed in Table B.7. Nominal values for these parameters were based on values in Kennedy and Strenge (1992); distributions for the parameters were subjectively developed, based on professional judgement and the scenario definition.

4.8.4.3 Material Densities

Four fixed values were used for the density of waste, ρ_w: 1) For the waste products that are similar to soil (i.e., BOF baghouse dust), a value identical to the nominal value used for ρ_s; 2) For those waste products that are similar to metal (e.g., scrap metal and refined metal product), a value derived and used for bulk density in the calculation of the geometry factors for metal products was used; 3) For immobilized EAF dust, a value of 1.36E+6 g/m^3 was used (Logan 1993); 4) For the disposal of slag the same density that was used for slag in a pile was used for slag in a landfill.

Three approaches were used to estimate a range for the bulk density of slag as used in various scenarios: industry contacts, appropriate references, and a theoretical approach. The three approaches result in a range of estimates that differ by a factor of a little over 3× (1.19 g/cm^3 - 3.9 g/cm^3). Two estimates of bulk density values were needed for use in the scenarios involving slag pile and roadbed, because the bulk density of slag would be different in the two scenarios. The information from industry contacts was judged to be the best source and was therefore emphasized, because it is specific to EAF steelmaking slag and does not depend on the use of assumptions. One literature source (IAEA 1992) does not provide justification for the value used, nor does it give detailed information about the type of slag (e.g., furnace source). The Handbook of Chemistry and Physics (CRC 1992) lists a value for slag bulk density, however it

does not list the type of slag (e.g., steelmaking, pig iron, other industry). The value listed in Lankford et al. (1985) is specific to steelmaking slag, but does not give information on type of furnace. Finally, a theoretical value was calculated by weighting the percentage of each chemical constituent of EAF slag, then summing and accounting for the void space presumed to be present in bulk slag. Although this approach is specific to EAF slag, it depends on an uncertain assumption for the porosity of the bulk slag.

To estimate values for the bulk density of a slag pile, the information from industry contacts was emphasized. The industry values are generally lower than those obtained from other sources, however it was judged that these slag processors would provide a more accurate value for bulk density of slag in a pile, since that is what they deal with on a daily basis. One possible explanation for the lower bulk density values from the slag processors is that the slag in their piles has expanded, due to hydration of free lime or magnesia in the slag (Lankford et al. 1985). A fixed value of 2.0 g/cm^3 was estimated by first obtaining an average value from the slag processors (1.74 g/cm^3), then adjusting it upward because of the literature value of 2.38 g/cm^3 (Lankford et al. 1985) (a value of 2.0 is a round number that is approximately midway between 1.74 and 2.38).

The slag as used in a roadbed would be different in two key respects from the slag in a slag pile: it would consist primarily of smaller pieces (0–1 in.[1]), and it would likely be compacted during road construction. The single density value for the smallest size fraction found in a survey of slag processors was used as the fixed value (2.4 g/cm^3). Although this is the highest value obtained from any of the slag processors, and it is also the maximum value for steelmaking slag in general (Lankford et al. 1985), it was used because of the nature of the use of slag in this scenario (small pieces and highly compacted).

4.8.4.4 Mixing of Cleared Material

A basic assumption of this analysis is that material that is cleared from a licensee would enter the general commercial sector. Any cleared material or refinery products could therefore be mixed with non-cleared, but otherwise similar material. This likelihood is incorporated into the analysis in three ways: 1) mixing of scrap that does not undergo any melting at a refinery and mixing of scrap that is melted at a refinery; 2) mixing of refinery slag when used as an additive in concrete; and 3) mixing of material that is disposed. These three concepts are discussed in the following subsections.

Mixing of Cleared Scrap

A “mixing factor” was calculated and is described in Appendix D. The mixing factor is a multiplicative factor that was used to incorporate the mixing of cleared scrap with other, similar scrap. The mixing factor range was used to modify the exposure duration in the scrap handling

[1]Personal communication M. McKenzie-Carter, SAIC and Alexander Mill Service, Plymouth, UT, May 14, 1996.

and scrap disposal scenarios. These scenarios model the direct use of scrap (no melting). Most other scenarios (except as described in next subsections) incorporate mixing by the use of appropriate values for cleared scrap and other scrap in the material flow model.

Dilution of refinery slag used in basement construction

An explicit dilution factor (DF) is used in the scenario involving use of refinery slag in the manufacture of concrete that is used in the construction of a basement or other building structure. This is to account for the amount of slag used in the commercial process where slag is blended with other cement ingredients, heated, and results in a cement clinker that can be ground to the required size. Based on information[1] that was obtained from the cement industry, a triangular distribution for DF from 0.5% to 3% was used, with a most likely value of 1.5%. For this one scenario, the parameter DF is used multiplicatively in Equation 4.55 to modify the radionuclide concentrations.

Mixing of waste in the landfill

In order to estimate the fraction of a landfill that could consist of waste from disposing of contaminated scrap or byproducts of recycling, landfill mixing factors were calculated for the resident and disposal activities scenarios. To make reasonable estimates, a bounding case for slag was first examined. It was calculated that if all of the slag generated from refining all of the slightly contaminated scrap steel likely to be cleared from a NRC licensed facility were disposed in a single landfill, it would comprise roughly 4% of the capacity of an average-sized sanitary landfill (40,000 m^3 out of 1 million m^3 capacity). This bounding analysis is unreasonable by itself, because industry practice and the economics of landfill disposal make it extremely unlikely that all slag from contaminated scrap recycle would be disposed in a single landfill. However, the unpredictable nature of future scrap cleared practices by a NRC licensed facility and the varying sizes of landfills must be considered. If the assumption is arbitrarily made that no more than 2% of the slag from scrap recycling were disposed of at a single landfill, the total amount disposed in a representative facility would be about 0.2% of capacity (2000 m^3). This value appears to be reasonable, and is consistent with the “reasonable maximum case” contained in Appendix G of EPA (1997a). In evaluating regional dilution of NRC licensee scrap, it is postulated in this reference that 22,500 t (24807 tons) of scrap could be refined at a single reference mill. Using a slag production rate of 15%, this would result in 3,375 t (3721 tons) (1,688 m^3) of slag amounting to 0.15% of capacity for an average landfill. The regional distribution of power plants and steel mills makes it unlikely that this rate of refining could be sustained for multiple years. If the total slag from scrap recycling disposed of at a single landfill were twice the “reasonable maximum” 1-year value, the result would be 6,750 t (7,442 tons) (3,375 m^3) or 0.31% of capacity.

Based on this rationale, it is unlikely that the amount of slag from refining contaminated steel present in a single landfill would exceed a few thousand cubic meters and is likely to be very

[1] Personal communication from W. C. Thurber of S.C. & A.

much less. However, the basic assumption behind the resident-on-landfill scenarios is that significant landfill disposal of slag from refining licensee scrap occurs for at least one licensed facility. Therefore, an estimate of 0.2% is used as the per cent of a landfill capacity comprised of slag that is a byproduct of recycling cleared steel scrap.

Using this rationale, and appropriate partitioning factors for other byproducts, the following landfill mixing fractions were estimated and used in the assessments of scenarios for residents on closed landfills:

Steel slag:	0.2% of landfill capacity
Steel scrap:	0.7% of landfill capacity
Baghouse dust:	0.02% of landfill capacity

These values formed the basis to estimate a range for the parameter FW, fraction of the volume of a landfill that is from cleared material. Ranges were developed by using values ±50% of the values listed above.

4.8.4.5 External Exposure Parameters

The parameter U_{GF} was used to account for uncertainty in external exposure rates. The fixed-value external dose factors used in this analysis come from two sources: Federal Guidance Report No. 12, and values calculated using the code Monte Carlo N-Particle (MCNP) specifically for this analysis. Federal Guidance Report No. 12 values were used in scenarios involving large areas of contaminated soil or similar materials that can be treated as a infinite planar source. The MCNP values were used for scenarios where finite objects of shapes and composition were modeled. The U_{GF} is a multiplicative factor based on an evaluation of the circumstances described in each scenario. A discussion of the calculation of GFs and development of distributions for U_{GF} are both discussed in Appendix C, as is a listing of the GF values used. Values for U_{GF} are tabulated in Appendix B.

Shielding factors were also used in this analysis to calculate the external exposure dose factors. A vehicle shielding factor, SF, was used in the disposal activity scenarios to account for the likely shielding afforded by the large equipment used at landfills (e.g., loaders and bulldozers). Based on interviews with equipment manufacturers and landfill operators, a geometric model was developed to characterize the effective shielding for operators of this type of large equipment. Transmission factors were developed sufficiently to determine a reasonable triangular distribution from 0.3 to 0.7, with a most likely value of 0.5. These values were used multiplicatively to reduce the external exposure dose factors for workers handling waste at landfills.

Shielding factors were also used for the types of activities in residential scenarios. Values for the parameters SFI and SFO were developed from the values used in Kennedy and Strenge (1992) because they represented reasonable values for a generic member of the public.

The external exposure pathway in the atmospheric release scenario uses a parameter for the period of long-term buildup for activity in soil, t_b. A fixed value of 5.48E+3 d is used for this parameter and was taken from NRC Regulatory Guide 1.109 (NRC 1977).

4.8.4.6 Inhalation Exposure Parameters

This section presents a description of the basis for parameter values for those radionuclide-independent parameters used in the calculation of inhalation exposure, including those that address mass loading, and breathing rate.

Breathing Rate

Two methods used to estimate breathing rates for dose assessments are the tidal volume and frequency method (ICRP 1974, ICRP 1994, and EPA 1989a) and the method using oxygen demand based on metabolic conversion of food nutrients (Layton 1993). Although the latter method is takes into account variations in oxygen uptake efficiency, lung physiology, and metabolic efficiency among individuals, it is not as widely accepted as the tidal volume method. Both the EPA and the ICRP base their average hourly breathing rates on the tidal volume (ml/breath) and the frequency (breaths/minute) for various activity levels, and that is the method adopted for this study.

The inhalation rates for different levels of activities in ICRP (1994) and EPA (1989a) were reviewed to determine a reasonable range to use for breathing rate in the scenarios in this analysis. Both reports are based on tidal volume (ml/breath) and frequency (breaths/min). The EPA listing is detailed and allows more interpretation of the values, and was judged to be more representative of workers and members of the public. Therefore, the EPA values were emphasized. Furthermore, the values for males were used because it is more likely that the jobs described in the exposure scenarios would be performed by males. The range for breathing rate given in EPA (1989a) is from 0.7 m^3/h during resting to 5.1 m^3/h for very heavy activity. The range in ICRP (1994) is from 0.45 m^3/h for resting to 3.0 m^3/h for heavy exercise. From these ranges, two triangular distributions were developed, one for outdoor activities and the other for indoor activities. The range used for outdoor activities is from 0.6 m^3/h to 3.0 m^3/h, and the range for indoor activities is 0.5 m^3/h to 1.2 m^3/h. Both distributions use a most likely value of 1.2 m^3/h, consistent with Volume 1 of NUREG/CR 5512 (Kennedy and Strenge 1992) and some of the scenarios values in Volume 3 of NUREG/CR-5512 (Beyeler et al, 1996).

Respirator Use

Only one work-related scenario, refinery baghouse operations, presents hazards that would typically require a worker to wear a respirator. In the refinery work environment, the inside of a baghouse represents a hazardous environment. The presence of airborne baghouse dust in a confined and congested area requires that precautions be taken; typically including protective clothing and a respirator. Therefore, in order to be realistic, use of a respirator is assumed.

Based on conversations with industry representatives[1,2,3,4] and the fact that there are regulations requiring the use of respiratory protection while working in dusty and hazardous environments, a worker entering the baghouse without a respirator is not considered realistic and, therefore, is not considered. Requirements stated in 42CFR84 list minimum efficiencies for three levels of respirators (95%, 99%, and 99.97%). According to Caesar[1] respirators in the steel recycle industry are selected and approved by management based on the physical and chemical properties of the air contaminants that will be encountered and the concentration level likely to be encountered by an employee. However, there are no reliable data on which to base a range, and it was judged that a range biased toward the lower end of efficiencies would be most likely. In order to account for use of less efficient respirators, as well as ill-fitting respirators, a range of 90% to 99.7% was used for respirator efficiency.

Mass Loading and Respirable Fraction

The mass loading (ML) factor used for the inhalation exposure pathway calculation is difficult to estimate. The usual approach to estimating intake via mass loading models assumes that the concentration of radioactivity in airborne particulates is the same as in the material from which those particulates are generated. In this case, airborne radioactivity is assumed to be associated exclusively with particulates originating from the scrap material or recycle product regardless of any other sources of particulates at the job site. For the scenarios that include the inhalation pathway, the mass loading factor used for the inhalation exposure pathway calculation must be typical of dusty work environments like that which would be found around a construction site. The mass loading factor approach was used so that the concentration of radionuclides in the dust could be directly related to an air concentration by use of an assumed mass of dust particulates in the air at the receptor location. A mass loading factor is typically used in environmental evaluations to relate soil concentrations to air concentrations. Although recycle scenarios are not strictly an environmental setting, and the dust volume is not *in situ* soil, the use of a mass loading approach is valid because it relates the source radioactivity concentration to an air radioactivity concentration using an appropriate value for dust loading.

The respirable fraction of resuspended material is another key parameter for the inhalation pathway. Fugitive emissions from the steel industry include open dust sources such as raw material storage piles from which emissions are generated by the forces of wind and machinery acting on exposed aggregate materials. The EPA has sponsored the Midwest Research Institute to measure particulate emissions and particle size distributions from a variety of sources including unpaved roads of mixed slag and soil in the vicinity of steel mill slag piles (Cowherd et al. 1979). Measurements include mass loading near areas disturbed by vehicular traffic and in undisturbed upwind areas.

[1]Personal communication, M. Anderson, SAIC with Vinnie Caesar, Midwesco Filter Resources, Inc., Oct. 1996.

[2]Personal Communication, S. Jones, SAID with Bill Fergeson, Arkansas Steel, May 9, 1996.

[3]Personal Communication, S. Jones, SAID with Many Morelac, Border Steel, April 26, 1996.

[4]Personal Communication, S. Jones, SAID with Al Pulliam, Bayou Steel, April 25, 1996.

The gross values presented in Cowherd et al. (1979, Table 3-4) were used to estimate mass loading and respirable fraction (data from roads treated for dust suppression were not included; values for profiler samplers, cascade impactors and hi-vol samplers (5m) were pooled). The summary statistics for these values are as follows:

n = 35 , range = 2.1 mg/m^3 to 13.6 mg/m^3, mean ± stnd. dev.= 7.0 ± 3.2 mg/m^3.

In addition, upwind background measurements were reported for representing undisturbed areas in the same vicinity. Values in Cowherd et al. (1979, Tables 3-4 and 3-14) were used to estimate background levels of particulates. The summary statistics for these values are as follows:

n = 13, range = 0.43 mg/m^3 to 1.2 mg/m^3, mean ± stnd. dev.= 0.79 ± 0.23 mg/m^3.

Based on the information presented here and in Cowherd et al. (1979) a triangular distribution between 1.3 mg/m^3 and 7.4 mg/m^3, and a mode of 3.9 mg/m^3 was calculated and used for the mass loading factor for dusty work-related scenarios (i.e., slag worker, scrap handling, dust handling, refinery product handling, road construction scenarios, and disposal activities with BOF dust and slag). This was calculated by incorporating an assumption that an individual spends one-half of the time upwind (.79 mg/m^3) and one-half in a high concentration area (7 mg/m^3).

Cowherd et al. (1979) also contains estimates of the mass median diameter, the fraction less than 30 µm, the fraction less than 5 µm, and the fraction greater than 50 µm. Linear interpolation between the fractions less than 30 µm and less than 5 µm was used here to estimate the fraction less than 10 µm. Respirable particles are considered to be less than 10 µm. From the summary statistics for these interpolated values listed below, a triangular distribution between 0.23 and 0.42 was used, with a mode of 0.33 was used for the respirable fraction, RF, when it is applied to resuspended slag.

n = 8, range = 0.23 to 0.42, mean ± stnd. dev.= 0.33 ± 0.07.

One special case scenario (refinery baghouse operations) occurs in an extremely dusty environment. Mass loading inside a baghouse is apparently not a commonly measured value, and inquiries to steel refineries did not result in locating any measured values. Some data are available, however, to support an estimation of this parameter value, i.e., measurements of the respirable fraction of dust; this was used to estimate the mass loading parameter value. The mass loading factor approach was used so that the concentration of radionuclides in the dust could be directly related to an air concentration by use of an assumed mass of dust particulates in the air inside the baghouse. A mass loading factor is typically used in environmental evaluations to relate soil concentrations to air concentrations. Although a baghouse is not strictly an environmental setting, and the dust volume is not *in situ* soil, the use of a mass loading approach is valid because it relates the dust source radioactivity concentration to an air radioactivity concentration using an appropriate value for dust loading. Background levels of dust can be estimated from environmental settings, where ambient air concentrations of dust particulates can

range up to 254 µg/m^3 in urban locations, and up to 79 µg/m^3 in nonurban locations (Healy 1980). A value of 100 µg/m^3 is often used for predictive purposes (e.g., Anspaugh et al. 1974), the EPA has used 100 µg/m^3 for screening calculations (EPA 1977), and often a value of 200 µg/m^3 is recommended for generic evaluations for sites that may include some mechanical disturbance (Healy 1980).

The basic approach used to estimate the mass loading and respirable fraction of dust for the baghouse worker was based on a limited amount of industry knowledge, measured data for respirable fraction of dust, and regulatory limits. The industry knowledge consists of an understanding that a steel refinery generates a large amount of dust [on the order of 15 kg dust per metric ton of steel produced, which is equivalent to several thousand metric tons per year for a typical steel refinery (EPRI 1993)], and therefore a large mass of dust must pass through a refinery baghouse.

Applicable data are presented in Jeffery and Vay (1986), which provides particle size data for emissions from EAF, BOF, and other processes. They cite a value of 0.58 for the mass fraction less than 10 µm from melting and refining carbon steel in an EAF. Szabo and Gerstle (1978) provides particle size data for particulate emissions from EAF and BOF processes, citing a value of 0.70 for the mass fraction less than 12 µm and 0.61 for the fraction less than 8 µm.

In addition, Cass and Langley (1977) provides data from a controlled experiment that measured dust characteristics from an EAF refining carbon steel. Measurements included particle size and mass at both the inlet and outlet of a baghouse. Ten separate experiments were run. The mass fraction less than 10 µm varied from a minimum of about 0.40 to a maximum of about 0.70 with a mean of about 0.60. These values are approximate because they were interpolated from graphs.

Finally, the regulatory information considered consists of an occupational Safety and Health Administration (OSHA) limit for the Permissible Exposure Limit for total suspended particulates at a work environment: the 8-hour time-weighted-average value for total dust allowed by OSHA is 15,000 µg/m^3, and the allowed respirable fraction is 5,000 µg/m^3 (NIOSH 1990). This suggests an implied RF value of 0.33.

From these sources, a triangular distribution between 1 mg/m^3 and 15 mg/m^3 was used for mass loading in a baghouse, with a mode of 10 mg/m^3. Likewise a triangular distribution was used for respirable fraction in this scenario, with a range of 0.4 to 0.7, and a mode of 0.6. This distribution was also used for scenarios involving handling EAF or BOF baghouse dust.

To put these estimates in context, they can be compared to values used in similar analyses. The range derived for use in this analysis for airborne dust concentration is within the range of 0.1 mg/m^3 to 40 mg/m^3 used in previous similar analyses [e.g., fixed value of 0.1 mg/m^3 used in IAEA (1992); fixed value of 5 mg/m^3 used in O'Donnell et al. (1978); fixed value of 40 mg/m^3 used in EPA (1997)].

Soil Suspension

Seven additional parameters are needed to model the suspension of soil for the residential scenarios. The mass loading values for indoor, outdoor, and dusty activities (i.e., ML_{in}, ML_{out}, ML_{dust}) as well as the indoor dust-loading on floors, P_d, and the indoor resuspension factor, RF_r, are taken from Kennedy and Strenge (1992). For refinery atmospheric release scenarios, when the plume passes over a house or building, only a fraction of the material in the plume enters the building, and is therefore respirable by the resident. Yu et al. (1993) estimated that the dust level inside a building is about 40% of that outdoors. Because conditions within a plume are similar to those with suspended soil, a value of 0.40 is used for the indoor fraction of outdoor radioactivity concentration, RFI.

For atmospheric release scenarios, the thickness of the soil layer that is available for suspension, RL, determines the amount of radioactivity that is suspended from the surface. The types of activities that could cause suspension are walking or driving on packed dirt or roadways. A value of 1 cm (0.01 m) is used for RL, based on the assumption that the particles that are deposited on the soil during an atmospheric release would not be mixed into the soil under normal conditions.

4.8.4.7 Inadvertent Secondary Ingestion Exposure Parameters

It is reasonable to include the secondary ingestion exposure pathway for all scenarios where inhalation exposure is assumed, because of the presence of dust in an industrial environment. If there is a resuspension of dust that is available for inhalation, then it is reasonable to assume that inadvertent secondary ingestion can also occur. The range used for the secondary ingestion, IR, of surface deposited material (e.g., slag, dust, or metal shavings) is based primarily on the review of surface-contamination ingestion data and soil ingestion rates contained in Volume 1 of NUREG/CR-5512 (Kennedy and Strenge 1992). The overall range cited in NUREG/CR-5512 for secondary soil ingestion is from 0 mg/d to 200 mg/d. These values were interpreted to be based on a variable number of hours per day, based on the assumed source of data (e.g., 8 hours for worker data, longer for resident data). From these data, a uniform distribution over the range of 2.1 mg/h–30 mg/h was used in this analysis. The upper-end value was selected following discussions with EPA contractors regarding consistency with the analyses being conducted for the EPA (EPA 1997a).

4.8.4.8 Drinking Water Ingestion Exposure Parameters

Radionuclide-independent parameters used in the evaluation of the drinking water exposure pathway include those that model the transport of radionuclides to the groundwater as well as human consumption. All the scenarios that include the drinking water ingestion exposure pathway assume that box 2 (unsaturated layer) and box 3 (aquifer) are initially free of contamination. Therefore, $A_{2(0)}$ and $A_{3(0)}$ are set equal to zero.

For several parameters used in the drinking water ingestion exposure pathway, it was determined that the values used in Kennedy and Strenge (1992) were appropriate for use as point estimates or estimates of central tendency for the drinking water exposure dose factor analysis (see Appendix B for values used). The parameters T_i (time period for infiltration and irrigation) and T_p (time period for pumping) were both fixed at the values used in Volume 1 of NUREG/CR-5512 (Kennedy and Strenge 1992). The Volume 1 NUREG/CR values for porosity, n_1 and n_2, and saturation ratios, f_1 and f_2, were used as most likely values in triangular distributions. The Volume 1 NUREG/CR values for A_c (area of land under cultivation) and I (infiltration rate) were used as the geometric means of lognormal distributions.

For the parameter U_w, analysis of survey data has shown that tap water averages about 60% of total water consumption (Roseberry and Burmaster 1992). These data support a lognormal distribution of total tap water consumption having a geometric mean of 0.957 L/d and a geometric standard deviation of 1.77. In addition, not all tap water consumption comes from one's own tap. A significant numbers of meals can be eaten outside one's home, for example. The data on the fraction of tap water from one's own tap are poor and are best represented by a uniform distribution having a minimum of a 0.5 and a maximum of 1.0. A Monte Carlo calculation of the product of the two parameters yields the value of 0.71 L/d used in this analysis for tap water consumption.

Kennedy and Strenge (1992) made the assumption that the amount of water needed for domestic purposes was for one person. Because the areas of the landfills in this analysis are so large, it is likely that more than one person would be living on the land over a closed landfill. Therefore, for this analysis, the geometric mean for the amount of water used for domestic purposes, V_{dd} and V_{dr}, is based on 10 people, 9.1E+5 L. The amount of water from the aquifer needed for irrigation is determined based on the average irrigation rate of 2.08 L/m^2-d, the area of land under cultivation, 2500 m^2, and 365 d/y (Kennedy and Strenge 1992). Therefore a value of 1.9E+6 L was used as the basis for a distribution for V_{irr} (volume of water used for irrigation purposes annually). A beta distribution was used for V_{irr} to be consistent with the distribution assumption for this parameter in Volume 3 of NUREG/CR-5512 (Beyeler et al. 1996).

Slag Pile at the Refinery

The size of the slag pile in the slag storage scenario affects the modeled concentration of radionuclides in the aquifer, and thus the drinking water dose. The size of the slag pile used is 20,000 t (22,050 tons), corresponding to a slag pile comprised of the annual amount produced at a typical steel refinery. This value is consistent with EPA (1997), and was judged to be a reasonable slag pile size to use for this scenario. This value seems reasonable because slag is typically stored to "cure" for 6 months or longer, and also because slag producers often keep large stockpiles to be able to participate in bids for projects seeking to purchase large amounts of slag (Kalyoncu 1996). The slag pile is modeled as a half-cylinder with a radius of 4 m (13 ft) and a length of 400 m (1,312 ft), resulting in a large rectangular base with the dimensions of 8 m (26 ft) wide by 400 m (1,312 ft) in length, and an area of 3.20E+3 m^2. The thickness of box 1 is assumed to be the height of the slag pile, 4.0 m. This results in a total volume of 1.0E+4 m^3 of

slag being stored, and assuming the density of slag in a pile is 2.0E+6 g/m^3, the most likely value for the total mass of slag present is 2.0+10 g (20,000 t [22,050 tons]). A value for the geometric mean for the thickness of box 2 in the drinking water model, from the bottom of the slag pile to the top of the aquifer, was obtained as the sum of the thicknesses of box 1 and box 2 in NUREG/CR-5512, 1.1 m (3.77 ft) (Kennedy and Strenge 1992). This is reasonable because, similar to the modeling done in NUREG/CR-5512, this scenario is intended to be generic for sites across the United States.

As described in the preceding paragraph, the size of the slag pile is based on a 1-year production of slag. Therefore, a 1-year delay period following clearance was incorporated into the modeling, and the drinking water dose over the 1-year period from 1 to 2 years following clearance was calculated for this scenario. As described earlier in Section 4, the TDS of the aquifer in the slag storage scenario was calculated over a long period of time. It was verified that based on these models, the aquifer remained potable during this period.

4.8.4.9 Ingestion Exposure Parameters

This section presents a description of uncertain values for those radionuclide-independent parameters used in the calculation of ingestion exposure. Values for most environmental and biotic transport of radionuclides and subsequent human consumption parameters were fixed and were taken from Volume 1 of NUREG/CR-5512 (Kennedy and Strenge 1992). These values were reviewed and were deemed appropriate and reasonable for the scenarios presented in this report.

Uncertainty in the food ingestion pathway was incorporated via the parameter for the fraction of an individual's annual diet derived from a home-grown garden. Two types of ingestion exposure pathways are calculated; irrigation and non-irrigation. Although a dose is calculated separately for each of these models, the same distribution of input values for the fraction of annual diet (DIET) from each of the types of food (irrigated and non-irrigated) was used. The most likely setting for the scenarios in this analysis were judged to be that of an urban or suburban garden supplying a relatively small fraction of dietary fresh vegetables on a seasonal basis. The triangular distribution used in this analysis for DIET (0–0.25, mode of 0.08) corresponds to the generic assessment scenario for an urban gardener in EPA's CAP-88 code (EPA 1991).

The soil ingestion pathway also includes uncertainty, incorporated in the modeling via the parameter for consumption rate of soil, U_{soil}. The range used is based on an extensive recent review of human soil ingestion (Simon 1998). The lognormal distribution used in this analysis is adopted from Simon (1998), for "suburban lifestyles (with homes)—including lawns, parks, recreational areas, some gardens."

The atmospheric release scenario requires the use of the thickness of box 1 (surface layer) for the ingestion exposure pathway. This parameter is used to calculate the radioactivity concentration in the soil from deposition, assuming complete mixing throughout box 1. The fixed value used for this parameter for the atmospheric scenario is the assumed depth of a plow layer, 0.15 m.

The transport of C-14 from atmospheric release to uptake into plant depends on a fractional equilibrium ration, p_{c-14}. According to Regulatory Guide 1.109, this ratio is set equal to 1.0 for a continuous release. Therefore, a value of 1.0 is used for p_{c-14}. The transport of H-3 from atmospheric release to uptake into plants depends on the absolute humidity of the atmosphere at the receptor, H. Till and Meyer (1983) states that atmospheric humidity varies greatly from one location to another in the United States. A graph in Till and Meyer (1983) shows that the absolute humidity ranges from an average of 4.9 g/m^3 in the west (e.g., Idaho, Utah) to an average of 13.8 g/m^3 in the southeast (e.g., Florida). A most likely value (mode) of 7 g/m^3 for the absolute humidity was calculated by incorporating the approximate percentage of the continental U.S. that had a particular average humidity, as shown in Till and Meyer (1983, Figure 9.1). The following assumptions were used to calculate a weighted average absolute humidity, H, of 7 g/m^3.

Percentage of U.S.	Average absolute humidity (g/m^3)
40%	4.9
20%	6.6
20%	8.4
15%	10.7
5%	13.8
Overall Weighted Average	**7.3**

An overall range of 3 g/m^3 to 16 g/m^3 was used based on the values in Till and Meyer (1983).

4.8.4.10 Atmospheric Release Parameters

The total mass of dust that is calculated to escape a refinery baghouse in a year, M_{ra} is calculated using the material flow model. The duration of release of refinery atmospheric effluent, is 1 year, in order to calculate an annual average release rate.

The uncertainty in the atmospheric dispersion calculations was incorporated via the parameter Chi/Q, the annual average dispersion factor. Historical data and statistical summaries for approximately 300 weather stations in the U.S. were obtained (Doty and Wallace 1976), and used to conduct a Monte Carlo analysis on the Gaussian plume dispersion equation. The median of the resulting output (3.76 E-06 s/m^3) was obtained and used as the geometric mean of a lognormal distribution, and an input distribution was fitted to the high end of the Monte Carlo distribution using a geometric standard deviation of 2.59.

The fraction of time during a year that each stability class occurs is taken from Doty and Wallace (1976). The average windspeed for stability classes A-F is calculated from data in Till and Meyer (1983, Table 2.1). In calculating average windspeeds, the lowest and highest windspeed

categories were not used (< 2 m/s and > 6 m/s), and the resulting average windspeeds are representative of typical windspeeds. A value of 1.0 is used for the average windspeed for stability class G.

The effective height of the refinery stack, H_e is assumed to be 40 m (131 ft) above the ground. This value is reasonable for refineries, based on the physical height of typical baghouses, the effluent velocity, and the temperature of the effluent. Because the distance from the refinery to the nearest receptor, x, is generic, and a typical resident is assumed (suburban garden) a fixed distance of 1,000 m (3,280 ft) is assumed.

The atmospheric scenario also uses a total deposition velocity, $V_d(T)$ for calculating external exposure from ground deposition (Equation 4.25) and internal dose from foliar deposition on plants (Equation 4.27). The value for this parameter is dependent on the type of element, so the radionuclides are grouped into three general groups: iodines, gases, and particulates (all others). The distributions used were developed using data and information in standard references (e.g., Miller 1984; Till and Meyer 1983) for deposition velocity and interception fractions.

4.8.4.11 Landfill Parameters

For the scenarios involving a resident on a landfill after closure, the total mass of contaminated material in the landfill, QT, is needed. This parameter is used to calculate the radioactivity concentration in the soil, assuming complete mixing. This mass includes the daily and final cover soil, and/or waste, depending on the type of waste. The total mass of material in a landfill was calculated using the following information for sanitary and hazardous waste landfills:

Sanitary Landfill Assumptions

- The depth of an average sanitary landfill unit is about 4 m (13 ft), using the average capacity (waste and daily cover soil) of 1.4E+6 m^3 and an average area of 3.4E+5 m^2 (Dehmel et al. 1994).

- The ratio of waste to daily cover soil is 4:1 (Dehmel et al. 1994), which results in an average of 80% (1.1E+6 m^3) of the capacity of the landfill consisting of waste, V_w, and the remaining 20% (2.8E+5 m^3) consisting of daily cover soil.

- EPA recommends that the final closure cover on a sanitary landfill consist of at least 0.46 m (1.5 ft) of soil for an infiltration layer and 0.15 m (0.5 ft) for an erosion layer, resulting in a total cover of 0.61 m (2 ft) (EPA 1993b). Therefore, the total volume of final cover soil on a sanitary landfill is 2.1E+5 m^3.

- The bulk densities of the wastes (as disposed) are as follows: BOF baghouse dust 1.6E+6 g/m^3, refinery slag 2.0E+6 g/m^3, and metal 3.93E+6 g/m^3.

- The radioactivity in the waste types that are similar to soil (i.e., BOF baghouse dust and refinery slag) are dispersed throughout the total mass (waste, daily cover soil, and final cover soil). However, for wastes that are similar to metals the radioactivity is dispersed only throughout the daily cover soil and final cover soil.

- For BOF baghouse dust disposal scenarios, the total volume of material in a sanitary landfill after closure is 1.6E+6 m^3 (waste = 1.1E+6 m^3, daily and final cover soil = 4.9E+5 m^3). Assuming a value of 1.60E+6 g/m^3 for the density of soil as well as for disposed BOF baghouse dust (EPA 1993a) a value of 2.54E+12 g is calculated for QT.

- For slag disposal scenarios, the total volume of waste in a sanitary landfill is 1.1E+6 m^3 while the total volume of soil in the landfill (daily and final cover soil) is 4.8E+5 m^3. Assuming a density of 1.60E+6g/m^3 for soil and 2.0E+6g/m^3 for slag, a value of 2.97E+12 g is used for QT.

- For scenarios involving the disposal of metal wastes, only the volume of soil (daily and final cover) is needed to calculate QT. Assuming 1.60E+6 g/m^3 for the density of soil, a value of 7.8E+11 g is calculated for QT.

- In order to account for the small fraction of a landfill that would likely consist of material derived from cleared scrap, a sanitary landfill dilution factor was calculated and discussed above (see Section 4.8.4.4). For estimates of the percent of a landfill that would be comprised of material derived from licensee scrap, the following dilution factors were applied to each waste category: Scrap metal (0.7%), slag (0.2%), baghouse dust (0.02%), and refined metal products (0.6%).

Hazardous Landfill Assumptions

- Based on landfill survey information in Dehmel et al. (1994), the depth, area, and capacity of an average hazardous landfill unit are 8.6 m (28 ft), 7.28E+4 m^2, and 6.58E+5 m^3, respectively.

- Based on information in EPRI (1993), a maximum of approximately 25% of the capacity of a hazardous landfill would consist of contaminated EAF dust. This results in 1.65E+5 m^3 of EAF dust and 4.94E+5 m^3 of daily cover soil and other waste.

- For hazardous landfills EPA recommends that a minimum depth of 1.5 m (5 ft) of cover material be in place upon closure (EPA 1989b). Therefore, the total volume of final cover soil on a hazardous landfill is 1.09E+5 m^3.

- The radioactivity in disposed EAF dust is assumed to be dispersed throughout the total volume of material in the landfill (waste and soil).

- The total volume of material in a hazardous landfill after closure (waste, daily cover soil, and final cover soil) is 7.68E+5 m^3. Assuming a density of 1.60E+6 g/m^3 (EPA 1993a) for the soil (daily and final cover), and a density of 1.36E+6 g/m^3 for the EAF dust, total mass of material in a hazardous landfill, QT, is 1.19E+12 g.

The thickness of box 1 (surface layer) in the landfill model, H_1, is the sum of the depths of the landfill and the final cover soil. Using a depth for an average sanitary landfill of 3.66 m (12 ft) (Dehmel et al. 1994) and a final closure cover depth of 24 inches (0.61 m), the thickness of box 1 for a sanitary landfill is 4.27 m (4 ft). According to Dehmel et al. the depth of an average hazardous landfill is 8.6 m (28 ft) (Dehmel et al. 1994). For hazardous landfills EPA recommends that a minimum depth of 1.5 m (4.9 ft) of cover material upon closure (EPA 1989b). Therefore, the total thickness for hazardous landfills is 10.1 m (33 ft).

As seen in the mathematical modeling for the resident on closed landfills, the leach rate parameter L_{12} is not used for metal waste (e.g., scrap metal or refined metal product). Therefore, the thickness of box 1 is not needed for these scenarios. The leach rate constant for the movement of radionuclides from disposed metal to the surrounding soil is dependent on the corrosion of the metal. The leach rate constant used for the movement of radionuclides from the metal waste to the soil, L_{ws}, is 4.17E-4/y (1.14E-6/d) (Maheras et al. 1994).

The thickness of box 2 (unsaturated zone), H_2, is the distance from the bottom edge of the landfill to the top of the water table (aquifer). A mean value of 27 m (87 ft) was used for sanitary landfills and 14.9 m (49 ft) for hazardous landfills for this distance (Dehmel et al. 1994).

The radionuclides in the waste placed in sanitary landfills are assumed to begin leaching immediately upon placement in the landfill. The time between beginning of leaching and the time radioactivity concentrations in groundwater are determined is treated as a probabilistic parameter. The distribution of times is based on what is realistic for the exposed group and the exposure situation addressed by each scenario.

For the sanitary landfill resident scenarios, leaching is assumed to begin immediately upon disposal of the cleared material, i.e., at the "beginning" of the scenario. Groundwater activity is determined between 50 y and 150 y after leaching begins (18,263–54,788 d). These times are based on professional judgement. The objective was to use a reasonable time frame, without being overly conservative. It was judged unreasonable to assume immediate residence on an abandoned sanitary landfill, yet it is also unreasonable to assume time frames far into the future.

For the sanitary landfill resident scenarios, the use of a uniform distribution for the time between beginning of leaching and the time radioactivity concentrations in groundwater are determined (between 50 y and 150 y after leaching begins) means that the 100-year range of time that is used to calculate groundwater radioactivity concentration corresponds to the 100 years immediately following the end of the post-closure monitoring period. This is because of the remaining 20 years of landfill operational, (one half of the 40-year total), followed by a 30-year monitoring period.

For the hazardous landfill resident scenario (for EAF dust), leaching is assumed to begin at the end of the post-closure monitoring period, approximately 45 years after clearance (following 15 years of landfill operation and 30 years of post-closure monitoring). The time frame for groundwater activity determination, between 50 y and 100 y after leaching begins (18,263–36,525 days), corresponds to the time period between 95 y and 145 y after clearance.

4.8.5 Steel Surface-to-Mass Ratio

The surface-to-mass ratios for various steel objects were evaluated to develop an appropriate range to use for this study. For this analysis, steel objects are assumed to have a density of 7.8 g/cm^3. Using this density, theoretical values for the surface-to-mass ratios for various objects vary over a wide range from approximately 0.01 cm^2/g for large spheres (30-cm radius) and bar stock (10-cm radius), up to approximately 2.0 cm^2/g for small bar stock, pipes, and sheets.

Data are not available provide an adequate basis for choosing a "best estimate" from this range of values. Using professional judgement and these theoretical data, the value of the surface-to-mass ratio for recycled steel scrap is best described by a loguniform distribution having a minimum of 0.1 cm^2/g and a maximum of 2.0 cm^2/g. The minimum value is characteristic of bar stock having a radius of 1.0 cm. The maximum value is characteristic of pipes and sheets having a thickness of 0.05 cm. These values are representative of bar stock, pipes, and sheets of various sizes with residual radioactivity on one side only. A wide variety of steel objects commonly found at nuclear facilities have surface-to-mass values that fall within this range.

This range can be compared to other estimates for studies similar to this one. The EPA Technical Support Document (EPA 1997) contains an estimated average surface-to-mass ratio of 0.3 cm^2/g for all potentially cleared steel from NRC licensed facilities and the DOE complex. O'Donnell et al. (1978) suggested a value of 0.14 cm^2/g as representative of typical heavy sheet steel, and O'Donnell's calculations are based on a reference steel object with a surface-to-mass ratio of 0.45cm^2/g.

4.9 Dose Factors for Recycle of Steel Scrap

This analysis of recycle of cleared steel scrap includes 27 separate scenarios evaluated for 85 radionuclides. Of these, 9 scenarios have the highest dose factor for at least one radionuclide. Table 4.10 lists the mass-based critical-group dose factors for each radionuclide. Table 4.11 lists the corresponding derived surficial critical-group dose factor for each radionuclide. Results for all 27 scenarios are tabulated in Appendix A.

The mean values of the critical-group dose factors for each radionuclide are listed in Table 4.10. These represent the dose to the average member of the critical group exposed to radioactivity distributed throughout the mass of cleared steel (Bq/g or pCi/g). The circumstances of that exposure are described by the scenario indicated in the right hand column. The 5^{th}, 50^{th}, and 95^{th} percentiles listed for each radionuclide represent the underlying distribution of dose factors calculated for each critical group. The range of values from the 5^{th} to the 95^{th} percentile is the

90% confidence interval on the dose factor. That is, there is a 90% certainty that the dose factor for the average member of the critical group lies within this interval. The confidence interval is a subjective measure of uncertainty in the dose factor that includes estimates of the variability and uncertainty in the parameters used in each scenario.

The ratio of the 95th to the 5th percentile is a useful measure of the relative width of the 90% confidence interval for comparison between scenarios. Smaller values of the 95/5 ratio indicate less uncertainty than larger values. The scenarios with the smallest uncertainty are those with the fewest number of exposure pathways and the least uncertainty in the parameters describing those pathways. Of the nine critical group scenarios listed in Table 4.10, the scrap transportation scenario has the smallest uncertainty with a 95/5 ratio of about 2 for most radionuclides. This scenario involves only the external dose pathway. It includes uncertainty only in the time of exposure for the truck driver, the external dose rate factor for the cargo of scrap, and the timing of the scenario. The uncertainty in the timing of the scenario is unimportant for most radionuclides. For a few radionuclides with very short half-lives uncertainty in the timing of the scenario contributes some what to the width of the confidence interval. For example, Re-186 with a 3.8 day half-life has a 95/5 ratio of about 3.

For all scenarios that take place subsequent to the initial transport of scrap, additional sources of uncertainty are introduced and wider confidence intervals result. Scenarios that address handling of scrap include uncertainty due to dilution with other scrap. They also include additional exposure pathways—inhalation of resuspended dust and inadvertent ingestion under dusty conditions. Scenarios that address handling and processing of refinery products such as baghouse dust and refinery slag include additional uncertainty in how much of each radionuclide is partitioned to these materials. This group of handling and processing scenarios have 95/5 ratios that range from about 10 to about 50. The relative contribution to this uncertainty from scenario timing, radioactivity partitioning, and internal dose pathways is nuclide-dependent. The uncertainty in these dose factors results from a complicated interaction of half-life, radioactive decay properties, and chemical behavior as well as uncertainties in describing the circumstances under which individuals are exposed.

Greater uncertainty is associated with scenarios that involve multiple exposure pathways and complex submodels. The atmospheric release scenarios, for example, include an atmospheric dispersion model and pathways for ingestion, inhalation, and external exposure. Dose factors for nuclides limited by the atmospheric release scenario have 95/5 ratios that range from about 60 to slightly over 200. Most of this uncertainty is due to the atmospheric dispersion model but additional contributions from partitioning to refinery off-gas and uncertainties in ingestion dose are nuclide-dependent.

Dose factors for the five radionuclides limited by the drinking water pathway in the slag storage scenario have the widest confidence intervals of all those analyzed in this report. The 95/5 ratios for dose factors limited by the slag storage scenarios range from about 350 for Tc-99 to about 1,500 for Np-237. This is due to the uncertainties associated with the groundwater transport model and the timing of the scenario. Over the period of time addressed by this scenario there is

a large uncertainty in the rate at which each radionuclide leaches to the drinking water supply and in the resulting radioactivity concentration in drinking water.

Figure 4.7 indicates how many radionuclides have critical groups described by each of these scenarios. Most limiting scenarios for steel recycle describe critical groups consisting of workers at scrap yards and steel refineries who transport, handle, and process scrap metal or refinery products such as slag and baghouse dust. Two critical group scenarios involving exposure to cleared scrap account for 53 of the 85 radionuclides—scrap transportation for 39 and scrap handling for 14 radionuclides. Eleven radionuclides have critical group scenarios involving exposure to EAF baghouse dust—dust transportation for 7 and dust processing for 4 radionuclides. Seven radionuclides are limited by the slag handling scenario. Four are limited by exposure to finished metal from a BOF refinery during manufacturing.

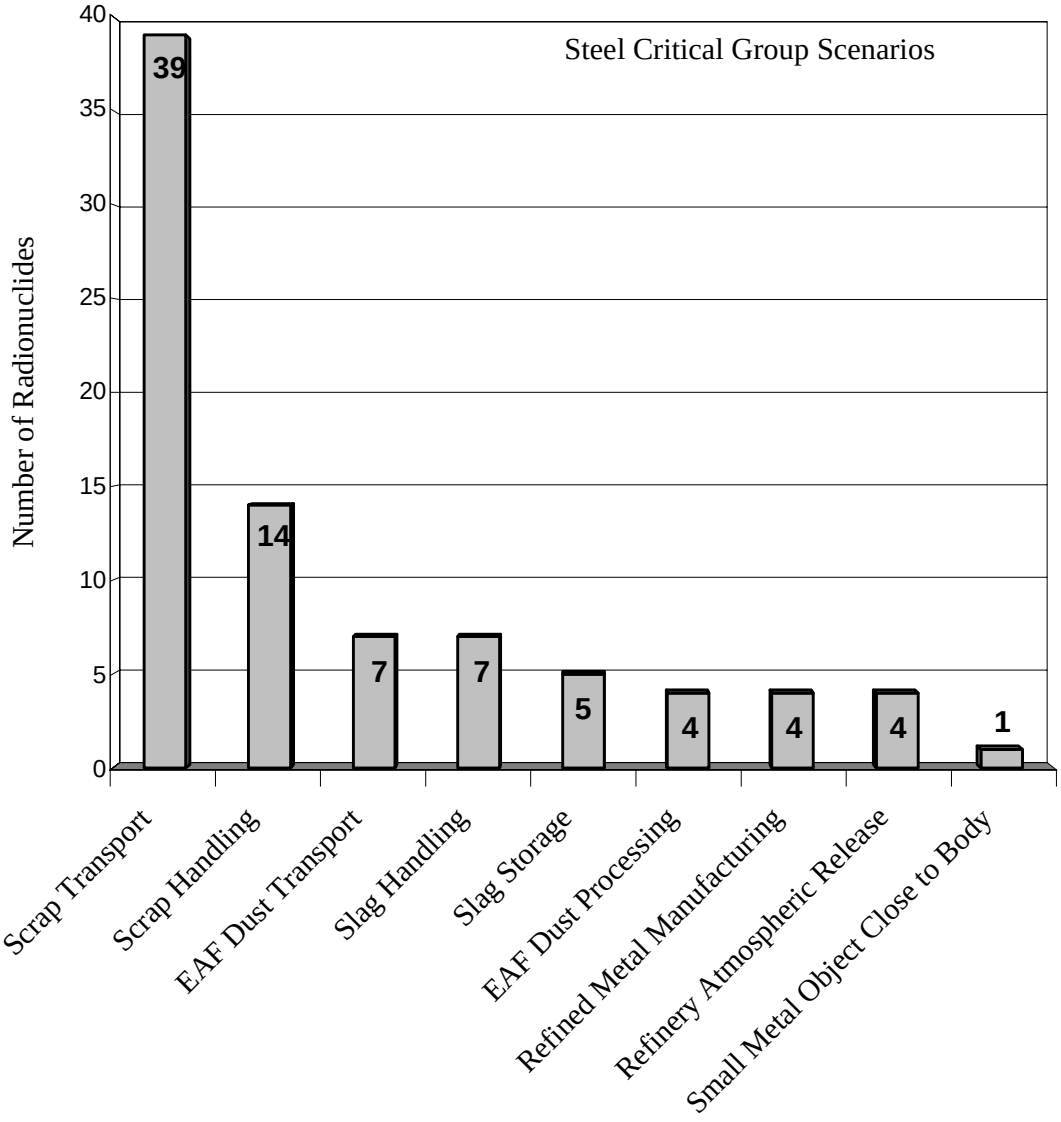

Figure 4.7 Scenarios describing critical groups for steel recycle

There are three reasons why the scrap transportation scenario is important for the largest number of radionuclides. First, there is minimal delay between clearance of scrap and transporting it to the scrap yard so no significant radioactive decay occurs before the scenario begins. Consequently, this scenario describes critical groups for many short-lived radionuclides that decay before later scenarios can occur. Second, unprocessed scrap has not yet been subjected to dilution with other materials or chemical partitioning during refining. This means that the initial radioactivity concentration is unchanged. Third, relatively large masses of scrap material are transported in each load so relatively larger amounts of radioactivity are present in this scenario than in most others. Because the scrap transportation scenario involves only the external dose pathway, the radionuclides limited by this scenario are all gamma emitters.

Radionuclides associated with slag, dust, and off-gas scenarios are those which concentrate in these materials during the refining process. All of these scenarios include internal dose pathways; inhalation of dust, inadvertent ingestion, consumption of drinking water or ingestion of garden produce. The radionuclides for which these material-specific scenarios are important all have relatively long half-lives and are alpha- or beta emitters that contribute to internal dose pathways.

Two types of radionuclides have critical groups consisting of members of the general public living in the vicinity of steel refineries. Critical groups for four volatile radionuclides with no external dose component are described by the atmospheric release scenario. Critical group for five-water soluble radionuclides with no external dose component result from the ground water pathway of the slag storage scenario.

Residual radioactivity in consumer products rarely yields critical groups. Only one radionuclide (Mo-93) is limited by exposure of an individual in the general public to a manufactured product. There are four reasons for this. First, the passage of time between clearance and the use of consumer products allows many radionuclides to decay to very small concentrations. Second, the amount of steel available from NRC licensed facilities is small compared to the total amount of steel that is recycled each year. It is not large even when compared to the capacity of some steel refineries. Mixing cleared steel with normal steel, even on a single charge basis, reduces concentrations of radioactivity in finished steel. Third, many radionuclides do not appear in finished steel. They are partitioned to slag or baghouse dust during refining. Finally, the relatively small size of consumer products compared to the amounts of steel encountered by refinery workers limits the amount of radioactivity to which any individual could be exposed. In contrast, workers at scrap yards and steel refineries can be exposed to relatively large amounts of cleared steel before mixing, processing, or radioactive decay can take place.

The mean values of the derived surficial dose factors for each radionuclide in Table 4.11 represent the dose to the average member of the critical group exposed to residual radioactivity initially distributed over the surface of cleared iron and steel (Bq/cm^2 or pCi/cm^2). Derived surficial dose factors are calculated from mass-based dose factors by use of a surface-to-mass ratio, appropriate for typical steel objects available for clearance. The value of The surface-to-mass ratio is used to derive surficial dose factors as described in Section 4.7.

The calculation of derived surficial dose factors is probabilistic. The parameter SM is represented by a distribution of values that incorporate the variability and uncertainty in the surface-to-mass ratio of steel objects available for clearance. This additional source of uncertainty results in wider confidence intervals for the surficial dose factors than for the mass-based dose factors from which they are derived. The relative importance of this additional uncertainty depends on the scenario. For scenarios with the narrowest confidence intervals, the added uncertainty can contribute as much as an additional 100% to the width of the confidence interval. The mass-based dose factor for the scrap transportation scenario has a 95/5 ratio of about 2 for most radionuclides. The corresponding derived surficial dose factors have a 95/5 ratio of about 4. The added uncertainty in surface-to-mass ratio has a relatively smaller effect on the confidence interval for scenarios with larger uncertainties, contributing an additional 10% to 50% to the 95/5 ratio.

Table 4.10 Steel recycle critical-group dose factors—mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
	Critical-group dose factor	90% Confidence interval			Critical-group dose factor	90% Confidence interval			
Radionuclide		5th (lower bound)	50th (median)	95th (upper bound)		5th (lower bound)	50th (median)	95th (upper bound)	Scenario
H-3	6.4E-04	3.8E-05	2.8E-04	2.4E-03	2.4E-06	1.4E-07	1.0E-06	8.8E-06	FE-ATMO-REFINER-N
C-14	2.8E-03	1.7E-04	2.1E-03	7.8E-03	1.0E-05	6.3E-07	7.8E-06	2.9E-05	FE-BOFM-HANDMAN-W
Na-22	4.1E+02	7.3E+01	2.9E+02	1.1E+03	1.5E+00	2.7E-01	1.1E+00	3.9E+00	FE-EAFD-TRANSPO-W
P-32	1.3E-01	8.1E-02	1.3E-01	1.8E-01	4.8E-04	3.0E-04	4.9E-04	6.7E-04	FE-SCRP-TRANSPO-W
S-35	7.6E-03	7.1E-04	4.4E-03	2.5E-02	2.8E-05	2.6E-06	1.6E-05	9.2E-05	FE-EAFD-PROCESS-W
Cl-36	2.7E+00	5.1E-02	9.3E-01	1.1E+01	1.0E-02	1.9E-04	3.4E-03	4.0E-02	FE-ATMO-REFINER-N
K-40	5.2E+01	9.2E+00	3.8E+01	1.4E+02	1.9E-01	3.4E-02	1.4E-01	5.1E-01	FE-EAFD-TRANSPO-W
Ca-41	1.3E-01	7.4E-04	2.7E-02	5.7E-01	4.9E-04	2.7E-06	1.0E-04	2.1E-03	FE-SLAG-STORAGE-N
Ca-45	8.2E-02	3.7E-04	1.2E-02	3.4E-01	3.0E-04	1.4E-06	4.3E-05	1.2E-03	FE-SLAG-STORAGE-N
Cr-51	2.5E+00	1.5E+00	2.5E+00	3.4E+00	9.1E-03	5.6E-03	9.2E-03	1.3E-02	FE-SCRP-TRANSPO-W
Mn-54	8.5E+01	5.3E+01	8.6E+01	1.2E+02	3.2E-01	2.0E-01	3.2E-01	4.3E-01	FE-SCRP-TRANSPO-W
Fe-55	1.0E-03	5.6E-05	8.4E-04	2.6E-03	3.8E-06	2.1E-07	3.1E-06	9.5E-06	FE-BOFM-HANDMAN-W
Co-57	3.8E+00	2.4E+00	3.8E+00	5.2E+00	1.4E-02	8.7E-03	1.4E-02	1.9E-02	FE-SCRP-TRANSPO-W
Co-58	9.5E+01	5.8E+01	9.6E+01	1.3E+02	3.5E-01	2.2E-01	3.5E-01	4.8E-01	FE-SCRP-TRANSPO-W
Fe-59	1.1E+02	7.0E+01	1.2E+02	1.6E+02	4.2E-01	2.6E-01	4.3E-01	5.8E-01	FE-SCRP-TRANSPO-W
Ni-59	4.5E-04	3.2E-05	4.0E-04	1.1E-03	1.6E-06	1.2E-07	1.5E-06	4.0E-06	FE-BOFM-HANDMAN-W
Co-60	2.5E+02	1.6E+02	2.6E+02	3.5E+02	9.4E-01	5.9E-01	9.5E-01	1.3E+00	FE-SCRP-TRANSPO-W
Ni-63	1.2E-03	7.3E-05	1.1E-03	2.8E-03	4.5E-06	2.7E-07	4.0E-06	1.1E-05	FE-BOFM-HANDMAN-W
Zn-65	2.1E+02	4.0E+01	1.5E+02	5.8E+02	7.9E-01	1.5E-01	5.4E-01	2.1E+00	FE-EAFD-TRANSPO-W
Cu-67	2.1E+00	1.0E+00	1.9E+00	3.6E+00	7.7E-03	3.8E-03	7.1E-03	1.3E-02	FE-SCRP-TRANSPO-W
Se-75	3.6E+01	1.5E+00	2.2E+01	1.2E+02	1.3E-01	5.6E-03	8.1E-02	4.3E-01	FE-EAFD-TRANSPO-W
Sr-85	4.7E+01	2.9E+01	4.7E+01	6.4E+01	1.7E-01	1.1E-01	1.7E-01	2.4E-01	FE-SCRP-TRANSPO-W
Sr-89	1.2E-01	7.1E-02	1.2E-01	1.6E-01	4.3E-04	2.6E-04	4.3E-04	5.9E-04	FE-SCRP-TRANSPO-W

Table 4.10 Steel recycle critical-group dose factors—mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
	Critical-group dose factor	90% Confidence interval			Critical-group dose factor	90% Confidence interval			
Radionuclide		5th (lower bound)	50th (median)	95th (upper bound)		5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Sr-90	1.0E+01	3.9E-02	1.0E+00	3.4E+01	3.8E-02	1.4E-04	3.8E-03	1.3E-01	FE-SLAG-STORAGE-N
Y-91	3.5E-01	2.1E-01	3.5E-01	4.7E-01	1.3E-03	7.9E-04	1.3E-03	1.7E-03	FE-SCRP-TRANSPO-W
Mo-93	1.4E-02	2.5E-03	1.1E-02	3.7E-02	5.2E-05	9.2E-06	4.2E-05	1.4E-04	FE-METL-SMOBJCT-N
Nb-93m	8.4E-03	1.2E-03	5.6E-03	2.6E-02	3.1E-05	4.4E-06	2.1E-05	9.6E-05	FE-SLAG-HANDLIN-W
Nb-94	1.6E+02	1.0E+02	1.6E+02	2.3E+02	6.1E-01	3.8E-01	6.1E-01	8.3E-01	FE-SCRP-TRANSPO-W
Nb-95	7.2E+01	4.5E+01	7.3E+01	9.9E+01	2.7E-01	1.6E-01	2.7E-01	3.7E-01	FE-SCRP-TRANSPO-W
Zr-95	7.2E+01	4.4E+01	7.2E+01	9.8E+01	2.7E-01	1.6E-01	2.7E-01	3.6E-01	FE-SCRP-TRANSPO-W
Tc-99	1.9E-01	1.8E-03	4.4E-02	9.2E-01	7.0E-04	6.8E-06	1.6E-04	3.4E-03	FE-SLAG-STORAGE-N
Ru-103	4.6E+01	2.9E+01	4.7E+01	6.4E+01	1.7E-01	1.1E-01	1.7E-01	2.4E-01	FE-SCRP-TRANSPO-W
Ru-106	2.1E+01	1.3E+01	2.1E+01	2.8E+01	7.6E-02	4.7E-02	7.7E-02	1.0E-01	FE-SCRP-TRANSPO-W
Ag-108m	1.6E+02	1.0E+02	1.6E+02	2.2E+02	6.0E-01	3.7E-01	6.0E-01	8.3E-01	FE-SCRP-TRANSPO-W
Cd-109	4.4E-01	6.2E-02	3.0E-01	1.2E+00	1.6E-03	2.3E-04	1.1E-03	4.3E-03	FE-EAFD-PROCESS-W
Ag-110m	2.8E+02	1.8E+02	2.8E+02	3.9E+02	1.0E+00	6.5E-01	1.1E+00	1.4E+00	FE-SCRP-TRANSPO-W
Sb-124	1.8E+02	1.1E+02	1.8E+02	2.5E+02	6.7E-01	4.1E-01	6.7E-01	9.2E-01	FE-SCRP-TRANSPO-W
I-125	2.7E+00	1.2E-01	1.3E+00	1.0E+01	1.0E-02	4.5E-04	4.8E-03	3.8E-02	FE-ATMO-REFINER-N
Sb-125	4.1E+01	2.5E+01	4.1E+01	5.6E+01	1.5E-01	9.4E-02	1.5E-01	2.1E-01	FE-SCRP-TRANSPO-W
I-129	6.1E+01	3.3E+00	2.7E+01	2.4E+02	2.3E-01	1.2E-02	9.9E-02	8.8E-01	FE-ATMO-REFINER-N
I-131	2.5E+01	1.5E+01	2.5E+01	3.6E+01	9.3E-02	5.7E-02	9.3E-02	1.3E-01	FE-SCRP-TRANSPO-W
Ba-133	2.8E+01	1.7E+01	2.8E+01	3.8E+01	1.0E-01	6.4E-02	1.0E-01	1.4E-01	FE-SCRP-TRANSPO-W
Cs-134	6.6E+02	1.1E+02	4.7E+02	1.7E+03	2.4E+00	3.9E-01	1.8E+00	6.3E+00	FE-EAFD-TRANSPO-W
Cs-137	2.6E+02	4.8E+01	1.8E+02	6.8E+02	9.5E-01	1.8E-01	6.7E-01	2.5E+00	FE-EAFD-TRANSPO-W
Ce-141	2.7E+00	1.7E+00	2.7E+00	3.7E+00	1.0E-02	6.2E-03	1.0E-02	1.4E-02	FE-SCRP-TRANSPO-W
Ce-144	3.3E+00	2.0E+00	3.3E+00	4.5E+00	1.2E-02	7.5E-03	1.2E-02	1.7E-02	FE-SCRP-TRANSPO-W
Pm-147	1.1E-02	1.6E-03	7.4E-03	3.3E-02	4.2E-05	5.9E-06	2.7E-05	1.2E-04	FE-SLAG-HANDLIN-W
Eu-152	1.1E+02	6.9E+01	1.1E+02	1.5E+02	4.1E-01	2.6E-01	4.1E-01	5.7E-01	FE-SCRP-TRANSPO-W
Eu-154	1.2E+02	7.5E+01	1.2E+02	1.7E+02	4.5E-01	2.8E-01	4.5E-01	6.2E-01	FE-SCRP-TRANSPO-W
Eu-155	1.1E+00	6.6E-01	1.1E+00	1.5E+00	3.9E-03	2.4E-03	3.9E-03	5.4E-03	FE-SCRP-TRANSPO-W
Re-186	2.5E-01	1.4E-01	2.4E-01	3.9E-01	9.1E-04	5.1E-04	8.8E-04	1.4E-03	FE-SCRP-TRANSPO-W
Ir-192	1.2E+02	6.3E+00	6.7E+01	4.0E+02	4.4E-01	2.3E-02	2.5E-01	1.5E+00	FE-EAFD-TRANSPO-W
Pb-210	1.5E+02	2.4E+01	9.9E+01	4.3E+02	5.7E-01	8.9E-02	3.7E-01	1.6E+00	FE-EAFD-PROCESS-W
Po-210	6.0E+01	8.1E+00	4.2E+01	1.6E+02	2.2E-01	3.0E-02	1.6E-01	6.0E-01	FE-EAFD-PROCESS-W
Bi-210	3.3E-02	7.3E-03	2.8E-02	7.6E-02	1.2E-04	2.7E-05	1.0E-04	2.8E-04	FE-SCRP-HANDLIN-W
Rn-222	8.6E+01	4.8E+01	8.2E+01	1.3E+02	3.2E-01	1.8E-01	3.0E-01	5.0E-01	FE-SCRP-TRANSPO-W
Ra-223	1.8E+01	1.1E+01	1.8E+01	2.5E+01	6.7E-02	4.2E-02	6.7E-02	9.4E-02	FE-SCRP-TRANSPO-W
Ra-224	6.1E+01	3.4E+01	5.9E+01	9.7E+01	2.3E-01	1.2E-01	2.2E-01	3.6E-01	FE-SCRP-TRANSPO-W

Table 4.10 Steel recycle critical-group dose factors—mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
	Critical-group dose factor	90% Confidence interval			Critical-group dose factor	90% Confidence interval			
Radionuclide		5th (lower bound)	50th (median)	95th (upper bound)		5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Ac-225	1.4E+01	8.8E+00	1.4E+01	2.0E+01	5.3E-02	3.2E-02	5.2E-02	7.4E-02	FE-SCRP-TRANSPO-W
Ra-225	1.8E+00	4.0E-01	1.5E+00	4.1E+00	6.7E-03	1.5E-03	5.6E-03	1.5E-02	FE-SCRP-HANDLIN-W
Ra-226	1.7E+02	1.1E+02	1.7E+02	2.4E+02	6.4E-01	4.0E-01	6.5E-01	8.9E-01	FE-SCRP-TRANSPO-W
Ac-227	3.4E+02	4.1E+01	2.1E+02	1.1E+03	1.3E+00	1.5E-01	7.8E-01	3.9E+00	FE-SLAG-HANDLIN-W
Th-227	5.9E+00	3.6E+00	5.9E+00	8.1E+00	2.2E-02	1.3E-02	2.2E-02	3.0E-02	FE-SCRP-TRANSPO-W
Th-228	1.3E+02	7.9E+01	1.3E+02	1.7E+02	4.7E-01	2.9E-01	4.7E-01	6.5E-01	FE-SCRP-TRANSPO-W
Ra-228	8.4E+01	5.2E+01	8.4E+01	1.2E+02	3.1E-01	1.9E-01	3.1E-01	4.3E-01	FE-SCRP-TRANSPO-W
Th-229	4.3E+02	6.2E+01	3.6E+02	1.0E+03	1.6E+00	2.3E-01	1.3E+00	3.8E+00	FE-SCRP-HANDLIN-W
Th-230	6.5E+01	9.3E+00	5.4E+01	1.6E+02	2.4E-01	3.4E-02	2.0E-01	5.8E-01	FE-SCRP-HANDLIN-W
Pa-231	2.3E+02	3.0E+01	1.3E+02	6.7E+02	8.3E-01	1.1E-01	5.0E-01	2.5E+00	FE-SLAG-HANDLIN-W
Th-231	1.5E-02	3.3E-03	1.1E-02	3.9E-02	5.5E-05	1.2E-05	3.9E-05	1.4E-04	FE-SCRP-TRANSPO-W
Th-232	2.9E+02	4.1E+01	2.4E+02	6.9E+02	1.1E+00	1.5E-01	8.8E-01	2.6E+00	FE-SCRP-HANDLIN-W
Pa-233	1.3E+01	8.1E+00	1.3E+01	1.8E+01	4.9E-02	3.0E-02	4.9E-02	6.8E-02	FE-SCRP-TRANSPO-W
U-233	3.4E+01	4.6E+00	2.8E+01	8.1E+01	1.2E-01	1.7E-02	1.0E-01	3.0E-01	FE-SCRP-HANDLIN-W
Th-234	7.3E-01	4.5E-01	7.4E-01	1.0E+00	2.7E-03	1.7E-03	2.7E-03	3.7E-03	FE-SCRP-TRANSPO-W
U-234	3.3E+01	4.5E+00	2.7E+01	7.9E+01	1.2E-01	1.7E-02	1.0E-01	2.9E-01	FE-SCRP-HANDLIN-W
U-235	3.2E+01	4.1E+00	2.2E+01	9.3E+01	1.2E-01	1.5E-02	8.2E-02	3.5E-01	FE-SLAG-HANDLIN-W
Np-237	2.0E+03	8.4E+00	3.1E+02	7.3E+03	7.4E+00	3.1E-02	1.1E+00	2.7E+01	FE-SLAG-STORAGE-N
Pu-238	7.1E+01	9.8E+00	5.9E+01	1.7E+02	2.6E-01	3.6E-02	2.2E-01	6.4E-01	FE-SCRP-HANDLIN-W
U-238	2.9E+01	4.1E+00	2.4E+01	7.1E+01	1.1E-01	1.5E-02	9.0E-02	2.6E-01	FE-SCRP-HANDLIN-W
Pu-239	7.6E+01	1.0E+01	6.3E+01	1.8E+02	2.8E-01	3.9E-02	2.3E-01	6.8E-01	FE-SCRP-HANDLIN-W
Pu-240	7.6E+01	1.0E+01	6.3E+01	1.8E+02	2.8E-01	3.9E-02	2.3E-01	6.8E-01	FE-SCRP-HANDLIN-W
Pu-241	1.2E+00	1.7E-01	1.0E+00	3.0E+00	4.5E-03	6.2E-04	3.8E-03	1.1E-02	FE-SCRP-HANDLIN-W
Am-241	1.1E+02	1.3E+01	8.0E+01	3.4E+02	4.2E-01	4.9E-02	3.0E-01	1.3E+00	FE-SLAG-HANDLIN-W
Cm-242	4.3E+00	6.7E-01	3.6E+00	1.0E+01	1.6E-02	2.5E-03	1.3E-02	3.8E-02	FE-SCRP-HANDLIN-W
Pu-242	7.3E+01	9.9E+00	6.0E+01	1.8E+02	2.7E-01	3.7E-02	2.2E-01	6.5E-01	FE-SCRP-HANDLIN-W
Cm-244	6.3E+01	7.4E+00	4.1E+01	1.9E+02	2.3E-01	2.7E-02	1.5E-01	7.1E-01	FE-SLAG-HANDLIN-W

Table 4.11 Steel recycle critical-group dose factors—surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
H-3	4.8E-04	2.2E-05	2.1E-04	1.7E-03	1.8E-06	8.1E-08	7.6E-07	6.3E-06	FE-ATMO-REFINER-N
C-14	2.1E-03	1.3E-04	1.4E-03	6.5E-03	7.8E-06	4.9E-07	5.2E-06	2.4E-05	FE-BOFM-HANDMAN-W
Na-22	3.2E+02	4.6E+01	1.9E+02	9.2E+02	1.2E+00	1.7E-01	7.2E-01	3.4E+00	FE-EAFD-TRANSPO-W
P-32	9.9E-02	4.2E-02	9.2E-02	1.8E-01	3.7E-04	1.6E-04	3.4E-04	6.6E-04	FE-SCRP-TRANSPO-W
S-35	5.6E-03	3.9E-04	3.1E-03	2.1E-02	2.1E-05	1.4E-06	1.2E-05	7.7E-05	FE-EAFD-PROCESS-W
Cl-36	2.1E+00	3.1E-02	6.6E-01	8.6E+00	7.7E-03	1.1E-04	2.4E-03	3.2E-02	FE-ATMO-REFINER-N
K-40	4.0E+01	5.7E+00	2.6E+01	1.2E+02	1.5E-01	2.1E-02	9.6E-02	4.5E-01	FE-EAFD-TRANSPO-W
Ca-41	9.8E-02	5.4E-04	1.9E-02	3.6E-01	3.6E-04	2.0E-06	7.1E-05	1.3E-03	FE-SLAG-STORAGE-N
Ca-45	6.1E-02	2.7E-04	8.1E-03	2.3E-01	2.2E-04	1.0E-06	3.0E-05	8.5E-04	FE-SLAG-STORAGE-N
Cr-51	1.9E+00	7.8E-01	1.7E+00	3.4E+00	6.9E-03	2.9E-03	6.4E-03	1.3E-02	FE-SCRP-TRANSPO-W
Mn-54	6.4E+01	2.7E+01	6.0E+01	1.2E+02	2.4E-01	1.0E-01	2.2E-01	4.3E-01	FE-SCRP-TRANSPO-W
Fe-55	7.6E-04	4.7E-05	5.6E-04	2.1E-03	2.8E-06	1.7E-07	2.1E-06	7.6E-06	FE-BOFM-HANDMAN-W
Co-57	2.9E+00	1.2E+00	2.7E+00	5.3E+00	1.1E-02	4.5E-03	9.9E-03	1.9E-02	FE-SCRP-TRANSPO-W
Co-58	7.2E+01	3.0E+01	6.6E+01	1.3E+02	2.7E-01	1.1E-01	2.5E-01	4.8E-01	FE-SCRP-TRANSPO-W
Fe-59	8.7E+01	3.6E+01	8.0E+01	1.6E+02	3.2E-01	1.3E-01	3.0E-01	5.8E-01	FE-SCRP-TRANSPO-W
Ni-59	3.4E-04	2.2E-05	2.7E-04	9.3E-04	1.2E-06	8.1E-08	9.8E-07	3.4E-06	FE-BOFM-HANDMAN-W
Co-60	1.9E+02	8.2E+01	1.8E+02	3.5E+02	7.1E-01	3.0E-01	6.6E-01	1.3E+00	FE-SCRP-TRANSPO-W
Ni-63	9.1E-04	5.2E-05	7.6E-04	2.5E-03	3.4E-06	1.9E-07	2.8E-06	9.1E-06	FE-BOFM-HANDMAN-W
Zn-65	1.6E+02	2.3E+01	1.0E+02	4.9E+02	6.0E-01	8.5E-02	3.8E-01	1.8E+00	FE-EAFD-TRANSPO-W
Cu-67	1.6E+00	5.6E-01	1.4E+00	3.1E+00	5.8E-03	2.1E-03	5.0E-03	1.2E-02	FE-SCRP-TRANSPO-W
Se-75	2.7E+01	1.0E+00	1.6E+01	9.3E+01	9.8E-02	3.8E-03	5.9E-02	3.4E-01	FE-EAFD-TRANSPO-W
Sr-85	3.6E+01	1.5E+01	3.3E+01	6.5E+01	1.3E-01	5.5E-02	1.2E-01	2.4E-01	FE-SCRP-TRANSPO-W
Sr-89	8.8E-02	3.7E-02	8.1E-02	1.6E-01	3.3E-04	1.4E-04	3.0E-04	5.9E-04	FE-SCRP-TRANSPO-W
Sr-90	7.5E+00	2.3E-02	7.3E-01	2.2E+01	2.8E-02	8.6E-05	2.7E-03	8.2E-02	FE-SLAG-STORAGE-N
Y-91	2.6E-01	1.1E-01	2.4E-01	4.7E-01	9.7E-04	4.1E-04	9.0E-04	1.8E-03	FE-SCRP-TRANSPO-W
Mo-93	1.1E-02	1.4E-03	7.9E-03	3.1E-02	3.9E-05	5.4E-06	2.9E-05	1.1E-04	FE-METL-SMOBJCT-N
Nb-93m	6.4E-03	8.0E-04	3.7E-03	2.1E-02	2.4E-05	3.0E-06	1.4E-05	7.6E-05	FE-SLAG-HANDLIN-W
Nb-94	1.2E+02	5.3E+01	1.1E+02	2.3E+02	4.6E-01	2.0E-01	4.2E-01	8.4E-01	FE-SCRP-TRANSPO-W
Nb-95	5.5E+01	2.3E+01	5.1E+01	9.9E+01	2.0E-01	8.5E-02	1.9E-01	3.7E-01	FE-SCRP-TRANSPO-W
Zr-95	5.4E+01	2.3E+01	5.0E+01	9.9E+01	2.0E-01	8.5E-02	1.9E-01	3.7E-01	FE-SCRP-TRANSPO-W
Tc-99	1.4E-01	1.3E-03	3.4E-02	6.7E-01	5.3E-04	4.9E-06	1.3E-04	2.5E-03	FE-SLAG-STORAGE-N
Ru-103	3.5E+01	1.5E+01	3.2E+01	6.4E+01	1.3E-01	5.4E-02	1.2E-01	2.4E-01	FE-SCRP-TRANSPO-W
Ru-106	1.6E+01	6.6E+00	1.4E+01	2.8E+01	5.8E-02	2.5E-02	5.4E-02	1.1E-01	FE-SCRP-TRANSPO-W
Ag-108m	1.2E+02	5.2E+01	1.1E+02	2.2E+02	4.5E-01	1.9E-01	4.2E-01	8.3E-01	FE-SCRP-TRANSPO-W
Cd-109	3.3E-01	3.9E-02	2.2E-01	1.0E+00	1.2E-03	1.5E-04	8.3E-04	3.7E-03	FE-EAFD-PROCESS-W

Table 4.11 Steel recycle critical-group dose factors—surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Ag-110m	2.1E+02	9.1E+01	2.0E+02	3.9E+02	7.9E-01	3.4E-01	7.3E-01	1.4E+00	FE-SCRP-TRANSPO-W
Sb-124	1.4E+02	5.7E+01	1.3E+02	2.5E+02	5.1E-01	2.1E-01	4.7E-01	9.2E-01	FE-SCRP-TRANSPO-W
I-125	2.1E+00	8.1E-02	9.0E-01	8.0E+00	7.8E-03	3.0E-04	3.3E-03	3.0E-02	FE-ATMO-REFINER-N
Sb-125	3.1E+01	1.3E+01	2.9E+01	5.6E+01	1.1E-01	4.8E-02	1.1E-01	2.1E-01	FE-SCRP-TRANSPO-W
I-129	4.6E+01	2.1E+00	1.9E+01	1.8E+02	1.7E-01	7.9E-03	7.2E-02	6.7E-01	FE-ATMO-REFINER-N
I-131	1.9E+01	8.0E+00	1.7E+01	3.4E+01	7.0E-02	3.0E-02	6.4E-02	1.3E-01	FE-SCRP-TRANSPO-W
Ba-133	2.1E+01	9.0E+00	2.0E+01	3.9E+01	7.8E-02	3.3E-02	7.2E-02	1.4E-01	FE-SCRP-TRANSPO-W
Cs-134	4.9E+02	7.2E+01	3.3E+02	1.3E+03	1.8E+00	2.7E-01	1.2E+00	4.9E+00	FE-EAFD-TRANSPO-W
Cs-137	2.0E+02	2.8E+01	1.3E+02	5.9E+02	7.3E-01	1.0E-01	4.7E-01	2.2E+00	FE-EAFD-TRANSPO-W
Ce-141	2.1E+00	8.6E-01	1.9E+00	3.7E+00	7.6E-03	3.2E-03	7.1E-03	1.4E-02	FE-SCRP-TRANSPO-W
Ce-144	2.5E+00	1.1E+00	2.3E+00	4.5E+00	9.2E-03	3.9E-03	8.5E-03	1.7E-02	FE-SCRP-TRANSPO-W
Pm-147	8.4E-03	9.4E-04	5.2E-03	2.5E-02	3.1E-05	3.5E-06	1.9E-05	9.2E-05	FE-SLAG-HANDLIN-W
Eu-152	8.4E+01	3.6E+01	7.8E+01	1.5E+02	3.1E-01	1.3E-01	2.9E-01	5.7E-01	FE-SCRP-TRANSPO-W
Eu-154	9.2E+01	3.9E+01	8.5E+01	1.7E+02	3.4E-01	1.4E-01	3.2E-01	6.2E-01	FE-SCRP-TRANSPO-W
Eu-155	8.0E-01	3.4E-01	7.5E-01	1.5E+00	3.0E-03	1.3E-03	2.8E-03	5.4E-03	FE-SCRP-TRANSPO-W
Re-186	1.9E-01	7.5E-02	1.7E-01	3.5E-01	6.9E-04	2.8E-04	6.2E-04	1.3E-03	FE-SCRP-TRANSPO-W
Ir-192	8.9E+01	3.7E+00	4.9E+01	3.4E+02	3.3E-01	1.4E-02	1.8E-01	1.2E+00	FE-EAFD-TRANSPO-W
Pb-210	1.2E+02	1.4E+01	6.8E+01	3.5E+02	4.3E-01	5.3E-02	2.5E-01	1.3E+00	FE-EAFD-PROCESS-W
Po-210	4.4E+01	5.3E+00	3.0E+01	1.3E+02	1.6E-01	1.9E-02	1.1E-01	4.9E-01	FE-EAFD-PROCESS-W
Bi-210	2.5E-02	4.3E-03	1.9E-02	6.5E-02	9.3E-05	1.6E-05	7.1E-05	2.4E-04	FE-SCRP-HANDLIN-W
Rn-222	6.5E+01	2.6E+01	5.9E+01	1.2E+02	2.4E-01	9.6E-02	2.2E-01	4.5E-01	FE-SCRP-TRANSPO-W
Ra-223	1.4E+01	5.7E+00	1.3E+01	2.5E+01	5.1E-02	2.1E-02	4.7E-02	9.1E-02	FE-SCRP-TRANSPO-W
Ra-224	4.6E+01	1.8E+01	4.2E+01	8.8E+01	1.7E-01	6.8E-02	1.5E-01	3.2E-01	FE-SCRP-TRANSPO-W
Ac-225	1.1E+01	4.5E+00	9.9E+00	1.9E+01	4.0E-02	1.7E-02	3.7E-02	7.1E-02	FE-SCRP-TRANSPO-W
Ra-225	1.4E+00	2.3E-01	1.1E+00	3.6E+00	5.1E-03	8.7E-04	3.9E-03	1.3E-02	FE-SCRP-HANDLIN-W
Ra-226	1.3E+02	5.6E+01	1.2E+02	2.4E+02	4.9E-01	2.1E-01	4.5E-01	8.9E-01	FE-SCRP-TRANSPO-W
Ac-227	2.5E+02	2.5E+01	1.5E+02	7.7E+02	9.4E-01	9.3E-02	5.6E-01	2.8E+00	FE-SLAG-HANDLIN-W
Th-227	4.4E+00	1.9E+00	4.1E+00	8.1E+00	1.6E-02	6.9E-03	1.5E-02	3.0E-02	FE-SCRP-TRANSPO-W
Th-228	9.6E+01	4.1E+01	8.9E+01	1.8E+02	3.6E-01	1.5E-01	3.3E-01	6.5E-01	FE-SCRP-TRANSPO-W
Ra-228	6.3E+01	2.7E+01	5.9E+01	1.2E+02	2.3E-01	1.0E-01	2.2E-01	4.3E-01	FE-SCRP-TRANSPO-W
Th-229	3.3E+02	3.8E+01	2.4E+02	8.6E+02	1.2E+00	1.4E-01	9.0E-01	3.2E+00	FE-SCRP-HANDLIN-W
Th-230	4.9E+01	5.6E+00	3.7E+01	1.3E+02	1.8E-01	2.1E-02	1.4E-01	4.8E-01	FE-SCRP-HANDLIN-W
Pa-231	1.7E+02	2.0E+01	9.7E+01	5.3E+02	6.3E-01	7.3E-02	3.6E-01	1.9E+00	FE-SLAG-HANDLIN-W
Th-231	1.1E-02	1.9E-03	7.7E-03	3.2E-02	4.2E-05	7.0E-06	2.9E-05	1.2E-04	FE-SCRP-TRANSPO-W
Th-232	2.2E+02	2.5E+01	1.6E+02	5.8E+02	8.0E-01	9.2E-02	6.0E-01	2.1E+00	FE-SCRP-HANDLIN-W

Table 4.11 Steel recycle critical-group dose factors—surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Pa-233	1.0E+01	4.2E+00	9.3E+00	1.8E+01	3.7E-02	1.5E-02	3.4E-02	6.8E-02	FE-SCRP-TRANSPO-W
U-233	2.5E+01	2.8E+00	1.9E+01	6.8E+01	9.4E-02	1.0E-02	7.0E-02	2.5E-01	FE-SCRP-HANDLIN-W
Th-234	5.5E-01	2.3E-01	5.1E-01	1.0E+00	2.0E-03	8.5E-04	1.9E-03	3.7E-03	FE-SCRP-TRANSPO-W
U-234	2.5E+01	2.7E+00	1.9E+01	6.6E+01	9.2E-02	1.0E-02	6.9E-02	2.4E-01	FE-SCRP-HANDLIN-W
U-235	2.4E+01	2.6E+00	1.5E+01	7.5E+01	8.9E-02	9.5E-03	5.5E-02	2.8E-01	FE-SLAG-HANDLIN-W
Np-237	1.4E+03	6.1E+00	2.2E+02	6.0E+03	5.3E+00	2.2E-02	8.0E-01	2.2E+01	FE-SLAG-STORAGE-N
Pu-238	5.4E+01	6.0E+00	4.0E+01	1.4E+02	2.0E-01	2.2E-02	1.5E-01	5.3E-01	FE-SCRP-HANDLIN-W
U-238	2.2E+01	2.5E+00	1.7E+01	5.9E+01	8.2E-02	9.1E-03	6.2E-02	2.2E-01	FE-SCRP-HANDLIN-W
Pu-239	5.8E+01	6.4E+00	4.3E+01	1.5E+02	2.1E-01	2.4E-02	1.6E-01	5.7E-01	FE-SCRP-HANDLIN-W
Pu-240	5.8E+01	6.4E+00	4.3E+01	1.5E+02	2.1E-01	2.4E-02	1.6E-01	5.7E-01	FE-SCRP-HANDLIN-W
Pu-241	9.3E-01	1.0E-01	7.0E-01	2.5E+00	3.4E-03	3.8E-04	2.6E-03	9.1E-03	FE-SCRP-HANDLIN-W
Am-241	8.5E+01	1.1E+01	6.3E+01	2.2E+02	3.2E-01	4.0E-02	2.3E-01	8.3E-01	FE-SLAG-HANDLIN-W
Cm-242	3.2E+00	4.1E-01	2.4E+00	8.6E+00	1.2E-02	1.5E-03	8.9E-03	3.2E-02	FE-SCRP-HANDLIN-W
Pu-242	5.5E+01	6.1E+00	4.1E+01	1.5E+02	2.0E-01	2.2E-02	1.5E-01	5.4E-01	FE-SCRP-HANDLIN-W
Cm-244	4.8E+01	4.6E+00	2.9E+01	1.5E+02	1.8E-01	1.7E-02	1.1E-01	5.5E-01	FE-SLAG-HANDLIN-W

5 EVALUATION OF RECYCLE AND DISPOSAL OF COPPER SCRAP

Twenty-three potential exposure scenarios for cleared copper scrap that are realistically based on current American industries are evaluated in this section. As in the steel evaluation, scenario categories include handling and processing, storage, transportation, product use, and disposal. A radionuclide-specific, probabilistic dose factor distribution was calculated for the members of all exposed groups, and a dose factor for an average member of each critical group was calculated in the same manner as for steel recycle. The mean dose factor for each critical group is reported in normalized units of μSv/y per Bq/g scrap (mrem/y per pCi/g) and μSv/y per Bq/cm^2 scrap (mrem/y per pCi/cm^2) for each radionuclide. Dose factors at the 5th, 50th, and 95th percentiles are also reported.

The copper recycle analyses yield similar critical groups as steel recycle. The most common critical groups are commercial truck drivers carrying cleared copper scrap and workers at copper refineries. Scenarios involving transport of scrap material resulted in critical group designation for approximately half (47) of the 85 radionuclides in the analysis. Other scenarios identifying critical groups for many radionuclides involve handling refinery slag (31 radionuclides). Only one critical group involves the use of steel consumer products: use of a generic small object close to the body made from refined copper.

Mean critical-group dose factors for the radionuclides range from a high of 3.3E+02 μSv/y per Bq/g (1.2 mrem/y per pCi/g) for Th-229 to a low of 4.2E-04 μSv/y per Bq/g (1.6E-06 mrem/y per pCi/g) for Ni-59. The surficial mean critical-group dose factors range from 2.9E+2 μSv/y per Bq/cm^2 (Th-229) down to 3.6E-4 μSv/y per Bq/cm^2 (Ni-59). The Th-229 dose factors are not unusual for the set of copper dose factors, as 16 other dose factors are within a factor of three of the Th-229 values. Seventy-three of the radionuclide-specific, copper critical-group dose factors are 135 μSv/y per Bq/g or lower (0.5 mrem/y per pCi/g).

This section describes the technical evaluation of the recycle and disposal of copper scrap that could be cleared from Nuclear Regulatory Commission (NRC) licensed facilities. Similar to steel scrap (Section 4), the flow of cleared material was probabilistically modeled, distributions of radionuclide concentrations in refined and disposed materials were calculated, and the mean dose factors for each potentially exposed group were estimated.

5.1 Introduction to Analysis

The analysis process for calculating potential exposure from copper recycle and disposal is essentially the same as described previously for iron and steel. A material flow model specific to copper scrap was developed, radionuclide concentrations were calculated, and scenario evaluations were conducted. Besides the material flow model (and calculated concentrations in refined and disposed materials), there are only minor differences between the steel and copper scrap analyses. There are several minor scenario parameter differences and one additional exposure scenario that is specific to recycled copper scrap (described in Section 5.6).

5.2 Flow of Recycled and Disposed Copper Scrap

The material flow model for copper represents the general processes that cleared material would go through from the time it is cleared by a licensed facility to the time of final disposal. Similar to steel, the copper material flow model is comprised of two types of models: conceptual and mathematical. The conceptual model describes the copper refining process and defines the limits of this analysis, while the mathematical model presents the mathematical equations that implement the information presented in the conceptual model.

The material flow model is based on a literature review of the U.S. secondary copper industry. It is intended to provide a defensible basis for developing appropriate exposure scenarios. In addition, the output of the material flow model provides key input to the dose calculations for each scenario. This input consists of radionuclide-specific concentrations in recycle byproducts, in effluents, and in waste products of the refining process. Because of the number of scenarios being analyzed and the differing times at which they occur, the mathematical model presented in this section does not include radioactive decay. However, radioactive decay is taken into account in the individual scenarios, in the same manner as in the steel recycle analysis.

This section presents the conceptual model that describes the movement of scrap through the normal refining process, beginning with the production of scrap, through refining, manufacturing, product use, and ending with disposal. Figure 5.1 presents a schematic diagram of the overall material flow for copper scrap. The mass of material and the amount of radioactivity are tracked separately so that the radioactivity concentration can be calculated at any point in the flow. The steps or processes in the refining process are shown in Figure 5.1. Each of these are discussed separately in the following subsections.

5.2.1 Sources of Material

Recyclers are the producers of scrap metal. Recyclers can be the general public (e.g., recycling copper wire), industry (e.g., recycle disused copper items), or manufacturers (e.g., scrap produced during manufacture of end products).

A total of 1.32E+6 t (1.5E+6 ton) of secondary copper—scrap—was consumed in the U.S. in 1995 (USBM 1997). Similar to steel scrap, there are three types of scrap metal used in the copper-making industry: home, new, and old. *Home scrap* consists of unusable metal produced during the processing or fabrication of copper into a form usable for manufacturing. Home scrap is usually high-grade metal with very few impurities. Even though home scrap is produced at the refinery, it is still considered a secondary metal because it is not the processed raw material. *New scrap* is produced during manufacture of end products. New scrap also is high-grade metal with very few impurities. *Old scrap* includes obsolete, worn-out or broken products that have been used by the general public or industry. Old scrap is usually low-grade metal and the chemical composition is not well-known. Therefore, it must first be sorted, sized, and classified. Cleared scrap metal from the nuclear industry is considered old scrap.

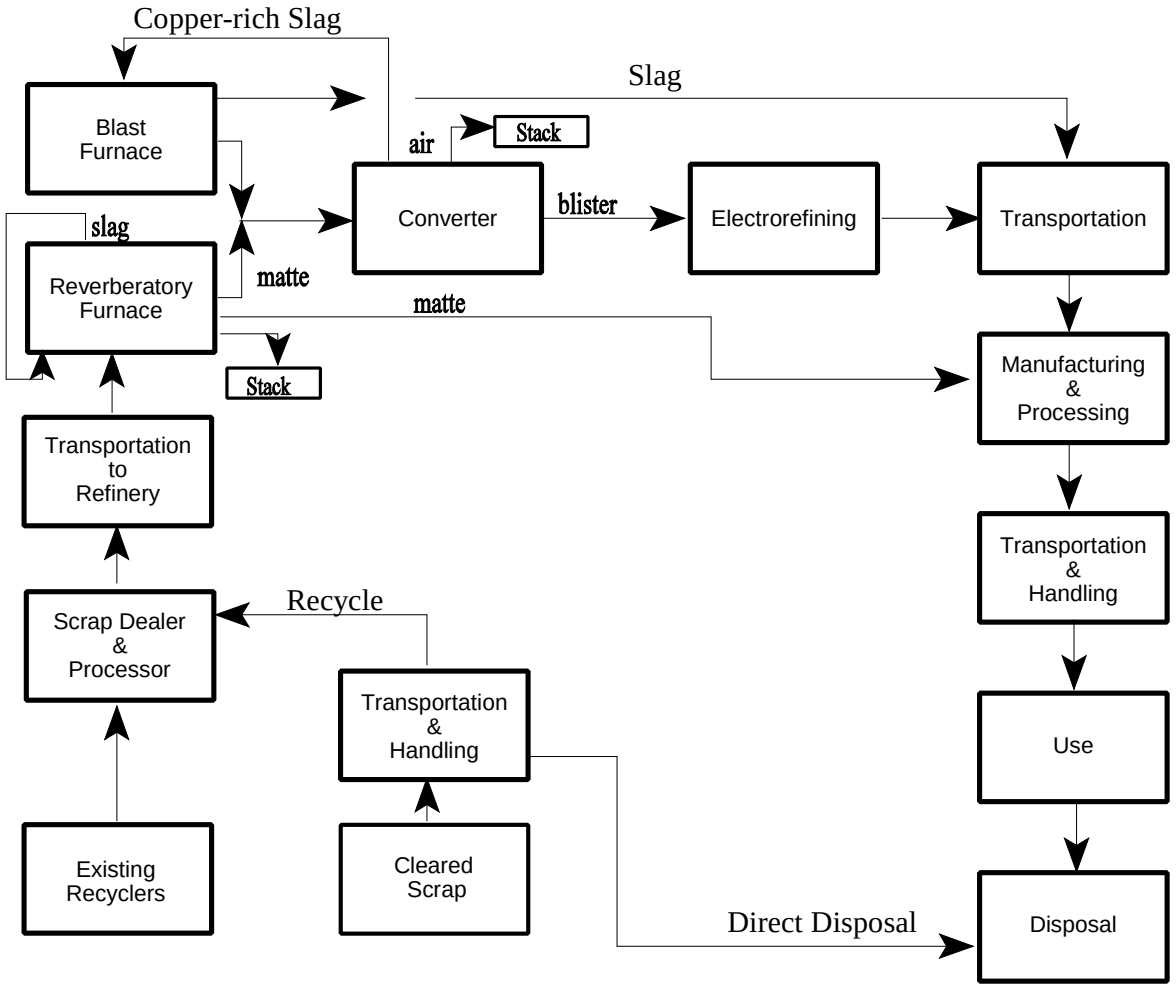

Figure 5.1 Material flow for copper scrap

The main producer of the scrap assumed for this study is the nuclear industry (decommissioned material from nuclear facilities), which consists mainly of commercial power plants, test and research reactors, and industrial nuclear facilities. Other producers of such scrap include the Department of Energy (DOE) weapons complex and the Department of Defense (DOD), which would contribute slightly contaminated scrap primarily from conventional weapons testing and army and navy test reactors. Approximately 1.0E+3 t/y (1.1E+3 ton/y) of potentially recyclable copper and brass scrap metal is generated each year from NRC licensed facilities. Increased dismantling and decommissioning activities could result in approximately 1.80E+4 t/y (2.0E+4 ton/y) of copper scrap (NUREG/CR-5610[1]) for a limited number of years. Current home, new,

[1]Recycle/Reuse Literature Search Report, SAIC, 1994 scheduled to be published as NUREG/CR-5610

and old scrap is essentially uncontaminated. Similar to the steel analysis, cleared copper scrap is assumed to be mixed with a single source of uncontaminated scrap.

5.2.2 Transportation and Processing

Scrap copper cleared from a nuclear facility must be transported to a scrap dealer or processor; this would most likely be done by a commercial company. Because not all licensee scrap is likely to be suitable for recycle, some would be transported directly to a disposal site. In all cases, transportation could occur either by truck or rail.

After scrap is processed at a scrap dealer, it is transported by either rail or truck to a refinery. The types of activities performed at the scrap refinery include shearing the metal into size, briquetting or crushing thin and lightweight materials (e.g., turnings and borings), magnetically separating iron, and cleaning and degreasing (Bever 1986). Slag, metal products, and dust produced at the refinery or mill are transported to manufacturers or processors by either truck, rail, or waterway.

5.2.3 Copper Mills

Copper scrap can be used in many different types of refineries and mills. According to Smith (1996) approximately 30% of the scrap consumed was in copper smelters and refiners, 51% in brass mills, 10% in brass and bronze ingot makers, and the remaining by miscellaneous manufacturers, foundries, and chemical plants. Brass mills use mainly new scrap while copper smelters and refiners use mainly old scrap. Because it is possible and likely that scrap from the nuclear industry would be recycled in brass mills as well as copper smelters and refiners, both have been analyzed. The typical furnace that scrap would enter for copper recycling is the reverberatory furnace. The output from the reverberatory furnace can then be further refined in a converter and electrorefiner.

5.2.3.1 Reverberatory Furnace

In the reverberatory furnace, the lighter impurities combine and float to the top of the melt as a slag that is skimmed off and discarded, while the copper, iron, most of the sulfur, and any contained precious metals form a product know as “matte” (USBM 1985). This molten matte is collected and is drawn off from the lower part of the furnace. The copper matte from the reverberatory furnace has a typical copper concentration between 50% and 75% (EPA 1995). According to industry, a typical reverberatory furnace operates at a temperature of about 1100°C (2000°F). Very small amounts of sand and limestone additives are typically added to the furnace.[1,2] A typical charge size for a reverberatory furnace ranges from 18–499 t (20-550 tons).[1] An average value of 227 t (250 tons) is used[2] in the model. A typical copper refinery using a

[1]Personal communication between M. Anderson, SAIC and G. Golebiowski, Muellar Copper Tube Co., May 27, 1997.

[2]Personal communication between M. Anderson, SAIC and J. Schuster, Cerro Copper Tube Co., May 27, 1997.

reverberatory furnace has an average of 1016 t (1,120 ton) of charge/furnace-day (Butts 1970). This results in about 4 charges/day for a single furnace or 1460 charges/year.

The brass refineries operate at temperatures similar to the reverberatory furnace. Brass refineries use either rotary or electric furnaces. A typical charge size for a rotary furnace ranges from 9–45 t (10–50 tons), while the electric furnace has a typical charge size of about 2.3 t (2.5 ton). There is no slag produced in the electric furnace. The output of a reverberatory furnace in brass refineries is assumed to be similar to the output of the copper refinery reverberatory furnace.

5.2.3.2 Converter

The matte from the reverberatory furnace is fed into the converter where air flowing through the matte burns off the sulfur, oxidizes the iron for removal in a slag, and yields a product called "blister" copper (USBM 1985). A typical converter must operate between 1220°C and 1350°C (2230°F–2460°F) (Butts 1970). Below 1220°C the temperature is too low to form a true slag, while above 1350°C the heat will wear out the basic lining very rapidly. Converter slags are generally disposed of by pouring them back into the blast furnaces (Butts 1970).

5.2.3.3 Electrorefiner

The blister copper from the converter is approximately 99.5% Cu. It is first cast into anodes that are fed into the electrorefiner. Electrorefining consists of placing the impure copper anodes and thin, pure-copper cathode starting sheets in a $CuSO_4$-H_2SO_4-H_2O electrolyte and passing a direct current between them. The electric current causes the copper to dissolve from the anode and plate in pure form on the cathode (Bever 1986). Cathodes are typically grown for 10-14 days to a weight of about 150 kg (330 lbs). The anodes are left in the electrolytic cells until they are almost completely dissolved, usually forming two batches of cathodes. The undissolved anode scrap is washed, melted, and recast as fresh anodes for further refining (Bever 1986). Solid impurities in the anodes fall to the bottom of the cell as a sludge where they are ultimately collected and processed for the recovery of precious metals such as gold and silver. This material is known as "anode slime" (EPA 1986).

The fumes that are generated during the refining of copper scrap are captured by the primary exhaust hood and transported via a duct system to a baghouse. The baghouse used in the refining of copper scrap is similar to those used in the iron and steel industry. Therefore, the same parameters for the baghouse are used for the recycling of copper (e.g., temperature, efficiency). The baghouse dust produced during the refining of copper scrap is not considered hazardous.[1,2]

[1]Personal communication between M. Anderson, SAIC and G. Golebiowski, Muellar Copper Tube Co., May 27, 1997.

[2]Personal communication between M. Anderson, SAIC and J. Schuster, Cerro Copper Tube Co., May 27, 1997.

5.2.3.4 Output of Refinery Processes

During each of the refining processes, the original metal separates into four different end products: off-gas, dust, slag, and metal (Figure 5.1). Each radionuclide is partitioned into these four materials in an element-specific manner. This process is described using mass partitioning factors and element-specific elemental partitioning factors. Partitioning factors are defined as the fraction of original radionuclide concentration or mass entering the refinery furnace that would be present in various end products. These partitioning factors for copper are discussed in detail in Section 5.3.

Each of the end products undergoes a different process, use, and final disposal process. The off-gas includes elements that are completely volatilized into stable gases or very fine particles during refining and then exit the refinery stack. Dust includes elements that are volatilized from the furnace, form particulates when cooled, and are collected in baghouse filters. (The air pollution control systems are not 100% efficient, and a small percentage of the dust entering the baghouse is released into the atmosphere with the off-gas.)

Slag is not considered a hazardous waste, therefore, it can be reprocessed or directly disposed of. After slag is removed from the furnace and cooled, it is stored in piles outdoors at the refinery until it is either used by the refinery or transported to a processor. Because of its high metal content, slag is usually fed back into the furnace as input material.

Manufacturing and processing converts slag and metal products created at the refineries and mills into finished products. Manufacturing involves activities such as cutting and shaping the metal. Processing of slag involves crushing and sizing. After a metal product or slag is manufactured into a finished product, it must be transported and distributed to the general public (i.e., end user). Facilities involved in the distribution of finished metal products include stores and warehouses. Slag is usually distributed and transported directly from the refinery where it is produced or the manufacturer where it is processed.

5.2.4 Product Use

Finished metal products, and occasionally slag, are used by the public for many applications. The largest use of copper metal is in electrical equipment and supplies. Copper and copper alloy wire are used in manufacturing electric motors and generators, power transmission lines, etc. Copper is also used in producing nonelectrical industrial machinery and parts, such as automobile parts, railroad equipment, and construction materials(e.g., roofing, gutters, nails, plumbing) (USBM 1985). When copper slag is used instead of being recycled, its use is similar to that of iron and steel slag (roadbed, railroad ballast).

5.2.5 Disposal

The ultimate endpoint for finished metal products, slag, and dust is disposal in a public sanitary landfill (Resource Conservation and Recovery Act [RCRA] Subtitle D). Discarded end products, waste from manufacturing, slag direct from the refinery, products made from slag, scrap not suitable for recycle, and dust are all metal byproducts that could be disposed of in a sanitary landfill.

5.3 Mass and Elemental Partitioning Factors for Refinery Operations

For this analysis, the mass of scrap metal entering a furnace during the refining process is redistributed into the three immediate products: metal product, slag, and dust. Radioactivity in incoming scrap metal is redistributed among those products, as well as in the off-gas leaving the refinery stack.

5.3.1 Mass Partitioning Factors

The mass partitioning factors for copper were estimated using information obtained from industry contacts. Mass partitioning factors were determined for the metal product, slag, and dust. Between 90% and 96% of the metal mass entering the reverberatory furnace ends up in the metal product.[1,2] Because the dust produced during the recycling of copper scrap is not considered hazardous, a record of the mass of dust produced per charge is not typically kept by refineries. However, industry estimates that about 1–2% of the original mass entering the furnace ends up in the dust. More dust is produced with dirtier scrap. Because very few additives are added during the recycling of copper, the remaining fraction is assumed to be the mass partitioning to slag.

No information is readily available to determine the mass partitioning for the converter and electrorefiner. However, because the metal product entering these furnaces has a higher content of copper than the metal entering the reverberatory furnace, the percentage of copper recovered is considered to be at least as great as that recovered for the reverberatory furnace. Therefore, for the converter, the same mass partitioning factors are used as for the reverberatory furnace. Very little dust and anode slime is produced during the electrorefining process because of the high purity of the anodes used in the process. Based on engineering judgement, partitioning to metal product is estimated to be as high as 98% for the electrorefiner. Partitioning to the anode slime and dust is estimated to be approximately 1% each.

[1]Personal communication between M. Anderson, SAIC and J. Schuster, Cerro Copper Tube Company, May 27, 1997.

[2]Personal communication between M. Anderson, SAIC and G. Golebiowski, Muellar Copper Tube Company, May 27, 1997.

5.3.2 Elemental Partitioning Factors

Copper recycling involves three steps: a reverberatory furnace, a converter furnace, and an electrorefinery. For the first two furnaces the primary mechanism for impurity removal is oxidation. The first furnace, the reverberatory furnace, removes those impurities that are significantly greater in oxidation potential than copper, while the second, the converter, removes most elements with oxidation potential less than that of copper. In the third step, the electrorefiner, copper preferentially plates out at the cathode while many impurities, such as lead and tin, are left in the anode slime. Nickel accumulates in the electrolyte. Extremely low concentrations of many impurities may be difficult to remove from the copper.

The elemental partitioning factors determined for the material flow model are intended to be representative of the expected behavior during melting beginning with a typical domestic reverberatory furnace. Direct thermodynamic calculations of the oxidation potential of each element were used in estimating elemental partition factors at temperatures typical of the reverberatory furnace and the converter. When these calculations were not possible, elemental partitioning factors were estimated based on the behavior of chemically similar elements. There is significant variability in the behavior of elements during copper refining depending on initial concentration, temperature of the melt, and the presence of chemically similar elements. Any single partitioning value used in the material flow model has some associated uncertainty. In order to address this uncertainty, ranges for the elemental partitioning values were used.

During refining, radionuclides could partition to one or both of the main melt components (i.e., the slag and metal phases) or discharge from the furnace in the volatilized gas. Some of the radionuclides that leave the furnace in the volatilized gas would remain in the vapor phase (off-gas) and some would condense or coalesce into particulates (dust). Radionuclides found in coarse particulates would be captured by the baghouse filter. Some of the fine particles and species in the vapor phase would escape in the off-gas exiting the stack.

Table 5.1 shows the resulting elemental partitioning factors (EPF) for each element. Note that the partitioning factors for some elements (e.g., iodine) do not sum to 100% since the values of the partitioning factors are estimated over a range.

5.4 Mathematical Model for Flow of Recycled Copper Scrap

This section presents the equations that represent the information discussed previously in Section 5.2 and 5.3 and are used to formulate the mathematical model. The equations estimate radionuclide concentrations in refined copper and other co-products of refining. The equations are entered into spreadsheets that have been organized and structured specifically for this analysis. The calculated radionuclide concentrations in refined copper, refinery slag, refinery baghouse dust, and the amount of radioactivity released out the refinery stack are used as input to the scenario analyses.

Table 5.1 Elemental partitioning factor ranges (%) for copper refining

Reverberatory Furnace				
Elements	Matte	Slag	Baghouse Dust	Off-gas
Cu	99–100	.99–1.01	0	0
Ag, Bi, Cd, Co, Cr, Fe, Ir, Mn, Mo, Nb, Ni, Pb, Sb	94–100	.95–1.05	0	0
Po, Re, Ru, Tc, Zr,	69–100	.7–1.3	0	0
Zn	89–99	.95–1.05	4.75–5.25	0
Ac, Am, Cm, Np, Pa, Pu, Th, U	0–5	95–100	0	0
P, S, Se	0–30	70–100	0	0
Ca, Cs, K, Na	0	94–100	.95–1.05	0
Ba, Sr	35–65	35–65	0	0
Ce, Eu, Pm, Y,	19–31	56–94	0	0
Ra	19–31	19–31	0	0
C	0	38–62	0	71–100
I	0	59–100	0	.6–1.4
Cl	0	30–70	29–69	.9–1.1
H, Rn	0–5	0	0	95–100

Converter				
Elements	Blister Copper	Slag	Baghouse Dust	Off-gas
Cu	98–100	.99–1.01	0	0
Ag, Ir	94–100	.05–1.05	0	0
Bi, Co, Cr, Fe, Mn, Mo, Nb, Ni, Sb	9.5–10.5	86–94	0	0
Re, Ru, Tc, Zr	7–13	63–100	0	0
Cd, Pb, Zn	9.5–10.5	0	86–94	0
Po	9.5–10.5	0	63–100	0
Ac, Am, Cm, Pa, Np, Pu, Th, U	0–5	95–100	0	0
P, S, Se	0–30	70–100	0	0
Ca, Cs, K, Na	0	94–100	.95–1.05	0
Ba, Sr	35–65	35–65	0	0
Ce, Eu, Pm, Ra Y	19–31	56–94	0	0
C	0	3.8–6.2	0	71–100
I	0	59–100	0	.6–1.4
Cl	0	30–70	29–69	.9–1.1
H, Rn	0–5	95–100	0	95–100

Electrorefiner				
Elements	Copper	Anode Slime	Baghouse Dust	Off-gas
Cu	99–100	0–1	0	0
Ac, Ag, Am, Ba, Bi, Ca, Cd, Ce, Cm, Co, Cr, Cs, Eu, Fe, Ir, K, Mn, Mo, Na, Nb, Ni, Np, Pa, Pb, Pm, Po, Pu, Ra, Re, Ru, Sb, Sr, Tc, Th, U, Y, Zn, Zr	0–1	99–100	0	0
P, S, Se	0–5	70–100	0	0
C, H, Rn	0–5	0	0	95–100
I	0–20	0	0	80–100
Cl	0	0	38–62	38–62

5.4.1 Mixing of Cleared and Other Scrap

There are only two processes by which the original concentration of each radionuclide in cleared copper scrap can be potentially changed. The first can occur upon mixing with other scrap metal prior to refining. This mixing is a radionuclide-independent process, so the radioactivity concentration of all radionuclides is effected the same when mixing cleared copper scrap with a given mass of other copper scrap. The second process is the refining process itself, which generally consists of melting the copper scrap metal results in a redistribution (partitioning) of mass and radioactivity. Partitioning of mass during melting is radionuclide independent, however, partitioning of radioactivity during refining is element dependent. The following equations are used to calculate the concentrations in refinery co-products at those points in the material flow which correspond to potential exposure scenarios.

The following set of equations is used for all three steps used in copper refining (reverberatory furnace, converter furnace, and electrorefiner). Copper refining is a sequential process (except for the reflux from the converter, which is assumed to be steady state), so the calculated mass and radioactivity concentrations in refined copper from the reverberatory furnace is used as input to the converter furnace. Similarly, the output from the converter furnace is used as input to the electrorefiner.

The total mass of material entering the furnace in a year, including cleared material, other scrap, and primary metal was calculated using Equation 5.1.

$$M_1 = M_0 + M_{NC} \qquad 5.1$$

where

M_1 = total mass of scrap metal entering the furnace per charge (g/charge)

and

M_0 = mass of cleared material entering the furnace per charge (g/charge)

M_{NC} = mass of other scrap metal entering the furnace per charge (g/charge)

Mixing of cleared scrap with metal from sources other than licensed facilities can occur at the scrap dealer (i.e., secondary metal pool) and at the refinery, where material from the primary metal pool enters the furnace. In this analysis, no distinction is made between the two sources of other metal. The mass of other metal includes contributions at the scrap yard and at the refinery.

The radionuclide concentration in the metal entering the furnace was calculated using Equation 5.2. The following equations are intended to be evaluated separately for each radionuclide in the analysis. Therefore, parameters such as concentration, decay factors, decay constants, and dose conversion factors are not explicitly subscripted for each radionuclide.

$$C_1 = \frac{M_0}{M_1} * C_0 \qquad 5.2$$

where

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)

and

M_0 = mass of cleared material entering the furnace per charge (g/charge)

M_1 = total mass of scrap metal entering the furnace per charge (g/charge)

C_0 = original radionuclide concentration in cleared material (pCi/g)

For slag, baghouse dust, and off-gas, Equations 5.1 and 5.2 were evaluated using annual average values for the masses of scrap entering the furnaces because all the exposure scenarios for these materials depend on annual average concentrations. For metal, both an annual average and a single charge evaluation of Equations 5.1 and 5.2 were conducted. This was done for metal because there are metal products that could easily be manufactured from a single refinery charge. The single charge concentrations were used in metal product-use exposure scenarios except where noted. (See Appendix D for additional details.)

5.4.2 Refinery Processes

To accurately account for concentration changes in the different products, the mass of each refinery product must be calculated. Equations 5.3, 5.4, and 5.5 are used to calculate the masses of slag, dust, and metal product, respectively (no mass is associated with the completely volatilized elements).

$$M_s = M_1 * f_{s1} * CPY \qquad 5.3$$

$$M_d = M_1 * f_{d1} * CPY \qquad 5.4$$

$$M_p = M_1 * f_{p1} * CPY \qquad 5.5$$

Where

M_s = mass of slag produced from a refinery per year (g/y)

M_d = mass of dust produced from a refinery per year (g/y)

M_p = mass of metal product produced from a refinery per year (g/y)

and

M_1 = total mass of scrap entering the furnace per charge (g/charge)

f_{s1} = mass partitioning factor for slag during the refining process (dimensionless)
f_{d1} = mass partitioning factor for dust during the refining process (dimensionless)
f_{p1} = mass partitioning factor for metal product during the refining process (dimensionless)
CPY = number of charges per refinery per year (charge)

The total amount of radioactivity in the original metal entering the furnace during the refining process is partitioned among four product materials. Equation 5.6 shows the calculation for radionuclide concentration in slag, taking into account both the mass and elemental partitioning factors.

$$C_s = \frac{C_1 * f_s * M_1}{M_1 * f_{s1}} = \frac{C_1 * f_s}{f_{s1}} \qquad 5.6$$

where
C_s = radionuclide concentration in slag after the refining process (pCi/g)
and
C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
f_s = slag elemental partitioning factor during the refining process (dimensionless)
M_1 = total mass of scrap entering the furnace per charge (g/charge)
f_{s1} = mass partitioning factor for slag during the refining process (dimensionless)

The concentration of radionuclides in the dust and metal product are similarly calculated using Equations 5.7 and 5.8, respectively.

$$C_d = \frac{C_1 * f_d}{f_{d1}} \qquad 5.7$$

where
C_d = radionuclide concentration in dust after the refining process (pCi/g)
and
C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
f_d = dust elemental partitioning factor during the refining process(dimensionless)
f_{d1} = mass partitioning factor for dust during the refining process (dimensionless)

$$C_p = \frac{C_1 * f_p}{f_{p1}} \quad 5.8$$

where

C_p = radionuclide concentration in metal product after the refining process (pCi/g)

and

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
f_p = metal product elemental partitioning factor during the refining process (dimensionless)
f_{p1} = mass partitioning factor for metal product during the refining process (dimensionless)

No mass is explicitly calculated for the refinery off-gas. Exposure scenarios for atmospheric effluents are based on the total amount of radioactivity released from the refinery stack each year. The annual amount of radioactivity in the off-gas was calculated using Equation 5.9.

$$A_g = C_1 * M_1 * f_g * CPY \quad 5.9$$

where

A_g = radioactivity in the off-gases leaving the refinery stack in a year (pCi/y)

and

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
M_1 = total mass of scrap entering the furnace per charge (g/charge)
f_g = off-gas elemental partitioning factor during the refining process (dimensionless)
CPY = number of charges per refinery per year (charge)

Equations 5.10 and 5.11 are used to calculate the mass of dust that escapes the baghouse filters and the mass that is captured in the baghouse, respectively.

$$M_{ra} = M_d * (1 - BH_{eff}) \quad 5.10$$

where

M_{ra} = total mass of dust that escapes the baghouse in a year (g/y)

and

M_d = mass of dust produced from the refining process in a year (g/y)
BH_{eff} = baghouse efficiency (dimensionless)

$$M_{db} = M_d - M_{ra} \quad 5.11$$

where

M_{db} = total mass of dust captured in the refinery baghouse in a year (g/y)

and

M_d = mass of dust produced from the refining process in a year (g/y)
M_{ra} = total mass of dust that escapes the baghouse in a year (g/y)

5.5 Radioactivity Concentrations in Copper Refining Co-products

Mean radionuclide concentrations in the co-products from copper refining are listed in Tables 5.2 through 5.4 for each of the three refining steps. These values represent estimated radioactivity concentrations in the refinery output. The values are normalized to a unit radioactivity concentration in scrap and are only listed in S.I. units since the values are numerically identical if expressed in conventional units (e.g., pCi/g product per pCi/g scrap).

As stated above, Tables 5.2 through 5.4 list the mean concentration of each radionuclide in each medium. Tabulations are limited to mean values simply because of the space that would be required if percentiles from the distributions were also tabulated. The entire distribution of values for each radionuclide in the appropriate medium was used as input for the exposure scenario analysis.

Table 5.2 Results of material flow model—copper reverberatory furnace

	Mean radionuclide concentrations in refinery products (Bq/g product per Bq/g scrap)				
	Refined Metal				Off-gas
Nuclide	Single Charge	Annual	Slag	Dust	(Bq per Bq/g)
H-3	1.4E-02	3.2E-04	0.0E+00	0.0E+00	3.1E+10
C-14	0.0E+00	0.0E+00	1.6E-02	0.0E+00	2.7E+10
Na-22	0.0E+00	0.0E+00	3.1E-01	1.6E-02	0.0E+00
P-32	1.3E-01	2.9E-03	2.7E-01	0.0E+00	0.0E+00
S-35	1.3E-01	2.9E-03	2.7E-01	0.0E+00	0.0E+00
Cl-36	0.0E+00	0.0E+00	1.6E-01	8.0E-01	3.1E+08
K-40	0.0E+00	0.0E+00	3.1E-01	0.0E+00	0.0E+00
Ca-41	0.0E+00	0.0E+00	3.1E-01	1.6E-02	0.0E+00
Ca-45	0.0E+00	0.0E+00	3.1E-01	1.6E-02	0.0E+00
Cr-51	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Mn-54	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Fe-55	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Co-57	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Co-58	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Fe-59	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Ni-59	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Co-60	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Ni-63	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Zn-65	8.1E-01	1.8E-02	3.1E-03	8.2E-02	0.0E+00
Cu-67	8.5E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Se-75	1.3E-01	3.0E-03	2.7E-01	0.0E+00	0.0E+00
Sr-85	4.3E-01	9.6E-03	1.6E-01	0.0E+00	0.0E+00
Sr-89	4.3E-01	9.6E-03	1.6E-01	0.0E+00	0.0E+00
Sr-90	4.3E-01	9.6E-03	1.6E-01	0.0E+00	0.0E+00
Y-91	2.2E-01	4.8E-03	2.3E-01	0.0E+00	0.0E+00
Mo-93	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Nb-93m	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Nb-94	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Nb-95	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Zr-95	7.3E-01	1.6E-02	3.1E-03	0.0E+00	0.0E+00
Tc-99	7.3E-01	1.6E-02	3.1E-03	0.0E+00	0.0E+00
Ru-103	7.3E-01	1.6E-02	3.1E-03	0.0E+00	0.0E+00
Ru-106	7.3E-01	1.6E-02	3.1E-03	0.0E+00	0.0E+00
Ag-108m	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Cd-109	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Ag-110m	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Sb-124	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
I-125	0.0E+00	0.0E+00	2.5E-01	0.0E+00	3.1E+08
Sb-125	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
I-129	0.0E+00	0.0E+00	2.5E-01	0.0E+00	3.1E+08
I-131	0.0E+00	0.0E+00	2.5E-01	0.0E+00	3.1E+08
Ba-133	4.3E-01	9.6E-03	1.6E-01	0.0E+00	0.0E+00
Cs-134	0.0E+00	0.0E+00	3.1E-01	1.6E-02	0.0E+00
Cs-137	0.0E+00	0.0E+00	3.1E-01	1.6E-02	0.0E+00

Table 5.2 Results of material flow model—copper reverberatory furnace

	Mean radionuclide concentrations in refinery products (Bq/g product per Bq/g scrap)				
	Refined Metal				Off-gas
Nuclide	Single Charge	Annual	Slag	Dust	(Bq per Bq/g)
Ce-141	2.2E-01	4.8E-03	2.4E-01	0.0E+00	0.0E+00
Ce-144	2.2E-01	4.8E-03	2.3E-01	0.0E+00	0.0E+00
Pm-147	2.2E-01	4.8E-03	2.4E-01	0.0E+00	0.0E+00
Eu-152	2.2E-01	4.8E-03	2.3E-01	0.0E+00	0.0E+00
Eu-154	2.2E-01	4.8E-03	2.4E-01	0.0E+00	0.0E+00
Eu-155	2.2E-01	4.8E-03	2.4E-01	0.0E+00	0.0E+00
Re-186	7.3E-01	1.6E-02	3.2E-03	0.0E+00	0.0E+00
Ir-192	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Pb-210	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Po-210	7.3E-01	1.6E-02	3.2E-03	0.0E+00	0.0E+00
Bi-210	8.4E-01	1.9E-02	3.1E-03	0.0E+00	0.0E+00
Rn-222	1.4E-02	3.2E-04	0.0E+00	0.0E+00	3.1E+10
Ra-223	2.2E-01	4.8E-03	7.8E-02	0.0E+00	0.0E+00
Ra-224	2.2E-01	4.8E-03	7.8E-02	0.0E+00	0.0E+00
Ac-225	1.4E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Ra-225	2.2E-01	4.8E-03	7.9E-02	0.0E+00	0.0E+00
Ra-226	2.2E-01	4.8E-03	7.8E-02	0.0E+00	0.0E+00
Ac-227	1.5E-02	3.3E-04	3.1E-01	0.0E+00	0.0E+00
Th-227	1.4E-02	3.3E-04	3.1E-01	0.0E+00	0.0E+00
Th-228	1.5E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Ra-228	2.2E-01	4.8E-03	7.8E-02	0.0E+00	0.0E+00
Th-229	1.4E-02	3.3E-04	3.1E-01	0.0E+00	0.0E+00
Th-230	1.4E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Pa-231	1.4E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Th-231	1.4E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Th-232	1.4E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Pa-233	1.5E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
U-233	1.5E-02	3.1E-04	3.1E-01	0.0E+00	0.0E+00
Th-234	1.4E-02	3.1E-04	3.1E-01	0.0E+00	0.0E+00
U-234	1.4E-02	3.1E-04	3.1E-01	0.0E+00	0.0E+00
U-235	1.5E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Np-237	1.5E-02	3.1E-04	3.1E-01	0.0E+00	0.0E+00
Pu-238	1.4E-02	3.1E-04	3.1E-01	0.0E+00	0.0E+00
U-238	1.4E-02	3.3E-04	3.1E-01	0.0E+00	0.0E+00
Pu-239	1.4E-02	3.3E-04	3.1E-01	0.0E+00	0.0E+00
Pu-240	1.4E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Pu-241	1.4E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Am-241	1.4E-02	3.3E-04	3.1E-01	0.0E+00	0.0E+00
Cm-242	1.5E-02	3.1E-04	3.1E-01	0.0E+00	0.0E+00
Pu-242	1.4E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00
Cm-244	1.4E-02	3.2E-04	3.1E-01	0.0E+00	0.0E+00

Table 5.3 Results of material flow model—copper converter furnace

	Mean radionuclide concentrations in refinery products (Bq/g product per Bq/g scrap)		
Nuclide	Refined Metal	Slag	Dust
H-3	5.7E-06	0.0E+00	0.0E+00
C-14	0.0E+00	0.0E+00	0.0E+00
Na-22	0.0E+00	0.0E+00	0.0E+00
P-32	4.7E-04	4.2E-02	0.0E+00
S-35	4.7E-04	4.2E-02	0.0E+00
Cl-36	0.0E+00	0.0E+00	0.0E+00
K-40	0.0E+00	0.0E+00	0.0E+00
Ca-41	0.0E+00	0.0E+00	0.0E+00
Ca-45	0.0E+00	0.0E+00	0.0E+00
Cr-51	2.0E-03	2.9E-01	0.0E+00
Mn-54	2.0E-03	2.9E-01	0.0E+00
Fe-55	2.0E-03	2.9E-01	0.0E+00
Co-57	2.0E-03	2.9E-01	0.0E+00
Co-58	2.0E-03	2.9E-01	0.0E+00
Fe-59	2.0E-03	2.9E-01	0.0E+00
Ni-59	2.0E-03	2.9E-01	0.0E+00
Co-60	2.0E-03	2.9E-01	0.0E+00
Ni-63	2.0E-03	2.9E-01	0.0E+00
Zn-65	1.9E-03	0.0E+00	1.5E+00
Cu-67	2.0E-02	3.3E-03	0.0E+00
Se-75	4.5E-04	4.2E-02	0.0E+00
Sr-85	5.1E-03	8.3E-02	0.0E+00
Sr-89	5.1E-03	8.3E-02	0.0E+00
Sr-90	5.1E-03	8.3E-02	0.0E+00
Y-90	1.3E-03	6.3E-02	0.0E+00
Y-91	1.3E-03	6.3E-02	0.0E+00
Mo-93	2.0E-03	2.9E-01	0.0E+00
Nb-93m	2.0E-03	2.9E-01	0.0E+00
Nb-94	2.0E-03	2.9E-01	0.0E+00
Nb-95	2.0E-03	2.9E-01	0.0E+00
Zr-95	1.7E-03	2.3E-01	0.0E+00
Tc-99	1.7E-03	2.3E-01	0.0E+00
Ru-103	1.7E-03	2.3E-01	0.0E+00
Ru-106	1.7E-03	2.3E-01	0.0E+00
Ag-108m	1.9E-02	2.3E-03	0.0E+00
Cd-109	2.0E-03	0.0E+00	1.6E+00
Ag-110m	1.9E-02	2.3E-03	0.0E+00
Sb-124	2.0E-03	2.9E-01	0.0E+00
I-125	0.0E+00	0.0E+00	0.0E+00
Sb-125	2.0E-03	2.9E-01	0.0E+00
I-129	0.0E+00	0.0E+00	0.0E+00
I-131	0.0E+00	0.0E+00	0.0E+00
Ba-133	5.1E-03	8.4E-02	0.0E+00
Cs-134	0.0E+00	0.0E+00	0.0E+00
Cs-137	0.0E+00	0.0E+00	0.0E+00
Ce-141	1.3E-03	6.3E-02	0.0E+00
Ce-144	1.3E-03	6.3E-02	0.0E+00
Pm-147	1.3E-03	6.2E-02	0.0E+00
Eu-152	1.3E-03	6.2E-02	0.0E+00
Eu-154	1.3E-03	6.2E-02	0.0E+00

Table 5.3 Results of material flow model—copper converter furnace

	Mean radionuclide concentrations in refinery products (Bq/g product per Bq/g scrap)		
Nuclide	Refined Metal	Slag	Dust
Eu-155	1.3E-03	6.2E-02	0.0E+00
Re-186	1.7E-03	2.3E-01	0.0E+00
Ir-192	2.0E-02	2.3E-03	0.0E+00
Pb-210	2.0E-03	0.0E+00	1.5E+00
Po-210	1.7E-03	0.0E+00	1.2E+00
Bi-210	2.0E-03	2.9E-01	0.0E+00
Rn-222	5.3E-06	0.0E+00	4.9E+08
Ra-223	1.3E-03	6.3E-02	0.0E+00
Ra-224	1.3E-03	6.3E-02	0.0E+00
Ac-225	5.6E-06	5.4E-03	0.0E+00
Ra-225	1.3E-03	6.3E-02	0.0E+00
Ra-226	1.3E-03	6.3E-02	0.0E+00
Ac-227	5.6E-06	5.4E-03	0.0E+00
Th-227	6.1E-06	5.6E-03	0.0E+00
Th-228	6.1E-06	5.6E-03	0.0E+00
Ra-228	1.3E-03	6.3E-02	0.0E+00
Th-229	6.1E-06	5.6E-03	0.0E+00
Th-230	6.1E-06	5.6E-03	0.0E+00
Pa-231	6.0E-06	5.6E-03	0.0E+00
Th-231	6.1E-06	5.6E-03	0.0E+00
Th-232	6.1E-06	5.6E-03	0.0E+00
Pa-233	6.0E-06	5.6E-03	0.0E+00
U-233	5.8E-06	5.5E-03	0.0E+00
Th-234	6.1E-06	5.6E-03	0.0E+00
U-234	5.8E-06	5.5E-03	0.0E+00
U-235	5.8E-06	5.5E-03	0.0E+00
Np-237	5.8E-06	5.4E-03	0.0E+00
Pu-238	5.7E-06	5.6E-03	0.0E+00
U-238	5.8E-06	5.5E-03	0.0E+00
Pu-239	5.7E-06	5.6E-03	0.0E+00
Pu-240	5.7E-06	5.6E-03	0.0E+00
Pu-241	5.7E-06	5.6E-03	0.0E+00
Am-241	5.8E-06	5.5E-03	0.0E+00
Cm-242	6.0E-06	5.5E-03	0.0E+00
Pu-242	5.7E-06	5.6E-03	0.0E+00
Cm-244	6.0E-06	5.5E-03	0.0E+00

NOTES:

1) All values are annual averages because single charge values are not needed for any scenarios.
2) Only one radionuclide is partitioned to off-gas, H-3, with an annual release of 5.02E+08 Bq per Bq/g scrap.
3) Radionuclides that have mean concentrations of zero for all refinery products have concentrations of 0 Bq/g in the matte input to the converter.

Table 5.4 Results of material flow model—copper electrorefinery

	Mean concentrations in refinery products (Bq/g product per Bq/g scrap)		
	Refined Metal		
Nuclide	Single Charge	Annual	Slag
H-3	4.2E-06	9.5E-08	0.0E+00
C-14	0.0E+00	0.0E+00	0.0E+00
Na-22	0.0E+00	0.0E+00	0.0E+00
P-32	3.2E-03	6.6E-05	2.4E-02
S-35	3.2E-03	7.4E-05	2.4E-02
Cl-36	0.0E+00	0.0E+00	0.0E+00
K-40	0.0E+00	0.0E+00	0.0E+00
Ca-41	0.0E+00	0.0E+00	0.0E+00
Ca-45	0.0E+00	0.0E+00	0.0E+00
Cr-51	3.0E-04	6.9E-06	1.2E-01
Mn-54	3.1E-04	6.9E-06	1.2E-01
Fe-55	3.0E-04	6.7E-06	1.2E-01
Co-57	3.0E-04	6.8E-06	1.2E-01
Co-58	3.0E-04	6.8E-06	1.2E-01
Fe-59	3.0E-04	6.7E-06	1.2E-01
Ni-59	3.0E-04	6.7E-06	1.2E-01
Co-60	3.0E-04	6.8E-06	1.2E-01
Ni-63	3.0E-04	6.7E-06	1.2E-01
Zn-65	2.9E-04	6.5E-06	1.2E-01
Cu-67	9.2E-01	2.0E-02	4.1E-03
Se-75	3.3E-03	7.2E-05	2.4E-02
Sr-85	7.8E-04	1.7E-05	3.1E-01
Sr-89	7.8E-04	1.7E-05	3.1E-01
Sr-90	7.8E-04	1.7E-05	3.1E-01
Y-91	2.0E-04	4.3E-06	7.8E-02
Mo-93	3.0E-04	6.7E-06	1.2E-01
Nb-93m	3.0E-04	6.8E-06	1.2E-01
Nb-94	3.0E-04	6.8E-06	1.2E-01
Nb-95	3.0E-04	6.8E-06	1.2E-01
Zr-95	2.6E-04	6.0E-06	1.1E-01
Tc-99	2.6E-04	6.0E-06	1.1E-01
Ru-103	2.6E-04	5.7E-06	1.1E-01
Ru-106	2.6E-04	5.7E-06	1.1E-01
Ag-108m	2.9E-03	6.6E-05	1.2E+00
Cd-109	3.1E-04	6.7E-06	1.2E-01
Ag-110m	2.9E-03	6.6E-05	1.2E+00
Sb-124	3.1E-04	6.8E-06	1.2E-01
I-125	0.0E+00	0.0E+00	0.0E+00
Sb-125	3.1E-04	6.8E-06	1.2E-01
I-129	0.0E+00	0.0E+00	0.0E+00
I-131	0.0E+00	0.0E+00	0.0E+00
Ba-133	7.7E-04	1.7E-05	3.1E-01
Cs-134	0.0E+00	0.0E+00	0.0E+00
Cs-137	0.0E+00	0.0E+00	0.0E+00
Ce-141	2.0E-04	4.4E-06	7.8E-02
Ce-144	2.0E-04	4.4E-06	7.8E-02
Pm-147	1.9E-04	4.4E-06	7.8E-02
Eu-152	1.9E-04	4.4E-06	7.8E-02
Eu-154	1.9E-04	4.4E-06	7.8E-02

Table 5.4 Results of material flow model—copper electrorefinery

	Mean concentrations in refinery products (Bq/g product per Bq/g scrap)		
	Refined Metal		
Nuclide	Single Charge	Annual	Slag
Eu-155	1.9E-04	4.4E-06	7.8E-02
Re-186	2.7E-04	5.9E-06	1.1E-01
Ir-192	3.0E-03	6.5E-05	1.2E+00
Pb-210	3.0E-04	6.9E-06	1.2E-01
Po-210	2.6E-04	5.8E-06	1.1E-01
Bi-210	3.0E-04	6.7E-06	1.2E-01
Rn-222	4.7E-06	9.5E-08	0.0E+00
Ra-223	1.9E-04	4.3E-06	7.8E-02
Ra-224	1.9E-04	4.3E-06	7.8E-02
Ac-225	7.9E-07	1.9E-08	3.4E-04
Ra-225	1.9E-04	4.3E-06	7.8E-02
Ra-226	1.9E-04	4.3E-06	7.8E-02
Ac-227	7.9E-07	1.9E-08	3.4E-04
Th-227	9.2E-07	1.7E-08	3.3E-04
Th-228	9.2E-07	1.7E-08	3.3E-04
Ra-228	1.9E-04	4.3E-06	7.8E-02
Th-229	9.2E-07	1.7E-08	3.3E-04
Th-230	9.2E-07	1.7E-08	3.3E-04
Pa-231	9.2E-07	2.0E-08	3.6E-04
Th-231	9.2E-07	1.7E-08	3.3E-04
Th-232	9.2E-07	1.7E-08	3.3E-04
Pa-233	9.2E-07	2.0E-08	3.6E-04
U-233	8.6E-07	1.9E-08	3.5E-04
Th-234	9.2E-07	1.7E-08	3.3E-04
U-234	8.6E-07	1.9E-08	3.5E-04
U-235	8.6E-07	1.9E-08	3.5E-04
Np-237	8.9E-07	2.0E-08	3.4E-04
Pu-238	7.6E-07	1.9E-08	3.4E-04
U-238	8.6E-07	1.9E-08	3.5E-04
Pu-239	7.6E-07	1.9E-08	3.4E-04
Pu-240	7.6E-07	1.9E-08	3.4E-04
Pu-241	7.6E-07	1.9E-08	3.4E-04
Am-241	8.5E-07	1.8E-08	3.3E-04
Cm-242	8.5E-07	2.0E-08	3.4E-04
Pu-242	7.6E-07	1.9E-08	3.4E-04
Cm-244	8.5E-07	2.0E-08	3.4E-04

NOTES:

1) Only one radionuclide is partitioned to off-gas, H-3, with an annual release of 1.56E+06 Bq per Bq/g scrap.
2) Radionuclides that have mean concentrations of zero for all electrorefinery products have concentrations of 0 Bq/g in the blister input to the electrorefinery.

5.6 Dose Assessment for Unique Copper Recycle and Disposal Scenarios

Most of the potential exposure scenarios for recycled and disposed copper scrap are adequately covered by adapting the steel scrap recycle scenarios described in Section 4. Only one scenario was added to the copper analysis that was not already described: the use of copper or bronze piping made of recycled copper scrap. This general scenario was included in the evaluation of copper recycling because it represents a scenario unique to copper and because of the large amount of copper piping in use in the U.S.

Recycled copper can be used to make piping or other plumbing fixtures. The additional scenario described below involves using copper or bronze piping made of recycled copper, where material that has leached from the piping into the drinking water might be ingested.

5.6.1 Exposure Pathways

Ingestion: If copper pipe is used to transport water, a small amount of material could leach from the inside surface of the pipe to the water. If the water is used for drinking or cooking, the leached material could be ingested.

Suspension of particulates from copper piping is unlikely, therefore, the inhalation pathway is not included. Also, external exposure to copper pipes and fixtures was judged to be small in comparison to ingestion of drinking water and was not included in the modeling.

5.6.2 Mathematical Representation

The annual total effective dose equivalent (TEDE) is equal to the effective dose equivalent from the ingestion exposure pathway. The TEDE for a member of the public using copper or bronze piping is represented by Equation 5.12.

$$D_T = D_{ing} \qquad 5.12$$

where

D_T = TEDE for the scenario (mrem/y)

and

D_{ing} = EDE due to ingestion (mrem/y)

Equation 5.13 calculates the radionuclide concentrations in the piping at the time use occurs. This accounts for radioactive decay from the time the scrap is cleared from a nuclear facility to the time the scenario begins. The reference to "source material" in the parameters of Equation 5.13 and other equations means the material that represents the source of exposure. In this scenario, the source material is copper or bronze piping.

$$C_0 = C_x e^{-\lambda_r t_s} \quad 5.13$$

where

C_0 = radionuclide concentration in the source material at time the scenario begins (pCi/g)

and

C_x = undecayed radionuclide concentration in the source material (pCi/g)

λ_r = radioactive decay constant (1/d)

t_s = time from clearance from nuclear facility to time scenario begins (d)

This scenario includes the assumption that while water is transported through a copper or bronze piping, a certain amount of piping material is leached from the pipe into the water. The dose due to this exposure pathway is presented in Equation 5.14.

$$D_{ing} = C_0 * CR_{Cu} * DI_W * F_W * t_{ys} * DF_{ing} * (1E-03) \quad 5.14$$

where

D_{ing} = EDE due to ingestion (mrem/y)

and

C_0 = radionuclide concentration in the source material at time the scenario begins (pCi/g)

CR_{Cu} = leaching rate for copper (mg Cu/L water)

DI_w = total water intake (L water/d)

F_W = fraction of total water intake that is from the copper pipes (dimensionless)

DF_{ing} = ingestion dose factor (mrem/pCi intake)

1E-03 = unit conversion factor (g/mg)

t_{ys} = annual number of days of exposure for the scenario (d/y)

5.7 Parameter Discussion for all Modeled Scenarios

Calculation of potential impacts from recycle of cleared copper scrap material depends on many parameter values. Parameter values are needed for both material flow and dose assessment models. The material flow parameter values rely on information from the U.S. secondary copper industry. The parameter values for the dose modeling are a function of receptor behavior, such as time on a specific job or breathing rate, as well as how the radionuclides are transported in the environment. The dose modeling parameter values are based on those used in the iron and steel modeling described in Section 4. Except for scenario timing assumptions, only those parameter values that are different from those used in the iron and steel modeling are discussed in this section.

Nominal parameter values are described below. Ranges were used to define some parameter values in the modeling. All values and ranges are given in Appendix B.

5.7.1 Scenario Timing

This section presents the basic assumptions used in defining the time periods for each of the copper recycle scenarios. They are based on the scenario timing for the basic oxygen furnace (BOF) iron and steel refinery modeling. The following list of basic assumptions was used in estimating the timing parameters for the scenarios:

Scrap Handling:

- All cleared scrap metal is assumed to be initially taken to a scrap dealer. It takes 4 days for the scrap metal to reach the scrap dealer.

- The scrap metal remains at the scrap dealer for a period of 7 days prior to reuse or disposal and 25 days for scrap metal that is recycled.

Refining and Processing:

- For recycled scrap metal, the refining process and associated product manufacture, final processing, and any on-site storage at the refinery takes a total of 15 days for each of the reverberatory, converter, and electrorefinery facilities.

- The metal product output from the reverberatory and converter facilities immediately enters the converter and electrorefinery, respectively.

- Following initial processing, reverberatory and electrorefinery products undergo further processing before use. This secondary processing, plus storage and handling takes 22 days.

- Distribution of products from the reverberatory and converter takes 7 days.

- Radionuclide releases into the atmospheric effluent from the reverberatory and converter occur at the time the scrap is refined, i.e., 29 and 44 days after clearance, respectively.

Use and Disposal:

- An electrorefinery metal product is used for 30 years, based on an assumed use in the construction industry. Use of a reverberatory metal product is 10 years, based on an assumed general purpose use (IAEA 1992).

- Reverberatory, converter and electrorefinery slag and baghouse dust are produced at the time refining occurs, 29, 44, and 59 days, respectively, after clearance of scrap metal from a licensee.

- Refinery slag that is sold for subsequent use is processed at the refinery 3 days after production and leaves the refinery in another 2 days. Slag is used within 2 days after distribution and is used for a period of 30 years. Once the period of use is completed, the products are disposed of in a sanitary landfill. Slag that is to be directly disposed is held at the refinery for 7 days, at which time it is transported to a disposal facility. The slag is assumed to be disposed immediately following handling at a sanitary landfill.

- Baghouse dust from the reverberatory, converter, and electrorefinery is disposed of onsite or sent to a sanitary disposal facility after 7 days. Storage and handling takes 4 days, at which time disposal occurs.

5.7.2 Dose Evaluation

This section presents a discussion of parameter values used for the analysis of copper recycle scenarios. In general, the same scenarios are analyzed for copper recycle as were analyzed for steel recycle in Section 4. Values used for many of the parameters are also the same as for the steel recycle analysis. For some parameters, however, values specific to the recycle of copper were used in order to more appropriately model the scenarios as they would likely occur for copper recycle. The following discussion is limited to these specific parameter values. If a parameter is not discussed below and listed in Table B.9, the same value as used for the steel evaluation (Table B.7) is used for copper.

5.7.2.1 Input Concentrations from the Material Flow

The undecayed radionuclide concentration in the source material, C_x, is used as the source material input radionuclide concentration for scenario evaluations. This parameter is radionuclide dependent and is calculated in the material flow modeling. Table B.11 lists the sources for C_x, as they appear in the mathematical modeling of the material flow (e.g., C_p, concentration in metal product after the refining process).

5.7.2.2 External Exposure Parameters

This section describes the value used for one parameter needed for calculating external exposure including those that address duration of exposure and material density. Values for these parameters are tabulated in Table B.9.

For the scrap disposal scenario a fixed value of 4.47E+6 g/m^3 is used for the density of waste, consistent with the value used in the calculation of the geometry factors for metal products.

5.7.2.3 Ingestion Exposure Parameters

This section describes the values used for those unique parameters needed for calculating ingestion exposure.

The use of copper or bronze pipes can increase 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, therefore enhancing leaching of copper from the pipes (U.S. Public Health Services 1990). 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 water), which is the EPA drinking-water limit (U.S. Public Health Services 1990). U.S. Public Health Services (1990) presents results from a number of different studies. One study in Canada found that the copper concentration in treated water that has not been exposed to copper pipes was generally very low, $\leq$ 10 ppb (0.01 mg Cu/L water). Another study in Seattle, WA showed the mean copper concentrations in running and standing water from copper pipes were 0.16 and 0.45 ppm, respectively, with an average value of 0.31 ppm (0.31 mg Cu/L water), and an increase in copper concentration due to leaching of copper from the pipes of 0.3 mg Cu/L water. A triangular distribution, with a minimum of 0.16 mg Cu/L, a most likely value of 0.3 mg Cu/L, and a maximum of 1.3 mg Cu/L is used to represent the variation in observed data for the parameter CR_{cu}, the concentration of copper in tap water due to leaching from pipes.

Analysis of survey data has shown that tap water averages about 60% of total water consumption (Roseberry and Burmaster 1992). This analysis supports a lognormal distribution for total tap water consumption having a geometric mean of 1400 ml/d and a geometric standard deviation of 1.78. In addition, not all tap water consumption comes from one's own tap. A significant number of meals are eaten outside one's home, for example. The data on the fraction of tap water from one's own tap are poor and are best represented by a uniform distribution having a minimum of 0.5 and a maximum of 1.0.

5.7.2.4 Atmospheric Release Parameters

The only parameter value for atmospheric dispersion of refinery stack releases from copper recycling facilities that is different from the steel analysis is the total mass of dust that escapes the refinery baghouse in a year, M_{ra}. This value is calculated in the material flow model, and values of 3.31E+06 g and 3.08E+06 g were calculated for the reverberatory and converter, respectively.

The surface-to-mass ratios of various objects (spheres) were examined in estimating values for this parameter for copper. Copper objects are assumed to have a density of 9.0 g/cm^3. Values for various copper objects ranges from approximately 0.01 cm^2/g for large-radius spheres, wire, and bar stock, up to approximately 2.2 for small radius spheres and thin sheets and pipes.

Data are not available to provide an adequate basis for choosing a "best estimate" from this range of values. Using professional judgement and these theoretical data, the value of the parameter SM for recycled copper scrap is best described by a loguniform distribution having a minimum of 0.2 cm^2/g and a maximum of 2.0 cm^2/g. The minimum value is characteristic of heavy wire having a radius of 0.5 cm. The maximum value is characteristic of pipes and sheets having a thickness of 0.05 cm. The range for copper is representative of wire, pipes, and sheets of various sizes with residual radioactivity on one side only. A wide variety of copper and copper alloy

(brass and bronze) objects commonly found at nuclear facilities have surface-to-mass values that fall within this range.

This range can be compared to an estimate from a studies similar to this one. O'Donnell (1978) suggested a generic value of 0.6 cm^2/g as representative of Number 2 copper wire, and O'Donnell's calculations are based on a reference copper object with a surface-to-mass ratio of 0.45cm^2/g.

5.8 Dose Factors for Recycle and Disposal of Copper Scrap

This analysis of recycled cleared copper scrap includes 23 separate scenarios evaluated for 85 radionuclides. Figure 5-2 shows which scenarios describe the critical groups and for how many radionuclides. There are six scenarios which have the highest dose factor for at least one radionuclide. The largest number of radionuclides have critical groups described by scenarios associated with transporting (47 radionuclides) or handling (1 radionuclide) unprocessed scrap. Individuals handling either reverberatory furnace, converter, or electrorefiner slag constitute the critical group for 31 radionuclides. For four volatile radionuclides, the critical group consists of individuals exposed to atmospheric releases from the refining process. Transporting baghouse dust describes the critical group for one radionuclide. Only one radionuclide is limited by a scenario associated with use of a consumer product made from refined copper. Table 5.5 lists the mass-based critical-group dose factors for each radionuclide. Table 5.6 lists the corresponding derived surficial dose factors for each radionuclide. Results for all 23 copper scenarios are tabulated in Appendix G.

The mean values of the critical-group dose factors for each radionuclide are listed in Table 5.5 as the "critical-group dose factor." These represent the dose to the average member of the critical group exposed to radioactivity distributed throughout the mass of cleared copper (Bq/g or pCi/g). The circumstances of that exposure are described by the scenario indicated in the right hand column. The 5^{th}, 50^{th}, and 95^{th} percentiles listed for each radionuclide represent the underlying distribution of dose factors calculated for each critical group. The range of values from the 5^{th} to the 95^{th} percentile is the 90% confidence interval on the dose factor. That is, there is a 90% certainty that the dose factor for the average member of the critical group lies within this interval. The confidence interval is a subjective measure of uncertainty in the dose factor that includes estimates of the variability and uncertainty in the parameters used in each scenario.

The ratio of the 95^{th} to the 5^{th} percentile is a useful measure of the relative width of the 90% confidence interval for comparison between scenarios. Smaller values of the 95/5 ratio indicate less uncertainty than larger values. The scenarios with the smallest uncertainty are those with the fewest number of exposure pathways and the least uncertainty in the parameters describing those pathways. The scrap transportation scenario accounts for 47 of the 85 radionuclides. It has the smallest uncertainty of all the critical group scenarios with a 95/5 ratio of about 2 for most

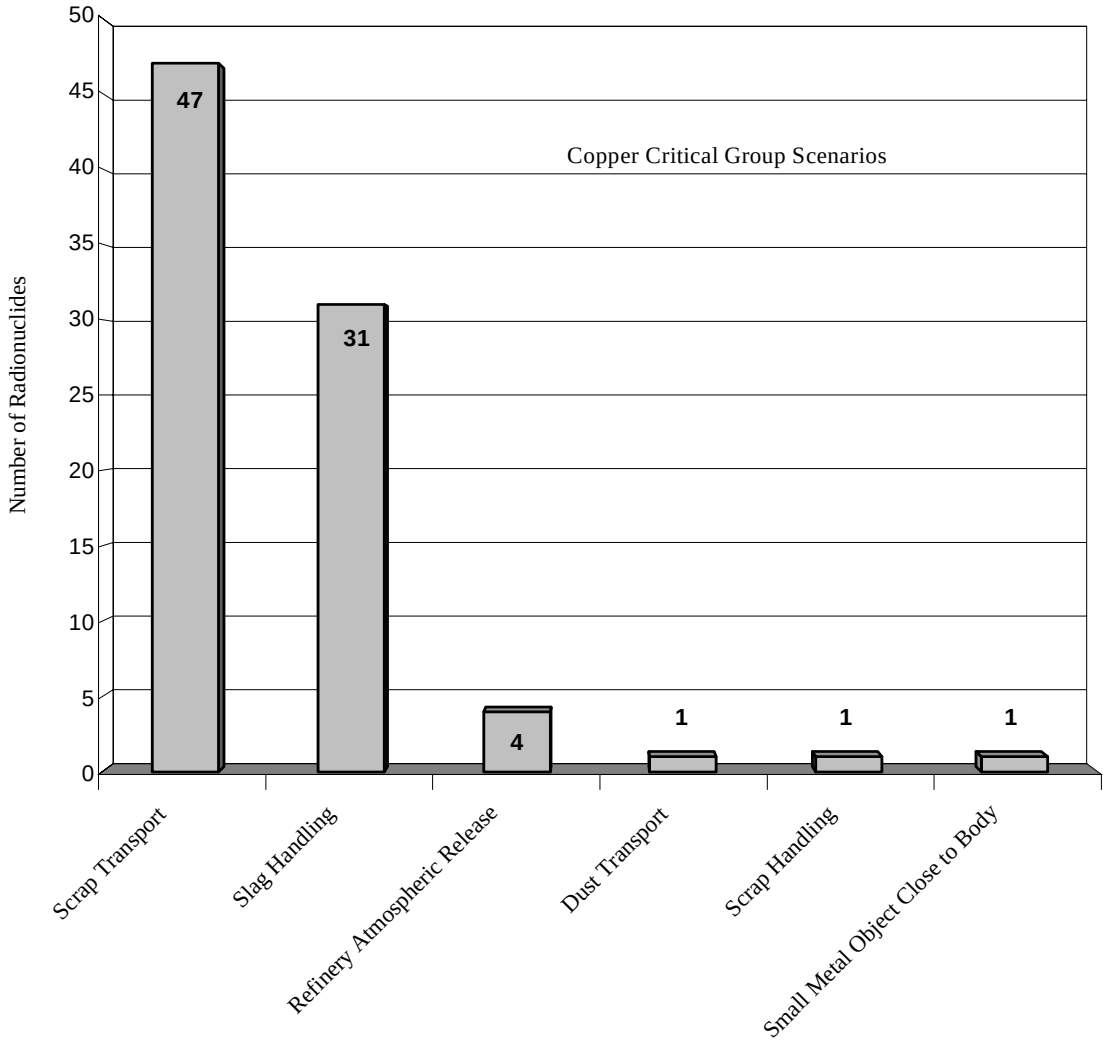

Figure 5.2 Scenarios describing critical groups for copper recycle

radionuclides. The sources of uncertainty in this scenario are similar to those for the steel scrap transportation scenario discussed in Section 4.9.

For all scenarios that take place subsequent to the initial transport of scrap, additional sources of uncertainty are introduced and wider confidence intervals result. Scenarios that address handling of scrap include uncertainty due to mixing with other scrap. They also include additional exposure pathways - inhalation of resuspended dust and inadvertent ingestion under dusty conditions. Scenarios that address handling and processing of refinery products such as baghouse dust and refinery slag include additional uncertainty in how much of each radionuclide is partitioned to these materials. For copper, this group of handling and processing scenarios have 95/5 ratios that range from about 10 to about 20.

Table 5.5 Copper recycle critical-group dose factors—mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
H-3	5.6E-04	6.1E-05	4.1E-04	1.7E-03	2.1E-06	2.2E-07	1.5E-06	6.2E-06	CU-ATMO-REVERAT-N
C-14	1.6E-02	1.7E-03	1.1E-02	5.1E-02	6.0E-05	6.4E-06	4.0E-05	1.9E-04	CU-ATMO-REVERAT-N
Na-22	2.2E+02	1.4E+02	2.2E+02	3.1E+02	8.1E-01	5.1E-01	8.1E-01	1.1E+00	CU-SCRP-TRANSPO-W
P-32	1.3E-01	8.2E-02	1.3E-01	1.8E-01	4.8E-04	3.0E-04	4.8E-04	6.8E-04	CU-SCRP-TRANSPO-W
S-35	7.8E-04	1.7E-04	6.1E-04	2.0E-03	2.9E-06	6.1E-07	2.3E-06	7.2E-06	CU-REVS-HANDLIN-W
Cl-36	5.2E-02	4.6E-03	3.4E-02	1.6E-01	1.9E-04	1.7E-05	1.3E-04	5.8E-04	CU-ATMO-REVERAT-N
K-40	1.6E+01	1.0E+01	1.6E+01	2.3E+01	6.0E-02	3.8E-02	6.0E-02	8.4E-02	CU-SCRP-TRANSPO-W
Ca-41	2.0E-03	3.3E-04	1.5E-03	5.2E-03	7.3E-06	1.2E-06	5.6E-06	1.9E-05	CU-REVS-HANDLIN-W
Ca-45	5.1E-03	1.0E-03	3.8E-03	1.3E-02	1.9E-05	3.8E-06	1.4E-05	5.0E-05	CU-REVS-HANDLIN-W
Cr-51	2.5E+00	1.6E+00	2.5E+00	3.4E+00	9.1E-03	5.8E-03	9.1E-03	1.3E-02	CU-SCRP-TRANSPO-W
Mn-54	8.5E+01	5.4E+01	8.5E+01	1.2E+02	3.2E-01	2.0E-01	3.1E-01	4.4E-01	CU-SCRP-TRANSPO-W
Fe-55	9.7E-04	1.9E-04	7.6E-04	2.5E-03	3.6E-06	7.1E-07	2.8E-06	9.2E-06	CU-CNVS-HANDLIN-W
Co-57	3.8E+00	2.4E+00	3.8E+00	5.3E+00	1.4E-02	8.9E-03	1.4E-02	2.0E-02	CU-SCRP-TRANSPO-W
Co-58	9.5E+01	6.1E+01	9.5E+01	1.3E+02	3.5E-01	2.2E-01	3.5E-01	4.9E-01	CU-SCRP-TRANSPO-W
Fe-59	1.1E+02	7.3E+01	1.2E+02	1.6E+02	4.2E-01	2.7E-01	4.3E-01	5.9E-01	CU-SCRP-TRANSPO-W
Ni-59	4.2E-04	1.0E-04	3.3E-04	9.8E-04	1.6E-06	3.8E-07	1.2E-06	3.6E-06	CU-CNVS-HANDLIN-W
Co-60	2.5E+02	1.6E+02	2.5E+02	3.6E+02	9.4E-01	5.9E-01	9.4E-01	1.3E+00	CU-SCRP-TRANSPO-W
Ni-63	1.1E-03	2.6E-04	8.8E-04	3.0E-03	4.2E-06	9.7E-07	3.3E-06	1.1E-05	CU-CNVS-HANDLIN-W
Zn-65	7.8E+01	2.2E+01	6.4E+01	1.9E+02	2.9E-01	8.1E-02	2.4E-01	6.9E-01	CU-CNVD-TRANSPO-W
Cu-67	2.1E+00	1.0E+00	1.9E+00	3.6E+00	7.7E-03	3.7E-03	7.2E-03	1.3E-02	CU-SCRP-TRANSPO-W
Se-75	2.4E+01	1.6E+01	2.5E+01	3.4E+01	9.1E-02	5.7E-02	9.1E-02	1.3E-01	CU-SCRP-TRANSPO-W
Sr-85	4.7E+01	3.0E+01	4.7E+01	6.6E+01	1.7E-01	1.1E-01	1.7E-01	2.4E-01	CU-SCRP-TRANSPO-W
Sr-89	1.2E-01	7.4E-02	1.2E-01	1.6E-01	4.3E-04	2.8E-04	4.3E-04	6.0E-04	CU-SCRP-TRANSPO-W
Sr-90	4.3E-01	1.0E-01	3.0E-01	1.2E+00	1.6E-03	3.8E-04	1.1E-03	4.4E-03	CU-ELRS-HANDLIN-W
Y-91	3.5E-01	2.2E-01	3.5E-01	4.8E-01	1.3E-03	8.2E-04	1.3E-03	1.8E-03	CU-SCRP-TRANSPO-W
Mo-93	1.1E-02	1.6E-03	8.6E-03	3.1E-02	4.1E-05	6.0E-06	3.2E-05	1.1E-04	CU-REVM-SMOBJCT-N
Nb-93m	5.9E-03	1.5E-03	4.7E-03	1.4E-02	2.2E-05	5.5E-06	1.7E-05	5.1E-05	CU-CNVS-HANDLIN-W
Nb-94	1.6E+02	1.0E+02	1.6E+02	2.3E+02	6.1E-01	3.8E-01	6.0E-01	8.5E-01	CU-SCRP-TRANSPO-W
Nb-95	7.2E+01	4.6E+01	7.3E+01	1.0E+02	2.7E-01	1.7E-01	2.7E-01	3.7E-01	CU-SCRP-TRANSPO-W
Zr-95	7.2E+01	4.6E+01	7.2E+01	1.0E+02	2.7E-01	1.7E-01	2.7E-01	3.7E-01	CU-SCRP-TRANSPO-W
Tc-99	2.9E-03	7.0E-04	2.2E-03	7.0E-03	1.1E-05	2.6E-06	8.3E-06	2.6E-05	CU-CNVS-HANDLIN-W
Ru-103	4.6E+01	2.9E+01	4.7E+01	6.5E+01	1.7E-01	1.1E-01	1.7E-01	2.4E-01	CU-SCRP-TRANSPO-W
Ru-106	2.1E+01	1.3E+01	2.1E+01	2.9E+01	7.6E-02	4.8E-02	7.6E-02	1.1E-01	CU-SCRP-TRANSPO-W
Ag-108m	1.6E+02	1.0E+02	1.6E+02	2.3E+02	6.0E-01	3.8E-01	6.0E-01	8.4E-01	CU-SCRP-TRANSPO-W
Cd-109	2.6E-02	6.2E-03	2.0E-02	6.4E-02	9.5E-05	2.3E-05	7.5E-05	2.4E-04	CU-ELRS-HANDLIN-W

Table 5.5 Copper recycle critical-group dose factors—mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
	Critical-group dose factor	90% Confidence interval			Critical-group dose factor	90% Confidence interval			
Radionuclide		5th (lower bound)	50th (median)	95th (upper bound)		5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Ag-110m	2.8E+02	1.8E+02	2.8E+02	4.0E+02	1.0E+00	6.6E-01	1.0E+00	1.5E+00	CU-SCRP-TRANSPO-W
Sb-124	1.8E+02	1.2E+02	1.8E+02	2.5E+02	6.7E-01	4.3E-01	6.7E-01	9.4E-01	CU-SCRP-TRANSPO-W
I-125	6.5E-02	4.2E-02	6.5E-02	9.1E-02	2.4E-04	1.5E-04	2.4E-04	3.4E-04	CU-SCRP-TRANSPO-W
Sb-125	4.1E+01	2.6E+01	4.1E+01	5.7E+01	1.5E-01	9.5E-02	1.5E-01	2.1E-01	CU-SCRP-TRANSPO-W
I-129	4.4E-01	4.4E-02	3.1E-01	1.3E+00	1.6E-03	1.6E-04	1.2E-03	4.7E-03	CU-ATMO-REVERAT-N
I-131	2.5E+01	1.5E+01	2.5E+01	3.6E+01	9.3E-02	5.5E-02	9.1E-02	1.3E-01	CU-SCRP-TRANSPO-W
Ba-133	2.8E+01	1.8E+01	2.8E+01	3.9E+01	1.0E-01	6.5E-02	1.0E-01	1.4E-01	CU-SCRP-TRANSPO-W
Cs-134	1.6E+02	1.0E+02	1.6E+02	2.2E+02	5.9E-01	3.7E-01	5.9E-01	8.3E-01	CU-SCRP-TRANSPO-W
Cs-137	6.2E+01	3.9E+01	6.2E+01	8.6E+01	2.3E-01	1.4E-01	2.3E-01	3.2E-01	CU-SCRP-TRANSPO-W
Ce-141	2.7E+00	1.7E+00	2.7E+00	3.8E+00	1.0E-02	6.4E-03	1.0E-02	1.4E-02	CU-SCRP-TRANSPO-W
Ce-144	3.3E+00	2.1E+00	3.3E+00	4.6E+00	1.2E-02	7.7E-03	1.2E-02	1.7E-02	CU-SCRP-TRANSPO-W
Pm-147	6.8E-03	1.5E-03	5.2E-03	1.7E-02	2.5E-05	5.5E-06	1.9E-05	6.2E-05	CU-REVS-HANDLIN-W
Eu-152	1.1E+02	7.0E+01	1.1E+02	1.6E+02	4.1E-01	2.6E-01	4.1E-01	5.8E-01	CU-SCRP-TRANSPO-W
Eu-154	1.2E+02	7.6E+01	1.2E+02	1.7E+02	4.5E-01	2.8E-01	4.5E-01	6.3E-01	CU-SCRP-TRANSPO-W
Eu-155	1.1E+00	6.7E-01	1.1E+00	1.5E+00	3.9E-03	2.5E-03	3.9E-03	5.5E-03	CU-SCRP-TRANSPO-W
Re-186	2.5E-01	1.3E-01	2.4E-01	3.9E-01	9.2E-04	5.0E-04	8.7E-04	1.4E-03	CU-SCRP-TRANSPO-W
Ir-192	7.1E+01	4.5E+01	7.1E+01	9.9E+01	2.6E-01	1.7E-01	2.6E-01	3.7E-01	CU-SCRP-TRANSPO-W
Pb-210	7.7E-01	2.8E+00	9.2E+00	9.2E+00	1.4E-02	2.8E-03	1.0E-02	3.4E-02	CU-ELRS-HANDLIN-W
Po-210	2.0E-01	7.7E-01	2.6E+00	2.6E+00	3.9E-03	7.6E-04	2.8E-03	9.7E-03	CU-ELRS-HANDLIN-W
Bi-210	3.1E-02	1.7E-02	3.0E-02	4.7E-02	1.2E-04	6.4E-05	1.1E-04	1.7E-04	CU-SCRP-TRANSPO-W
Rn-222	8.6E+01	4.6E+01	8.2E+01	1.3E+02	3.2E-01	1.7E-01	3.0E-01	5.0E-01	CU-SCRP-TRANSPO-W
Ra-223	1.8E+01	1.1E+01	1.8E+01	2.6E+01	6.7E-02	4.1E-02	6.6E-02	9.5E-02	CU-SCRP-TRANSPO-W
Ra-224	6.1E+01	3.3E+01	5.8E+01	9.7E+01	2.3E-01	1.2E-01	2.2E-01	3.6E-01	CU-SCRP-TRANSPO-W
Ac-225	1.4E+01	8.6E+00	1.4E+01	2.0E+01	5.3E-02	3.2E-02	5.1E-02	7.5E-02	CU-SCRP-TRANSPO-W
Ra-225	4.7E-01	1.3E-01	4.2E-01	9.5E-01	1.7E-03	4.9E-04	1.5E-03	3.5E-03	CU-SCRP-HANDLIN-W
Ra-226	1.7E+02	1.1E+02	1.7E+02	2.4E+02	6.4E-01	4.0E-01	6.4E-01	9.0E-01	CU-SCRP-TRANSPO-W
Ac-227	2.6E+02	5.1E+01	2.0E+02	6.5E+02	9.7E-01	1.9E-01	7.6E-01	2.4E+00	CU-REVS-HANDLIN-W
Th-227	5.9E+00	3.7E+00	5.8E+00	8.2E+00	2.2E-02	1.4E-02	2.2E-02	3.0E-02	CU-SCRP-TRANSPO-W
Th-228	1.3E+02	8.0E+01	1.3E+02	1.8E+02	4.7E-01	3.0E-01	4.7E-01	6.6E-01	CU-SCRP-TRANSPO-W
Ra-228	8.4E+01	5.3E+01	8.4E+01	1.2E+02	3.1E-01	2.0E-01	3.1E-01	4.3E-01	CU-SCRP-TRANSPO-W
Th-229	3.3E+02	6.2E+01	2.5E+02	9.3E+02	1.2E+00	2.3E-01	9.2E-01	3.4E+00	CU-REVS-HANDLIN-W
Th-230	5.0E+01	1.0E+01	3.6E+01	1.4E+02	1.9E-01	3.8E-02	1.3E-01	5.1E-01	CU-REVS-HANDLIN-W
Pa-231	1.8E+02	3.3E+01	1.4E+02	4.4E+02	6.7E-01	1.2E-01	5.1E-01	1.6E+00	CU-REVS-HANDLIN-W
Th-231	1.5E-02	3.3E-03	1.1E-02	3.8E-02	5.6E-05	1.2E-05	4.1E-05	1.4E-04	CU-SCRP-TRANSPO-W
Th-232	2.2E+02	4.0E+01	1.6E+02	6.1E+02	8.3E-01	1.5E-01	6.1E-01	2.3E+00	CU-REVS-HANDLIN-W

Table 5.5 Copper recycle critical-group dose factors—mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Pa-233	1.3E+01	8.4E+00	1.3E+01	1.8E+01	4.9E-02	3.1E-02	4.9E-02	6.8E-02	CU-SCRP-TRANSPO-W
U-233	2.5E+01	4.8E+00	2.0E+01	6.2E+01	9.3E-02	1.8E-02	7.2E-02	2.3E-01	CU-REVS-HANDLIN-W
Th-234	7.3E-01	4.6E-01	7.3E-01	1.0E+00	2.7E-03	1.7E-03	2.7E-03	3.8E-03	CU-SCRP-TRANSPO-W
U-234	2.5E+01	4.3E+00	1.9E+01	6.6E+01	9.2E-02	1.6E-02	7.0E-02	2.5E-01	CU-REVS-HANDLIN-W
U-235	2.5E+01	5.7E+00	1.9E+01	6.2E+01	9.2E-02	2.1E-02	7.2E-02	2.3E-01	CU-REVS-HANDLIN-W
Np-237	1.1E+02	2.1E+01	8.3E+01	3.2E+02	4.1E-01	7.9E-02	3.1E-01	1.2E+00	CU-REVS-HANDLIN-W
Pu-238	5.5E+01	9.7E+00	4.1E+01	1.5E+02	2.0E-01	3.6E-02	1.5E-01	5.7E-01	CU-REVS-HANDLIN-W
U-238	2.3E+01	4.0E+00	1.6E+01	6.4E+01	8.5E-02	1.5E-02	5.9E-02	2.4E-01	CU-REVS-HANDLIN-W
Pu-239	5.8E+01	1.0E+01	4.4E+01	1.5E+02	2.2E-01	3.8E-02	1.6E-01	5.6E-01	CU-REVS-HANDLIN-W
Pu-240	5.7E+01	1.2E+01	4.2E+01	1.6E+02	2.1E-01	4.6E-02	1.5E-01	5.8E-01	CU-REVS-HANDLIN-W
Pu-241	9.4E-01	1.8E-01	7.0E-01	2.6E+00	3.5E-03	6.5E-04	2.6E-03	9.7E-03	CU-REVS-HANDLIN-W
Am-241	9.0E+01	1.8E+01	6.7E+01	2.4E+02	3.3E-01	6.7E-02	2.5E-01	8.9E-01	CU-REVS-HANDLIN-W
Cm-242	3.0E+00	6.3E-01	2.3E+00	7.6E+00	1.1E-02	2.3E-03	8.6E-03	2.8E-02	CU-REVS-HANDLIN-W
Pu-242	5.4E+01	9.7E+00	4.3E+01	1.2E+02	2.0E-01	3.6E-02	1.6E-01	4.6E-01	CU-REVS-HANDLIN-W
Cm-244	4.9E+01	9.8E+00	3.7E+01	1.3E+02	1.8E-01	3.6E-02	1.4E-01	4.7E-01	CU-REVS-HANDLIN-W

Table 5.6 Copper recycle critical-group dose factors—surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
H-3	4.8E-04	4.5E-05	3.3E-04	1.4E-03	1.8E-06	1.7E-07	1.2E-06	5.0E-06	CU-ATMO-REVERAT-N
C-14	1.4E-02	1.3E-03	8.4E-03	4.6E-02	5.1E-05	4.6E-06	3.1E-05	1.7E-04	CU-ATMO-REVERAT-N
Na-22	1.9E+02	9.3E+01	1.8E+02	3.2E+02	7.0E-01	3.4E-01	6.5E-01	1.2E+00	CU-SCRP-TRANSPO-W
P-32	1.1E-01	5.4E-02	1.0E-01	1.9E-01	4.1E-04	2.0E-04	3.9E-04	6.9E-04	CU-SCRP-TRANSPO-W
S-35	6.6E-04	1.3E-04	5.0E-04	1.8E-03	2.5E-06	4.7E-07	1.8E-06	6.5E-06	CU-REVS-HANDLIN-W
Cl-36	4.4E-02	4.5E-03	2.8E-02	1.3E-01	1.6E-04	1.7E-05	1.1E-04	4.9E-04	CU-ATMO-REVERAT-N
K-40	1.4E+01	6.9E+00	1.3E+01	2.4E+01	5.1E-02	2.5E-02	4.8E-02	8.9E-02	CU-SCRP-TRANSPO-W
Ca-41	1.7E-03	2.5E-04	1.2E-03	4.7E-03	6.2E-06	9.1E-07	4.4E-06	1.7E-05	CU-REVS-HANDLIN-W
Ca-45	4.3E-03	7.0E-04	3.1E-03	1.2E-02	1.6E-05	2.6E-06	1.1E-05	4.6E-05	CU-REVS-HANDLIN-W
Cr-51	2.1E+00	1.0E+00	2.0E+00	3.5E+00	7.8E-03	3.8E-03	7.3E-03	1.3E-02	CU-SCRP-TRANSPO-W
Mn-54	7.3E+01	3.6E+01	6.8E+01	1.3E+02	2.7E-01	1.3E-01	2.5E-01	4.6E-01	CU-SCRP-TRANSPO-W
Fe-55	8.3E-04	1.5E-04	6.1E-04	2.2E-03	3.1E-06	5.6E-07	2.3E-06	8.1E-06	CU-CNVS-HANDLIN-W
Co-57	3.3E+00	1.6E+00	3.0E+00	5.6E+00	1.2E-02	6.0E-03	1.1E-02	2.1E-02	CU-SCRP-TRANSPO-W
Co-58	8.1E+01	4.0E+01	7.5E+01	1.4E+02	3.0E-01	1.5E-01	2.8E-01	5.1E-01	CU-SCRP-TRANSPO-W
Fe-59	9.8E+01	4.8E+01	9.1E+01	1.7E+02	3.6E-01	1.8E-01	3.4E-01	6.1E-01	CU-SCRP-TRANSPO-W
Ni-59	3.6E-04	8.2E-05	2.8E-04	9.0E-04	1.3E-06	3.0E-07	1.0E-06	3.3E-06	CU-CNVS-HANDLIN-W
Co-60	2.2E+02	1.1E+02	2.0E+02	3.8E+02	8.1E-01	4.0E-01	7.5E-01	1.4E+00	CU-SCRP-TRANSPO-W
Ni-63	9.7E-04	1.8E-04	7.5E-04	2.6E-03	3.6E-06	6.6E-07	2.8E-06	9.5E-06	CU-CNVS-HANDLIN-W
Zn-65	6.7E+01	1.5E+01	5.0E+01	1.6E+02	2.5E-01	5.7E-02	1.9E-01	6.0E-01	CU-CNVD-TRANSPO-W
Cu-67	1.8E+00	6.8E-01	1.6E+00	3.3E+00	6.5E-03	2.5E-03	5.9E-03	1.2E-02	CU-SCRP-TRANSPO-W
Se-75	2.1E+01	1.0E+01	1.9E+01	3.6E+01	7.7E-02	3.8E-02	7.2E-02	1.3E-01	CU-SCRP-TRANSPO-W
Sr-85	4.0E+01	2.0E+01	3.7E+01	6.9E+01	1.5E-01	7.3E-02	1.4E-01	2.5E-01	CU-SCRP-TRANSPO-W
Sr-89	9.9E-02	4.9E-02	9.2E-02	1.7E-01	3.7E-04	1.8E-04	3.4E-04	6.2E-04	CU-SCRP-TRANSPO-W
Sr-90	3.7E-01	7.2E-02	2.5E-01	1.1E+00	1.4E-03	2.7E-04	9.2E-04	4.1E-03	CU-ELRS-HANDLIN-W
Y-91	3.0E-01	1.5E-01	2.7E-01	5.0E-01	1.1E-03	5.4E-04	1.0E-03	1.9E-03	CU-SCRP-TRANSPO-W
Mo-93	9.5E-03	1.2E-03	6.9E-03	2.6E-02	3.5E-05	4.3E-06	2.6E-05	9.6E-05	CU-REVM-SMOBJCT-N
Nb-93m	5.0E-03	1.1E-03	3.9E-03	1.3E-02	1.9E-05	3.9E-06	1.4E-05	4.8E-05	CU-CNVS-HANDLIN-W
Nb-94	1.4E+02	6.9E+01	1.3E+02	2.4E+02	5.2E-01	2.6E-01	4.8E-01	8.9E-01	CU-SCRP-TRANSPO-W
Nb-95	6.2E+01	3.0E+01	5.8E+01	1.0E+02	2.3E-01	1.1E-01	2.1E-01	3.9E-01	CU-SCRP-TRANSPO-W
Zr-95	6.2E+01	3.0E+01	5.7E+01	1.1E+02	2.3E-01	1.1E-01	2.1E-01	3.9E-01	CU-SCRP-TRANSPO-W
Tc-99	2.5E-03	4.7E-04	1.9E-03	6.4E-03	9.1E-06	1.7E-06	6.9E-06	2.4E-05	CU-CNVS-HANDLIN-W
Ru-103	4.0E+01	1.9E+01	3.7E+01	6.7E+01	1.5E-01	7.2E-02	1.4E-01	2.5E-01	CU-SCRP-TRANSPO-W
Ru-106	1.8E+01	8.7E+00	1.6E+01	3.0E+01	6.5E-02	3.2E-02	6.1E-02	1.1E-01	CU-SCRP-TRANSPO-W
Ag-108m	1.4E+02	6.9E+01	1.3E+02	2.4E+02	5.1E-01	2.5E-01	4.8E-01	8.9E-01	CU-SCRP-TRANSPO-W
Cd-109	2.2E-02	4.6E-03	1.6E-02	5.7E-02	8.2E-05	1.7E-05	6.1E-05	2.1E-04	CU-ELRS-HANDLIN-W

Table 5.6 Copper recycle critical-group dose factors—surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Ag-110m	2.4E+02	1.2E+02	2.2E+02	4.2E+02	8.9E-01	4.4E-01	8.3E-01	1.5E+00	CU-SCRP-TRANSPO-W
Sb-124	1.5E+02	7.6E+01	1.4E+02	2.6E+02	5.7E-01	2.8E-01	5.3E-01	9.7E-01	CU-SCRP-TRANSPO-W
I-125	5.6E-02	2.7E-02	5.2E-02	9.5E-02	2.1E-04	1.0E-04	1.9E-04	3.5E-04	CU-SCRP-TRANSPO-W
Sb-125	3.5E+01	1.7E+01	3.2E+01	6.0E+01	1.3E-01	6.4E-02	1.2E-01	2.2E-01	CU-SCRP-TRANSPO-W
I-129	3.7E-01	4.0E-02	2.6E-01	1.1E+00	1.4E-03	1.5E-04	9.6E-04	4.1E-03	CU-ATMO-REVERAT-N
I-131	2.1E+01	1.0E+01	2.0E+01	3.6E+01	7.9E-02	3.7E-02	7.5E-02	1.3E-01	CU-SCRP-TRANSPO-W
Ba-133	2.4E+01	1.2E+01	2.2E+01	4.1E+01	8.8E-02	4.4E-02	8.2E-02	1.5E-01	CU-SCRP-TRANSPO-W
Cs-134	1.4E+02	6.8E+01	1.3E+02	2.4E+02	5.1E-01	2.5E-01	4.7E-01	8.7E-01	CU-SCRP-TRANSPO-W
Cs-137	5.3E+01	2.6E+01	4.9E+01	9.1E+01	2.0E-01	9.7E-02	1.8E-01	3.4E-01	CU-SCRP-TRANSPO-W
Ce-141	2.3E+00	1.1E+00	2.2E+00	3.9E+00	8.6E-03	4.2E-03	8.0E-03	1.4E-02	CU-SCRP-TRANSPO-W
Ce-144	2.8E+00	1.4E+00	2.6E+00	4.8E+00	1.0E-02	5.2E-03	9.7E-03	1.8E-02	CU-SCRP-TRANSPO-W
Pm-147	5.8E-03	1.2E-03	4.2E-03	1.7E-02	2.1E-05	4.4E-06	1.6E-05	6.2E-05	CU-REVS-HANDLIN-W
Eu-152	9.5E+01	4.7E+01	8.9E+01	1.6E+02	3.5E-01	1.7E-01	3.3E-01	6.1E-01	CU-SCRP-TRANSPO-W
Eu-154	1.0E+02	5.1E+01	9.7E+01	1.8E+02	3.8E-01	1.9E-01	3.6E-01	6.6E-01	CU-SCRP-TRANSPO-W
Eu-155	9.1E-01	4.5E-01	8.5E-01	1.6E+00	3.4E-03	1.7E-03	3.1E-03	5.8E-03	CU-SCRP-TRANSPO-W
Re-186	2.1E-01	9.0E-02	2.0E-01	3.6E-01	7.8E-04	3.3E-04	7.4E-04	1.3E-03	CU-SCRP-TRANSPO-W
Ir-192	6.1E+01	3.0E+01	5.6E+01	1.0E+02	2.2E-01	1.1E-01	2.1E-01	3.8E-01	CU-SCRP-TRANSPO-W
Pb-210	5.9E-01	2.3E+00	8.8E+00	8.8E+00	1.2E-02	2.2E-03	8.4E-03	3.3E-02	CU-ELRS-HANDLIN-W
Po-210	1.5E-01	6.6E-01	2.5E+00	2.5E+00	3.3E-03	5.7E-04	2.4E-03	9.2E-03	CU-ELRS-HANDLIN-W
Bi-210	2.7E-02	1.2E-02	2.5E-02	4.5E-02	9.8E-05	4.4E-05	9.4E-05	1.7E-04	CU-SCRP-TRANSPO-W
Rn-222	7.3E+01	3.1E+01	6.9E+01	1.3E+02	2.7E-01	1.2E-01	2.6E-01	4.6E-01	CU-SCRP-TRANSPO-W
Ra-223	1.5E+01	7.4E+00	1.5E+01	2.6E+01	5.7E-02	2.7E-02	5.4E-02	9.5E-02	CU-SCRP-TRANSPO-W
Ra-224	5.2E+01	2.2E+01	4.9E+01	9.0E+01	1.9E-01	8.2E-02	1.8E-01	3.3E-01	CU-SCRP-TRANSPO-W
Ac-225	1.2E+01	5.7E+00	1.1E+01	2.0E+01	4.5E-02	2.1E-02	4.2E-02	7.4E-02	CU-SCRP-TRANSPO-W
Ra-225	4.0E-01	9.9E-02	3.4E-01	9.0E-01	1.5E-03	3.7E-04	1.3E-03	3.3E-03	CU-SCRP-HANDLIN-W
Ra-226	1.5E+02	7.4E+01	1.4E+02	2.6E+02	5.5E-01	2.7E-01	5.1E-01	9.5E-01	CU-SCRP-TRANSPO-W
Ac-227	2.3E+02	3.9E+01	1.7E+02	6.6E+02	8.4E-01	1.5E-01	6.1E-01	2.4E+00	CU-REVS-HANDLIN-W
Th-227	5.0E+00	2.4E+00	4.7E+00	8.4E+00	1.9E-02	9.0E-03	1.7E-02	3.1E-02	CU-SCRP-TRANSPO-W
Th-228	1.1E+02	5.4E+01	1.0E+02	1.9E+02	4.0E-01	2.0E-01	3.7E-01	6.9E-01	CU-SCRP-TRANSPO-W
Ra-228	7.2E+01	3.6E+01	6.7E+01	1.2E+02	2.7E-01	1.3E-01	2.5E-01	4.6E-01	CU-SCRP-TRANSPO-W
Th-229	2.9E+02	5.2E+01	2.0E+02	8.1E+02	1.1E+00	1.9E-01	7.3E-01	3.0E+00	CU-REVS-HANDLIN-W
Th-230	4.3E+01	7.8E+00	2.9E+01	1.3E+02	1.6E-01	2.9E-02	1.1E-01	4.7E-01	CU-REVS-HANDLIN-W
Pa-231	1.6E+02	2.7E+01	1.1E+02	4.0E+02	5.7E-01	1.0E-01	3.9E-01	1.5E+00	CU-REVS-HANDLIN-W
Th-231	1.3E-02	2.3E-03	9.3E-03	3.5E-02	4.7E-05	8.7E-06	3.4E-05	1.3E-04	CU-SCRP-TRANSPO-W
Th-232	1.9E+02	3.1E+01	1.4E+02	5.1E+02	7.0E-01	1.1E-01	5.1E-01	1.9E+00	CU-REVS-HANDLIN-W

Table 5.6 Copper recycle critical-group dose factors—surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Pa-233	1.1E+01	5.5E+00	1.1E+01	1.9E+01	4.2E-02	2.0E-02	3.9E-02	7.0E-02	CU-SCRP-TRANSPO-W
U-233	2.1E+01	4.0E+00	1.6E+01	5.8E+01	7.9E-02	1.5E-02	5.8E-02	2.2E-01	CU-REVS-HANDLIN-W
Th-234	6.2E-01	3.0E-01	5.8E-01	1.0E+00	2.3E-03	1.1E-03	2.2E-03	3.9E-03	CU-SCRP-TRANSPO-W
U-234	2.1E+01	3.4E+00	1.5E+01	6.1E+01	7.9E-02	1.2E-02	5.5E-02	2.3E-01	CU-REVS-HANDLIN-W
U-235	2.1E+01	4.1E+00	1.6E+01	6.1E+01	7.9E-02	1.5E-02	6.0E-02	2.3E-01	CU-REVS-HANDLIN-W
Np-237	9.4E+01	1.6E+01	6.6E+01	2.7E+02	3.5E-01	5.9E-02	2.4E-01	1.0E+00	CU-REVS-HANDLIN-W
Pu-238	4.8E+01	7.1E+00	3.4E+01	1.3E+02	1.8E-01	2.6E-02	1.2E-01	4.9E-01	CU-REVS-HANDLIN-W
U-238	2.0E+01	3.0E+00	1.4E+01	5.8E+01	7.3E-02	1.1E-02	5.1E-02	2.1E-01	CU-REVS-HANDLIN-W
Pu-239	5.0E+01	8.4E+00	3.6E+01	1.4E+02	1.9E-01	3.1E-02	1.3E-01	5.2E-01	CU-REVS-HANDLIN-W
Pu-240	4.9E+01	9.0E+00	3.6E+01	1.3E+02	1.8E-01	3.3E-02	1.3E-01	4.9E-01	CU-REVS-HANDLIN-W
Pu-241	8.1E-01	1.3E-01	5.7E-01	2.5E+00	3.0E-03	4.7E-04	2.1E-03	9.3E-03	CU-REVS-HANDLIN-W
Am-241	7.8E+01	1.4E+01	5.5E+01	2.1E+02	2.9E-01	5.1E-02	2.0E-01	7.9E-01	CU-REVS-HANDLIN-W
Cm-242	2.5E+00	5.0E-01	1.9E+00	6.9E+00	9.4E-03	1.8E-03	6.9E-03	2.6E-02	CU-REVS-HANDLIN-W
Pu-242	4.6E+01	8.0E+00	3.2E+01	1.2E+02	1.7E-01	2.9E-02	1.2E-01	4.3E-01	CU-REVS-HANDLIN-W
Cm-244	4.2E+01	7.4E+00	3.1E+01	1.1E+02	1.5E-01	2.7E-02	1.1E-01	4.2E-01	CU-REVS-HANDLIN-W

Greater uncertainty is associated with scenarios that involve multiple exposure pathways and complex submodels. Four volatile radionuclides (H-3, C-14, Cl-36, and I-129) have critical groups consisting of individuals living in the vicinity of a copper refinery and exposed to atmospheric releases. This scenario includes an atmospheric dispersion model and pathways for ingestion, inhalation, and external exposure, each of which contributes to uncertainty in the dose factor. For copper, radionuclides limited by the atmospheric release scenario have 95/5 ratios that range from about 30 to about 35. Most of this uncertainty is due to the atmospheric dispersion model but additional contributions from partitioning to refinery off-gas and uncertainties in ingestion dose are nuclide-dependent.

The mean values of the derived surficial dose factors for each radionuclide in Table 5.6 represent the dose to the average member of the critical group exposed to radioactivity initially distributed over the surface cleared copper scrap (Bq/cm^2 or pCi/cm^2). Derived surficial dose factors are calculated from mass-based dose factors by use of a surface-to-mass ratio, SM, appropriate for typical copper objects available for clearance. The use of this parameter to derive surficial dose factors is described in Section 4.7.

The calculation of derived surficial dose factors is probabilistic. The parameter SM is represented by a distribution of values that incorporate the variability and uncertainty in the surface-to-mass ratio of typical copper objects available for clearance. This additional source of uncertainty results in wider confidence intervals for the surficial dose factors than for the mass-

based dose factors from which they are derived. The relative importance of this additional uncertainty depends on the scenario. For scenarios with the narrowest confidence intervals, the added uncertainty can contribute as much as an additional 50% to the width of the confidence interval. The mass-based dose factor for the scrap transportation scenario has a 95/5 ratio of about 2 for most radionuclides. The corresponding derived surficial dose factors have a 95/5 ratio of about 3. The added uncertainty in surface-to-mass ratio has a relatively smaller impact on the confidence interval for scenarios with larger uncertainties, contributing an additional 10% to 30%.

6 EVALUATION OF RECYCLE AND DISPOSAL OF ALUMINUM SCRAP

Seventeen potential exposure scenarios for cleared aluminum scrap that are realistically based on current American industries are evaluated in this section. As in the steel evaluation, scenario categories include handling and processing, storage, transportation, product use, and disposal. A radionuclide-specific, probabilistic dose factor distribution was calculated for the members of all exposed groups, and dose factors for an average member of each critical group was calculated in the same manner as for steel recycle. The mean dose factor for each critical group is reported in normalized units of μSv/y per Bq/g scrap (mrem/y per pCi/g) and μSv/y per Bq/cm^2 scrap (mrem/y per pCi/cm^2) for each radionuclide. Dose factors at the 5th, 50th, and 95th percentiles are also reported.

Similar to steel and copper, the most common critical group consists of commercial truck drivers carrying cleared aluminum scrap. Scenarios involving transport of scrap material resulted in critical group designation for over half (52) of the 85 radionuclides in the analysis. Other scenarios identifying critical groups for many radionuclides involve handling aluminum scrap material (17 radionuclides). Unlike the other metals evaluated, use of aluminum products identify critical groups for several radionuclides. Use of aluminum cookware accounts for 11 critical groups, and use of a generic, small metal object accounts for 2 critical groups.

Mean critical-group dose factors range from a high of 6 μSv/y per Bq/g (0.02 mrem/y per pCi/g) for Ag-110m to a low of 2E-06 μSv/y per Bq/g (7E-09 mrem/y per pCi/g) for H-3. The surficial mean critical-group dose factors range from 23 μSv/y per Bq/cm^2 (Ag-110m) down to 7E-06 μSv/y per Bq/cm^2 (H-3). Scenarios involving scrap transport account for the highest critical-group dose factors. Seventy-eight of the radionuclide-specific, mean dose factors for aluminum critical groups are 270 μSv/y per Bq/g or lower (1 mrem/y per pCi/g).

This section describes the technical evaluation of the recycle and disposal of aluminum scrap that could be cleared from Nuclear Regulatory Commission (NRC) licensed facilities. Similar to steel scrap (Section 4), the flow of cleared material was probabilistically modeled, distributions of radionuclide concentrations in refined and disposed materials were calculated, and the mean dose factors for each potentially exposed group were estimated.

6.1 Introduction to Analysis

The analysis process for potential exposures from aluminum recycle and disposal is essentially the same as described previously for steel and copper. A material flow model specific to aluminum scrap was developed, radionuclide concentrations were calculated, and scenario evaluations were conducted. Besides the material flow model (and calculated concentrations in refined and disposed materials), there are only minor differences between the steel and aluminum scrap analyses. There are several minor scenario parameter differences and one additional exposure scenario that is specific to recycled aluminum scrap (described in Section 6.6).

6.2 Flow of Recycled and Disposed Aluminum Scrap

The material flow model for aluminum represents the general processes that cleared material would go through from the time it is cleared by a NRC licensed facility to the time of final disposal. Similar to steel and copper, the aluminum material flow model is comprised of two types of models: conceptual and mathematical. The conceptual model describes the aluminum refining process and defines the limits of this analysis, while the mathematical model presents the mathematical equations that implement the information presented in the conceptual model.

The material flow model is based on a literature review of the U.S. secondary aluminum industry. It is intended to provide a defensible basis for developing appropriate exposure scenarios. In addition, the output of the material flow model provides key input to the dose calculations for each scenario. This input consists of radionuclide-specific concentrations in recycle by-products, in effluent, and in waste products of the refining process. Because of the number of scenarios being analyzed and the differing times at which they occur, the mathematical model presented in this section does not include radioactive decay. However, radioactive decay is taken into account in the individual scenarios, in the same manner as in the analyses for steel and copper.

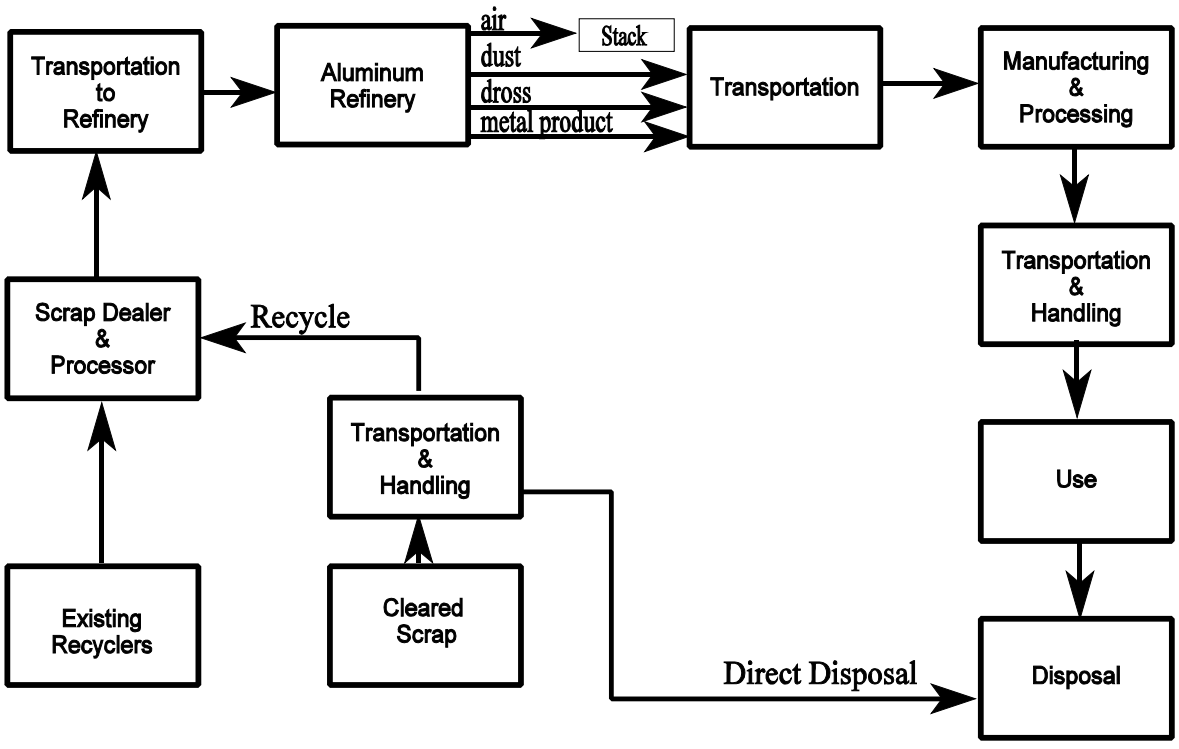

Figure 6.1 Material flow for aluminum scrap

This section presents the conceptual model that describes the movement of aluminum scrap through the normal refining process, beginning with the production of scrap, through refining, manufacturing, product use, and ending with disposal. Figure 6.1 presents a schematic diagram of the overall material flow conceptual model for aluminum. Both the mass and radioactivity follow this flow model. There are several distinct steps or processes in the refining process. These are discussed in the following subsections.

6.2.1 Sources of Material

Similar to steel and copper, aluminum recyclers can be the general public (e.g., recycling aluminum cans), industry (e.g., recycling aluminum siding), or manufacturers (e.g., scrap produced during the manufacture of end products).

There are three types of scrap metal used in the aluminum making industry: home, new, and old. *Home scrap* consists of unusable metal produced during the processing or fabrication of aluminum into a form usable for manufacturing. Home scrap is usually high-grade metal with very few impurities. Even though home scrap is produced at the refinery, it is still considered a secondary metal because it is not the processed raw material. *New scrap* is produced during manufacture of end products. New scrap also is high-grade metal with very few impurities. *Old scrap* includes obsolete, worn out or broken products that have been used by the general public or industry. Old scrap is usually low grade metal and the chemical composition is not well-known. Therefore, it must first be sorted, sized, and classified. Recyclable scrap metal from the nuclear industry is considered old scrap. A total of 3.19E+06 t (3.5 E+06 tons) of secondary aluminum (scrap) was consumed in the U.S. in 1995, and almost half of that was old scrap (USBM 1997).

The main producer of the scrap assumed for this study is the nuclear industry (decommissioned material from nuclear facilities), which consists mainly of commercial power plants, test and research reactors, and industrial nuclear facilities. Other producers of such scrap include the Department of Energy (DOE) weapons complex and the Department of Defense (DOD), which would contribute scrap primarily from conventional weapons testing and army and navy test reactors. Approximately 2.5E+02 t/y (2.75 E+02 ton/y) of potentially recyclable aluminum scrap metal is generated each year by NRC licensed facilities. Increased dismantling and decommissioning activities could result in up to 4.50E+03 t/y (5.0E+03 ton/y) of aluminum scrap from these facilities for a limited number of years (NUREG/CR-5610[1]).

Similar to the steel and copper analyses, cleared aluminum scrap is assumed to be mixed with a single source of uncontaminated scrap.

[1]Recycle/Reuse Literature Search Report, SAIC, 1994 scheduled to be published as NUREG/CR-5610

6.2.2 Transportation and Processing

Scrap aluminum cleared from a nuclear facility could be transported to a scrap dealer or processor; this would most likely be done by a commercial company. Because not all scrap aluminum would be suitable for recycle, some may be transported directly to a disposal site. In all cases, transportation could occur either by truck or rail.

After scrap is processed at a scrap dealer, it is transported by either rail or truck to a refinery. Dross (refining slag), metal products, and dust also would be transported from the refinery to manufacturers or processors by either truck, rail, or waterway.

6.2.3 Aluminum Mills

There are five types of refineries and mills that use aluminum scrap as input: primary scrap processors, secondary smelters, foundries, fabricators, and chemical plants. However, the aluminum scrap produced at nuclear facilities would most likely enter a secondary smelter. Secondary smelters most commonly use an oil or gas-fired reverberatory furnace. Key modeling parameter values for an aluminum secondary smelter are shown in Table 6.1.

Table 6.1 Key modeling assumptions for aluminum secondary smelter

Assumptions	Value
End product and use	sheet, plate, foil, ingot, rod, bar and wire
End use of the dust	disposed of in a sanitary landfill
Temperature inside furnace	650°C
Temperature inside the baghouse	190°C
Chemical form of elements entering baghouse	oxides
Efficiency of baghouse	99.9%
Average size of a charge	50 t
Average number of charges per year for a single refinery	5580

In 1996, secondary smelters consumed approximately 1.4E+6 t (1.5E+6 tons) of scrap (new + used). The typical input material for this type of furnace is aluminum scrap and occasionally a small amount of additives (silicon, titanium, and strontium rods). The capacity of a typical reverberatory furnace is approximately 50 t (55 tons). No data were available at the time of this analysis to determine the average number of charges per year for an aluminum refinery; the value used for steel BOF refineries (5580 charges/y) was judged to be adequate for aluminum references.

The fumes that are generated during the refining of aluminum scrap are captured by the primary exhaust hood and transported via a duct system to a baghouse. The baghouses used in the refining of aluminum scrap are similar to those used in the iron and steel industry.[1] Therefore, the same parameters for the baghouse are used for the recycling of aluminum (e.g., temperature, efficiency). Occasionally dirty aluminum scrap undergoes pretreatment to remove iron, oil, and water. Pretreatment consists of crushing and/or drying (using an afterburner). The dust produced during pretreatment is collected in the same baghouse as for the furnace. 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 not considered hazardous. Therefore, for this analysis the baghouse dust is considered to be nonhazardous.

During the refining process, the original metal separates into four different end products: off-gas, dust, dross, and metal (Figure 6.1). Both the mass and radioactivity partition into the different end products. To account for this in the material flow modeling, partitioning factors for both mass and elements were developed and are discussed in detail in Section 6.3.

Each of the end products undergoes a different process, use, and final disposal process. The off-gas includes elements that are completely volatilized into stable gases or very fine particles during refining and exit the refinery stack. Dust includes elements that are volatilized from the furnace, form particulates when cooled, and are collected in baghouse filters. (The air pollution control systems are not 100% efficient, and a small percentage of the dust is released into the atmosphere with the off-gas.)

Dross is not considered a hazardous waste, therefore, it can be recycled, reprocessed, or directly disposed of. After dross is removed from the furnace and cooled, it is stored outdoors in piles at the refinery until it is either used by the refinery or transported to a processor. Because of its high metal content, dross can be fed back into the furnace as input material.

Manufacturing and processing converts dross and metal products created at the refineries and mills into finished products. Manufacturing involves activities such as cutting and shaping the metal. Processing of dross involves crushing and sizing. After a metal product or dross is manufactured into a finished product, it must be transported and distributed to the general public (i.e., end user). Facilities involved in the distribution of finished metal products include stores, warehouses, and car lots. If it is not recycled on-site, dross is usually distributed and transported directly from the refinery where it is produced or from the manufacturer where it is processed.

6.2.4 Product Use

Dross or finished metal products are used by the public for many applications. Aluminum metal products are used in containers and packaging, building and construction, transportation, electrical products, consumer durables, and machinery and equipment. Use of dross is similar to that of iron and steel slag (e.g., roadbed, railroad ballast).

6.2.5 Disposal

The ultimate endpoint for finished metal products, dross, and dust is disposal in a public sanitary landfill (i.e., a Resource Conservation and Recovery Act [RCRA] Subtitle D landfill). The types of objects that could end up in a public sanitary landfill include discarded end products, waste from manufacturing, dross directly from the refinery, products made from dross, scrap not suitable for recycle, and dust.

6.3 Mass and Elemental Partitioning Factors for Refinery Operations

Partitioning of the radioactivity and mass present in scrap entering the refinery furnace is modeled in order to estimate concentrations of radionuclides in various end products. Partitioning factors are defined as the estimated fraction of original radionuclide concentration or mass entering the refinery furnace that would be present in various end products. As modeled in this analysis, the mass of scrap metal entering a furnace during the refining process is redistributed into the three immediate products: metal product, dross, and dust. Partitioning of radioactivity to these products is also modeled, as well as for the off-gas leaving the refinery stack.

6.3.1 Mass Partitioning Factors

Mass partitioning factors for aluminum were estimated using information obtained from industry contacts for the metal product, dross, and dust. According to Alchem Aluminum,[1] 40% to 90% of the metal mass entering the furnace ends up in the metal product. If cleaner scrap (new scrap) is used, the percent yield is close to 90%. However, if dross is used with the scrap as input, the percent yield is closer to 40%. The cleared aluminum material being analyzed in this material flow is assumed to be fairly clean and representative of new scrap. Therefore, a range of 40% to 90% is used as the distribution for the mass partitioning for metal product. Because the dust produced during the recycling of aluminum scrap is not considered hazardous, a record of the mass produced per charge is not typically kept by refineries. Between 0.5% and 2% of the original mass entering the furnace is estimated to end up in the dust. The dirtier the scrap input, the more dust is produced. There are very few additives used during the refining of aluminum scrap, so the remaining fraction is assumed to be the mass partitioning for dross.

6.3.2 Elemental Partitioning Factors

In order to simplify the material flow modeling, elements of concern were grouped according to their elemental partitioning factors. It was assumed that there were no isotopic effects and that all isotopes of a given element would behave identically.

The primary methods for removing impurities from the melt in the reverberatory furnace are bubbling chlorine through the melt and/or using fluoride fluxes. Whether or not an element

[1] Personal communication between Mary Anderson of SAIC and Jim Bopp of Alchem Aluminum, May 23, 1997.

remains in the melt depends primarily on its propensity to form chlorides or fluorides. Calcium is added to the melt to increase the formation of intermetallic compounds with cadmium, lead, bismuth, and antimony. These compounds float to the top and are incorporated into the dross. In addition to these factors, the chemical and physical properties of the elements in question were also considered, particularly for those elements for which only limited data are available. Where no direct estimates of partitioning were available, elemental partitioning factors were estimated based on the behavior of chemically similar elements.

The elemental partitioning factor ranges determined for the aluminum material flow model are intended to be representative of the expected behavior during melting in a typical domestic aluminum reverberatory furnace. Both lack of knowledge about the behavior of elements during the refining of aluminum and variability in refinery conditions contribute to uncertainty in the estimates of elemental partitioning factors. In order to address this uncertainty, ranges for the partitioning values were used, similar to the analyses for steel and copper.

During refining, elements could partition to one or both of the main melt components (i.e., the dross and/or metal phases) or discharge from the furnace in the volatilized gas. Some of the radionuclides that leave the furnace in the volatilized gas would remain in the vapor phase (off-gas) and some would condense or coalesce into particulates (dust). Elements found in coarse particulates would be captured by the baghouse filter. Some of the fine particles and species in the vapor phase would escape in the off-gas exiting the stack.

The furnace is assumed to be operating at an average temperature of about 650°C (1200°F). The average temperature of the baghouse is assumed to be 190°C (375°F). It is assumed that the air flowing through the baghouse is cooled to this temperature. The assumptions listed in Table 6.1 of this report are also used.

Table 6.2 shows the resulting elemental partitioning factor (EPF) ranges for each element. Note that the partitioning factors for some elements (e.g., iodine) do not sum to 100%. This is due to the use of ranges for partitioning factors. However, this is acceptable because only one material is present in each exposure scenario, and a strict mass balance is not necessary.

6.4 Mathematical Model for Flow of Recycled Aluminum Scrap

This section presents the equations that represent the information discussed previously in Section 6.2 and 6.3 and are used to formulate the mathematical model. The equations estimate radionuclide concentrations in refined aluminum and other co-products of refining. The equations are entered into spreadsheets that have been organized and structured specifically for this analysis. The calculated radionuclide concentrations in refined aluminum, dross (refinery slag), refinery baghouse dust, and the amount of radioactivity released out the refinery stack are used as input to the scenario analyses.

6.4.1 Mixing of Cleared Scrap and Other Scrap

There are only two processes by which the original concentration of each radionuclide in cleared aluminum scrap can be potentially changed. The first can occur upon mixing with other scrap metal prior to refining. This mixing is a radionuclide-independent process, so the radioactivity concentration of all radionuclides is effected the same when mixing cleared aluminum scrap with a given mass of other aluminum scrap. The second process is the refining process itself, which generally consists of melting the aluminum scrap metal, resulting in a redistribution (partitioning) of mass and radioactivity. Partitioning of mass during melting is radionuclide-independent, however, partitioning of radioactivity during refining is element-dependent. The following

Table 6.2 Elemental partitioning factor ranges (%) for aluminum refining

Elements	Metal Product	Baghouse Dust	Dross	Off-gas
Ac, Th, Pa, U, Np, Pu, Am, Cm, Cr, Fe, Co, Ni, Cu, Mo, Nb, Ag, Cd, Sb, Ir, Pb, Bi, Ra	95–100	0	0–5	0
Tc, Ru, Re, Po	70–100	0	0–30	0
C	71–100	0	3.8–6.2	0
Zn	90–99.8	4.8–5.2	0	0
Sr, Ba, Zr	38–62	0	38–62	0
Y, Ce, Pm, Eu	19–31	0	56–94	0
Na, K, Cs, Ca, Mn	0	.95–1.05	94–100	0
P, S, Se	0	0–30	70–100	0
I	0	0	59–100	.6–1.4
Cl	0	29–69	30–70	.9–1.1
H, Rn	0–5	0	0	95–100

equations are used to calculate the concentrations in refinery co-products at those points in the material flow which correspond to potential exposure scenarios.

The total mass of material entering the furnace in a year, including cleared and other scrap, was calculated using Equation 6.1.

$$M_1 = M_0 + M_{NC} \qquad 6.1$$

where

M_1 = total mass of scrap metal entering the furnace per charge (g/charge)

and

M_0 = mass of cleared material entering the furnace per charge (g/charge)

M_{NC} = mass of other scrap metal entering the furnace per charge (g/charge)

Mixing of cleared scrap with metal from sources other than licensed facility can occur at the scrap dealer (i.e., secondary metal pool) and at the refinery, where material from the primary metal pool enters the furnace. In this analysis, no distinction is made between the two sources of other metal. The mass of other metal includes contributions at the scrap yard and at the refinery.

The radionuclide concentration in the metal entering the furnace was calculated using Equation 6.2. The following equations are intended to be evaluated separately for each radionuclide in the analysis. Therefore, parameters such as concentration, decay factors, decay constants, and dose conversion factors are not explicitly subscripted for each radionuclide.

$$C_1 = \frac{M_0}{M_1} * C_0 \qquad 6.2$$

where

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)

and

M_0 = mass of cleared material entering the furnace per charge (g/charge)
M_1 = total mass of scrap metal entering the furnace per charge (g/charge)
C_0 = original concentration of cleared material (pCi/g)

For slag, baghouse dust, and off-gas, Equations 6.1 and 6.2 were evaluated using annual average values for the masses of scrap entering the furnaces because all the exposure scenarios for these materials depend on annual average concentrations. For metal, both an annual average and a single charge evaluation of Equations 6.1 and 6.2 were conducted. This was done for metal because there are metal products that could easily be manufactured from a single refinery charge. The single charge concentrations were used in metal product-use exposure scenarios except where noted. (See Appendix D for additional details.)

6.4.2 Refinery Process

To accurately account for concentration changes in the different products, the mass of each refinery product must be calculated. Equations 6.3, 6.4, and 6.5 are used to calculate the masses of slag, dust, and metal product, respectively.

$$M_s = M_1 * f_{s1} * CPY \quad 6.3$$

$$M_d = M_1 * f_{d1} * CPY \quad 6.4$$

$$M_p = M_1 * f_{p1} * CPY \quad 6.5$$

where

M_s = mass of slag produced from a refinery per year (g/y)
M_d = mass of dust produced from a refinery per year (g/y)
M_p = mass of metal product produced from a refinery per year (g/y)

and

M_1 = total mass of scrap entering the furnace per charge (g/charge)
f_{s1} = mass partitioning factor for slag during the refining process (dimensionless)
f_{d1} = mass partitioning factor for dust during the refining process (dimensionless)
f_{p1} = mass partitioning factor for metal product during the refining process (dimensionless)
CPY = number of charges per refinery per year (charge)

The total amount of radioactivity in the original metal entering the furnace during the refining process is partitioned among four product materials. Equation 6.6 shows the calculation for radionuclide concentration in slag, taking into account both the mass and elemental partitioning factors.

$$C_s = \frac{C_1 * f_s * M_1}{M_1 * f_{s1}} = \frac{C_1 * f_s}{f_{s1}} \qquad 6.6$$

where

C_s = radionuclide concentration in slag after the refining process (pCi/g)

and

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
f_s = slag elemental partitioning factor during the refining process (dimensionless)
M_1 = total mass of scrap entering the furnace per charge (g/charge)
f_{s1} = mass partitioning factor for slag during the refining process (dimensionless)

The concentration of radionuclides in the dust and metal product are similarly calculated using Equations 6.7 and 6.8, respectively.

$$C_d = \frac{C_1 * f_d}{f_{d1}} \qquad 6.7$$

where

C_d = radionuclide concentration in dust after the refining process (pCi/g)

and

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
f_d = dust elemental partitioning factor during the refining process(dimensionless)
f_{d1} = mass partitioning factor for dust during the refining process (dimensionless)

$$C_p = \frac{C_1 * f_p}{f_{p1}} \qquad 6.8$$

where

C_p = radionuclide concentration in metal product after the refining process (pCi/g)

and

C_1 = radionuclide concentration in scrap entering the refining process (pCi/g)
f_p = metal product elemental partitioning factor during the refining process (dimensionless)
f_{p1} = mass partitioning factor for metal product during the refining process (dimensionless)

No mass is explicitly calculated for the off-gas. Exposure scenarios for atmospheric effluents are based on the total amount of radioactivity released from the refinery stack each year. The annual amount of radioactivity in the off-gas was calculated using Equation 6.9.

$$A_g = C_1 * M_1 * f_g * CPY \quad 6.9$$

where

A_g	=	radioactivity in the off-gases leaving the refinery stack in a year (pCi/y)

and

C_1	=	radionuclide concentration in scrap entering the refining process (pCi/g)
M_1	=	total mass of scrap entering the furnace per charge (g/charge)
f_g	=	off-gas elemental partitioning factor during the refining process (dimensionless)
CPY	=	number of charges per refinery per year (charge)

Equations 6.10 and 6.11 are used to calculate the mass of dust that escapes the baghouse filters and the mass that is captured in the baghouse, respectively.

$$M_{ra} = M_d * (1 - BH_{eff}) \quad 6.10$$

where

M_{ra}	=	total mass of dust that escapes the baghouse in a year (g)

and

M_d	=	mass of dust produced from the refining process in a year (g)
BH_{eff}	=	baghouse efficiency (dimensionless)

$$M_{db} = M_d - M_{ra} \quad 6.11$$

where

M_{db}	=	total mass of dust captured in the refinery baghouse in a year (g)

and

M_d	=	mass of dust produced from the refining process in a year (g)
M_{ra}	=	total mass of dust that escapes the baghouse in a year (g)

6.5 Radioactivity Concentrations in Aluminum Refining Co-Products

Mean radionuclide concentrations in the co-products of aluminum refining are listed in Table 6.3. These values represent estimated radioactivity concentrations in the refinery output. The values are normalized to a unit radioactivity concentration in scrap and are only listed in S.I.

units since the values are numerically identical if expressed in conventional units (e.g. pCi/g product per pCi/g scrap).

As stated above, Table 6.3 lists the mean concentration of each radionuclide in each medium. Tabulations are limited to mean values simply because of the space that would be required if percentiles from the distributions were also tabulated. The entire distribution of values for each radionuclide in the appropriate medium was used as input for the exposure scenario analysis.

6.6 Dose Assessment for Unique Aluminum Recycle and Disposal Scenarios

Most of the potential exposure scenarios for recycled and disposed aluminum scrap are adequately covered by adapting the steel scrap scenarios described in Section 4. Only one scenario was added to the aluminum analysis that is not already described: a piece of cookware made out of recycled aluminum that is used by a member of the general public in a home situation. This scenario was not included in the set of scenarios for steel because of the small potential doses previously calculated in other analyses (e.g., O'Donnell 1978). However, it was included here because aluminum had not been analyzed in previous studies and because aluminum cookware is commonly used in the U.S.

Recycled aluminum can be made into a variety of cookware, including large pots, baking pans, skillets, and coffee pots. The scenario described below involves using an aluminum pot, where material corroded from the pot might be ingested through the food cooked in it.

6.6.1 Exposure pathways

External: This scenario includes external exposure to penetrating radiation from the volume source of an aluminum pot.

Ingestion: If an aluminum pot is used to boil water or cook food, a small amount of material could corrode off the pot and transfer to the water or food in the pot. This material would then be ingested with the prepared food.

Suspension of particulates from aluminum cookware is unlikely, therefore the inhalation pathway is not included.

6.6.2 Mathematical Representation

The annual total effective dose equivalent (TEDE) is calculated by adding the effective dose equivalents from the external and ingestion exposure pathways. The TEDE for a member of the public using an aluminum pot is represented by Equation 6.12.

$$D_T = D_{ext} + D_{ing} \qquad 6.12$$

where

D_T = TEDE for the scenario (mrem/y)

and

D_{ext} = EDE due to external exposure (mrem/y)

D_{ing} = EDE due to ingestion (mrem/y)

Table 6.3 Results of material flow model—aluminum refinery

	Mean radionuclide concentrations in refinery products (Bq/g product per Bq/g scrap)				
	Refined Metal				Off-gas
Nuclide	Single Charge	Annual	Slag	Dust	(Bq per Bq/g)
H-3	5.8E-04	9.4E-06	0.0E+00	0.0E+00	9.6E+07
C-14	3.1E-02	4.8E-04	8.4E-05	0.0E+00	0.0E+00
Na-22	0.0E+00	0.0E+00	1.6E-03	3.6E-04	0.0E+00
P-32	0.0E+00	0.0E+00	1.4E-03	5.3E-03	0.0E+00
S-35	0.0E+00	0.0E+00	1.4E-03	5.3E-03	0.0E+00
Cl-36	0.0E+00	0.0E+00	8.4E-04	1.8E-02	9.7E+05
K-40	0.0E+00	0.0E+00	1.6E-03	3.6E-04	0.0E+00
Ca-41	0.0E+00	0.0E+00	1.6E-03	3.6E-04	0.0E+00
Ca-45	0.0E+00	0.0E+00	1.6E-03	3.6E-04	0.0E+00
Cr-51	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Mn-54	0.0E+00	0.0E+00	1.6E-03	3.6E-04	0.0E+00
Fe-55	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00
Co-57	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Co-58	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Fe-59	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Ni-59	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Co-60	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Ni-63	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Zn-65	3.4E-02	5.3E-04	0.0E+00	1.8E-03	0.0E+00
Cu-67	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Se-75	0.0E+00	0.0E+00	1.4E-03	5.3E-03	0.0E+00
Sr-85	1.8E-02	2.8E-04	8.4E-04	0.0E+00	0.0E+00
Sr-89	1.8E-02	2.8E-04	8.4E-04	0.0E+00	0.0E+00
Sr-90	1.8E-02	2.8E-04	8.4E-04	0.0E+00	0.0E+00
Y-91	8.9E-03	1.4E-04	1.3E-03	0.0E+00	0.0E+00
Mo-93	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Nb-93m	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00
Nb-94	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00
Nb-95	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Zr-95	1.8E-02	2.8E-04	8.4E-04	0.0E+00	0.0E+00
Tc-99	3.0E-02	4.8E-04	2.5E-04	0.0E+00	0.0E+00
Ru-103	3.0E-02	4.8E-04	2.6E-04	0.0E+00	0.0E+00
Ru-106	3.0E-02	4.8E-04	2.5E-04	0.0E+00	0.0E+00
Ag-108m	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Cd-109	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Ag-110m	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Sb-124	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00
I-125	0.0E+00	0.0E+00	1.3E-03	0.0E+00	9.7E+05
Sb-125	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
I-129	0.0E+00	0.0E+00	1.3E-03	0.0E+00	9.8E+05
I-131	0.0E+00	0.0E+00	1.3E-03	0.0E+00	9.6E+05
Ba-133	1.8E-02	2.8E-04	8.4E-04	0.0E+00	0.0E+00
Cs-134	0.0E+00	0.0E+00	1.6E-03	3.6E-04	0.0E+00
Cs-137	0.0E+00	0.0E+00	1.6E-03	3.6E-04	0.0E+00

Table 6.3 Results of material flow model—aluminum refinery

	Mean radionuclide concentrations in refinery products (Bq/g product per Bq/g scrap)				
	Refined Metal				Off-gas
Nuclide	Single Charge	Annual	Slag	Dust	(Bq per Bq/g)
Ce-141	9.0E-03	1.4E-04	1.3E-03	0.0E+00	0.0E+00
Ce-144	9.0E-03	1.4E-04	1.3E-03	0.0E+00	0.0E+00
Pm-147	8.9E-03	1.4E-04	1.3E-03	0.0E+00	0.0E+00
Eu-152	8.9E-03	1.4E-04	1.3E-03	0.0E+00	0.0E+00
Eu-154	9.0E-03	1.4E-04	1.3E-03	0.0E+00	0.0E+00
Eu-155	8.9E-03	1.4E-04	1.3E-03	0.0E+00	0.0E+00
Re-186	3.0E-02	4.8E-04	2.6E-04	0.0E+00	0.0E+00
Ir-192	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Pb-210	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Po-210	3.0E-02	4.8E-04	2.5E-04	0.0E+00	0.0E+00
Bi-210	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Rn-222	5.9E-04	9.7E-06	0.0E+00	0.0E+00	9.6E+07
Ra-223	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00
Ra-224	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00
Ac-225	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Ra-225	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Ra-226	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Ac-227	3.5E-02	5.5E-04	3.0E-05	0.0E+00	0.0E+00
Th-227	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Th-228	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Ra-228	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Th-229	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Th-230	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Pa-231	3.5E-02	5.5E-04	3.0E-05	0.0E+00	0.0E+00
Th-231	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Th-232	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00
Pa-233	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
U-233	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Th-234	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00
U-234	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
U-235	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00
Np-237	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Pu-238	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
U-238	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Pu-239	3.5E-02	5.5E-04	2.8E-05	0.0E+00	0.0E+00
Pu-240	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Pu-241	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Am-241	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Cm-242	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Pu-242	3.5E-02	5.5E-04	2.7E-05	0.0E+00	0.0E+00
Cm-244	3.5E-02	5.5E-04	2.9E-05	0.0E+00	0.0E+00

The mathematical representations for each exposure pathway are discussed in the following three subsections.

Equation 6.13 estimates the radionuclide concentration in the aluminum pot at the time use. This incorporates radioactive decay from the time the scrap aluminum is cleared by a NRC licensed facility to the time the scenario begins. The reference to "source material" in the parameters of Equation 6.13 and other equations refers to the material that represents the source of radioactivity. In this scenario, the source material is an aluminum pot.

$$C_0 = C_x e^{-\lambda_r t_s} \quad 6.13$$

where

C_0 = radionuclide concentration in the source material at time the scenario begins (pCi/g)

and

C_x = undecayed radionuclide concentration in the source material (pCi/g)
λ_r = radioactive decay constant (1/d)
t_s = time from clearance from nuclear facility to time scenario begins (d)

External Exposure

An individual in close proximity to the pot while using it would be exposed to penetrating radiation from the mass of aluminum in the pot. This external exposure is calculated using Equation 6.14.

$$D_{ext} = C_0 * GF * U_{GF} * t_{xs} * t_{ys} \quad 6.14$$

where

D_{ext} = EDE due to external exposure (mrem/y)

and

C_0 = radionuclide concentration in the source material at time the scenario begins (pCi/g)
GF = geometry factor for the scenario (mrem/h per pCi/g)
U_{GF} = uncertainty in geometry factor (dimensionless)
t_{xs} = daily number of hours of exposure for the scenario (h/d)
t_{ys} = annual number of days of exposure for the scenario (d/y)

Ingestion Exposure

While food is being cooked in an aluminum pot, a certain amount of aluminum could corrode off the pot and transfer to the food. The dose due to this exposure pathway is presented in Equation 6.15.

$$D_{ing} = C_0 * CR_{Al} * DI_t * F_{DI} * t_{ys} * DF_{ing} * (1E-03) \quad 6.15$$

where

D_{ing}	=	EDE due to ingestion (mrem/y)

and

C_0	=	radionuclide concentration in the source material at time the scenario begins (pCi/g)
CR_{Al}	=	corrosion and transfer rate for aluminum (mg Al/kg food)
DI_t	=	total dietary intake (kg food/d)
F_{DI}	=	fraction of total dietary intake that is cooked in aluminum pot (dimensionless)
DF_{ing}	=	ingestion dose factor (mrem/pCi intake)
1E-03	=	unit conversion factor (g/mg)
t_{ys}	=	annual number of days of exposure for the scenario (d/y)

6.7 Parameter Discussion for all Modeled Scenarios

Calculation of potential impacts from recycle of cleared aluminum scrap material depends on many parameter values. Parameter values are needed for both material flow and dose assessment models. The material flow parameter values rely on information from the U.S. secondary aluminum industry. The parameter values for the dose modeling are a function of receptor behavior, such as time on a specific job or breathing rate, as well as how the radionuclides are transported in the environment. The dose modeling parameter values are based on those used in the iron and steel modeling described in Section 4. Only those parameter values that are different from those used in the iron and steel modeling are discussed in this section.

6.7.1 Scenario Timing

The same scenario-timing assumptions that are presented for the BOF steel modeling (Section 4) are used for the aluminum modeling.

6.7.2 Dose Evaluation

This section presents a discussion of parameter values used for the analysis of aluminum recycle scenarios. In general, the same scenarios are analyzed for aluminum recycle as were analyzed for steel recycle in Section 4. Values used for many of the parameters are also the same as for the steel recycle analysis. For some parameters, however, values specific to the recycle of aluminum were used in order to more appropriately model the scenarios as they would likely occur for aluminum recycle. The following discussion is limited to these specific parameter values. If a parameter is not discussed below and listed in Table B.12, the same value as used for the steel evaluation (Table B.7) is used for aluminum.

6.7.2.1 Input Concentrations from the Material Flow

The undecayed radionuclide concentration in the source material, C_x, is used as the source material input concentration for scenario evaluations. This parameter is radionuclide dependent and is calculated in the material flow modeling. Table B.14 lists the sources for C_x, as they appear in the mathematical modeling of the material flow (e.g., C_p, concentration in metal product after the refining process).

6.7.2.2 External Exposure Parameters

This section presents values for those radionuclide-independent parameters used in calculating external exposure, including those that address duration of exposure and material density. Values for these parameters are tabulated in Table B.12.

The dose factors for the additional scenario involving use of an aluminum pot are based on the assumption that the use occurs once per day for approximately 30 minutes. A normal residence period of 350 days per year is assumed. From these assumptions, a range of .375 to .5 h/d was used for t_{xs}.

For the scrap disposal scenario a fixed value of 1.35E+6 g/m^3 was used for the density of waste.

6.7.2.3 Ingestion Exposure Parameters

Radionuclide-independent parameters used in the evaluation of ingestion exposure include those that address environmental and biotic transport, as well as human consumption. This section describes the values for those unique parameters used in the calculation of ingestion exposure. The only parameters that are different in the aluminum recycling analysis are for the scenario addressing use of aluminum cookware.

When an aluminum pot is used to cook foods, a certain amount of aluminum is corroded and transferred to the food. According to the US Public Health Service, acidic foods, such as tomatoes, tomato sauce and applesauce, tend to accumulate more aluminum than other foods (U.S. Public Health Service 1992). Aluminum concentrations in precooked foods (applesauce, green beans, beef, eggs, ham, pudding, rice, and tomato sauce) range from less than 0.10 to 21.6 mg Al/kg food. However, if these foods are cooked in an aluminum pot, the concentrations range from 0.24 to 125 mg Al/kg food (U.S. Public Health Services 1992). This means the increase in aluminum concentration due to cooking in an aluminum pot is from 0.14 to 103.4 mg Al/kg. This range was used for this scenario evaluation, and the average value of 52 mg Al/kg food was used as the most likely value for CR_{A1}.

A value for dietary intake was calculated using “The Exposure Factors Sourcebook” (AIHC 1995), which presents data for total dietary intake. Data range from 1.4 kg/d for the UK to 1.6 kg/d for the U.S. and are based on food purchased minus a certain percent for waste. Ten percent waste is assumed in the UK while 15% waste is assumed in the U.S. AIHC (1995) suggests a

value of 1.6 kg/d be used for purposes of non-U.S. FDA risk assessments. Therefore, a uniform range of 1.3 to 1.6 was used for the total dietary intake, DI_t. The corrosion and transfer rate discussed above is for a wide variety of foods, so a range of .33 to 1.0 is used for the fraction of total dietary intake that is cooked in the aluminum pot, F_{DI}.

6.7.2.4 Atmospheric Release Parameters

This section presents the values for those radionuclide-independent parameters used for calculating atmospheric dispersion of refinery stack releases from aluminum recycling facilities. The only radionuclide-independent parameter different from the steel analysis is the total mass of dust that escapes the refinery baghouse in a year, M_{ra}. The distribution calculated in the material flow model is used as the input distribution for this parameter.

6.7.3 Aluminum Surface-to-Mass Ratio

The surface-to-mass ratios of various aluminum objects (spheres and cylindrical bar stock) were examined in estimating a range for aluminum scrap. Aluminum objects are assumed to have a density of 2.7 g/cm^3. Surface-to-mass ratios for various aluminum objects ranges from approximately 0.04 cm^2/g for large-radius spheres and bar stock, up to 10 cm^2/g or higher for very thin sheets and pipes.

Data are not available to provide an adequate basis for choosing a "best estimate" from this range of values. Based on these data and assumptions, the value of surface-to-mass ratio for aluminum is best described by a uniform distribution having a minimum of 1.0 cm^2/g and a maximum of 7.0 cm^2/g. The minimum value is characteristic of pipes and sheets having a thickness of 0.25 cm. The maximum value is characteristic of pipes and sheets having a thickness of 0.05 cm. These surface-to-mass ratios for aluminum are representative of pipes and sheets of various sizes with residual contamination on one side only. A wide variety of aluminum objects commonly found at nuclear facilities have surface-to-mass values that fall within this range.

6.8 Dose Factors for Recycle and Disposal of Aluminum Scrap

This analysis of recycle of cleared aluminum scrap includes 17 separate scenarios evaluated for 85 radionuclides. Figure 6.2 shows which scenarios describe the critical groups and for how many radionuclides. There are six scenarios which have the highest mean dose factor for at least one radionuclide. The largest number of radionuclides have critical groups described by scenarios associated with transporting (52 radionuclides) or handling (17 radionuclide) unprocessed scrap. Individuals handling aluminum dross (slag) constitute the critical group for 2 radionuclides. For one volatile radionuclide (H-3), the critical group consists of individuals exposed to atmospheric releases from the refining process. Thirteen radionuclides are limited by scenarios associated with use of consumer products made from recycled aluminum. Use of aluminum cookware accounts for 11 of these radionuclides and use of a small metal object close to the body accounts for two of them. Table 6.4 lists the mass-based dose factors for each

radionuclide. Table 6.5 lists the corresponding derived surficial dose factors for each radionuclide. Results for all 17 aluminum scenarios are tabulated in Appendix H.

The mean values of the critical-group dose factors for each radionuclide are listed in Table 6.4 as the "critical-group dose factor." These represent the dose to the average member of the critical group exposed to radioactivity distributed throughout the mass of cleared aluminum (Bq/g or pCi/g). The circumstances of that exposure are described by the scenario indicated in the right hand column. The 5^{th}, 50^{th}, and 95^{th} percentiles listed for each radionuclide represent the underlying distribution of dose factors calculated for each critical group. The range of values from the 5^{th} to the 95^{th} percentile is the 90% confidence interval on the dose factor. That is, there is a 90% certainty that the dose factor for the average member of the critical group lies within this interval. The confidence interval is a subjective measure of uncertainty in the dose factor that includes estimates of the variability and uncertainty in the parameters used in each scenario.

The ratio of the 95^{th} to the 5^{th} percentile is a useful measure of the relative width of the 90% confidence interval for comparison between scenarios. Smaller values of the 95/5 ratio indicate less uncertainty than larger values. The scenarios with the smallest uncertainty are those with the fewest number of exposure pathways and the least uncertainty in the parameters describing those pathways. The scrap transportation scenario accounts for 52 of the 85 radionuclides. It has the smallest uncertainty of all the critical group scenarios with a 95/5 ratio of about 2 for most radionuclides. The sources of uncertainty in this scenario are similar to those for the steel scrap transportation scenario discussed in Section 4.9.

For all scenarios that take place subsequent to the initial transport of scrap, additional sources of uncertainty are introduced and wider confidence intervals result. Scenarios that address handling of scrap include uncertainty due to dilution with other scrap. They also include additional exposure pathways—inhalation of resuspended dust and inadvertent ingestion under dusty conditions. Scenarios that address handling of refinery products such as aluminum dross include additional uncertainty in how much of each radionuclide is partitioned to these materials. In addition, the aluminum cookware scenario includes uncertainty in dietary practices. For aluminum, this group of handling, processing, and consumer product scenarios have 95/5 ratios that range from about 10 to about 20.

Greater uncertainty is associated with scenarios that involve multiple exposure pathways and complex submodels. One radionuclide (H-3) has a critical group consisting of individuals living in the vicinity of an aluminum refinery and exposed to atmospheric releases. This scenario includes an atmospheric dispersion model and pathways for ingestion, inhalation, and external exposure, each of which contributes to uncertainty in the dose factor. In this case, the atmospheric release scenario has a 95/5 ratio of 50. Most of this uncertainty is due to the atmospheric dispersion model with additional contributions from uncertainties in the ingestion dose pathway.

The mean values of the derived surficial dose factors for each radionuclide in Table 6.5 represent the dose to the average member of the critical group exposed to radioactivity initially distributed

over the surface cleared aluminum scrap (Bq/cm^2 or pCi/cm^2). Derived surficial dose factors are calculated from mass-based dose factors by use of a surface-to-mass ratio, appropriate for typical aluminum objects available for clearance**.** The surface-to-mass ratio is used to derive surficial dose factors as described in Section 4.7.

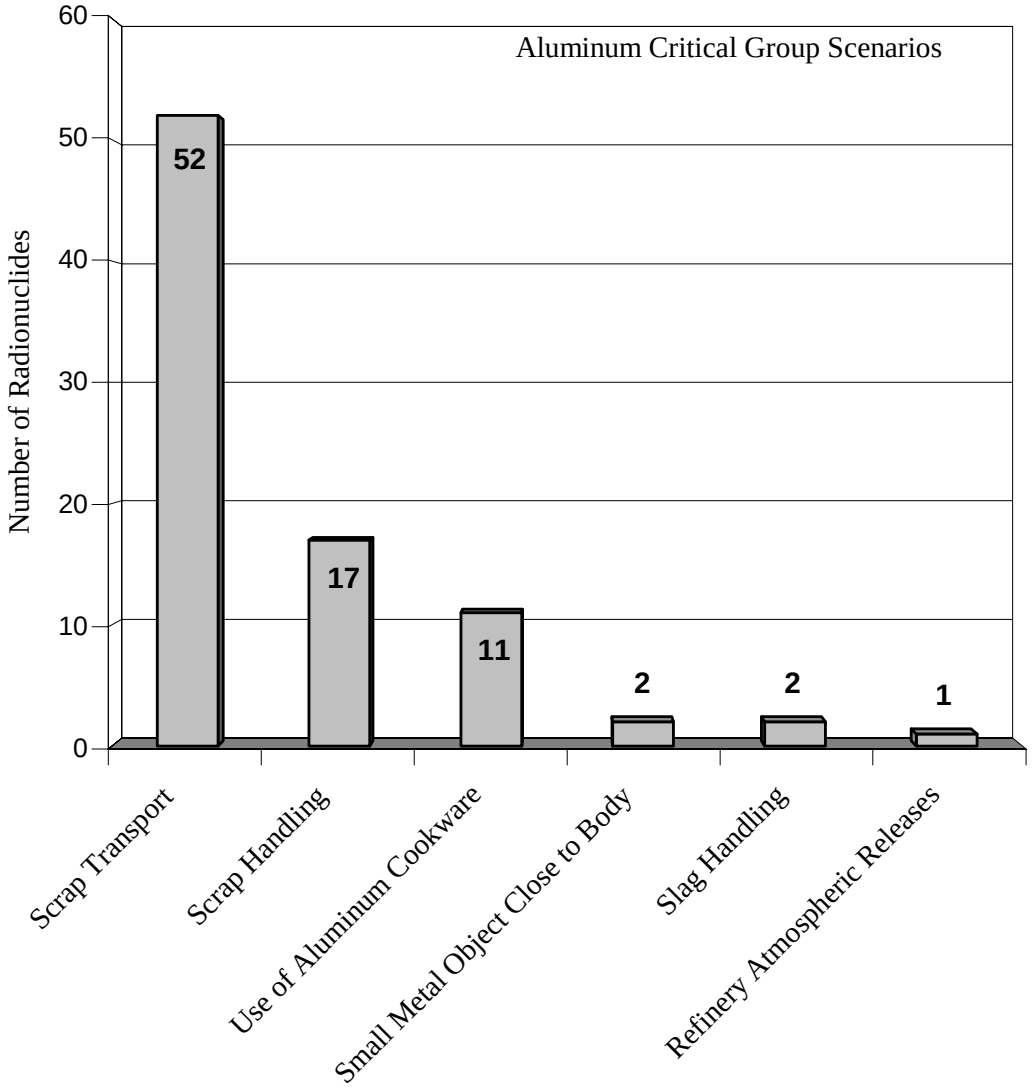

Figure 6.2 Scenarios describing critical groups for aluminum recycle

Table 6.4 Aluminum recycle critical-group dose factors–mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
H-3	1.8E-06	1.3E-07	9.4E-07	6.6E-06	6.6E-09	4.9E-10	3.5E-09	2.5E-08	AL-ATMO-REFINER-N
C-14	2.6E-04	5.2E-05	2.1E-04	5.8E-04	9.4E-07	1.9E-07	7.9E-07	2.2E-06	AL-METL-COOKWAR-N
Na-22	4.4E+00	2.8E+00	4.4E+00	6.0E+00	1.6E-02	1.0E-02	1.6E-02	2.2E-02	AL-SCRP-TRANSPO-W
P-32	2.6E-03	1.7E-03	2.6E-03	3.6E-03	9.7E-06	6.2E-06	9.6E-06	1.3E-05	AL-SCRP-TRANSPO-W
S-35	8.6E-06	5.5E-06	8.7E-06	1.2E-05	3.2E-08	2.0E-08	3.2E-08	4.4E-08	AL-SCRP-TRANSPO-W
Cl-36	6.8E-04	4.4E-04	6.8E-04	9.4E-04	2.5E-06	1.6E-06	2.5E-06	3.5E-06	AL-SCRP-TRANSPO-W
K-40	3.2E-01	2.1E-01	3.3E-01	4.5E-01	1.2E-03	7.7E-04	1.2E-03	1.6E-03	AL-SCRP-TRANSPO-W
Ca-41	1.0E-05	1.2E-06	6.9E-06	2.9E-05	3.8E-08	4.4E-09	2.6E-08	1.1E-07	AL-DROS-HANDLIN-W
Ca-45	3.0E-05	1.9E-05	3.0E-05	4.2E-05	1.1E-07	7.1E-08	1.1E-07	1.5E-07	AL-SCRP-TRANSPO-W
Cr-51	4.9E-02	3.2E-02	4.9E-02	6.8E-02	1.8E-04	1.2E-04	1.8E-04	2.5E-04	AL-SCRP-TRANSPO-W
Mn-54	1.7E+00	1.1E+00	1.7E+00	2.3E+00	6.3E-03	4.0E-03	6.3E-03	8.7E-03	AL-SCRP-TRANSPO-W
Fe-55	7.3E-05	1.6E-05	6.3E-05	1.6E-04	2.7E-07	5.9E-08	2.3E-07	6.1E-07	AL-METL-COOKWAR-N
Co-57	7.6E-02	4.9E-02	7.6E-02	1.0E-01	2.8E-04	1.8E-04	2.8E-04	3.9E-04	AL-SCRP-TRANSPO-W
Co-58	1.9E+00	1.2E+00	1.9E+00	2.6E+00	7.0E-03	4.5E-03	7.0E-03	9.7E-03	AL-SCRP-TRANSPO-W
Fe-59	2.3E+00	1.5E+00	2.3E+00	3.2E+00	8.5E-03	5.4E-03	8.4E-03	1.2E-02	AL-SCRP-TRANSPO-W
Ni-59	2.9E-05	6.2E-06	2.4E-05	6.7E-05	1.1E-07	2.3E-08	9.0E-08	2.5E-07	AL-METL-COOKWAR-N
Co-60	5.1E+00	3.3E+00	5.1E+00	7.0E+00	1.9E-02	1.2E-02	1.9E-02	2.6E-02	AL-SCRP-TRANSPO-W
Ni-63	8.2E-05	1.8E-05	7.0E-05	1.9E-04	3.0E-07	6.7E-08	2.6E-07	6.9E-07	AL-METL-COOKWAR-N
Zn-65	1.2E+00	7.6E-01	1.2E+00	1.6E+00	4.4E-03	2.8E-03	4.4E-03	6.1E-03	AL-SCRP-TRANSPO-W
Cu-67	4.1E-02	2.1E-02	3.8E-02	7.2E-02	1.5E-04	7.9E-05	1.4E-04	2.7E-04	AL-SCRP-TRANSPO-W
Se-75	4.9E-01	3.1E-01	4.9E-01	6.8E-01	1.8E-03	1.2E-03	1.8E-03	2.5E-03	AL-SCRP-TRANSPO-W
Sr-85	9.4E-01	6.0E-01	9.4E-01	1.3E+00	3.5E-03	2.2E-03	3.5E-03	4.8E-03	AL-SCRP-TRANSPO-W
Sr-89	2.3E-03	1.5E-03	2.3E-03	3.2E-03	8.6E-06	5.5E-06	8.6E-06	1.2E-05	AL-SCRP-TRANSPO-W
Sr-90	1.0E-02	1.9E-03	8.8E-03	2.4E-02	3.8E-05	7.1E-06	3.3E-05	8.9E-05	AL-METL-COOKWAR-N
Y-91	6.9E-03	4.4E-03	6.9E-03	9.6E-03	2.6E-05	1.6E-05	2.6E-05	3.5E-05	AL-SCRP-TRANSPO-W
Mo-93	5.5E-04	8.4E-05	4.1E-04	1.6E-03	2.1E-06	3.1E-07	1.5E-06	5.8E-06	AL-METL-SMOBJCT-N
Nb-93m	8.7E-05	1.5E-05	6.5E-05	2.4E-04	3.2E-07	5.4E-08	2.4E-07	8.8E-07	AL-METL-SMOBJCT-N
Nb-94	3.3E+00	2.1E+00	3.3E+00	4.5E+00	1.2E-02	7.8E-03	1.2E-02	1.7E-02	AL-SCRP-TRANSPO-W
Nb-95	1.4E+00	9.3E-01	1.4E+00	2.0E+00	5.4E-03	3.4E-03	5.3E-03	7.4E-03	AL-SCRP-TRANSPO-W
Zr-95	1.4E+00	9.2E-01	1.4E+00	2.0E+00	5.3E-03	3.4E-03	5.3E-03	7.4E-03	AL-SCRP-TRANSPO-W
Tc-99	1.8E-04	4.1E-05	1.4E-04	4.5E-04	6.7E-07	1.5E-07	5.2E-07	1.7E-06	AL-METL-COOKWAR-N
Ru-103	9.3E-01	5.9E-01	9.2E-01	1.3E+00	3.4E-03	2.2E-03	3.4E-03	4.7E-03	AL-SCRP-TRANSPO-W
Ru-106	4.1E-01	2.6E-01	4.1E-01	5.7E-01	1.5E-03	9.8E-04	1.5E-03	2.1E-03	AL-SCRP-TRANSPO-W
Ag-108m	3.2E+00	2.1E+00	3.2E+00	4.5E+00	1.2E-02	7.7E-03	1.2E-02	1.6E-02	AL-SCRP-TRANSPO-W
Cd-109	1.3E-03	2.8E-04	1.1E-03	2.8E-03	4.7E-06	1.0E-06	4.0E-06	1.0E-05	AL-METL-COOKWAR-N

Table 6.4 Aluminum recycle critical-group dose factors–mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Ag-110m	5.7E+00	3.6E+00	5.7E+00	7.8E+00	2.1E-02	1.3E-02	2.1E-02	2.9E-02	AL-SCRP-TRANSPO-W
Sb-124	3.6E+00	2.3E+00	3.6E+00	5.0E+00	1.3E-02	8.5E-03	1.3E-02	1.9E-02	AL-SCRP-TRANSPO-W
I-125	1.3E-03	8.3E-04	1.3E-03	1.8E-03	4.8E-06	3.1E-06	4.8E-06	6.7E-06	AL-SCRP-TRANSPO-W
Sb-125	8.1E-01	5.2E-01	8.1E-01	1.1E+00	3.0E-03	1.9E-03	3.0E-03	4.1E-03	AL-SCRP-TRANSPO-W
I-129	1.9E-03	2.7E-04	1.1E-03	5.6E-03	6.9E-06	1.0E-06	4.1E-06	2.1E-05	AL-DROS-HANDLIN-N
I-131	5.0E-01	3.2E-01	4.9E-01	7.2E-01	1.9E-03	1.2E-03	1.8E-03	2.7E-03	AL-SCRP-TRANSPO-W
Ba-133	5.6E-01	3.6E-01	5.6E-01	7.7E-01	2.1E-03	1.3E-03	2.1E-03	2.8E-03	AL-SCRP-TRANSPO-W
Cs-134	3.2E+00	2.1E+00	3.2E+00	4.4E+00	1.2E-02	7.6E-03	1.2E-02	1.6E-02	AL-SCRP-TRANSPO-W
Cs-137	1.2E+00	7.9E-01	1.2E+00	1.7E+00	4.6E-03	2.9E-03	4.6E-03	6.3E-03	AL-SCRP-TRANSPO-W
Ce-141	5.4E-02	3.5E-02	5.4E-02	7.5E-02	2.0E-04	1.3E-04	2.0E-04	2.8E-04	AL-SCRP-TRANSPO-W
Ce-144	6.6E-02	4.2E-02	6.6E-02	9.1E-02	2.4E-04	1.6E-04	2.4E-04	3.4E-04	AL-SCRP-TRANSPO-W
Pm-147	5.5E-05	1.2E-05	4.5E-05	1.2E-04	2.0E-07	4.6E-08	1.7E-07	4.6E-07	AL-SCRP-HANDLIN-W
Eu-152	2.2E+00	1.4E+00	2.2E+00	3.1E+00	8.2E-03	5.3E-03	8.2E-03	1.1E-02	AL-SCRP-TRANSPO-W
Eu-154	2.4E+00	1.6E+00	2.4E+00	3.3E+00	9.0E-03	5.8E-03	9.0E-03	1.2E-02	AL-SCRP-TRANSPO-W
Eu-155	2.1E-02	1.4E-02	2.1E-02	2.9E-02	7.9E-05	5.0E-05	7.9E-05	1.1E-04	AL-SCRP-TRANSPO-W
Re-186	4.9E-03	2.9E-03	4.7E-03	8.0E-03	1.8E-05	1.1E-05	1.7E-05	2.9E-05	AL-SCRP-TRANSPO-W
Ir-192	1.4E+00	9.1E-01	1.4E+00	2.0E+00	5.2E-03	3.3E-03	5.2E-03	7.2E-03	AL-SCRP-TRANSPO-W
Pb-210	7.5E-01	1.7E-01	5.9E-01	1.8E+00	2.8E-03	6.3E-04	2.2E-03	6.8E-03	AL-METL-COOKWAR-N
Po-210	7.4E-02	1.6E-02	6.2E-02	1.6E-01	2.7E-04	5.8E-05	2.3E-04	6.0E-04	AL-METL-COOKWAR-N
Bi-210	6.2E-04	3.8E-04	6.0E-04	9.5E-04	2.3E-06	1.4E-06	2.2E-06	3.5E-06	AL-SCRP-TRANSPO-W
Rn-222	1.7E+00	1.0E+00	1.6E+00	2.8E+00	6.3E-03	3.7E-03	6.0E-03	1.0E-02	AL-SCRP-TRANSPO-W
Ra-223	3.6E-01	2.3E-01	3.6E-01	5.1E-01	1.3E-03	8.5E-04	1.3E-03	1.9E-03	AL-SCRP-TRANSPO-W
Ra-224	1.2E+00	7.2E-01	1.2E+00	2.0E+00	4.5E-03	2.6E-03	4.3E-03	7.3E-03	AL-SCRP-TRANSPO-W
Ac-225	2.8E-01	1.8E-01	2.8E-01	4.0E-01	1.0E-03	6.7E-04	1.0E-03	1.5E-03	AL-SCRP-TRANSPO-W
Ra-225	9.6E-03	2.4E-03	8.0E-03	2.0E-02	3.5E-05	8.7E-06	3.0E-05	7.6E-05	AL-SCRP-HANDLIN-W
Ra-226	3.5E+00	2.2E+00	3.5E+00	4.8E+00	1.3E-02	8.3E-03	1.3E-02	1.8E-02	AL-SCRP-TRANSPO-W
Ac-227	1.9E+00	4.4E-01	1.7E+00	4.2E+00	7.1E-03	1.6E-03	6.2E-03	1.6E-02	AL-METL-COOKWAR-N
Th-227	1.2E-01	7.6E-02	1.2E-01	1.6E-01	4.3E-04	2.8E-04	4.3E-04	6.0E-04	AL-SCRP-TRANSPO-W
Th-228	2.5E+00	1.6E+00	2.5E+00	3.5E+00	9.4E-03	6.0E-03	9.4E-03	1.3E-02	AL-SCRP-TRANSPO-W
Ra-228	1.7E+00	1.6E+00	2.5E+00	3.5E+00	6.2E-03	6.0E-03	9.4E-03	1.3E-02	AL-SCRP-TRANSPO-W
Th-229	2.3E+00	4.2E-01	1.9E+00	5.2E+00	8.4E-03	1.6E-03	6.9E-03	1.9E-02	AL-SCRP-HANDLIN-W
Th-230	3.4E-01	6.3E-02	2.8E-01	7.9E-01	1.3E-03	2.3E-04	1.0E-03	2.9E-03	AL-SCRP-HANDLIN-W
Pa-231	1.5E+00	3.0E-01	1.3E+00	3.7E+00	5.5E-03	1.1E-03	4.8E-03	1.4E-02	AL-METL-COOKWAR-N
Th-231	3.0E-04	6.6E-05	2.2E-04	7.7E-04	1.1E-06	2.5E-07	8.0E-07	2.8E-06	AL-SCRP-TRANSPO-W
Th-232	1.5E+00	2.8E-01	1.2E+00	3.5E+00	5.6E-03	1.0E-03	4.6E-03	1.3E-02	AL-SCRP-HANDLIN-W

Table 6.4 Aluminum recycle critical-group dose factors–mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Pa-233	2.6E-01	1.7E-01	2.6E-01	3.6E-01	9.8E-04	6.3E-04	9.7E-04	1.3E-03	AL-SCRP-TRANSPO-W
U-233	1.8E-01	3.2E-02	1.4E-01	4.1E-01	6.5E-04	1.2E-04	5.4E-04	1.5E-03	AL-SCRP-HANDLIN-W
Th-234	1.5E-02	9.5E-03	1.5E-02	2.0E-02	5.4E-05	3.5E-05	5.4E-05	7.4E-05	AL-SCRP-TRANSPO-W
U-234	1.7E-01	3.1E-02	1.4E-01	4.0E-01	6.4E-04	1.2E-04	5.2E-04	1.5E-03	AL-SCRP-HANDLIN-W
U-235	1.6E-01	1.0E-01	1.6E-01	2.2E-01	6.0E-04	3.9E-04	6.1E-04	8.3E-04	AL-SCRP-TRANSPO-W
Np-237	7.2E-01	1.5E-01	5.9E-01	1.7E+00	2.7E-03	5.5E-04	2.2E-03	6.1E-03	AL-SCRP-HANDLIN-W
Pu-238	3.8E-01	6.8E-02	3.1E-01	8.7E-01	1.4E-03	2.5E-04	1.1E-03	3.2E-03	AL-SCRP-HANDLIN-W
U-238	1.5E-01	2.8E-02	1.3E-01	3.6E-01	5.7E-04	1.0E-04	4.7E-04	1.3E-03	AL-SCRP-HANDLIN-W
Pu-239	4.0E-01	7.3E-02	3.3E-01	9.3E-01	1.5E-03	2.7E-04	1.2E-03	3.4E-03	AL-SCRP-HANDLIN-W
Pu-240	4.0E-01	7.3E-02	3.3E-01	9.3E-01	1.5E-03	2.7E-04	1.2E-03	3.4E-03	AL-SCRP-HANDLIN-W
Pu-241	6.5E-03	1.2E-03	5.3E-03	1.5E-02	2.4E-05	4.3E-06	2.0E-05	5.5E-05	AL-SCRP-HANDLIN-W
Am-241	5.9E-01	1.2E-01	4.9E-01	1.4E+00	2.2E-03	4.4E-04	1.8E-03	5.0E-03	AL-SCRP-HANDLIN-W
Cm-242	2.3E-02	4.5E-03	1.9E-02	5.2E-02	8.4E-05	1.7E-05	6.8E-05	1.9E-04	AL-SCRP-HANDLIN-W
Pu-242	3.8E-01	7.0E-02	3.1E-01	8.8E-01	1.4E-03	2.6E-04	1.2E-03	3.3E-03	AL-SCRP-HANDLIN-W
Cm-244	3.3E-01	6.7E-02	2.7E-01	7.6E-01	1.2E-03	2.5E-04	1.0E-03	2.8E-03	AL-SCRP-HANDLIN-W

Table 6.5 Aluminum recycle critical-group dose factors–surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
	Critical-group dose factor	90% Confidence interval			Critical-group dose factor	90% Confidence interval			
Radionuclide		5th (lower bound)	50th (median)	95th (upper bound)		5th (lower bound)	50th (median)	95th (upper bound)	Scenario
H-3	6.8E-06	5.1E-07	3.1E-06	2.3E-05	2.5E-08	1.9E-09	1.2E-08	8.5E-08	AL-ATMO-REFINER-N
C-14	1.0E-03	1.5E-04	7.5E-04	2.7E-03	3.8E-06	5.5E-07	2.8E-06	1.0E-05	AL-METL-COOKWAR-N
Na-22	1.8E+01	4.7E+00	1.6E+01	3.4E+01	6.6E-02	1.7E-02	6.1E-02	1.2E-01	AL-SCRP-TRANSPO-W
P-32	1.1E-02	2.9E-03	9.6E-03	2.0E-02	3.9E-05	1.1E-05	3.6E-05	7.6E-05	AL-SCRP-TRANSPO-W
S-35	3.5E-05	9.2E-06	3.2E-05	6.6E-05	1.3E-07	3.4E-08	1.2E-07	2.4E-07	AL-SCRP-TRANSPO-W
Cl-36	2.8E-03	7.3E-04	2.5E-03	5.2E-03	1.0E-05	2.7E-06	9.4E-06	1.9E-05	AL-SCRP-TRANSPO-W
K-40	1.3E+00	3.5E-01	1.2E+00	2.5E+00	4.9E-03	1.3E-03	4.5E-03	9.2E-03	AL-SCRP-TRANSPO-W
Ca-41	4.1E-05	3.4E-06	2.5E-05	1.3E-04	1.5E-07	1.3E-08	9.2E-08	4.8E-07	AL-DROS-HANDLIN-W
Ca-45	1.2E-04	3.2E-05	1.1E-04	2.3E-04	4.5E-07	1.2E-07	4.2E-07	8.6E-07	AL-SCRP-TRANSPO-W
Cr-51	2.0E-01	5.3E-02	1.8E-01	3.8E-01	7.4E-04	2.0E-04	6.7E-04	1.4E-03	AL-SCRP-TRANSPO-W
Mn-54	6.9E+00	1.8E+00	6.3E+00	1.3E+01	2.5E-02	6.7E-03	2.3E-02	4.8E-02	AL-SCRP-TRANSPO-W
Fe-55	2.9E-04	4.4E-05	2.2E-04	7.9E-04	1.1E-06	1.6E-07	8.1E-07	2.9E-06	AL-METL-COOKWAR-N
Co-57	3.1E-01	8.1E-02	2.8E-01	5.8E-01	1.1E-03	3.0E-04	1.1E-03	2.2E-03	AL-SCRP-TRANSPO-W
Co-58	7.7E+00	2.0E+00	7.0E+00	1.5E+01	2.8E-02	7.5E-03	2.6E-02	5.4E-02	AL-SCRP-TRANSPO-W
Fe-59	9.3E+00	2.5E+00	8.5E+00	1.8E+01	3.4E-02	9.1E-03	3.1E-02	6.5E-02	AL-SCRP-TRANSPO-W
Ni-59	1.2E-04	1.8E-05	9.0E-05	3.1E-04	4.3E-07	6.6E-08	3.3E-07	1.1E-06	AL-METL-COOKWAR-N
Co-60	2.1E+01	5.4E+00	1.9E+01	3.9E+01	7.6E-02	2.0E-02	7.0E-02	1.4E-01	AL-SCRP-TRANSPO-W
Ni-63	3.2E-04	5.3E-05	2.5E-04	8.1E-04	1.2E-06	2.0E-07	9.2E-07	3.0E-06	AL-METL-COOKWAR-N
Zn-65	4.8E+00	1.3E+00	4.5E+00	9.1E+00	1.8E-02	4.7E-03	1.6E-02	3.4E-02	AL-SCRP-TRANSPO-W
Cu-67	1.7E-01	4.2E-02	1.4E-01	3.8E-01	6.2E-04	1.6E-04	5.3E-04	1.4E-03	AL-SCRP-TRANSPO-W
Se-75	2.0E+00	5.2E-01	1.8E+00	3.8E+00	7.3E-03	1.9E-03	6.7E-03	1.4E-02	AL-SCRP-TRANSPO-W
Sr-85	3.8E+00	1.0E+00	3.5E+00	7.2E+00	1.4E-02	3.7E-03	1.3E-02	2.7E-02	AL-SCRP-TRANSPO-W
Sr-89	9.4E-03	2.5E-03	8.6E-03	1.8E-02	3.5E-05	9.2E-06	3.2E-05	6.6E-05	AL-SCRP-TRANSPO-W
Sr-90	4.0E-02	5.7E-03	2.8E-02	1.2E-01	1.5E-04	2.1E-05	1.0E-04	4.3E-04	AL-METL-COOKWAR-N
Y-91	2.8E-02	7.4E-03	2.6E-02	5.3E-02	1.0E-04	2.7E-05	9.5E-05	2.0E-04	AL-SCRP-TRANSPO-W
Mo-93	2.2E-03	2.4E-04	1.4E-03	6.4E-03	8.1E-06	8.8E-07	5.2E-06	2.4E-05	AL-METL-SMOBJCT-N
Nb-93m	3.4E-04	3.7E-05	2.3E-04	1.1E-03	1.3E-06	1.4E-07	8.4E-07	4.0E-06	AL-METL-SMOBJCT-N
Nb-94	1.3E+01	3.5E+00	1.2E+01	2.5E+01	4.9E-02	1.3E-02	4.5E-02	9.3E-02	AL-SCRP-TRANSPO-W
Nb-95	5.8E+00	1.6E+00	5.3E+00	1.1E+01	2.2E-02	5.8E-03	2.0E-02	4.1E-02	AL-SCRP-TRANSPO-W
Zr-95	5.8E+00	1.5E+00	5.3E+00	1.1E+01	2.2E-02	5.7E-03	2.0E-02	4.1E-02	AL-SCRP-TRANSPO-W
Tc-99	7.2E-04	1.2E-04	5.0E-04	1.9E-03	2.7E-06	4.3E-07	1.8E-06	7.1E-06	AL-METL-COOKWAR-N
Ru-103	3.7E+00	1.0E+00	3.4E+00	7.1E+00	1.4E-02	3.7E-03	1.3E-02	2.6E-02	AL-SCRP-TRANSPO-W
Ru-106	1.7E+00	4.4E-01	1.5E+00	3.2E+00	6.2E-03	1.6E-03	5.7E-03	1.2E-02	AL-SCRP-TRANSPO-W
Ag-108m	1.3E+01	3.4E+00	1.2E+01	2.5E+01	4.8E-02	1.3E-02	4.5E-02	9.2E-02	AL-SCRP-TRANSPO-W
Cd-109	5.1E-03	8.3E-04	3.9E-03	1.4E-02	1.9E-05	3.1E-06	1.5E-05	5.1E-05	AL-METL-COOKWAR-N

Table 6.5 Aluminum recycle critical-group dose factors–surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Ag-110m	2.3E+01	6.0E+00	2.1E+01	4.3E+01	8.5E-02	2.2E-02	7.8E-02	1.6E-01	AL-SCRP-TRANSPO-W
Sb-124	1.5E+01	3.9E+00	1.3E+01	2.8E+01	5.4E-02	1.4E-02	5.0E-02	1.0E-01	AL-SCRP-TRANSPO-W
I-125	5.3E-03	1.4E-03	4.8E-03	1.0E-02	1.9E-05	5.1E-06	1.8E-05	3.7E-05	AL-SCRP-TRANSPO-W
Sb-125	3.3E+00	8.7E-01	3.0E+00	6.2E+00	1.2E-02	3.2E-03	1.1E-02	2.3E-02	AL-SCRP-TRANSPO-W
I-129	7.5E-03	6.1E-04	4.6E-03	2.5E-02	2.8E-05	2.3E-06	1.7E-05	9.1E-05	AL-DROS-HANDLIN-N
I-131	2.0E+00	5.6E-01	1.9E+00	4.0E+00	7.5E-03	2.1E-03	6.9E-03	1.5E-02	AL-SCRP-TRANSPO-W
Ba-133	2.3E+00	5.9E-01	2.1E+00	4.3E+00	8.3E-03	2.2E-03	7.7E-03	1.6E-02	AL-SCRP-TRANSPO-W
Cs-134	1.3E+01	3.4E+00	1.2E+01	2.4E+01	4.8E-02	1.3E-02	4.4E-02	9.1E-02	AL-SCRP-TRANSPO-W
Cs-137	5.0E+00	1.3E+00	4.6E+00	9.5E+00	1.8E-02	4.9E-03	1.7E-02	3.5E-02	AL-SCRP-TRANSPO-W
Ce-141	2.2E-01	5.9E-02	2.0E-01	4.1E-01	8.1E-04	2.2E-04	7.4E-04	1.5E-03	AL-SCRP-TRANSPO-W
Ce-144	2.7E-01	7.0E-02	2.5E-01	5.0E-01	9.8E-04	2.6E-04	9.1E-04	1.9E-03	AL-SCRP-TRANSPO-W
Pm-147	2.2E-04	3.6E-05	1.7E-04	5.9E-04	8.2E-07	1.3E-07	6.2E-07	2.2E-06	AL-SCRP-HANDLIN-W
Eu-152	9.0E+00	2.4E+00	8.3E+00	1.7E+01	3.3E-02	8.8E-03	3.1E-02	6.3E-02	AL-SCRP-TRANSPO-W
Eu-154	9.8E+00	2.6E+00	9.1E+00	1.9E+01	3.6E-02	9.6E-03	3.4E-02	6.9E-02	AL-SCRP-TRANSPO-W
Eu-155	8.6E-02	2.3E-02	7.9E-02	1.6E-01	3.2E-04	8.4E-05	2.9E-04	6.0E-04	AL-SCRP-TRANSPO-W
Re-186	2.0E-02	5.5E-03	1.8E-02	4.2E-02	7.4E-05	2.1E-05	6.7E-05	1.6E-04	AL-SCRP-TRANSPO-W
Ir-192	5.7E+00	1.5E+00	5.2E+00	1.1E+01	2.1E-02	5.6E-03	1.9E-02	4.0E-02	AL-SCRP-TRANSPO-W
Pb-210	3.0E+00	4.5E-01	2.2E+00	8.1E+00	1.1E-02	1.7E-03	8.3E-03	3.0E-02	AL-METL-COOKWAR-N
Po-210	2.9E-01	4.3E-02	2.2E-01	7.8E-01	1.1E-03	1.6E-04	8.1E-04	2.9E-03	AL-METL-COOKWAR-N
Bi-210	2.5E-03	7.2E-04	2.3E-03	5.1E-03	9.3E-06	2.7E-06	8.6E-06	1.9E-05	AL-SCRP-TRANSPO-W
Rn-222	6.9E+00	1.9E+00	6.3E+00	1.5E+01	2.6E-02	7.1E-03	2.3E-02	5.4E-02	AL-SCRP-TRANSPO-W
Ra-223	1.5E+00	4.1E-01	1.3E+00	2.9E+00	5.4E-03	1.5E-03	4.9E-03	1.1E-02	AL-SCRP-TRANSPO-W
Ra-224	4.9E+00	1.4E+00	4.5E+00	1.1E+01	1.8E-02	5.1E-03	1.7E-02	3.9E-02	AL-SCRP-TRANSPO-W
Ac-225	1.1E+00	3.2E-01	1.0E+00	2.3E+00	4.2E-03	1.2E-03	3.9E-03	8.3E-03	AL-SCRP-TRANSPO-W
Ra-225	3.9E-02	6.8E-03	2.9E-02	1.0E-01	1.4E-04	2.5E-05	1.1E-04	3.7E-04	AL-SCRP-HANDLIN-W
Ra-226	1.4E+01	3.7E+00	1.3E+01	2.7E+01	5.2E-02	1.4E-02	4.8E-02	9.8E-02	AL-SCRP-TRANSPO-W
Ac-227	7.6E+00	9.8E-01	5.8E+00	1.9E+01	2.8E-02	3.6E-03	2.2E-02	7.2E-02	AL-METL-COOKWAR-N
Th-227	4.7E-01	1.3E-01	4.3E-01	9.1E-01	1.8E-03	4.8E-04	1.6E-03	3.4E-03	AL-SCRP-TRANSPO-W
Th-228	1.0E+01	2.7E+00	9.5E+00	1.9E+01	3.8E-02	1.0E-02	3.5E-02	7.2E-02	AL-SCRP-TRANSPO-W
Ra-228	6.8E+00	1.8E+00	6.3E+00	1.3E+01	2.5E-02	6.6E-03	2.3E-02	4.8E-02	AL-SCRP-TRANSPO-W
Th-229	9.2E+00	1.3E+00	6.7E+00	2.5E+01	3.4E-02	4.6E-03	2.5E-02	9.3E-02	AL-SCRP-HANDLIN-W
Th-230	1.4E+00	1.9E-01	1.0E+00	3.8E+00	5.1E-03	7.0E-04	3.8E-03	1.4E-02	AL-SCRP-HANDLIN-W
Pa-231	5.9E+00	9.1E-01	4.3E+00	1.5E+01	2.2E-02	3.4E-03	1.6E-02	5.5E-02	AL-METL-COOKWAR-N
Th-231	1.2E-03	1.8E-04	7.4E-04	4.0E-03	4.5E-06	6.6E-07	2.8E-06	1.5E-05	AL-SCRP-TRANSPO-W
Th-232	6.1E+00	8.4E-01	4.5E+00	1.7E+01	2.3E-02	3.1E-03	1.7E-02	6.2E-02	AL-SCRP-HANDLIN-W

Table 6.5 Aluminum recycle critical-group dose factors–surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Pa-233	1.1E+00	2.8E-01	9.8E-01	2.0E+00	3.9E-03	1.1E-03	3.6E-03	7.5E-03	AL-SCRP-TRANSPO-W
U-233	7.2E-01	9.5E-02	5.2E-01	2.0E+00	2.6E-03	3.5E-04	1.9E-03	7.3E-03	AL-SCRP-HANDLIN-W
Th-234	5.9E-02	1.6E-02	5.4E-02	1.1E-01	2.2E-04	5.8E-05	2.0E-04	4.1E-04	AL-SCRP-TRANSPO-W
U-234	7.0E-01	9.3E-02	5.1E-01	1.9E+00	2.6E-03	3.4E-04	1.9E-03	7.1E-03	AL-SCRP-HANDLIN-W
U-235	6.6E-01	1.7E-01	6.1E-01	1.3E+00	2.4E-03	6.4E-04	2.3E-03	4.6E-03	AL-SCRP-TRANSPO-W
Np-237	2.9E+00	4.2E-01	2.2E+00	8.0E+00	1.1E-02	1.6E-03	8.0E-03	2.9E-02	AL-SCRP-HANDLIN-W
Pu-238	1.5E+00	2.0E-01	1.1E+00	4.2E+00	5.6E-03	7.5E-04	4.1E-03	1.5E-02	AL-SCRP-HANDLIN-W
U-238	6.3E-01	8.3E-02	4.6E-01	1.7E+00	2.3E-03	3.1E-04	1.7E-03	6.4E-03	AL-SCRP-HANDLIN-W
Pu-239	1.6E+00	2.2E-01	1.2E+00	4.5E+00	6.0E-03	8.0E-04	4.4E-03	1.7E-02	AL-SCRP-HANDLIN-W
Pu-240	1.6E+00	2.2E-01	1.2E+00	4.5E+00	6.0E-03	8.0E-04	4.4E-03	1.7E-02	AL-SCRP-HANDLIN-W
Pu-241	2.6E-02	3.5E-03	1.9E-02	7.2E-02	9.7E-05	1.3E-05	7.0E-05	2.7E-04	AL-SCRP-HANDLIN-W
Am-241	2.4E+00	3.4E-01	1.8E+00	6.5E+00	8.9E-03	1.3E-03	6.6E-03	2.4E-02	AL-SCRP-HANDLIN-W
Cm-242	9.1E-02	1.3E-02	6.7E-02	2.5E-01	3.4E-04	4.7E-05	2.5E-04	9.3E-04	AL-SCRP-HANDLIN-W
Pu-242	1.5E+00	2.1E-01	1.1E+00	4.2E+00	5.7E-03	7.6E-04	4.2E-03	1.6E-02	AL-SCRP-HANDLIN-W
Cm-244	1.3E+00	1.9E-01	9.9E-01	3.6E+00	4.9E-03	7.0E-04	3.7E-03	1.4E-02	AL-SCRP-HANDLIN-W

The calculation of derived surficial dose factors is probabilistic. The parameter SM is represented by a distribution of values that incorporate the variability and uncertainty in the surface-to-mass ratio of typical aluminum objects available for clearance. This additional source of uncertainty results in wider confidence intervals for the surficial dose factors than for the mass-based dose factors from which they are derived. The relative importance of this additional uncertainty depends on the scenario. For scenarios with the narrowest confidence intervals, the added uncertainty can contribute as much as an additional 50% to the width of the confidence interval. The mass-based dose factor for the scrap transportation scenario has a 95/5 ratio of about 2 for most radionuclides. The corresponding derived surficial dose factors have a 95/5 ratio of about 3. The added uncertainty in surface-to-mass ratio has a relatively smaller impact on the confidence interval for scenarios with larger uncertainties, contributing an additional 10% to 30%.

7 EVALUATION OF RECYCLE AND DISPOSAL OF CONCRETE

Seven potential exposure scenarios for cleared concrete debris that are realistically based on current American industries are evaluated in this section. As in the evaluations for metals, concrete scenario categories include handling and processing, transportation, product use, and disposal. Unique to the concrete evaluation is the inclusion of a scenario involving a resident on the site of a closed landfill. A radionuclide-specific, probabilistic dose factor distribution was calculated for the members of all exposed groups. Dose factors for an average member of each critical group was calculated in the same manner as for metals recycle. The mean dose factor for each critical group is reported in normalized units of μSv/y per Bq/g scrap (mrem/y per pCi/g) and μSv/y per Bq/cm^2 (mrem/y per pCi/cm^2) for each radionuclide. Dose factors at the 5th, 50th, and 95th percentiles are also reported.

Similar to the metals analyses, the most common critical group consists of commercial truck drivers carrying cleared concrete debris, accounting for critical group designation for almost half (33) of the 85 radionuclides in the analysis. Unlike the metals analyses, the scenario involving a resident on a closed landfill containing cleared concrete debris was analyzed and included in critical group determination. This scenario accounts for critical group designation for one-third (28) of the radionuclides in the analysis. Scenarios involving handling concrete debris accounted for most of the remaining critical groups.

Mean critical-group dose factors range from a high of 7E+04 μSv/y per Bq/g (3E+02 mrem/y per pCi/g) for Np-237 to a low of 3E-03 μSv/y per Bq/g (1.3E-05 mrem/y per pCi/g) for Fe-55. The surficial mean critical-group dose factors range from 1.4E+03 μSv/y per Bq/cm^2 (Np-237) down to 5E-05 μSv/y per Bq/cm^2 (S-35). The Np-237 highest mean dose factors are a factor of 30 higher than the next highest mean dose factor. The high mean dose factor of Np-237 is the highest calculated for all materials (metals and concrete) and is attributed to the drinking-water exposure pathway in a residential scenario on the site of a closed landfill. Seventy-four of the radionuclide-specific, mean dose factors for concrete critical groups are 270 μSv/y per Bq/g or lower (1 mrem/y per pCi/g).

This section describes the technical evaluation of the recycle and disposal of concrete debris that could be cleared by Nuclear Regulatory Commission (NRC) licensed facilities. Similar to the analyses of metal scrap (Sections 4, 5, and 6), the likely flow of cleared concrete was probabilistically modeled, distributions of radionuclide concentrations in recycled products and disposed materials were calculated, and potential doses to average members of potential critical groups were estimated.

7.1 Introduction to Analysis

The analysis process for calculating potential exposures from concrete recycle and disposal is relatively simple when compared to the analyses conducted for recycled and disposed metals. A simple material flow model specific to concrete recycle and disposal was developed, radioactivity concentrations in reprocessed concrete were calculated, and scenario evaluations were conducted. In contrast to the metal analyses, the processing of concrete does not involve redistribution of radionuclides, and there is only one resulting end product. The exposure scenario evaluations for concrete are similar to those for the metals, with only several minor scenario parameter

differences, and only one fundamentally different scenario is used in the determination of critical groups (resident on a closed landfill site).

7.2 Flow of Recycled and Disposed Concrete

The material flow model for concrete represents the general processes that concrete cleared by NRC licensed facilities would go through from the time of clearance to the time of final disposal. Decontamination is assumed to have already taken place and is not included in the model. The material flow model comprises two types of models: conceptual and mathematical. The conceptual model describes the recycling process and defines the limits of this analysis, while the mathematical model presents the mathematical equations that implement the information presented in the conceptual model.

The material flow model is based largely on information gathered from personal communications with individuals in the concrete recycling industry. It is intended to provide a defensible basis for developing appropriate exposure scenarios for recycled concrete. In addition, the output of the material flow model provides key input to the dose calculations for each scenario. This input consists of radionuclide-specific concentrations in recycle products containing recycled concrete, in effluents, and in waste products of the recycling process. Because of the number of scenarios being analyzed and the differing times at which they occur, the mathematical model presented in this section does not include radioactive decay. Like other materials, this is accounted for in the scenario evaluations.

This section presents the conceptual model that follows the concrete through a typical recycling process, beginning with cleared concrete debris, through the recycling process, product use, and ending with disposal. Figure 7.1 presents a schematic diagram of the conceptual model of the overall flow of recycled and disposed concrete. The modeling of both mass and radioactivity in recycled concrete follow this flow model. As seen in Figure 7.1, there are several distinct steps in the recycling process. Each of these are discussed separately in the following subsections.

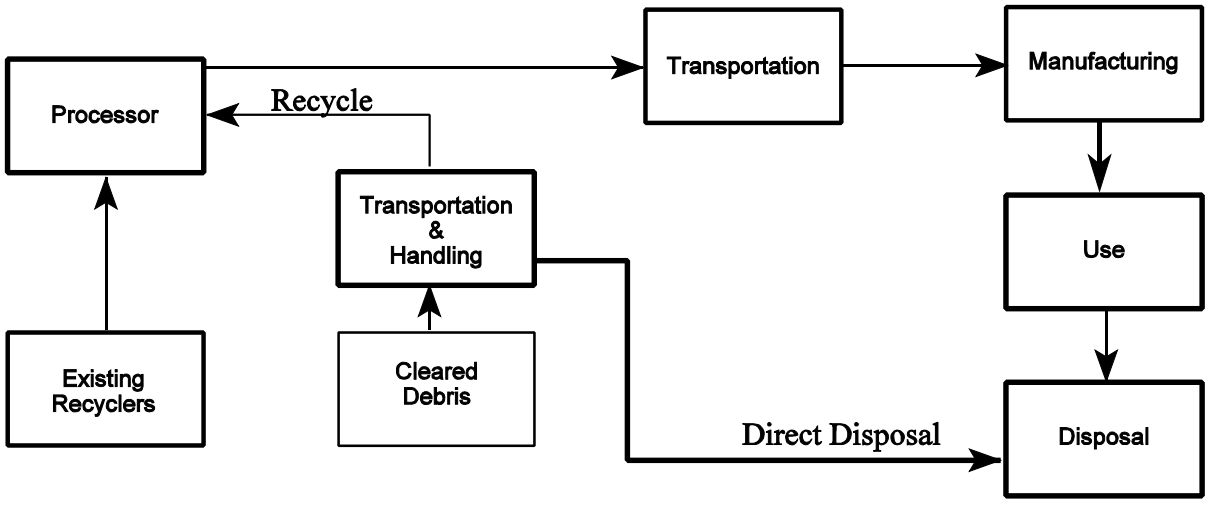

Figure 7.1 Conceptual model of the overall flow of recycled and disposed concrete

7.2.1 Source of Material

Concrete for recycling comes mainly from commercial sources, which contributes concrete from demolished buildings or parking lots.

The main producer of concrete debris (scrap) for this analysis is the nuclear industry, which consists mainly of commercial power plants, test and research reactors, and industrial nuclear facilities. Other producers of concrete debris include the Department of Energy (DOE) weapons complex and the Department of Defense (DOD), which could contribute concrete debris primarily from conventional weapons testing and army and navy test reactors.

Unlike the metals analyzed, concrete is more likely to be recycled only during the decontamination and decommissioning (D&D) of a nuclear facility. This would result in a large amount of concrete available for recycling during a very short period of time. The D&D of a typical pressurized water reactor would result in about 180,000 t (198,000 tons), whereas approximately 348,000 t (383,000 tons) would be available from a typical boiling water reactor (NUREG/CR-5610[1]). Large masses of concrete could also be available during the D&D of non-reactor facilities.

7.2.2 Transportation and Processing

Concrete debris cleared from a nuclear facility may be transported, usually by a commercial company, to the processor. Processing could also occur at the origination site of the concrete debris. The operations at both places are similar. Because not all concrete debris is likely to be suitable for recycle, some would be transported directly to a disposal site. In both cases, transportation would occur by truck. This transportation could occur either before or after processing occurs.

Prior to use, concrete debris must be crushed and sorted. Any steel rebar in the concrete would be removed with a magnet prior to crushing and sent to an iron and steel refinery. The concrete must be in blocks approximately 1.5 x 1.5 x 0.8 m to be crushed. During crushing, water is sprayed on the dust to contain it. Although not required by regulation, workers near the site typically wear dust respirators. One major recycler of concrete, Dykes Paving & Construction Co., Inc., recycles about 230,000 t (250,000 tons) of concrete per year.[2]

As soon as the concrete debris is needed after processing and crushing, it is transported by truck to the site of the final use.

[1]Recycle/Reuse Literature Search Report, SAIC, 1994 scheduled to be published as NUREG/CR-5610

[2]Personal communication between M. Anderson, SAIC and J. Dykes, Dykes Paving and Construction Co., Inc., January 13, 1997.

7.2.3 Manufacturing

In order to prepare recycled, crushed concrete debris for final use, it is mixed with a small amount of additives. The additives are added to promote adhesion. According to Dykes,[1] it is very common for the final concrete end product to be made of entirely recycled concrete and additives, although occasionally other aggregate is added to the recycled concrete. If the recycled concrete is used just as aggregate, such as for the base of roadways, then there is no additional processing after the crushing and sizing at the scrap dealer/processor.

7.2.4 Product Use

Typical end products for recycled concrete include the base for roads, a stabilizer for asphalt, and an aggregate for non-structural materials. Recycled concrete is not used as aggregate in structural concrete, such as that used in houses or buildings.[1]

7.2.5 Disposal

The ultimate endpoint for some concrete is a public sanitary landfill (i.e., Resource Conservation and Recovery Act (RCRA) Subtitle D landfill). Concrete debris that is not suitable for recycling is sent directly to a landfill. Also, end products containing recycled concrete can also be sent to a landfill after use.

7.3 Mathematical Model for the Flow of Recycled Concrete Debris

This section presents the equations that represent the information discussed previously in Section 7.2 and are used to formulate the mathematical model

According to the material flow conceptual model, there is only one point at which the cleared concrete debris radionuclide concentration is potentially changed: mixing with other concrete or aggregate before or during recycling. Dilution with other concrete is radionuclide-independent. The following equations calculate the concentrations at points of interest (i.e., where scenarios would occur).

The total mass of material entering the recycling facility in a year, including cleared concrete debris and other concrete/aggregate was calculated using Equation 7.1.

$$M_T = M_C + M_{CA} \qquad 7.1$$

where

[1] Personal communication between M. Anderson, SAIC and J. Dykes, Dykes Paving and Construction Co., Inc., January 13, 1997.

M_T = total mass of material entering the recycling facility in a year (g/y)

and

M_C = mass of cleared concrete debris entering the recycling facility per year (g/y)

M_{CA} = mass of other concrete debris/aggregate entering the recycling facility per year (g/y)

The radionuclide concentration in the recycled concrete entering the manufacturing process was calculated using Equation 7.2. The following equations are intended to be evaluated separately for each radionuclide in the analysis. Therefore, parameters such as radionuclide concentration, decay factors, decay constants, and dose conversion factors are not explicitly subscripted for each radionuclide.

$$C_T = \frac{M_C}{M_T} * C_C \qquad 7.2$$

where

C_T = radionuclide concentration in recycled concrete entering the manufacturing process (pCi/g)

and

M_C = mass of cleared concrete debris entering the recycling facility per year (g/y)

M_T = total mass of material entering the recycling facility in a year (g/y)

C_C = original radionuclide concentration of cleared concrete debris (pCi/g)

7.4 Radioactivity Concentrations in Concrete Recycle Products

Radioactivity concentrations in concrete recycle products are calculated using the models described in the previous sections. The evaluation for concrete recycle and disposal assumes some mixing of cleared concrete debris with other concrete debris. No mass or elemental partitioning occurs during processing. Therefore, for a unit radionuclide concentration in cleared concrete, the concentration in concrete recycle products would be the same for all radionuclides and all scenarios except immediate handling or transport of cleared concrete.

The radioactivity concentrations that characterize the distribution calculated in the concrete material flow model are listed in Table 7.1.

Table 7.1 Results of concrete material flow model

	Radionuclide concentrations in recycled concrete (Bq/g per Bq/g concrete debris)			
Scenario Category	Mean	5th	50th	95th
Large Object[a]	8.7E-01	7.82E-01	8.83E-01	9.40E-01
Other Scenarios	9.71E-01	8.61E-01	9.93E-01	1.00E+00

a. The only concrete scenario using this set of radionuclide concentrations is CN-SCRP-LGMASS-N.

7.5 Dose Assessment for Concrete Recycle and Disposal

There are no scenarios in addition to those discussed for steel that are used for the evaluation of concrete recycling and disposal. However, because landfill disposal of large masses of concrete is more likely than for metals, a landfill resident scenario was included in the determination of critical groups for concrete. For other scenarios, the analyses are the same as described for steel recycle in Section 4, except for several parameter value differences. These are discussed in the next section.

7.6 Parameter Discussion

Calculation of potential impacts from recycle of cleared concrete depends on many parameter values. Parameter values are needed for both material flow and dose assessment models. The material flow parameter values rely on information from the concrete recycling industry. The parameter values for the dose modeling are a function of receptor behavior, such as time on a specific job or breathing rate, as well as how the radionuclides are transported in the environment. The dose modeling parameter values used for evaluation of concrete recycling and disposal are generally the same as those used in the iron and steel modeling. Only those parameter values that are different than those used in the iron and steel modeling are discussed in this section.

7.6.1 Scenario Timing

As described previously, all exposure scenarios were derived from the material flow conceptual modeling, and scenarios were assumed to occur at specific points in time following clearance from the NRC licensed facility. In order to incorporate radioactive decay between clearance and scenario dose modeling, the specific times were quantified as described in this section. Where a reference was used as a basis for the assumed time period, it is cited. If no citation is given, general knowledge of practices gained from talking with industry personnel combined with professional judgement was used as the basis. The following is a list of basic assumptions that were used in developing the timing of the concrete recycle scenarios:

Scrap Handling:

- All scrap concrete is assumed to be initially taken to a scrap processor. It takes approximately 4 days for the scrap concrete to reach the scrap dealer.

Refining and Processing:

- The scrap concrete remains at the scrap processor for a period of approximately 7 days prior to use or disposal.

Use and Disposal:

- A recycled concrete product is used for 30 years, based on an assumed use in the construction industry.

Post Disposal:

- A sanitary landfill operates for 40 years.
- Disposed items are placed in the landfill at the midpoint of the landfill operating period.
- Post-closure monitoring of landfills is done for 30 years.
- A disposal site is released for potential residential use after post-closure monitoring ends.

Specific scenario timing values are listed in Appendix B, Table B.15.

7.6.2 Dose Evaluation

This section presents a discussion of parameter values used for the analysis of concrete recycle scenarios. The analysis of seven concrete scenarios is based on the scenario descriptions provided in the steel analysis (section 4). Similar scenarios are analyzed using the same models as for the steel recycle analysis. Values used for many of the parameters are also the same as for the steel recycle analysis. For some parameters, however, values specific to the recycle of concrete were used in order to more appropriately model the scenarios as they would likely occur for concrete recycle. The following discussion is limited to these specific parameter values. If a parameter is not discussed below and listed in Table B.15, the same value as used for the steel evaluation (Table B.7) is used for concrete.

7.6.2.1 Input Concentrations from the Material Flow

The undecayed radionuclide concentration in the source material, C_x, is used as the source material input concentration for scenario evaluations. For concrete recycling, this parameter is radionuclide-independent and is calculated in the material flow modeling. Representative values from the input concentration are listed in Table 7.1.

7.6.2.2 External Exposure Parameters

The only unique parameter value used for evaluation of the external pathway for concrete recycle is the density of concrete, for which a fixed value of 2.33E+6 g/m^3 was used.

7.6.3 Concrete Surface-to-Mass Ratio

The surface-to-mass ratio for concrete is representative of concrete slabs (e.g., floors and walls) with residual radioactivity on only one side. The surface-to-mass ratio is not sensitive to the size of the pieces made from these slabs but is sensitive to the original thickness of the slabs. The surface-to-mass ratio is also dependent on the density of concrete.

The typical thickness of wall and floor slabs is assumed to range from 15 to 46 cm (6 to 18 in). Concrete for normal construction purposes ranges in density from 1.6 to 3.2 g/cm^3 (100 to 200 lb/ft^3) (Chen, 1995). Data are not available to provide an adequate basis for choosing a "best estimate" for either thickness or density of concrete slabs at NRC licensees. Based on these data and assumptions, the value of the parameter SM for concrete is best described by a uniform distribution with a minimum of 0.007 cm^2/g and a maximum of 0.04 cm^2/g. The minimum value corresponds to a thick slab of high-density, e.g., a 46 cm (18 in) slab with a density of 3.2 g/cm^3 (200 lb/ft^3). The maximum value corresponds to a thin slab of low density, e.g., a 15 cm (6 in) slab with a density of 3.2 g/cm^3 (100 lb/ft^3).

7.7 Dose Factors for Concrete Recycle and Disposal

This analysis of recycle of cleared concrete scrap includes 7 separate scenarios evaluated for 85 radionuclides. Figure 7.2 shows which scenarios describe the critical groups and for how many radionuclides. There are four scenarios which have the highest dose factor for at least one radionuclide. The largest number of radionuclides have critical groups described by scenarios associated with transporting (33 radionuclides) or handling (14 radionuclides) unprocessed debris. Individuals engaged in roadbed construction activities using cleared concrete scrap constitute the critical group for 10 radionuclides. For 28 radionuclides, the critical group consists of individuals residing on closed landfills containing buried concrete scrap. Table 7.2 lists the limiting mass-based dose factors for each radionuclide. Table 7.3 lists the corresponding derived surficial dose factors for each radionuclide. Results for all 7 concrete scenarios are tabulated in Appendix I.

The mean values of the critical-group dose factors for each radionuclide are listed in Table 7.2 as the "critical-group dose factor." These represent the dose to the average member of the critical group exposed to radioactivity distributed throughout the mass of cleared concrete (Bq/g or pCi/g). The circumstances of that exposure are described by the scenario indicated in the right hand column. The 5th, 50th, and 95th percentiles listed for each radionuclide represent the underlying distribution of dose factors calculated for each critical group. The range of values from the 5th to the 95th percentile is the 90% confidence interval on the dose factor. That is, there is a 90% certainty that the dose factor for the average member of the critical group lies within this interval. The confidence interval is a subjective measure of uncertainty in the dose factor that includes estimates of the variability and uncertainty in the parameters used in each scenario.

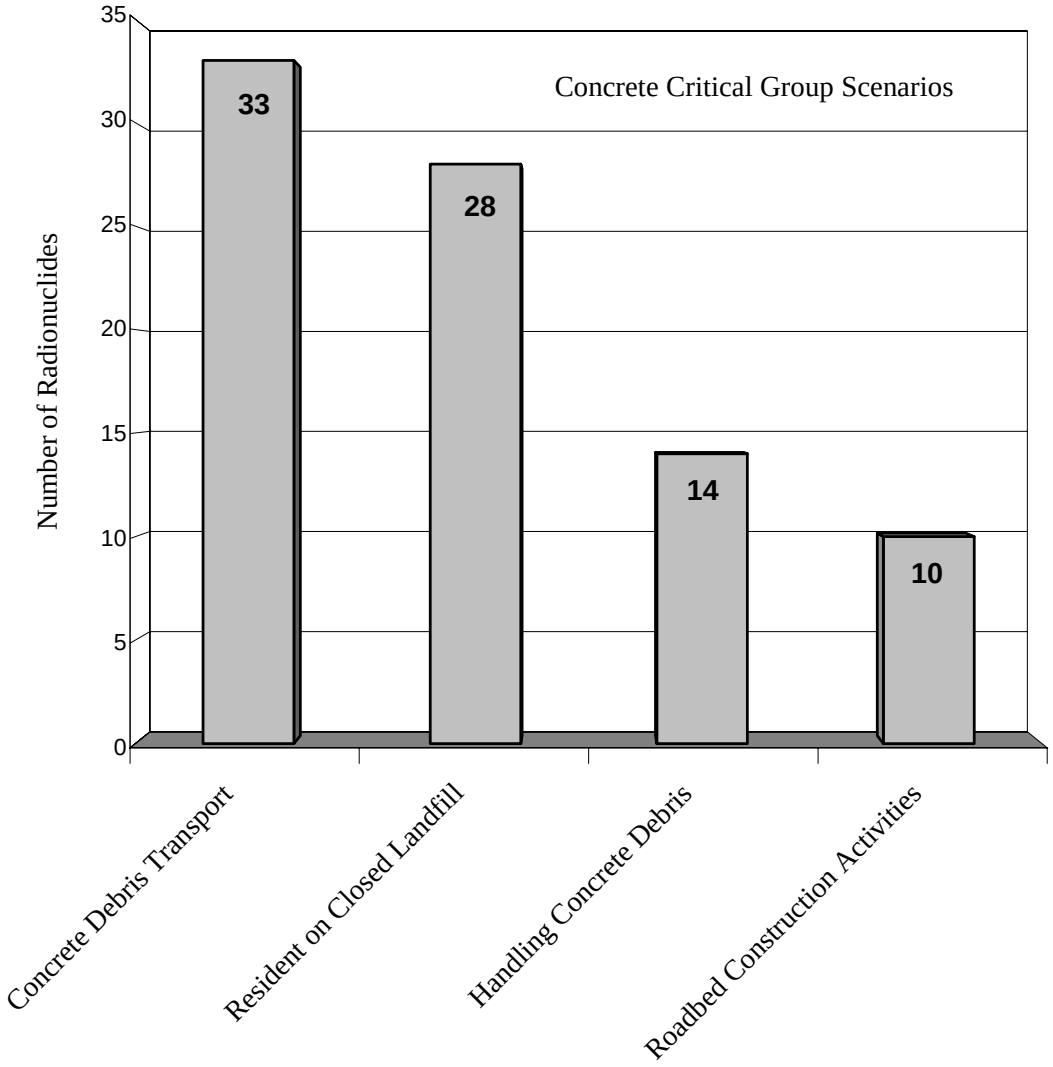

Figure 7.2 Scenarios describing critical groups for concrete recycle

Table 7.2 Concrete recycle critical-group dose factors—mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
	Critical-group dose factor	90% Confidence interval			Critical-group dose factor	90% Confidence interval			
Radionuclide		5th (lower bound)	50th (median)	95th (upper bound)		5th (lower bound)	50th (median)	95th (upper bound)	Scenario
H-3	8.8E-03	9.9E-06	5.0E-04	3.9E-02	3.3E-05	3.7E-08	1.9E-06	1.5E-04	CN-SCRP-LANDFIL-N
C-14	1.6E+01	2.7E-02	1.1E+00	5.7E+01	5.9E-02	1.0E-04	4.1E-03	2.1E-01	CN-SCRP-LANDFIL-N
Na-22	2.2E+02	1.4E+02	2.2E+02	3.0E+02	8.1E-01	5.3E-01	8.1E-01	1.1E+00	CN-SCRP-TRANSPO-W
P-32	1.4E-01	8.6E-02	1.4E-01	1.9E-01	5.1E-04	3.2E-04	5.0E-04	7.2E-04	CN-SCRP-TRANSPO-W
S-35	3.5E-03	1.5E-03	3.3E-03	6.2E-03	1.3E-05	5.4E-06	1.2E-05	2.3E-05	CN-SCRP-HANDLIN-W
Cl-36	1.6E+02	1.0E+00	1.9E+01	5.4E+02	5.9E-01	3.9E-03	6.9E-02	2.0E+00	CN-SCRP-LANDFIL-N
K-40	4.7E+01	1.9E-01	5.7E+00	2.2E+02	1.7E-01	6.9E-04	2.1E-02	8.2E-01	CN-SCRP-LANDFIL-N
Ca-41	4.8E+00	1.4E-02	4.6E-01	1.9E+01	1.8E-02	5.2E-05	1.7E-03	7.0E-02	CN-SCRP-LANDFIL-N
Ca-45	1.8E-02	6.4E-03	1.7E-02	3.4E-02	6.7E-05	2.4E-05	6.2E-05	1.3E-04	CN-SCRP-HANDLIN-W
Cr-51	2.5E+00	1.6E+00	2.5E+00	3.5E+00	9.4E-03	5.9E-03	9.2E-03	1.3E-02	CN-SCRP-TRANSPO-W
Mn-54	8.5E+01	5.6E+01	8.4E+01	1.2E+02	3.2E-01	2.1E-01	3.1E-01	4.4E-01	CN-SCRP-TRANSPO-W
Fe-55	3.4E-03	1.1E-03	3.2E-03	6.5E-03	1.3E-05	4.2E-06	1.2E-05	2.4E-05	CN-SCRP-HANDLIN-W
Co-57	6.6E+00	1.4E+00	5.9E+00	1.3E+01	2.4E-02	5.3E-03	2.2E-02	5.0E-02	CN-SCRP-ROADBED-W
Co-58	9.6E+01	6.2E+01	9.5E+01	1.3E+02	3.5E-01	2.3E-01	3.5E-01	4.9E-01	CN-SCRP-TRANSPO-W
Fe-59	1.2E+02	7.4E+01	1.2E+02	1.6E+02	4.3E-01	2.8E-01	4.3E-01	6.0E-01	CN-SCRP-TRANSPO-W
Ni-59	7.4E-03	1.8E-05	8.1E-04	3.0E-02	2.7E-05	6.8E-08	3.0E-06	1.1E-04	CN-SCRP-LANDFIL-N
Co-60	2.5E+02	1.7E+02	2.5E+02	3.5E+02	9.4E-01	6.1E-01	9.3E-01	1.3E+00	CN-SCRP-TRANSPO-W
Ni-63	1.0E-02	2.7E-05	1.0E-03	3.8E-02	3.7E-05	1.0E-07	3.7E-06	1.4E-04	CN-SCRP-LANDFIL-N
Zn-65	6.0E+01	3.9E+01	5.9E+01	8.3E+01	2.2E-01	1.4E-01	2.2E-01	3.1E-01	CN-SCRP-TRANSPO-W
Cu-67	2.9E+00	1.1E+00	2.5E+00	5.6E+00	1.1E-02	3.9E-03	9.2E-03	2.1E-02	CN-SCRP-TRANSPO-W
Se-75	2.5E+01	5.5E+00	2.3E+01	5.2E+01	9.3E-02	2.0E-02	8.4E-02	1.9E-01	CN-SCRP-ROADBED-W
Sr-85	4.7E+01	3.0E+01	4.7E+01	6.6E+01	1.8E-01	1.1E-01	1.7E-01	2.4E-01	CN-SCRP-TRANSPO-W
Sr-89	1.4E-01	5.3E-02	1.3E-01	2.7E-01	5.3E-04	1.9E-04	4.8E-04	9.8E-04	CN-SCRP-ROADBED-W
Sr-90	2.2E+00	3.0E-03	1.3E-01	7.6E+00	8.3E-03	1.1E-05	4.8E-04	2.8E-02	CN-SCRP-LANDFIL-N
Y-91	4.3E-01	1.2E-01	3.9E-01	8.7E-01	1.6E-03	4.6E-04	1.4E-03	3.2E-03	CN-SCRP-ROADBED-W
Mo-93	3.8E+01	9.9E-02	3.5E+00	1.6E+02	1.4E-01	3.7E-04	1.3E-02	6.1E-01	CN-SCRP-LANDFIL-N
Nb-93m	2.0E-02	7.8E-03	1.8E-02	4.2E-02	7.5E-05	2.9E-05	6.7E-05	1.6E-04	CN-SCRP-HANDLIN-W
Nb-94	2.9E+02	4.4E-01	2.1E+01	1.1E+03	1.1E+00	1.6E-03	7.9E-02	3.9E+00	CN-SCRP-LANDFIL-N
Nb-95	7.4E+01	4.7E+01	7.3E+01	1.0E+02	2.7E-01	1.7E-01	2.7E-01	3.8E-01	CN-SCRP-TRANSPO-W
Zr-95	7.3E+01	4.7E+01	7.2E+01	1.0E+02	2.7E-01	1.7E-01	2.7E-01	3.7E-01	CN-SCRP-TRANSPO-W
Tc-99	1.2E+02	8.8E-01	1.8E+01	4.6E+02	4.4E-01	3.3E-03	6.7E-02	1.7E+00	CN-SCRP-LANDFIL-N
Ru-103	4.7E+01	3.0E+01	4.7E+01	6.6E+01	1.7E-01	1.1E-01	1.7E-01	2.4E-01	CN-SCRP-TRANSPO-W
Ru-106	2.1E+01	1.3E+01	2.0E+01	2.9E+01	7.6E-02	5.0E-02	7.6E-02	1.1E-01	CN-SCRP-TRANSPO-W
Ag-108m	1.7E+02	2.3E-01	1.2E+01	7.4E+02	6.4E-01	8.6E-04	4.4E-02	2.7E+00	CN-SCRP-LANDFIL-N
Cd-109	2.5E-01	8.8E-02	2.3E-01	4.7E-01	9.2E-04	3.2E-04	8.5E-04	1.7E-03	CN-SCRP-ROADBED-W

Table 7.2 Concrete recycle critical-group dose factors—mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Ag-110m	2.8E+02	1.8E+02	2.8E+02	3.9E+02	1.0E+00	6.8E-01	1.0E+00	1.4E+00	CN-SCRP-TRANSPO-W
Sb-124	1.8E+02	1.2E+02	1.8E+02	2.5E+02	6.8E-01	4.3E-01	6.7E-01	9.3E-01	CN-SCRP-TRANSPO-W
I-125	3.0E-01	1.1E-01	2.9E-01	5.8E-01	1.1E-03	4.1E-04	1.1E-03	2.2E-03	CN-SCRP-ROADBED-W
Sb-125	4.1E+01	2.6E+01	4.0E+01	5.6E+01	1.5E-01	9.8E-02	1.5E-01	2.1E-01	CN-SCRP-TRANSPO-W
I-129	2.4E+03	1.5E+01	2.6E+02	8.4E+03	8.9E+00	5.4E-02	9.6E-01	3.1E+01	CN-SCRP-LANDFIL-N
I-131	2.8E+01	1.6E+01	2.7E+01	4.0E+01	1.0E-01	5.9E-02	1.0E-01	1.5E-01	CN-SCRP-TRANSPO-W
Ba-133	2.8E+01	1.8E+01	2.8E+01	3.9E+01	1.0E-01	6.7E-02	1.0E-01	1.4E-01	CN-SCRP-TRANSPO-W
Cs-134	1.6E+02	1.0E+02	1.6E+02	2.2E+02	5.9E-01	3.9E-01	5.9E-01	8.2E-01	CN-SCRP-TRANSPO-W
Cs-137	6.2E+01	4.0E+01	6.1E+01	8.5E+01	2.3E-01	1.5E-01	2.3E-01	3.2E-01	CN-SCRP-TRANSPO-W
Ce-141	3.4E+00	7.5E-01	3.1E+00	7.1E+00	1.3E-02	2.8E-03	1.2E-02	2.6E-02	CN-SCRP-ROADBED-W
Ce-144	3.3E+00	2.1E+00	3.3E+00	4.6E+00	1.2E-02	7.9E-03	1.2E-02	1.7E-02	CN-SCRP-TRANSPO-W
Pm-147	2.8E-02	1.1E-02	2.5E-02	5.7E-02	1.0E-04	3.9E-05	9.3E-05	2.1E-04	CN-SCRP-HANDLIN-W
Eu-152	1.1E+02	7.2E+01	1.1E+02	1.5E+02	4.1E-01	2.7E-01	4.1E-01	5.7E-01	CN-SCRP-TRANSPO-W
Eu-154	1.2E+02	7.9E+01	1.2E+02	1.7E+02	4.5E-01	2.9E-01	4.4E-01	6.2E-01	CN-SCRP-TRANSPO-W
Eu-155	2.5E+00	5.6E-01	2.3E+00	5.0E+00	9.1E-03	2.1E-03	8.3E-03	1.9E-02	CN-SCRP-ROADBED-W
Re-186	3.1E-01	1.4E-01	2.8E-01	5.2E-01	1.1E-03	5.3E-04	1.0E-03	1.9E-03	CN-SCRP-TRANSPO-W
Ir-192	7.2E+01	4.6E+01	7.1E+01	9.9E+01	2.6E-01	1.7E-01	2.6E-01	3.7E-01	CN-SCRP-TRANSPO-W
Pb-210	1.1E+01	2.9E+01	5.9E+01	5.9E+01	1.2E-01	4.0E-02	1.1E-01	2.2E-01	CN-SCRP-HANDLIN-W
Po-210	4.9E+00	1.2E+01	2.4E+01	2.4E+01	4.9E-02	1.8E-02	4.5E-02	8.7E-02	CN-SCRP-HANDLIN-W
Bi-210	9.9E-02	4.3E-02	9.0E-02	1.9E-01	3.7E-04	1.6E-04	3.3E-04	7.0E-04	CN-SCRP-HANDLIN-W
Rn-222	1.1E+02	5.0E+01	9.7E+01	1.8E+02	3.9E-01	1.8E-01	3.6E-01	6.6E-01	CN-SCRP-TRANSPO-W
Ra-223	1.9E+01	1.2E+01	1.9E+01	2.8E+01	7.1E-02	4.3E-02	7.0E-02	1.0E-01	CN-SCRP-TRANSPO-W
Ra-224	7.6E+01	3.6E+01	7.0E+01	1.3E+02	2.8E-01	1.3E-01	2.6E-01	4.9E-01	CN-SCRP-TRANSPO-W
Ac-225	1.5E+01	9.1E+00	1.5E+01	2.2E+01	5.7E-02	3.4E-02	5.6E-02	8.1E-02	CN-SCRP-TRANSPO-W
Ra-225	5.2E+00	2.0E+00	4.8E+00	1.0E+01	1.9E-02	7.4E-03	1.8E-02	3.9E-02	CN-SCRP-HANDLIN-W
Ra-226	5.3E+02	1.2E+00	5.0E+01	2.1E+03	2.0E+00	4.4E-03	1.9E-01	7.7E+00	CN-SCRP-LANDFIL-N
Ac-227	8.4E+02	3.0E+02	7.4E+02	1.8E+03	3.1E+00	1.1E+00	2.7E+00	6.6E+00	CN-SCRP-HANDLIN-W
Th-227	1.1E+01	4.8E+00	1.0E+01	2.1E+01	4.1E-02	1.8E-02	3.7E-02	7.9E-02	CN-SCRP-HANDLIN-W
Th-228	2.7E+02	9.7E+01	2.5E+02	4.9E+02	9.9E-01	3.6E-01	9.2E-01	1.8E+00	CN-SCRP-ROADBED-W
Ra-228	8.9E+01	2.7E+01	8.1E+01	1.8E+02	3.3E-01	9.8E-02	3.0E-01	6.5E-01	CN-SCRP-ROADBED-W
Th-229	1.4E+03	1.8E+00	1.0E+02	4.3E+03	5.0E+00	6.5E-03	3.7E-01	1.6E+01	CN-SCRP-LANDFIL-N
Th-230	2.2E+02	2.9E-01	1.6E+01	6.9E+02	8.2E-01	1.1E-03	6.0E-02	2.6E+00	CN-SCRP-LANDFIL-N
Pa-231	2.1E+03	3.4E+00	1.8E+02	6.7E+03	7.7E+00	1.2E-02	6.6E-01	2.5E+01	CN-SCRP-LANDFIL-N
Th-231	3.9E-02	3.5E-03	2.1E-02	1.3E-01	1.5E-04	1.3E-05	7.9E-05	4.6E-04	CN-SCRP-TRANSPO-W
Th-232	1.3E+03	1.9E+00	1.1E+02	4.6E+03	4.9E+00	6.9E-03	3.9E-01	1.7E+01	CN-SCRP-LANDFIL-N

Table 7.2 Concrete recycle critical-group dose factors—mass

	(μSv/y per Bq/g)				(mrem/y per pCi/g)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Pa-233	1.4E+01	8.6E+00	1.3E+01	1.9E+01	5.0E-02	3.2E-02	5.0E-02	7.0E-02	CN-SCRP-TRANSPO-W
U-233	1.7E+02	6.8E-01	1.7E+01	6.0E+02	6.1E-01	2.5E-03	6.3E-02	2.2E+00	CN-SCRP-LANDFIL-N
Th-234	7.5E-01	4.7E-01	7.4E-01	1.0E+00	2.8E-03	1.7E-03	2.7E-03	3.9E-03	CN-SCRP-TRANSPO-W
U-234	1.7E+02	4.0E-01	1.6E+01	6.5E+02	6.2E-01	1.5E-03	6.1E-02	2.4E+00	CN-SCRP-LANDFIL-N
U-235	1.4E+02	5.1E-01	1.8E+01	6.1E+02	5.2E-01	1.9E-03	6.7E-02	2.2E+00	CN-SCRP-LANDFIL-N
Np-237	7.1E+04	9.0E+01	4.0E+03	2.2E+05	2.6E+02	3.3E-01	1.5E+01	8.0E+02	CN-SCRP-LANDFIL-N
Pu-238	1.7E+02	5.4E+01	1.5E+02	3.8E+02	6.4E-01	2.0E-01	5.6E-01	1.4E+00	CN-SCRP-HANDLIN-W
U-238	1.3E+02	4.0E-01	1.5E+01	5.7E+02	4.8E-01	1.5E-03	5.5E-02	2.1E+00	CN-SCRP-LANDFIL-N
Pu-239	2.2E+02	2.8E-01	1.6E+01	7.1E+02	8.3E-01	1.0E-03	5.8E-02	2.6E+00	CN-SCRP-LANDFIL-N
Pu-240	2.2E+02	2.7E-01	1.5E+01	7.1E+02	8.2E-01	1.0E-03	5.7E-02	2.6E+00	CN-SCRP-LANDFIL-N
Pu-241	1.7E+01	2.1E-02	8.9E-01	7.2E+01	6.4E-02	7.6E-05	3.3E-03	2.7E-01	CN-SCRP-LANDFIL-N
Am-241	3.3E+02	4.2E-01	2.3E+01	1.1E+03	1.2E+00	1.6E-03	8.7E-02	3.9E+00	CN-SCRP-LANDFIL-N
Cm-242	1.1E+01	3.6E+00	9.3E+00	2.3E+01	3.9E-02	1.3E-02	3.4E-02	8.5E-02	CN-SCRP-HANDLIN-W
Pu-242	2.1E+02	2.7E-01	1.5E+01	6.8E+02	7.9E-01	9.8E-04	5.7E-02	2.5E+00	CN-SCRP-LANDFIL-N
Cm-244	1.6E+02	5.5E+01	1.4E+02	3.4E+02	5.8E-01	2.0E-01	5.1E-01	1.2E+00	CN-SCRP-HANDLIN-W

Table 7.3 Concrete recycle critical-group dose factors—surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
H-3	1.9E-04	1.9E-07	1.1E-05	7.9E-04	7.1E-07	7.1E-10	4.0E-08	2.9E-06	CN-SCRP-LANDFIL-N
C-14	3.7E-01	6.4E-04	2.4E-02	1.2E+00	1.4E-03	2.4E-06	8.9E-05	4.6E-03	CN-SCRP-LANDFIL-N
Na-22	3.2E+00	1.8E+00	5.0E+00	1.0E+01	1.9E-02	6.7E-03	1.8E-02	3.7E-02	CN-SCRP-TRANSPO-W
P-32	5.2E-03	1.1E-03	3.1E-03	6.1E-03	1.2E-05	4.1E-06	1.1E-05	2.3E-05	CN-SCRP-TRANSPO-W
S-35	5.3E-05	1.4E-05	4.4E-05	1.2E-04	2.0E-07	5.1E-08	1.6E-07	4.3E-07	CN-SCRP-ROADBED-W
Cl-36	3.2E+00	1.8E-02	3.9E-01	1.2E+01	1.2E-02	6.7E-05	1.5E-03	4.4E-02	CN-SCRP-LANDFIL-N
K-40	1.1E+00	4.0E-03	1.3E-01	5.5E+00	4.0E-03	1.5E-05	4.7E-04	2.0E-02	CN-SCRP-LANDFIL-N
Ca-41	1.2E-01	3.2E-04	9.7E-03	4.7E-01	4.3E-04	1.2E-06	3.6E-05	1.7E-03	CN-SCRP-LANDFIL-N
Ca-45	4.2E-04	9.5E-05	3.6E-04	1.0E-03	1.6E-06	3.5E-07	1.3E-06	3.7E-06	CN-SCRP-HANDLIN-W
Cr-51	6.0E-02	2.1E-02	5.7E-02	1.1E-01	2.2E-04	7.6E-05	2.1E-04	4.2E-04	CN-SCRP-TRANSPO-W
Mn-54	2.0E+00	7.0E-01	1.9E+00	3.9E+00	7.4E-03	2.6E-03	7.1E-03	1.4E-02	CN-SCRP-TRANSPO-W
Fe-55	8.0E-05	1.7E-05	6.7E-05	1.9E-04	3.0E-07	6.3E-08	2.5E-07	7.1E-07	CN-SCRP-HANDLIN-W
Co-57	1.5E-01	2.6E-02	1.2E-01	3.9E-01	5.7E-04	9.5E-05	4.5E-04	1.4E-03	CN-SCRP-ROADBED-W
Co-58	2.3E+00	7.9E-01	2.1E+00	4.4E+00	8.4E-03	2.9E-03	7.9E-03	1.6E-02	CN-SCRP-TRANSPO-W
Fe-59	2.7E+00	9.6E-01	2.6E+00	5.3E+00	1.0E-02	3.5E-03	9.7E-03	2.0E-02	CN-SCRP-TRANSPO-W
Ni-59	1.8E-04	3.9E-07	1.6E-05	6.9E-04	6.5E-07	1.4E-09	6.0E-08	2.6E-06	CN-SCRP-LANDFIL-N
Co-60	6.0E+00	2.1E+00	5.7E+00	1.2E+01	2.2E-02	7.7E-03	2.1E-02	4.3E-02	CN-SCRP-TRANSPO-W
Ni-63	2.4E-04	5.4E-07	2.2E-05	9.0E-04	8.8E-07	2.0E-09	8.2E-08	3.3E-06	CN-SCRP-LANDFIL-N
Zn-65	1.4E+00	5.0E-01	1.3E+00	2.7E+00	5.2E-03	1.8E-03	5.0E-03	1.0E-02	CN-SCRP-TRANSPO-W
Cu-67	6.8E-02	1.6E-02	5.7E-02	1.6E-01	2.5E-04	6.1E-05	2.1E-04	5.9E-04	CN-SCRP-TRANSPO-W
Se-75	5.9E-01	9.8E-02	4.6E-01	1.5E+00	2.2E-03	3.6E-04	1.7E-03	5.5E-03	CN-SCRP-ROADBED-W
Sr-85	1.1E+00	3.9E-01	1.1E+00	2.2E+00	4.1E-03	1.4E-03	3.9E-03	8.0E-03	CN-SCRP-TRANSPO-W
Sr-89	3.3E-03	8.4E-04	2.7E-03	7.6E-03	1.2E-05	3.1E-06	9.9E-06	2.8E-05	CN-SCRP-ROADBED-W
Sr-90	5.5E-02	5.5E-05	2.6E-03	1.6E-01	2.0E-04	2.0E-07	9.7E-06	6.0E-04	CN-SCRP-LANDFIL-N
Y-91	1.0E-02	2.1E-03	7.8E-03	2.5E-02	3.7E-05	7.8E-06	2.9E-05	9.2E-05	CN-SCRP-ROADBED-W
Mo-93	8.5E-01	2.3E-03	6.7E-02	3.3E+00	3.1E-03	8.5E-06	2.5E-04	1.2E-02	CN-SCRP-LANDFIL-N
Nb-93m	4.7E-04	1.3E-04	4.0E-04	1.1E-03	1.8E-06	4.8E-07	1.5E-06	4.0E-06	CN-SCRP-HANDLIN-W
Nb-94	7.3E+00	8.4E-03	4.6E-01	2.5E+01	2.7E-02	3.1E-05	1.7E-03	9.3E-02	CN-SCRP-LANDFIL-N
Nb-95	1.7E+00	6.0E-01	1.7E+00	3.4E+00	6.4E-03	2.2E-03	6.2E-03	1.2E-02	CN-SCRP-TRANSPO-W
Zr-95	1.7E+00	6.0E-01	1.6E+00	3.3E+00	6.3E-03	2.2E-03	6.0E-03	1.2E-02	CN-SCRP-TRANSPO-W
Tc-99	2.6E+00	1.9E-02	4.1E-01	9.5E+00	9.5E-03	7.1E-05	1.5E-03	3.5E-02	CN-SCRP-LANDFIL-N
Ru-103	1.1E+00	3.9E-01	1.1E+00	2.2E+00	4.1E-03	1.4E-03	3.9E-03	8.0E-03	CN-SCRP-TRANSPO-W
Ru-106	4.9E-01	1.7E-01	4.7E-01	9.4E-01	1.8E-03	6.3E-04	1.7E-03	3.5E-03	CN-SCRP-TRANSPO-W
Ag-108m	4.3E+00	5.0E-03	2.5E-01	1.4E+01	1.6E-02	1.9E-05	9.2E-04	5.1E-02	CN-SCRP-LANDFIL-N
Cd-109	5.8E-03	1.4E-03	4.6E-03	1.4E-02	2.2E-05	5.2E-06	1.7E-05	5.1E-05	CN-SCRP-ROADBED-W

Table 7.3 Concrete recycle critical-group dose factors—surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Ag-110m	6.7E+00	2.3E+00	6.4E+00	1.3E+01	2.5E-02	8.7E-03	2.4E-02	4.8E-02	CN-SCRP-TRANSPO-W
Sb-124	4.3E+00	1.5E+00	4.1E+00	8.3E+00	1.6E-02	5.6E-03	1.5E-02	3.1E-02	CN-SCRP-TRANSPO-W
I-125	7.1E-03	1.9E-03	6.0E-03	1.6E-02	2.6E-05	6.9E-06	2.2E-05	5.9E-05	CN-SCRP-ROADBED-W
Sb-125	9.6E-01	3.3E-01	9.2E-01	1.8E+00	3.5E-03	1.2E-03	3.4E-03	6.8E-03	CN-SCRP-TRANSPO-W
I-129	5.1E+01	2.9E-01	5.3E+00	2.0E+02	1.9E-01	1.1E-03	2.0E-02	7.6E-01	CN-SCRP-LANDFIL-N
I-131	6.5E-01	2.1E-01	6.1E-01	1.3E+00	2.4E-03	7.7E-04	2.2E-03	4.6E-03	CN-SCRP-TRANSPO-W
Ba-133	6.6E-01	2.3E-01	6.3E-01	1.3E+00	2.4E-03	8.5E-04	2.3E-03	4.7E-03	CN-SCRP-TRANSPO-W
Cs-134	3.8E+00	1.3E+00	3.6E+00	7.2E+00	1.4E-02	4.9E-03	1.3E-02	2.7E-02	CN-SCRP-TRANSPO-W
Cs-137	1.5E+00	5.1E-01	1.4E+00	2.8E+00	5.4E-03	1.9E-03	5.1E-03	1.0E-02	CN-SCRP-TRANSPO-W
Ce-141	8.0E-02	1.3E-02	6.2E-02	2.1E-01	3.0E-04	4.8E-05	2.3E-04	7.6E-04	CN-SCRP-ROADBED-W
Ce-144	7.8E-02	2.7E-02	7.4E-02	1.5E-01	2.9E-04	1.0E-04	2.7E-04	5.5E-04	CN-SCRP-TRANSPO-W
Pm-147	4.4E-04	1.0E-04	3.6E-04	1.2E-03	1.6E-06	3.8E-07	1.3E-06	4.3E-06	CN-SCRP-ROADBED-W
Eu-152	2.6E+00	9.1E-01	2.5E+00	5.0E+00	9.7E-03	3.4E-03	9.3E-03	1.9E-02	CN-SCRP-TRANSPO-W
Eu-154	2.9E+00	1.0E+00	2.7E+00	5.5E+00	1.1E-02	3.7E-03	1.0E-02	2.0E-02	CN-SCRP-TRANSPO-W
Eu-155	5.8E-02	9.9E-03	4.5E-02	1.5E-01	2.1E-04	3.7E-05	1.7E-04	5.4E-04	CN-SCRP-ROADBED-W
Re-186	7.2E-03	2.0E-03	6.4E-03	1.5E-02	2.7E-05	7.3E-06	2.4E-05	5.7E-05	CN-SCRP-TRANSPO-W
Ir-192	1.7E+00	5.9E-01	1.6E+00	3.3E+00	6.2E-03	2.2E-03	5.9E-03	1.2E-02	CN-SCRP-TRANSPO-W
Pb-210	1.6E-01	6.2E-01	1.7E+00	1.7E+00	2.7E-03	5.9E-04	2.3E-03	6.4E-03	CN-SCRP-HANDLIN-W
Po-210	7.4E-02	2.6E-01	6.9E-01	6.9E-01	1.1E-03	2.7E-04	9.7E-04	2.5E-03	CN-SCRP-HANDLIN-W
Bi-210	2.3E-03	6.6E-04	2.0E-03	5.2E-03	8.6E-06	2.5E-06	7.3E-06	1.9E-05	CN-SCRP-HANDLIN-W
Rn-222	2.5E+00	6.8E-01	2.2E+00	5.3E+00	9.2E-03	2.5E-03	8.3E-03	2.0E-02	CN-SCRP-TRANSPO-W
Ra-223	4.5E-01	1.5E-01	4.3E-01	8.7E-01	1.7E-03	5.6E-04	1.6E-03	3.2E-03	CN-SCRP-TRANSPO-W
Ra-224	1.8E+00	4.9E-01	1.6E+00	3.8E+00	6.6E-03	1.8E-03	6.0E-03	1.4E-02	CN-SCRP-TRANSPO-W
Ac-225	3.6E-01	1.2E-01	3.4E-01	6.9E-01	1.3E-03	4.4E-04	1.2E-03	2.6E-03	CN-SCRP-TRANSPO-W
Ra-225	1.2E-01	3.3E-02	1.1E-01	2.7E-01	4.5E-04	1.2E-04	3.9E-04	1.0E-03	CN-SCRP-HANDLIN-W
Ra-226	1.3E+01	2.4E-02	1.0E+00	5.0E+01	4.8E-02	9.0E-05	3.7E-03	1.8E-01	CN-SCRP-LANDFIL-N
Ac-227	2.0E+01	4.8E+00	1.6E+01	4.6E+01	7.2E-02	1.8E-02	6.1E-02	1.7E-01	CN-SCRP-HANDLIN-W
Th-227	2.6E-01	7.2E-02	2.3E-01	5.8E-01	9.6E-04	2.7E-04	8.4E-04	2.1E-03	CN-SCRP-HANDLIN-W
Th-228	6.3E+00	1.6E+00	5.2E+00	1.4E+01	2.3E-02	5.8E-03	1.9E-02	5.3E-02	CN-SCRP-ROADBED-W
Ra-228	2.1E+00	4.4E-01	1.6E+00	5.0E+00	7.7E-03	1.6E-03	6.0E-03	1.9E-02	CN-SCRP-ROADBED-W
Th-229	3.3E+01	3.8E-02	2.1E+00	1.2E+02	1.2E-01	1.4E-04	7.7E-03	4.5E-01	CN-SCRP-LANDFIL-N
Th-230	5.3E+00	6.3E-03	3.4E-01	1.9E+01	2.0E-02	2.3E-05	1.3E-03	7.1E-02	CN-SCRP-LANDFIL-N
Pa-231	5.0E+01	7.6E-02	3.7E+00	1.9E+02	1.9E-01	2.8E-04	1.4E-02	7.2E-01	CN-SCRP-LANDFIL-N
Th-231	9.2E-04	5.8E-05	4.7E-04	3.5E-03	3.4E-06	2.2E-07	1.8E-06	1.3E-05	CN-SCRP-TRANSPO-W
Th-232	3.2E+01	4.1E-02	2.3E+00	1.2E+02	1.2E-01	1.5E-04	8.6E-03	4.4E-01	CN-SCRP-LANDFIL-N

Table 7.3 Concrete recycle critical-group dose factors—surficial

	(μSv/y per Bq/cm^2)				(mrem/y per pCi/cm^2)				
		90% Confidence interval				90% Confidence interval			
Radionuclide	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Critical-group dose factor	5th (lower bound)	50th (median)	95th (upper bound)	Scenario
Pa-233	3.2E-01	1.1E-01	3.1E-01	6.1E-01	1.2E-03	4.1E-04	1.1E-03	2.3E-03	CN-SCRP-TRANSPO-W
U-233	3.8E+00	1.3E-02	3.4E-01	1.3E+01	1.4E-02	5.0E-05	1.3E-03	4.9E-02	CN-SCRP-LANDFIL-N
Th-234	1.8E-02	6.1E-03	1.7E-02	3.4E-02	6.5E-05	2.2E-05	6.3E-05	1.2E-04	CN-SCRP-TRANSPO-W
U-234	3.8E+00	9.7E-03	3.5E-01	1.4E+01	1.4E-02	3.6E-05	1.3E-03	5.2E-02	CN-SCRP-LANDFIL-N
U-235	3.2E+00	1.2E-02	4.0E-01	1.3E+01	1.2E-02	4.3E-05	1.5E-03	4.7E-02	CN-SCRP-LANDFIL-N
Np-237	1.4E+03	1.6E+00	8.3E+01	5.0E+03	5.2E+00	5.9E-03	3.1E-01	1.9E+01	CN-SCRP-LANDFIL-N
Pu-238	4.0E+00	9.2E-01	3.3E+00	1.0E+01	1.5E-02	3.4E-03	1.2E-02	3.7E-02	CN-SCRP-HANDLIN-W
U-238	3.1E+00	8.9E-03	3.4E-01	1.1E+01	1.1E-02	3.3E-05	1.3E-03	3.9E-02	CN-SCRP-LANDFIL-N
Pu-239	5.4E+00	6.9E-03	3.4E-01	2.0E+01	2.0E-02	2.5E-05	1.3E-03	7.5E-02	CN-SCRP-LANDFIL-N
Pu-240	5.4E+00	7.2E-03	3.4E-01	2.0E+01	2.0E-02	2.7E-05	1.3E-03	7.5E-02	CN-SCRP-LANDFIL-N
Pu-241	4.0E-01	3.4E-04	1.8E-02	1.6E+00	1.5E-03	1.3E-06	6.8E-05	5.8E-03	CN-SCRP-LANDFIL-N
Am-241	8.0E+00	1.1E-02	5.1E-01	3.1E+01	3.0E-02	4.1E-05	1.9E-03	1.2E-01	CN-SCRP-LANDFIL-N
Cm-242	2.5E-01	5.9E-02	2.1E-01	6.0E-01	9.2E-04	2.2E-04	7.6E-04	2.2E-03	CN-SCRP-HANDLIN-W
Pu-242	5.1E+00	6.2E-03	3.3E-01	1.9E+01	1.9E-02	2.3E-05	1.2E-03	7.1E-02	CN-SCRP-LANDFIL-N
Cm-244	3.7E+00	8.8E-01	3.1E+00	8.8E+00	1.4E-02	3.3E-03	1.1E-02	3.3E-02	CN-SCRP-HANDLIN-W

The ratio of the 95th to the 5th percentile is a useful measure of the relative width of the 90% confidence interval for comparison between scenarios. Smaller values of the 95/5 ratio indicate less uncertainty than larger values. The scenarios with the smallest uncertainty are those with the fewest number of exposure pathways and the least uncertainty in the parameters describing those pathways. The scrap transportation scenario accounts for 33 of the 85 radionuclides. It has the smallest uncertainty of all the critical group scenarios with a 95/5 ratio of about 2 for most radionuclides. The sources of uncertainty in this scenario are similar to those for the steel scrap transportation scenario discussed in Section 4.9.

For all scenarios that take place subsequent to the initial transport of scrap, additional sources of uncertainty are introduced and wider confidence intervals result. Scenarios that address handling concrete scrap or using it in roadbed construction include uncertainty due to mixing with other scrap. They also include additional exposure pathways—inhalation of suspended dust and inadvertent ingestion under dusty conditions. For concrete, this group of handling and construction scenarios have 95/5 ratios that range from about 5 to about 35.

The landfill resident scenario is limiting for 28 radionuclides. Uncertainty in this scenario includes contributions from the ground water transport model and pathways for ingestion, inhalation, and external exposure. Dose factors for nuclides limited by this scenario have 95/5 ratios that range from about 500 to about 6500 and are typically about 2000. This is due to the uncertainties associated with the groundwater transport model and the timing of the scenario.

Over the period of time addressed by this scenario there is a large uncertainty in the rate at which each radionuclide leaches to the drinking water supply and in the resulting concentration in drinking water. Some radionuclides undergo significant radioactive decay and some have radioactive progeny that are increasing over this time scale. Uncertainty in timing is magnified by the exponential processes of radioactive decay and progeny ingrowth.

The mean values of the derived surficial dose factors for each radionuclide in Table 7.3 represent the dose to the average member of the critical group exposed to radioactivity initially distributed over the surface of cleared concrete scrap (Bq/cm^2 or pCi/cm^2). Derived surficial dose factors are calculated from mass-based dose factors by use of a surface-to-mass ratio appropriate for concrete slabs of typical thicknesses. The surface-to-mass ratio is used to derive surficial dose factors as described in Section 4.7.

The calculation of derived surficial dose factors is probabilistic. The parameter SM is represented by a distribution of values that incorporate the variability and uncertainty in the surface-to-mass ratio of typical concrete slabs available for clearance. This additional source of uncertainty results in wider confidence intervals for the surficial dose factors than for the mass-based dose factors from which they are derived. The relative importance of this additional uncertainty depends on the scenario. The uncertainty in the surface-to-mass ratio is somewhat larger for concrete slabs than for typical steel, copper, and aluminum objects due to the wide range of slab thicknesses and the variability in the density of concrete. For this reason, the confidence intervals for derived surficial dose factors are relatively wider for concrete relative to the mass-based dose factors. For scenarios with the narrowest confidence intervals, the added uncertainty can result in confidence intervals about three times wider than the corresponding mass-based dose factors. The mass-based dose factor for the scrap transportation scenario has a 95/5 ratio of about 2 for most radionuclides. The corresponding derived surficial dose factors have a 95/5 ratio of about 6. The added uncertainty in surface-to-mass ratio has a relatively smaller impact on the confidence interval for scenarios with larger uncertainties, contributing an additional 50% to 100% for the scrap handling and roadbed construction scenarios. For the landfill resident scenario the uncertainty in surface-to-mass ratio is small compared to the uncertainties in the ground water model and ingestion dose pathways. For this scenario, the 95/5 ratio for the derived surficial dose factors ranges from zero to about 30% larger than for the corresponding mass-based dose factors.

8 QUALITY CONTROL PROGRAM

In order to ensure that the reuse and recycle assessments are defensible, accurate, and verifiable, a Quality Control Plan (QCP) was prepared and followed during conduct of this evaluation. The QCP includes specification of procedures and conventions adopted to implement quality control for the recycle and reuse modeling efforts. The QCP also describes requirements for model development, equation and parameter definitions, and spreadsheet implementation, and also specifically addresses requirements for preparation, review, calculation checks, documentation, and record keeping of technical information. The QCP therefore provides a documented system for ensuring accuracy of results, as well as a basis for tracing assumptions. The QCP incorporated quality assurance guidelines provided by both the NRC and other recognized authoritative references.

The pathway model components developed for this analysis served as the design description for spreadsheet software development. A Quality Assurance (QA) administrator ensured that appropriate steps were taken to implement the quality control, documentation and configuration management requirements of the analyses. The QA administrator acted as a central hub for the review process; all material passed through the QA administrator for each step of the review and final documentation of technical information. All technical information developed for the project was peer reviewed. This included conceptual models, equations and spreadsheets. Specific items to be reviewed were indicated on the review checklist that accompanied all review packets. In addition to in-house peer review, aspects of the analyses were peer reviewed by an outside consultant. This review function was to ensure technical adequacy and reasonableness of the analysis, interpretation of the results, and other aspects of the analysis.

In order to meet the documentation requirements in an organized, retrievable manner, a formal system of document review and filing was implemented. The project QA administrator was responsible for maintaining the organization and contents of the Project Engineering Cabinet, which served as a repository for the master versions of all controlled project documents. In addition, a system was implemented for assigning electronic file names, in order to maintain proper document control.

As described in Section 1, the purpose of this evaluation is to provide the technical basis for implementing criteria for clearance of equipment and material from nuclear facilities licensed by the Nuclear Regulatory Commission (NRC). A defensible dose assessment for rulemaking purposes 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 Control Plan (QCP) was prepared and followed while conducting this evaluation.

The QCP includes specification of procedures and conventions adopted to implement quality control for the recycle and reuse modeling efforts. The QCP also describes requirements for model development, equation and parameter definitions, and spreadsheet implementation, as well as addressing requirements for preparation, review, calculation checks, documentation, and record keeping of technical information. The QCP, therefore, provides a documented system for ensuring accuracy of results, as well as a basis for tracing assumptions. The QCP was revised and updated as the project progressed, in order to address changes in the technical requirements.

The QCP identified the procedures and conventions that were adopted to implement quality control for the project. In keeping with the nature of the tasks, special emphasis was placed upon quality assurance for spreadsheet model development and documentation. The QCP incorporated quality assurance guidelines provided by the following references:

- NQA-1b-1987, *Quality Assurance Program Requirements for Nuclear Facilities*
- NQA-2a-1990 *Quality Assurance Program Requirements for Nuclear Facilities*
- ANSI/ANS-10.4, *Guidelines for the Validation and Verification of Scientific and Engineering Computer Programs for Nuclear Facilities*
- NUREG/CR-0167, *Software Quality Assurance Program and Guidelines*

The QCP also discusses incorporation of the technical approach into the quality control guidelines. The remainder of this section describes information and criteria contained in the QCP.

8.1 Technical Approach to Model Implementation

As required by NRC, computer applications and models met the requirements of the NRC Policy and Procedures Manual, Section 2.2. Spreadsheet models were developed on PC-based platforms running proprietary, commercial software. Other commercially available software was used to precalculate "lumped" parameter values for use in the spreadsheet models. Prior to use, software was approved by the SAIC Task Manager and Project Manager. With only one exception, all of the codes listed below were run on personal computers (the MCNP code was run on a workstation). This listing does not include non-technical codes such as word processing or project management software. The following software applications were approved and used in this analysis.

Crystal Ball 4.0 (Decisioneering 1996). Crystal Ball, a forecasting and risk analysis program, is used as an add-on to Excel. It uses the Monte Carlo sampling methods to calculate uncertainty in a model result. Crystal Ball will sample from an assumption cell in the Excel worksheet that contains a probability distribution defined by the user and calculate a range of possible outcomes in the forecast cell as well as the likelihood of achieving each of them. The Monte Carlo method, as used by Crystal Ball, is accomplished with three simple steps which are repeated for a set number of times defined by the user. These steps are (1) generating random numbers for assumption cells, (2) calculating the entire spreadsheet, and (3) displaying results in a forecast chart. This program was used as an uncertainty analysis tool.

Excel 97 (SR-1) (Microsoft 1997). Excel is a general purpose, spreadsheet analysis application. Excel provides the tools necessary to perform data analysis, list-keeping, and calculations. Excel also enables the user to present the results efficiently. Worksheets enable the user to store, manipulate, calculate, and analyze data. Macros are also available in Excel, which enable the user to automate frequently performed tasks and perform specialized calculations. Excel was used as the platform for all calculations.

MCNP (Briesmeister 1993). MCNP (Monte Carlo N-Particle) is a three-dimensional transport code which treats an arbitrary configuration of materials in cells bounded by surfaces. Pointwise, continuous-energy cross-section data are used. The transport equation is solved by the method of random walk (Monte Carlo). Energy specific sources and response functions may be used to estimate dosimetric quantities of interest for virtually any configuration. MCNP was used to calculate all of the external exposure geometry factors except those obtained from Environmental Protection Agency (EPA) documents.

MicroShield 4 (Negin and Worku 1992a). MicroShield analyzes shielding and estimates exposure from gamma radiation. This version allows versatile geometries with offsets from axes of symmetry. Sensitivity analyses are available for dimensional variations within a single case. Results are calculated with and without buildup simultaneously. MicroShield has the capability to handle photon energies between .015 and 15 MeV. Data for attenuation coefficients, buildup factors, and buildup factor coefficients are obtained from information distributed by the Radiation Shielding Information Center and included in ANS 6.4.3. MicroShield was used in the development of uncertainty ranges for the geometry factors and occasionally as a quality assurance check for the geometry factors calculated with MCNP.

RadDecay 4 (Negin and Worku 1992b). RadDecay contains radioactive decay information for 497 radionuclides. Data includes the half-lives, radioactive daughters, probabilities per decay, and decay product energies for alphas, betas, positrons, electrons, X-rays, and gamma rays. Given an initial radioactivity and decay time, RadDecay will calculate the remaining radioactivity of a radionuclide and the radioactivity level of its progeny. The decay chain is calculated and displayed for up to 20 generations. Identical daughters generated along different branches of the parent decay chain are combined. RadDecay also has the capability to search for gammas and X-rays in a specific energy range set by the user (Negin and Worku 1992b). RadDecay was used primarily to calculate ingrowth of radioactive progeny.

RADTRAN 4 (Neuhauser and Kanipe 1994). The RADTRAN 4 code combines user-supplied input data with health physics data to calculate the expected radiological consequences and risks resulting from the transportation of radioactive material. Estimates of radiological consequences and risks are derived by numerically modeling the path and behavior of each package from the time that transportation begins until it arrives at its destination.

8.2 Quality Requirements

The exposure pathway model components developed for this analysis, including scenario descriptions, parameter tables, mathematical equations and pathway flow diagrams, served as the design description for spreadsheet software development. All staff involved in model development were apprised of these quality control, documentation, and configuration management requirements, and a Quality Assurance (QA) administrator ensured that appropriate steps were taken to implement the requirements. Each model developer was responsible for assuring that the data and formulas encoded as spreadsheet models were accurate, complete,

verifiable, and properly documented. The basic quality requirements imposed on this analysis are listed below.

- The source and evolution of all model parameter values and algorithms must be documented. Documentation must be sufficient to permit the completion of independent verification and quality reviews and to allow ready verification of configuration management functions by audit.

- Documents and references necessary to establish the basis of a model must be maintained in the Project Engineering Cabinet.

- Design changes must be documented and traceable.

- Where appropriate, parameters and units must be named in a manner consistent with Section 2.2 of NUREG/CR-5512 (Kennedy and Strenge 1992) or Volume 3 of NUREG/CR-5512 (Beyeler et al. 1996).

- Spreadsheet applications must contain sufficient internal documentation so that users do not have to consult external manuals for routine operation of the spreadsheet. If external manuals or other documents are necessary, the spreadsheet must contain complete citations for these documents. Documentation must be sufficient to permit a user to identify and track any changes to the spreadsheet made under the configuration control procedures.

- Spreadsheets must conform to a standard structure, consisting of a title page followed by several principal sections. The banner/title page must identify the model, the version number, and the responsible author. The spreadsheet must also contain a workbook or spreadsheet description, macro fields and macro listings. Another section of the spreadsheet must list the parameter names, symbols, units, default values, as well as references that are applied in the spreadsheet. Another section must contain the data input fields for radionuclide-independent and dependent parameters. The calculational fields of the model must be delineated in another section. Other sections of the spreadsheet must be identified as needed.

- Numeric formats must be consistent. Appropriate significant figures should be used for final results.

- To the extent practicable, standard functions within the spreadsheet applications software should be used in lieu of custom functions. To the extent practicable, if custom functions are used, they will be consistently applied to all calculations performed.

8.3 Document Review, Control and Configuration Management

In order to meet the documentation requirements in an organized, retrievable manner, a formal system of document review and filing was implemented. A QA administrator acted as a central hub for the review process; all material passed through the QA administrator for each step of the review and final documentation of technical information.

When a scenario model, material flow description, or other technical description was sufficiently developed, the author was responsible for transmitting a packet containing descriptions, references and electronic copies to the project QA administrator for document control. The QA Administrator would then review the submittal for completeness, log-in and file the model, and submit the packet for peer review.

Because of the complexity of many of the spreadsheet models in this analysis, documentation and review of the scenario descriptions were completed prior to encoding the spreadsheet.

8.4 QA Review of Technical Information

All technical information developed for the project was peer-reviewed. This included conceptual models, equations and spreadsheets. Specific items to be reviewed were indicated on the review checklist that accompanied all review packets.

The QA review for a new or revised version of a spreadsheet model included, at a minimum, a review of the following six elements: parameters, benchmark check, calculation model, documentation, transcription, and verification. Parameter values were checked against sources for accuracy and transcription; documentation was checked for completeness. Verification involved a check of whether or not the mathematical model algorithms were accurately implemented. Benchmark checks included a comparison of the computation results of a specific spreadsheet or workbook with the results (printed version) of a reference spreadsheet or workbook used to analyze the same or comparable problem. QA reviews of interim revisions were limited in scope, but were sufficient to address the documented changes.

In addition to in-house peer-review by SAIC technical personnel, the analyses were peer-reviewed by an outside contractor. This review function was to ensure that the analyses were reasonable and technically adequate and the results were interpreted satisfactorily.

8.5 Recordkeeping: Project Engineering Cabinet

The project QA administrator was responsible for maintaining the organization and contents of the Project Engineering Cabinet, which served as a repository for the master versions of all controlled project documents. Individual files were separately labeled and coded by the QA Administrator, and the cabinet was organized to include the sections outlined below.

Master Directory

The master directory contained information applicable to all aspects of the project. This includes master scenario lists, document status tables, procedures, and general project information. The master directory served as a key section of the project engineering cabinet and is the starting point for anyone looking for specific technical information about the project.

Scenario Files

The scenario is a primary, organizational unit for this analysis. As such, project documentation and quality review functions were structured around scenario development. Documentation of the description, modeling, and review for each scenario was maintained as a unit: a discrete file in the project engineering cabinet. A completed scenario file contains all descriptions, documents, and forms indicated for that individual scenario. It includes a full-version history of the model and provides for traceability of configuration control, model validation, and other elements of the QA review.

Scenario model development usually proceeded in three stages, where the conceptual framework and mathematical representation of the scenario model was completed and reviewed prior to encoding the deterministic model into a spreadsheet. In turn, encoding and review of the deterministic model served as the basis for probabilistic modeling. This process was reflected in the Engineering Cabinet documentation.

The file structure described above for printed documents in the cabinet is duplicated for electronic versions of the scenario files. A controlled electronic media repository was maintained by the QA Administrator. Each electronic file was assigned a unique, 8-character name according to the conventions described in Section 8.6. Three-digit file extensions (e.g.,*.xxx) were used to indicate individual document types and revision numbers maintained in the scenario file. For example, the scenario file for the transportation of dust was labeled as **tdu03fei**. The original (revision 0) scenario spreadsheet was labeled as **tdu03fei.ds0.**

Material Flow Files

The Material Flow section contains all the information used to develop the conceptual and mathematical models, as well as the initial version and supporting documentation, for the material flow. For purposes of project documentation and quality review, material flow models and spreadsheets were considered to be the same as scenario models, and met the same set of requirements. Information in this section also contains the original review checklist form attached to the appropriate material.

Background Documentation Files

Background documentation refers to technical information about the project that does not clearly fall into one of the other specified sections of the Engineering Cabinet. An Engineering Design

File (EDF) system provided a formal structure for document review and control for additional technical descriptions and reference documents that needed to be included in the project files. For instance, the EDF format was used to document the technical development and justification of parameters such as the surface-to-mass ratios.

All background documents to be reviewed or filed required an EDF coversheet followed by the body of the report, references, and any appendices. A completed EDF coversheet included the EDF log number (assigned by QA Administrator), the report title, a report summary, and signatures of all authors and reviewers.

Geometry Factor Files

The Geometry Factors section of the Engineering File Cabinet contains details of the calculations needed to develop Geometry Factors for the scenarios evaluated. The Geometry Factor is a "lumped parameter," therefore, the content of this file section is different than other sections of the cabinet, but still contains a complete documentation record.

Quality Assurance Administration Files

The Project QA Documentation section contains the quality assurance documents for the overall project (i.e., the Project Quality Control Plan with all the attached appendices). The QA Forms section also contains all completed QA forms (i.e., spreadsheet QA form). The QA forms were printed on colored paper so they were easy to identify.

Project Management Files

The Project Management section was for items such as monthly reports, memoranda, and other items applicable to various aspects of management of the project.

Report Files

The Report section contains all draft and final versions of formal reports produced for the NRC as part of this analysis.

References

All references that are used are kept in the Reference section.

8.6 Instructions for Naming Files and Scenarios

The following criteria were used when assigning electronic file names to scenario files for this evaluation. In general, the first eight file characters are reserved for each of the following six classifications: scenario category, material type, restricted or unrestricted uses, scenario

description number, initial product material type, and target population. The final criterion specifies the file extension criteria.

1) The first character was reserved for the scenario category. The following scenario categories have been identified:

h	=	handling and processing	d	=	disposal
s	=	storage	t	=	transportation
p	=	product use	x	=	applies to all categories

2) The second character was reserved for the product material type. The following material types have been identified:

a	=	atmospheric emission	d	=	dust and dust byproducts
m	=	scrap metal	r	=	refined metal product
s	=	slag from steel refining	x	=	applies to all end product material types

3 The third character was reserved for designating whether the scenarios is a restricted use or an unrestricted use scenario, as follows:

r	=	restricted use	u	=	unrestricted use
x	=	all uses			

Note: "Restricted" and "unrestricted" terms were used in the early phases of this analysis, but were dropped during the course of the analysis. There are no "restricted use" scenarios evaluated, so this character is unnecessary.

4) The fourth and fifth characters were reserved for a scenario description number (1–99). This number can be cross-referenced to the Scenario Description Table to provide a complete scenario description.

5) The sixth and seventh characters were reserved for the initial product material being reused or recycled. Standard chemical symbols were used when possible:

al	=	aluminum	fe	=	iron/steel
cu	=	copper	cn	=	concrete
xx	=	applies to all initial product materials			

6) The eighth character was used to identify the target population, using the following abbreviations:

i	=	onsite worker, individual	o	=	onsite worker, population
g	=	general public, individual	p	=	general public, population
v	=	visitor, individual	x	=	applies to all target populations

7) File extensions reflected the document type and revision number (used only for exposure scenarios). The first and second characters indicate the document type and the third character indicates the revision number:
   *.pd# = probabilistic description, revision number #
   *.dd# = deterministic description, revision number #
   *.ps# = probabilistic spreadsheet, revision number #
   *.ds# = deterministic spreadsheet, revision number #

Following the above file naming criteria, file **tdu03fei.dd1** is the first revision of a deterministic scenario description and technical justification for the unrestricted transportation of dust. This scenario is the third in the transportation category, thus it has a scenario description number of 03. The initial source material being recycled is steel. The dose is evaluated for an individual onsite worker.

For the purposes of this report, additional scenario abbreviations were developed. The use of these abbreviations does not affect the electronic file names. A cross-reference between the two sets of file names is included in Appendix A.

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GLOSSARY OF TERMS

(* = terms that are defined specifically for this analysis; others use standard definitions)

average member of the critical group: A hypothetical individual that represents the average (mean) member of the critical group in terms of potential dose.

bias: The tendency for an estimate to deviate from an actual or real event. Bias may be the tendency for a model to over- or underpredict. (Till and Meyer 1983)

bremsstrahlung: Photons emitted from an atom as a result of an electron losing energy as it passes near the highly charged nucleus of a heavy element.

byproduct: See co-products

****clearance:*** The release of sources of radioactive material from regulatory control. Clearance of items could result in reuse, recycle, or direct disposal of equipment or material.

****clearance level:*** The level of activity or activity concentration at which clearance occurs.

****cleared material:*** Equipment or material that has been cleared from regulatory control.

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%).

conservative bias: Intentional bias toward overestimation. (Till and Meyer 1983)

co-products: In the context of *refinery co-products*, this term refers to the major products resulting from the refining of scrap metal. These co-products (also referred to as byproducts) are refined metal, slag, baghouse dust, and off-gas.

critical group: The group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances (10CFR20.1003). In this analysis for clearance of equipment and material, there is a critical group for each radionuclide evaluated. In this analysis, the critical group for each radionuclide is the group of individuals described in the exposure scenario that results in the highest mean dose factor for that radionuclide.

****critical-group dose factor:*** The point-estimate dose factor for the average member of the critical group. This is the mean (average) dose factor from the distribution of dose factors calculated for the critical group for each radionuclide. For each material analyzed, there is a critical-group dose factor for each radionuclide.

deep dose equivalent: (H_d), which applies to external whole-body exposure, is the dose equivalent at a tissue depth of 1 cm (1000 mg/cm^2). (10CFR20)

descriptive statistics: Simple statistical measures that characterize a distribution of values. These are also refered to as moments of a distribution. Common descriptive statistics include the mean, the variance, and the standard deviation.

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)

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). (10CFR20)

dose factor: A radionuclide-specific, hypothetical, dose calculated for the average member of a critical group, normalized to a unit radionuclide concentration in cleared material (i.e., μSv/a per Bq/g). The point estimate for the dose factor is the mean of the distribution of possible dose factors.

effective dose equivalent (H_E): the sum of the products of the dose equivalent to the organ or tissue (H_r) and the weighting factors (W_r) applicable to each of the body organs or tissues that are irradiated ($H_E = W_T H_{r)}$. (10CFR20)

element-dependent parameter: Typically refers to a parameter whose value is specific to a given element, and therefore may be different for every element.

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

****geometry factor:*** The dose rate from an external source of radiation from a specific source and source-receptor relationship.

Latin Hypercube sampling: A sampling method for probabilistic uncertainty analysis that divides a probability distribution into intervals of equal probability. Compared with conventional Monte Carlo random sampling, Latin Hypercube sampling is more precise because the entire range of the distribution is sampled in a more even, consistent manner. Latin Hypercube sampling was used in this analysis.

licensed material: source material, special nuclear material, or byproduct material received, possessed, used, transferred or disposed of under a general or specific license issued by the Commission. (10CFR20)

mass loading: A factor that relates concentration of a constituent in soil to the concentration of that constituent in air.

****material flow model:*** A model that describes the flow of material and associated radioactivity during recycle.

mean: 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. (see geometric mean)

median: Strictly, a value in a distribution such that there is a 0.5 probability that the actual value of the variable is less than that value. In common usage, it is the value in a distribution such that half of the values are bigger, and half of the values are smaller.

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

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

****partitioning:*** The differential movement of one material as compared to another material. For this analysis, partitioning is used in the context of the steel refining process, specifically during melting in a furnace.

mass partitioning: the redistribution of mass during melting in a refinery furnace. The mass of the material in a furnace is distributed to refined metal, slag, and dust during the refining process.

element partitioning**:** the redistribution of chemical elements during melting in a refinery furnace. The elements in the material in a furnace are distributed to refined metal, slag, dust, and offgas during the refining process depending on their chemical characteristics.

percentile: Strictly, a value in a distribution, expressed as a percentage, such that there is a given probability that any value in the distribution is less than that value. In common usage, it is 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 95-percentile value.

probabilistic model: A system whose input and output is expressed as a distribution of possible values. The output distribution results from uncertainty in the input parameters.

probability distribution: A set of all possible values of a parameter, and their associated probability. The probability distributions used in this analysis are uniform, triangular, normal, and lognormal.

progeny: The nuclide 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.

radionuclide: An atom that, due to its atomic instability, undergoes spontaneous nuclear disintegration. Nuclear disintegration is accompanied by the emission of charged particles and/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 every radionuclide.

radionuclide-independent parameter: A parameter whose value is not specific to a given radionuclide, and therefore is the same for every 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.

****recycle:*** Conversion of materials (i.e., steel, copper, aluminum, concrete) present in components from a nuclear facility to form new products through normal industrial processes, which would then be available in the public sector.

****refining:*** In the context of clearance of equipment and material, refining means melting in a furnace at a metals refinery. Refining results in the production of the co-products refined metal, slag, baghouse dust, and off-gas.

****reuse:*** Transfer of a functional component or material from a nuclear facility without any processing, to some other application where it would be used to carry out its original function.

saturated zone: That portion of porous ground media in which the interconnecting interstices are filled with water. (Till and Meyer 1983)

****scrap material:*** manufactured items or parts that are no longer useful for their original purpose that have value as material for reprocessing.

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 and dust.

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)

spreadsheet: A calculational computer software application.

total effective dose equivalent (TEDE): the sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures). (10CFR20)

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

uncertainty analysis: The computation of the total uncertainty induced in the output by quantified uncertainty in the inputs and models, and the attributes of the relative importance of the input uncertainties in terms of their contributions. (NCRP 1996)

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.

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