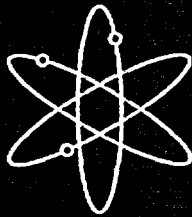
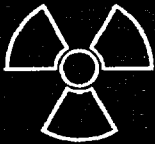




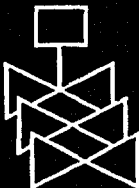
# **Radiological Assessments for Clearance of Materials from Nuclear Facilities**



## **Main Report**



**U.S. Nuclear Regulatory Commission  
Office of Nuclear Regulatory Research  
Washington, DC 20555-0001**



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# **Radiological Assessments for Clearance of Materials from Nuclear Facilities**

## **Main Report**

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**ABSTRACT**

This report provides a complete description of calculations and their results estimating potential annual doses, normalized to a unit concentration, to an individual following the clearance of specific materials. These materials are scrap iron and steel, copper, aluminum, and concrete rubble from licensed nuclear facilities. Clearance means the removal of radiological controls by the licensing authority. The estimated potential doses are calculated probabilistically to account for a large number of possible variations in each of the 86 scenarios. These scenarios encompass the full range of realistic situations likely to yield the greatest normalized doses. Each scenario was analyzed with the 115 radionuclides considered most likely to be associated with materials from licensed nuclear facilities. The design basis of the analyses is to realistically model current processes, to identify critical groups on a nuclide-by-nuclide basis, and to enable the conversion of a dose criterion to a concentration.

Material for recycle or disposal was evaluated using material flow models and dose assessment models. Both models are based on probabilistic methods. This resulted in distributions of nuclide-by-nuclide normalized doses from one year of exposure per mass- or surface-based concentrations. The means and the 5th, 50th, 90th, and 95th percentiles are reported. These percentiles can be used to generically evaluate the likelihood that the derived mean concentration would correspond to a particular dose criterion. Additionally, they can be used to quantify the confidence that a safety goal is not exceeded.

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- B Parameter Values**
- C External Exposure Dose Coefficients**
- D Mixing of Cleared Materials**
- E Ingrowth of Radioactive Progeny**

### **Volume 3: Appendices F – G**

- F Results of Assessments of Iron and Steel Scrap**
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### **Volume 4: Appendices H – O**

- H Results of Assessments of Aluminum Scrap**
- I Results of Assessments of Concrete Rubble**
- J Partitioning Factors and Mass Fractions**
- K Normalized Radionuclide Concentrations**
- L Chemical Form and Particle Size**
- M Results of Single Heat Scenarios in Steel Analysis**
- N Scoping Analyses**
- O Quality Management Plan**

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## EXECUTIVE SUMMARY

This report provides a complete description of calculations and their results estimating potential annual doses to an individual following the clearance of specific materials. These materials are scrap iron and steel, copper, aluminum, and concrete rubble from licensed nuclear facilities. Clearance means the removal of radiological controls by the licensing authority—in this case, the U.S. Nuclear Regulatory Commission. The estimated potential doses are calculated probabilistically to account for a large number of possible variations in each of the 86 scenarios. These scenarios encompass the full range of realistic situations likely to yield the greatest normalized doses. Each scenario was analyzed with the 115 radionuclides considered most likely to be associated with materials from licensed nuclear facilities.

The design objectives of this report include incorporating more realistic modeling of current industrial practices in the United States, as well as current data on the living habits of the U.S. population. This objective was implemented to minimize unnecessary conservatism, i.e., overestimation of potential doses. The results of these analyses can be used as part of the technical basis to support regulatory considerations. Specifically, they can be used to identify critical groups and to relate a dose-based requirement to a mass-based or surface-based concentration of a radionuclide. However, this technical report, in itself, cannot be inferred to represent any regulatory policy or any regulatory decision.

This final report addresses and resolves public and NRC staff comments on the draft, as well as the comments received from two independent reviews. One was a peer review conducted by the Center for Nuclear Waste Analyses; the other was a review by the National Research Council, part of the National Academies. The draft of this report was published in March 1999. This final report is organized as a main report, volume 1, that summarizes the approaches, the mathematical formulations and the main results. The appendices are published in succeeding volumes and provide the detailed technical inputs to the calculations and the detailed results. A description of the main report and the titles of the appendices follow.

Chapter 1 describes the design objectives and the general approaches for the analyses. A brief description of how the uncertainties for each analysis were generated is as follows. Each individual calculation, whether it is the assessment of a radiation dose in a given scenario or the concentration of a given radionuclide in a given medium, is deterministic—it employs a set of fixed values of the relevant parameters and produces a fixed result. For parameters that are uncertain or variable, Monte Carlo sampling methods are used to pick the particular set of values in a given calculation, called a realization. In the present analysis, the estimation of each dose, radionuclide concentration, or other intermediate parameter involved between 5,800 and 10,000 realizations. These 5,800 to 10,000 results themselves form a probability distribution. The mean value and the 5th, 50th, 90th, and 95th percentile values of each such distribution are listed in subsequent parts of the present report. These percentiles can be used to generically evaluate the likelihood that the derived mean concentration would correspond to a particular dose criterion. Additionally, they can be used to quantify the confidence that a safety goal is not exceeded.

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Two different dosimetric quantities were calculated in these analyses. One is the effective dose equivalent (EDE). The EDE is based on recommendations presented in ICRP (International Commission on Radiation Protection) Publication 26, published in 1977. NRC radiation protection regulations are based on these recommendations. The second is the effective dose. The calculations of effective dose are based on the current recommendations, adopted by the ICRP in 1990. These are presented in ICRP Publication 60, and incorporate the respiratory tract model described in ICRP Publication 66 as well as new bio-kinetic models for specific radionuclides presented in ICRP Publications 56, 67, and 69. The results are normalized to initial unit activity concentrations at the point of clearance, that is, from the licensed facility. The results are expressed in terms of the EDE and effective dose from one year of exposure per unit activity in a gram or on a square centimeter of cleared material, for each separate radionuclide in each material.

Chapter 2 is an overall summary of the results. It takes into account all scenarios, radionuclides, and materials. The highest mass-based normalized doses from about 80% of the radionuclides are from the clearance of concrete rubble, the critical group for about 40 of these nuclides comprising workers using the rubble for road construction. For the remainder of the radionuclides, the highest results were from the steel scenarios. The results, normalized to unit surficial activities on scrap and concrete rubble, were highest for steel for most of the radionuclides. Copper scenarios yielded the remainder of the high surficial results.

Chapter 3 addresses the recycling and disposal of steel scrap. It also lays the mathematical formulations of the assessments and serves as the template for the analyses of other materials. The assessment addresses 37 scenarios that depict exposures resulting from the handling and processing of cleared scrap and the products of melting and refining this scrap at steel mills and foundries, emission of airborne effluents from these facilities, transportation of scrap and furnace products, the use of these products, the landfill disposal of cleared scrap and furnace by-products, and the infiltration of well water by leachate from landfills and storage piles containing cleared scrap or furnace by-products. The analyses utilize data on ferrous metal recycling, as currently practiced in the United States, and on contemporary U.S. work practices and living habits. The mean doses to the groups of exposed individuals characterized by 30 of these scenarios are ranked to determine the critical groups for each radionuclide. The analyses and results of the remaining seven scenarios were placed in an appendix of this report, because they were considered to be a special case and not representative of general industrial practices. The critical group for the largest number of radionuclides, accounting for over one-third of the 115 radionuclides in the analyses, consists of workers processing scrap at a scrap yard. The critical groups for the remaining radionuclides are distributed among eight other scenarios.

Chapter 4 addresses copper scrap recycling and disposal. The assessments address 20 scenarios that depict exposures resulting from the handling and processing of cleared scrap and the products of melting and refining this scrap at secondary copper producers, emission of airborne effluents from these facilities, transportation of scrap and furnace products, the use of copper products, the landfill disposal of cleared scrap and reverberatory furnace slag, and the infiltration of well water by leachate from landfills containing cleared scrap or reverberatory furnace slag. The analyses utilize data on secondary copper production, as currently practiced in the United



States, and on contemporary U.S. work practices and living habits. The critical group for the largest number of radionuclides, accounting for over three-fourths of the 115 radionuclides in the analyses, consists of workers handling copper slag at a secondary fire refinery. The critical group accounting for the second largest number of nuclides comprises workers processing copper scrap at a scrap yard. Three other scenarios give rise to the critical groups for the remaining nuclides, which constitute less than eight percent of the total.

Chapter 5, on aluminum scrap recycling and disposal, is similar in approach. The assessments address 21 scenarios that depict exposures resulting from the handling and processing of cleared scrap and the products of melt-refining this scrap at secondary aluminum smelters, emission of airborne effluents from these facilities, transportation of scrap and smelter products, the use of aluminum products, the landfill disposal of cleared scrap and aluminum dross, and the infiltration of well water by leachate from landfills containing cleared scrap or dross. The analyses utilize current data on U.S. secondary aluminum smelters, and on contemporary U.S. work practices and living habits. The critical group for the largest number of radionuclides, accounting for most of the 115 radionuclides in the analysis, consists of workers processing scrap at a scrap yard. Scenarios involving the use of aluminum products—the owner-operator of a taxi with an aluminum engine block or a person using an aluminum cooking utensil—give rise to most of the remaining critical groups.

Chapter 6 is on the recycling and disposal of concrete rubble. The assessments address eight scenarios that depict exposures resulting from the handling and processing of cleared concrete rubble, transportation of the rubble, the use of recycled concrete in road construction, the landfill disposal of concrete rubble, and the infiltration of well water by leachate from landfills containing concrete rubble. The analyses utilize data on concrete recycling and disposal, as currently practiced in the United States, and on contemporary U.S. work practices and living habits. The critical group for almost one-half of the 115 radionuclides addressed by the present analysis consists of workers processing concrete rubble for recycling or disposal. Workers building a road with recycled concrete constitute the critical group for most of the remaining nuclides.

Chapter 7 is a description of the quality control program that was used throughout the formulation of the analysis and the calculation and reporting of the results. The purpose this program was to ensure that the radiological assessments of the recycling and disposal of cleared materials are defensible, accurate, and verifiable. A Quality Management Plan (QMP) was prepared and followed during the conduct of this analysis. The QMP includes specification of procedures and conventions adopted to implement quality control for the present analysis. The QMP also describes requirements for model development, mathematical analyses, and software implementation, and also specifically addresses requirements for the preparation, review, verification, documentation, and record keeping of technical information. The QMP therefore provides a documented system for ensuring accuracy of results, as well as a basis for tracing calculations. The QMP incorporated quality assurance guidelines provided by the NRC and other recognized authorities.

Chapter 8, the final chapter, is a glossary of technical terms.

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The following is a listing of the appendices contained in Volumes 2, 3 and 4:

**Volume 2: Appendices A – E**

- A Inventory of Materials from NRC and Agreement State Licensees**
- B Parameter Values**
- C External Exposure Dose Coefficients**
- D Mixing of Cleared Materials**
- E Ingrowth of Radioactive Progeny**

**Volume 3: Appendices F – G**

- F Results of Assessments of Iron and Steel Scrap**
- G Results of Assessments of Copper Scrap**

**Volume 4: Appendices H – O**

- H Results of Assessments of Aluminum Scrap**
- I Results of Assessments of Concrete Rubble**
- J Partitioning Factors and Mass Fractions**
- K Normalized Radionuclide Concentrations**
- L Chemical Form and Particle Size**
- M Results of Single Heat Scenarios in Steel Analysis**
- N Scoping Analyses**
- O Quality Management Plan**

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## FOREWORD

This report provides a complete description of calculations and their results. The results are estimates of potential annual doses, normalized to a unit of radioactivity in a gram or on a square centimeter of surface, to an individual following the clearance of three kinds of metal scrap and of concrete rubble from licensed nuclear facilities. Clearance means the removal of radiological controls by the licensing authority—in this case, the U.S. Nuclear Regulatory Commission. The estimated potential doses are calculated probabilistically to account for a large number of possible variations in each of the respective scenarios. The assessments specifically address steel, copper and aluminum scrap, and concrete rubble. These materials represent a large fraction of those that potentially could be cleared from licensed facilities. Additional assessments of potential doses following the clearance of equipment for reuse, ordinary trash, and soils are planned for a supplement to this report.

This final report addresses and resolves public and NRC staff comments on the draft, as well as the comments received from two independent reviews. One was a peer review conducted by the Center for Nuclear Waste Analyses; the other was a review by the National Research Council, part of the National Academies. The draft of this report was published in March 1999. The design objectives of the final report include incorporating more realistic modeling of current industrial practices in the United States, as well as current data on the living habits of the U.S. population. The results were calculated by design to avoid needlessly conservative assumptions in the formulation of the models and the selection of the parameters used with the models. Consequently, as a significant part of the technical basis for the potential regulatory applications listed below, this report relates directly to the NRC Performance Goals that speak to: protecting the environment, implementing more effective, efficient, and realistic activities and decisions, increasing public confidence, and reducing unnecessary regulatory burden.

A considerable amount of data was obtained from the secondary metals and concrete recycling industries. The study also utilized the detailed information that had been compiled by the U.S. Environmental Protection Agency (EPA) on the consumption of foods and water from various sources, and on time devoted to various daily activities, by various segments of U.S. population. The results of the revised analyses provide much more realistic quantitative estimates of potential doses and their corresponding uncertainties. Estimated potential doses were assessed for one year of exposure and normalized to either a unit of radioactivity in a gram of cleared material or on a square centimeter of the surface of such material.

Two different dosimetric quantities were calculated in these analyses. One is the effective dose equivalent (EDE). The EDE, based on recommendations presented in ICRP (International Commission on Radiation Protection) Publication 26, is the basis of the EPA's Federal Guidance Reports Nos. 11 and 12, and is also the basis for the NRC's current regulations for radiological protection. The second is the effective dose. The calculations of effective dose are based on more current recommendations presented in ICRP Publication 60, and incorporate the respiratory tract model described in ICRP Publication 66 as well as new bio-kinetic models for specific radionuclides presented in ICRP Publications 56, 67, and 69. These methodologies are the basis of EPA's Federal Guidance Report No. 13.

## **Regulatory Applications of this Report**

For generic rulemaking, individuals in the scenario with the greatest mean normalized dose can be identified as the critical group for that material on a radionuclide-by-radionuclide basis. Regulatory decisions that concern the dose to an individual typically are based on the average dose in the critical group. Limiting the potential dose to critical group individuals ensures that the average potential dose to any other group would be smaller. A total of 86 exposure scenarios were judged to be realistic candidates for identification of the critical groups among the materials analyzed. These scenarios were assessed for each of the 115 radionuclides considered most likely to be associated with materials in licensed nuclear facilities. For each radionuclide, the greatest mean normalized dose among all the materials analyzed can be used to generically limit the concentration for that radionuclide among all the materials. Alternatively, concentrations corresponding to a dose criterion could be used for metals collectively or specifically applied to each type of metal, and concentrations derived from the analyses of critical groups for concrete could be separately applied.

Additionally, for rulemaking considerations, estimated potential doses to collections of individuals in a large variety of scenarios may be used as a starting point for evaluation of the collective dose in cost-benefit analyses. A cost-benefit analysis is required in the Generic Environmental Impact Statement and the Regulatory Analysis to justify a regulatory change.

Case-by-case regulatory decisions are required in response to requests from licensees. The large variety of scenarios analyzed in this report may be realistically applied to certain situations in licensing requests. In other cases, the models and scenarios may be adapted to specifically fit the situation at hand. Such applications are facilitated by the explicit presentation of the exposure scenarios, calculational models, modeling parameters, and mathematical formulations in this report. The dose assessments in this report may also be used to reconstruct doses, when the exposure situation is sufficiently similar to the ones analyzed.

The effective dose calculations, based on the current ICRP recommendations and models, facilitate comparisons with similar assessments for clearance by the International Atomic Energy Agency (IAEA) and the European Commission. These comparisons may be valuable when making comparisons of import and export practices for these commodities.

Regulatory policies, decisions, guidance, and regulations are distinct from this technical report. This report is limited to technical information and cannot be used to infer any of the above regulatory instruments.

**Other uses for this report**

Licensees may use the approaches, models, or results of this report to evaluate operational situations or to prepare requests for action from the NRC or State regulators. Others who are interested in the subject matter may use this report to better understand industry processes and the modern methods of dose assessment used in radiation protection.

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**Office of Nuclear Regulatory Research**

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**ABBREVIATIONS**

<b>AISE</b>	<b>Association of Iron and Steel Engineers</b>
<b>AISI</b>	<b>American Iron and Steel Institute</b>
<b>AMAD</b>	<b>activity median aerodynamic diameter</b>
<b>APCD</b>	<b>air pollution control device</b>
<b>AWG</b>	<b>American wire gauge</b>
<b>BNL</b>	<b>Brookhaven National Laboratory</b>
<b>BOF</b>	<b>basic oxygen furnace</b>
<b>BWR</b>	<b>boiling water reactor</b>
<b>C&amp;D</b>	<b>construction and demolition (landfill)</b>
<b>CFR</b>	<b>Code of Federal Regulations</b>
<b>CZO</b>	<b>crude zinc oxide</b>
<b>DCF</b>	<b>dose conversion factor</b>
<b>DOE</b>	<b>Department of Energy (U.S.)</b>
<b>DOT</b>	<b>Department of Transportation (U.S.)</b>
<b>DRI</b>	<b>direct reduced iron</b>
<b>EAF</b>	<b>electric arc furnace</b>
<b>EC</b>	<b>European Commission</b>
<b>EDE</b>	<b>effective dose equivalent</b>
<b>EPA</b>	<b>Environmental Protection Agency (U.S.)</b>
<b>EPRI</b>	<b>Electric Power Research Institute</b>
<b>ESP</b>	<b>electrostatic precipitator</b>
<b>FGR</b>	<b>Federal Guidance Report</b>
<b>HRDC</b>	<b>Horsehead Resource Development Company</b>
<b>HTMR</b>	<b>high-temperature metals recovery</b>
<b>I&amp;SS</b>	<b>Iron &amp; Steel Society</b>
<b>IAEA</b>	<b>International Atomic Energy Agency</b>
<b>ICRP</b>	<b>International Commission on Radiological Protection</b>
<b>JIT</b>	<b>just-in-time</b>
<b>LLRW</b>	<b>low-level radioactive waste</b>
<b>MSW</b>	<b>municipal solid waste</b>
<b>NCRP</b>	<b>National Council on Radiation Protection and Measurement</b>
<b>NESHAP</b>	<b>National Emission Standard for Hazardous Air Pollutants</b>
<b>NRC</b>	<b>Nuclear Regulatory Commission (U.S.)</b>
<b>NWSW</b>	<b>Northwestern Steel and Wire Company</b>
<b>OSHA</b>	<b>Occupational Safety and Health Administration (U.S.)</b>
<b>PEL</b>	<b>permissible exposure limit</b>
<b>PNL</b>	<b>Pacific Northwest Laboratory</b>
<b>PWR</b>	<b>pressurized water reactor</b>
<b>QA</b>	<b>quality assurance</b>
<b>Q-BOP</b>	<b>bottom-blown BOF</b>
<b>QMP</b>	<b>Quality Management Plan</b>
<b>RCM</b>	<b>recycled concrete material</b>
<b>RCRA</b>	<b>Resource Conservation and Recovery Act</b>



## Abbreviations

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SAE	Society of Automotive Engineers
SAIC	Science Applications International Corporation
SC&A	SC&A, Inc.
SCBA	Self-contained breathing apparatus
TWA	time-weighted average
UBC	used beverage can
UNREP	<u>underway replenishment</u> (U.S. Navy)
USGS	United States Geological Survey

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## 1 INTRODUCTION

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*This is a report of the assessments of potential radiation doses to individuals from the recycling or disposal of solid materials that could be cleared from nuclear facilities. The assessments address four types of material: steel, copper and aluminum scrap, and concrete rubble. The exposures of individuals to such materials at key steps in recycling and disposal are characterized by exposure scenarios. These exposures are assessed to identify the critical groups for each of 115 radionuclides that are potential components of the residual radioactivity of such materials. The results are normalized to initial unit activity concentrations of each separate radionuclide in each material, and are expressed in terms of the effective dose equivalent (EDE) (ICRP 1977) and effective dose (ICRP 1991).*

*The group of individuals with the highest mean EDE or effective dose from a given nuclide is designated the EDE- or effective dose-critical group for that nuclide. Four sets of critical groups—one for each of the four types of materials—are identified for each nuclide. In addition to the mean values, the 5th, 50th, 90th, and 95th percentile values of EDE and effective dose in each exposure scenario via each pathway are presented and discussed in subsequent sections of the report.*

*The calculations are designed to be realistic. To the extent possible, data on current U.S. industrial and commercial practices are used to characterize the anticipated recycling and disposal of cleared materials. The variability and uncertainty in the values of parameters characterizing these practices and the physico-chemical processes of the melting and refining of scrap metals are expressed as probability distributions. The parameter values used in the analysis are selected by Monte Carlo sampling of these distributions, resulting in distributions of estimated normalized EDEs and effective doses.*

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Clearance (unrestricted release from regulatory control) of materials is defined as the removal of all radiological restrictions on the use or disposal of such materials. Of the many possible fates of such materials, it is most likely that they would be processed for recycling or, at the option of the licensee, disposed of in a landfill. The radiological assessment of the recycling or disposal of cleared materials is presented in the following chapters of this report.

### 1.1 Purpose and Scope

The purpose of the present analysis is to assess the potential radiation exposures of individuals resulting from the clearance of materials from NRC- and Agreement State-licensed facilities. The analysis addresses the clearance of iron and steel scrap, scrap aluminum, scrap copper, and concrete rubble. These categories comprise the bulk of components that would be potentially cleared from licensed facilities.

The end points of the analysis are the effective dose equivalent (EDE) (ICRP 1977) and the effective dose (ICRP 1991) from one year of exposure, normalized to an initial unit activity concentration of each separate radionuclide in each material at the time of clearance. The EDE and the effective dose are calculated separately—in the subsequent discussions, unless otherwise specified, the term “dose” encompasses both EDE and effective dose. Calculation of both EDE and effective dose are required for appropriate comparisons within the current regulatory context, which is based on the recommendations in ICRP Publication 26 (ICRP 1977), and with the more current approaches of the European Commission, the International Atomic Energy

Agency, and the U.S. Environmental Protection Agency's Federal Guidance Report No. 13 (Eckerman et al. 1999), all of which are based on the recommendations in ICRP Publication 60 (ICRP 1991).

At the time the materials are cleared, the residual activities could either reside on the surface or be distributed throughout the volume of bulk material. In either case, the radiation exposure of an individual to batches of material, which consist of many individual components of differing sizes and shapes, can be approximated by assuming an average uniform distribution of the activity in the entire mass. The doses calculated in this analysis are normalized to mass activity concentrations (specific activities).<sup>1</sup> A second calculation is performed to derive doses normalized to areal activity concentrations by dividing the mass-based normalized doses by the mass-to-surface ratio specific to each of the four materials. Thus, the results of the analysis are reported as both mass-based ( $\mu\text{Sv}$  per Bq/g) and surficial normalized doses ( $\mu\text{Sv}$  per Bq/cm<sup>2</sup>). These doses are integrated over the period of assessment. Since the analysis assesses the doses over a period of one year, these become normalized doses from exposures occurring during this one-year period, and can be expressed in  $\mu\text{Sv}/\text{y}$ .<sup>2</sup>

The design objective is to realistically estimate the mean dose to individual members of the critical group from each radionuclide that is a potential component of the residual radioactivities of cleared materials. The critical group is defined in 10 CFR 20.1003 as "the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances."

## 1.2 Exposure Scenarios

The focal point of the analysis is identifying the critical group for each radionuclide in the four types of cleared materials listed in Section 1.1, above. Situations in which individuals are likely to be exposed to the residual radioactivities in cleared materials can be characterized by exposure scenarios.

The range of possible scenarios is virtually unlimited. It includes all known or potential uses of cleared materials, and the many processes by which such material can be recycled or disposed of. The scenarios selected for the analysis represent current U.S. industrial and commercial practices. The scenarios were selected to encompass the likely critical groups for each radionuclide in each type of material in the present analysis. Since the purpose of the analysis is to characterize the exposures of critical groups, which comprise significant numbers of individuals, unlikely scenarios, or those involving only a very few individuals, were excluded.

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<sup>1</sup> The specific activity is an average value that applies to the entire batch of cleared material in a particular analysis. It is derived by dividing the total initial activity of a given batch of cleared material by the total mass of that material.

<sup>2</sup> It should be noted, however, that these are 50-y committed doses per year of exposure, not annual dose rates.

### 1.3 Parameter Values

Each exposure scenario is characterized by a set of parameters that constitute a mathematical description of that scenario. Examples of such parameters include the average hours of exposure to the source of radiation, such as the hours per week a truck driver hauling cleared material spends in the cab of his truck, and the average concentration of airborne dust generated by the processing of steel scrap. The analysis of iron and steel scrap alone includes over 300 radionuclide-independent parameters—those parameters that are applicable to the assessments of all radionuclides.

Each scenario models the exposure of a group of individuals to the residual activity of a given medium. The concentration of a given radionuclide in such a medium is the result of one or more processes: the mixing of cleared material (e.g., scrap metal) with similar material from sources other than nuclear facilities, the melt-refining of scrap metal by a secondary metal producer, the commingling of material disposed of in a landfill with wastes from other sources, etc. Each of these processes is characterized by additional parameters.

Many of the parameters employed in the analysis are estimates based on published sources or industry contacts. Some references (e.g., EPA 1997a) present parameter values (e.g., the daily consumption of drinking water) in the form of frequency distributions. Other sources may present minimum, maximum, and average values of certain parameters. In still other cases, a set of discrete values is obtained from one or more sources.

Some parameters have fixed values. Among these are physical constants (e.g., radioactive half-lives) and radiobiological parameters (e.g., dose conversion factor for the intake of each radionuclide). Fixed parameters, such as the distance from the source of airborne effluent emissions to the receptor location, are also used to define particular scenarios.

#### 1.3.1 Probabilistic Analyses

In the present analysis, a parameter that does not have a single fixed value is characterized by a probability distribution. The forms of these distributions are discussed and presented in the following chapters. A general discussion of the types of probability distributions used in the present analysis and a listing of the values and distributions of each parameter are presented in Appendix B.

Each individual calculation, whether it is the assessment of a radiation dose in a given scenario or the concentration of a given radionuclide in a given medium, is deterministic—it employs a set of fixed values of the relevant parameters and produces a fixed result. For parameters that are uncertain or variable, Monte Carlo sampling methods are used to pick the particular set of values in a given calculation, called a realization. In the present analysis, the estimation of each dose, radionuclide concentration, or other intermediate parameter involved between 5,800 and 10,000 realizations. These 5,800 – 10,000 results themselves form a probability distribution. The mean value and the 5th, 50th, 90th, and 95th percentile values of each such distribution are listed in subsequent parts of the present report.

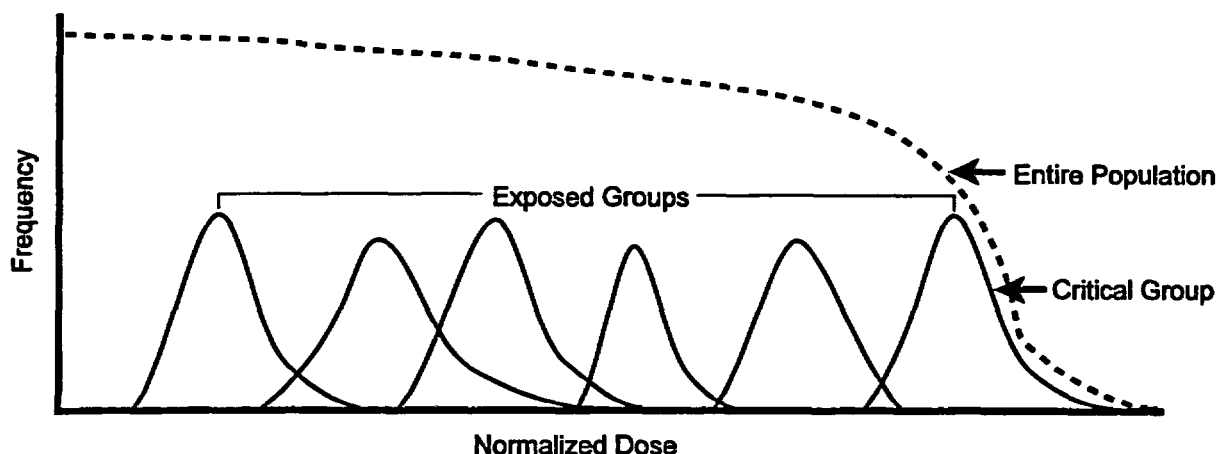
In all cases where an intermediate parameter is calculated using Monte Carlo sampling methods, each of the calculated values is used as input to the next step in the calculation. For example, although the mean and the 5th, 50th, 90th, and 95th percentile values of concentrations of radionuclides are listed in Appendix K, these are solely for the information of the reader. In estimating a radiation dose using 10,000 realizations, for instance, each realization uses each of 10,000 radionuclide concentrations in succession.

This probabilistic approach follows the general guidance of the U.S. Environmental Protection Agency's Guiding Principles for Monte Carlo Analysis (EPA 1997b), NCRP Commentary Number 14 (NCRP 1996), and IAEA Safety Series Number 100 (IAEA 1989).

#### 1.4 Critical Groups

The critical group for each radionuclide in each of the four types of cleared materials is the group receiving the highest mean dose from among all the exposure scenarios addressing the given type of material. Since EDEs and effective doses were calculated separately, there are both EDE- and effective-dose critical groups. In most but not all cases, the same scenario characterizes both the EDE- and effective dose-critical group for a given radionuclide in a given material. Between eight and 30 scenarios are analyzed and compared for each material.

Figure 1.1 depicts an idealized diagram of frequency distributions of normalized doses from some hypothetical source to members of six hypothetical groups, including the critical group, as well as to the entire U.S. population. (This diagram is solely for the purposes of illustration and does not represent actual results of the present analysis.) The number of individuals receiving a given dose is plotted along the vertical axis. Because of the variability of exposure parameters discussed in Section 1.3, the doses to individual members of each group will also vary.



**Figure 1.1** Frequency distributions of normalized doses from a hypothetical source

As described by the International Commission on Radiation Protection (ICRP 1985):

The [critical] group should be representative of those individuals in the population expected to receive the highest dose . . . . The Commission [i.e., the ICRP] believes that it will be reasonable to apply the appropriate dose-equivalent limit for individual members of the public to the *mean dose* equivalent in the critical group [italics added for emphasis].

Most members of the public will not be exposed to this hypothetical source and will receive a dose that is essentially zero. That segment of the population is not depicted in Figure 1.1. The dotted curve represents the doses to all members of the public, including the six groups represented by the solid curves. The dotted curve indicates that there are some exposed individuals that are not included in any of the six groups examined in this hypothetical analysis. Furthermore, there are a few individuals who, perhaps due to aberrant behavior, unusual habits or work practices, etc., could potentially receive doses that are higher than those received by members of the critical group. Such individuals are not within the scope of the present analysis.

## 1.5 Radionuclide Selection

A key step in the analyses is identifying the radionuclides that are potential components of the residual radioactivities of cleared materials. These 115 nuclides are selected from a number of references, which are discussed below. Table 1.1 presents a list of these nuclides and presents the basis for their selection.

**NRC Correspondence with IAEA.**<sup>3</sup> Radionuclides constituting the residual activities in cleared material are likely to be similar to those in low-level radioactive waste. Radionuclides listed in this correspondence constitute more than 90% of the total activities disposed of at U.S. commercial LLRW disposal sites during the three years: 1988 – 1990.

**1992 State-by-State Assessment of Low-Level Radioactive Wastes Received at Commercial Disposal Sites** (Fuchs and McDonald 1993). This document lists radionuclides in wastes from various sources—indirect (shipments from the generator to the disposal facility through an intermediary), reactors, academic, medical, industrial, and government—that were disposed of at commercial LLRW disposal sites in 1992.

**Radionuclides in United States Commercial Nuclear Power Reactors** (Dyer 1995). This article presents data from several studies on the radionuclide inventories found in nuclear power plant systems and materials (specifically stainless steel). The study included only those radionuclides with half-lives longer than 50 days.

**Activation products.** Activation products likely to be found in or on cleared materials as a result of neutron irradiation were added to the list of radionuclides.

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<sup>3</sup> Robert A. Meck, NRC, letter to Gordon Linsley, Scientific Secretary, Division of Nuclear Fuel Cycle and Waste Management, International Atomic Energy Agency, November 9, 1992.

**Table 1.1 Radionuclides of interest in the analysis of recycling and disposal of cleared materials**

H-3 <sup>a</sup>	Co-58 <sup>a</sup>	Tc-97 <sup>f</sup>	Cs-135 <sup>f</sup>	W-185 <sup>f</sup>	U-234 <sup>e</sup>	Cm-244 <sup>c</sup>
C-14 <sup>a</sup>	Co-60 <sup>a</sup>	Tc-97m <sup>f</sup>	Cs-137 <sup>a</sup>	Os-185 <sup>f</sup>	U-235 <sup>b</sup>	Cm-245 <sup>f</sup>
Na-22 <sup>a</sup>	Ni-59 <sup>b</sup>	Tc-99 <sup>a</sup>	Ba-133 <sup>b</sup>	Ir-192 <sup>b</sup>	U-236 <sup>f</sup>	Cm-246 <sup>f</sup>
P-32 <sup>a</sup>	Ni-63 <sup>a</sup>	Ru-103 <sup>a</sup>	Ce-139 <sup>f</sup>	Tl-204 <sup>f</sup>	U-238 <sup>a</sup>	Cm-247 <sup>f</sup>
S-35 <sup>a</sup>	Zn-65 <sup>a</sup>	Ru-106 <sup>a</sup>	Ce-141 <sup>a</sup>	Pb-210 <sup>a</sup>	Np-237 <sup>e</sup>	Cm-248 <sup>f</sup>
Cl-36 <sup>a</sup>	As-73 <sup>f</sup>	Ag-108m <sup>c</sup>	Ce-144 <sup>a</sup>	Bi-207 <sup>f</sup>	Pu-236 <sup>f</sup>	Bk-249 <sup>f</sup>
K-40 <sup>b</sup>	Se-75 <sup>a</sup>	Ag-110m <sup>a</sup>	Pm-147 <sup>a</sup>	Po-210 <sup>a</sup>	Pu-238 <sup>c</sup>	Cf-248 <sup>f</sup>
Ca-41 <sup>d</sup>	Sr-85 <sup>b</sup>	Cd-109 <sup>b</sup>	Sm-151 <sup>f</sup>	Ra-226 <sup>f</sup>	Pu-239 <sup>c</sup>	Cf-249 <sup>f</sup>
Ca-45 <sup>a</sup>	Sr-89 <sup>c</sup>	Sn-113 <sup>f</sup>	Eu-152 <sup>b</sup>	Ra-228 <sup>f</sup>	Pu-240 <sup>c</sup>	Cf-250 <sup>f</sup>
Sc-46 <sup>f</sup>	Sr-90 <sup>a</sup>	Sb-124 <sup>a</sup>	Eu-154 <sup>b</sup>	Ac-227 <sup>e</sup>	Pu-241 <sup>a</sup>	Cf-251 <sup>f</sup>
Cr-51 <sup>a</sup>	Y-91 <sup>c</sup>	Sb-125 <sup>b</sup>	Eu-155 <sup>c</sup>	Th-228 <sup>b</sup>	Pu-242 <sup>f</sup>	Cf-252 <sup>f</sup>
Mn-53 <sup>f</sup>	Zr-93 <sup>f</sup>	Te-123m <sup>f</sup>	Gd-153 <sup>f</sup>	Th-229 <sup>e</sup>	Pu-244 <sup>f</sup>	Cf-254 <sup>f</sup>
Mn-54 <sup>a</sup>	Zr-95 <sup>a</sup>	Te-127m <sup>f</sup>	Tb-160 <sup>f</sup>	Th-230 <sup>e</sup>	Am-241 <sup>b</sup>	Es-254 <sup>f</sup>
Fe-55 <sup>a</sup>	Nb-93m <sup>c</sup>	I-125 <sup>a</sup>	Tm-170 <sup>f</sup>	Th-232 <sup>a</sup>	Am-242m <sup>f</sup>	
Fe-59 <sup>a</sup>	Nb-94 <sup>c</sup>	I-129 <sup>a</sup>	Tm-171 <sup>f</sup>	Pa-231 <sup>e</sup>	Am-243 <sup>f</sup>	
Co-56 <sup>f</sup>	Nb-95 <sup>a</sup>	I-131 <sup>a</sup>	Ta-182 <sup>f</sup>	U-232 <sup>f</sup>	Cm-242 <sup>c</sup>	
Co-57 <sup>a</sup>	Mo-93 <sup>c</sup>	Cs-134 <sup>a</sup>	W-181 <sup>f</sup>	U-233 <sup>e</sup>	Cm-243 <sup>f</sup>	

<sup>a</sup> NRC correspondence with IAEA<sup>b</sup> Fuchs and McDonald (1993)<sup>c</sup> Dyer (1995)<sup>d</sup> activation product<sup>e</sup> radioactive progeny<sup>f</sup> EC 1998

**Radioactive progeny of radionuclides on the list.** Potentially significant (half-life greater than 30 days) radioactive progeny from parent radionuclides identified in the sources listed above were explicitly included on the list. Radioactive progeny with half-lives of less than 30 days are assumed to be in secular equilibrium with their parents (as described in Appendix E), and are therefore implicitly included in the analysis of the parents.

**Radiation Protection 89 (EC 1998).** Radionuclides were included if they were addressed in the European Commission's recommended radiological protection criteria for recycling of metals from nuclear installations.

**Radionuclides excluded.** Radionuclides with half-lives longer than that of Th-232 (greater than  $1.41 \times 10^{10}$  years) were not included in the analysis. The specific activities of such nuclides (e.g., Sm-147) would be so low that no significant doses would result from the limited amounts that would be found in cleared materials. With the exception of P-32 and I-131, nuclides with half-lives of less than 30 days were also excluded. It is unlikely that any significant activities of such short-lived nuclides would be found on cleared materials. The two afore-mentioned nuclides were included because of their uses in medicine and research, and because I-131 is a major fission product.

## 1.6 Exposure Pathways

In each exposure scenario, the radiation dose can be delivered via one or more pathways. The pathways included in the present analysis fall into two categories—external and internal—which are discussed in the following sections.

### 1.6.1 External Exposure

All but three of the radionuclides in the present analysis—the exceptions are H-3, Ca-41 and Mn-53—emit calculable photon radiation, as either  $\gamma$ - or x-rays emitted during the radioactive decay of the atomic nucleus, or bremsstrahlung x-rays generated following  $\beta$ -decay. The external exposure to this direct, penetrating radiation is assessed in each scenario in which individuals are in proximity to residually radioactive materials.

The dose rate from external exposure for a given source is calculated as follows:

$$d_{ix} = C_i F_{ix} U_x \quad 1.1$$

$d_{ix}$  = dose rate from external exposure to nuclide  $i$  ( $\mu\text{Sv/h}$ )

$C_i$  = activity concentration of nuclide  $i$  in source material (Bq/g)

$F_{ix}$  = dose coefficient for external exposure to nuclide  $i$  ( $\mu\text{Sv/h per Bq/g}$ )

$U_x$  = uncertainty factor

The parameter  $F_{ix}$  is a nuclide- and scenario-specific dose rate factor. When the source is relatively compact or has a complex geometry, the values of  $F_{ix}$  are derived by means of a computer simulation of the emission of photons and  $\beta$ -rays from the source, which has a prescribed shape, dimensions, density, and elemental composition. The simulation, which utilizes the Los Alamos Monte Carlo code, MCNP Version 4C, includes the interaction of these emitted particles with the source material and with other objects and environmental media in the vicinity, such as air, underlying soil or pavement, and other materials that shield or scatter the radiation. The source is assumed to be uniformly contaminated throughout its mass with one of the 115 radionuclides, along with its short-lived progeny. In most cases, the dose rates for each exposure geometry are calculated at two or more receptor locations. These dose rates are then combined to determine a rate at the desired location. The variation of dose rate with position is used to calculate an uncertainty factor,  $U_x$ . This factor is assigned a uniform distribution with a mean value,  $\bar{U}_x = 1$ . In some scenarios, the receptor location is assumed to be fixed. In still other scenarios, the calculation is averaged over the occupied area or volume. In those cases,  $U_x \equiv 1$ . The calculation of  $F_{ix}$  and  $U_x$  are discussed in greater detail in Appendix C.

Two sets of calculations are performed for each exposure geometry and source material. The EDE coefficients are calculated using the tissue weighting factors of ICRP Publication 26 (ICRP 1977), while effective dose coefficients utilize the ICRP 60 factors (ICRP 1991).



Extended sources that can be approximated by an infinite plane utilize dose coefficients listed in Federal Guidance Report (FGR) No. 12 (Eckerman and Ryman 1993), which includes EDE coefficients for semi-infinite slabs of soil contaminated on the surface, as well as for soil contaminated to an infinite depth. Effective dose coefficients for the same sources, based on the FGR 12 calculations but employing ICRP 1991 tissue weighting factors, are listed in EPA 2000. The values of  $F_{ix}$  derived from the FGR 12 coefficients are listed in Appendix B of the present report. The value of  $U_x$  used for such sources is based on engineering judgment, and is discussed as part of the description of the relevant scenarios.

Other external exposure pathways, such as the external exposure from a cloud of resuspended aerosols or from a plume of airborne effluent emissions from a furnace recycling cleared metal scrap, would make insignificant contributions to the dose assessments and are not included in the present analysis.

### 1.6.2 Internal Exposure

The detailed discussion of the assessment of internal exposures due to the inhalation and ingestion of residually radioactive material is presented in the sections describing the various scenarios later in this report. Federal Guidance Report (FGR) No. 11 (Eckerman et al. 1988) lists dose conversion factors (DCFs) for inhalation and ingestion that relate the intake of a unit activity of a given radionuclide to the EDE to the individual. Similarly, ICRP Publication 68 (ICRP 1994) lists effective dose coefficients for intakes of radionuclides by workers. Since, as will be seen in later chapters of this report, the critical groups for a large majority of the radionuclides comprise workers, these are the appropriate coefficients for use in the present analysis.

For many radionuclides, DCFs and effective dose coefficients have different values, depending on the chemical form of the nuclide. ICRP 1994 further distinguishes the coefficients for inhalation on the basis of particle size. In order to perform realistic assessments, the DCFs and dose coefficients in each scenario were selected on the basis of the most likely chemical form of each radionuclide in a given medium and the most likely particle size of the suspended aerosols in that scenario. These chemical forms and particle sizes are discussed in greater detail in Appendix L. The DCFs and dose coefficients assigned to each radionuclide in each medium are listed in Appendix B.

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## 2 SUMMARY OF RESULTS

*Radiological assessments of 79 exposure scenarios have been performed in order to identify the critical groups for each of 115 radionuclides that are potential components of the residual radioactivities of steel, copper and aluminum scrap, and concrete rubble. Monte Carlo sampling methods were used to calculate distributions of effective dose equivalents (EDEs) and effective doses from each radionuclide in each of the four materials. The results are normalized to initial unit activity concentrations in the cleared material and are expressed as both mass-based and surficial doses (e.g.,  $\mu\text{Sv/y}$  per Bq/g or  $\mu\text{Sv/y}$  per Bq/cm<sup>2</sup>).*

*The highest mass-based normalized doses from about 80% of the radionuclides are from the clearance of concrete rubble, the critical group for about 40 of these nuclides comprising workers using the rubble for road construction. The highest mean mass-based normalized EDE is 1,400  $\mu\text{Sv/y}$  per Bq/g from Cf-254. The critical group comprises workers processing concrete rubble. The corresponding mass-based effective dose (from the same nuclide) has the same value. The highest mean surficial normalized EDE is 69  $\mu\text{Sv/y}$  per Bq/cm<sup>2</sup> from Th-229. The critical group comprises workers processing copper slag. The highest mean surficial normalized effective dose is 64  $\mu\text{Sv/y}$  per Bq/cm<sup>2</sup> from I-129. The critical group is the individuals drinking water from wells down gradient from a storage pile of steel slag.*

The results of the analyses of the clearance of solid materials from NRC-licensed facilities are used to identify the critical groups for each of 115 radionuclides in four types of cleared materials: steel, copper and aluminum scrap, and concrete rubble. The mean doses to the members of each of these critical groups, normalized to initial unit activity concentrations in the cleared material, are presented in this chapter. Comparisons are presented of the mean mass-based and surficial normalized doses from each radionuclide in the four types of materials.

### 2.1 Summary of Effective Dose Equivalents (EDEs)

Table 2.1 presents the mean values of normalized effective dose equivalents (EDEs) to the critical groups. The mass-based EDEs from each material are listed on the left-hand side of the table—the highest mean dose from among the four materials is displayed in boldface type. The corresponding surficial EDEs are displayed on the right-hand side.

#### 2.1.1 Mass-based EDEs

The highest mean mass-based normalized EDEs from 88 of the 115 radionuclides are from the clearance of concrete rubble. Forty-one of the critical groups for these nuclides in this material are road construction workers using cleared concrete rubble as the base for the pavement and as part of the aggregate in the asphaltic concrete. The remaining critical groups are workers processing concrete for recycling or disposal or individuals drinking water from wells down gradient from landfills used for the disposal of cleared concrete rubble.

The main reason why cleared concrete rubble accounts for the preponderance of the critical groups is the large quantities of this material that would be generated during the dismantlement of a large nuclear facility, such as a commercial nuclear power plant. As discussed in Chapter 6 and documented in greater detail in Appendix A, such a facility would generate between 143 and 281 kt of cleared concrete rubble. The quantities of other materials from such a plant would be

far smaller: between 15 and 24 kt<sup>1</sup> of cleared steel scrap and much smaller quantities of other metals. The large amount of concrete rubble would most likely be processed at or near the site of the plant undergoing dismantlement, and is not likely to be mixed with concrete material from other sources. Thus, workers would be exposed to the undiluted residual activity concentrations in the cleared material.

The highest mean mass-based EDEs for the remaining 27 nuclides are from the recycling of steel scrap. Almost all of the critical groups for these nuclides comprise workers handling or processing slag that is a byproduct of iron- and steelmaking furnaces.

### 2.1.2 Surficial EDEs

The highest mean surficial EDEs from 74 of the 115 nuclides are from the recycling or disposal of steel scrap. Most of the critical groups for this material are workers processing scrap at a scrap yard. The reason why different materials are responsible for mass-based and surficial normalized doses stems from the definition of the normalized surficial dose. As stated in Section 1.1, each surficial dose is derived by dividing the corresponding mass-based normalized dose by the mass-to-surface ratio of the material in question. The 10,000 realizations of the mass-to-surface ratio for steel yield a mean of approximately 5.1 g/cm<sup>2</sup>, while the corresponding value for concrete is 280 g/cm<sup>2</sup>. This approximately 50-fold difference is why the clearance of steel scrap yields the highest mean surficial EDEs.

The highest mean surficial EDEs from the remaining 41 nuclides are from the recycling of copper scrap. These critical groups comprise workers processing copper slag at a secondary fire-refining facility.

## 2.2 Summary of Effective Doses

Table 2.2, which presents the mean values of normalized effective doses, has the same structure as Table 2.1. The highest mass-based normalized effective doses from 95 nuclides are from the clearance of concrete rubble. The reasons for the dominance of this material are the same as those for the EDE-critical groups discussed in Section 2.1.1.

For the remaining 20 nuclides, the highest mass-based normalized effective doses are from the recycling of steel scrap. Almost all of these critical groups comprise workers handling or processing scrap or slag.

The highest surficial effective doses are from the recycling or disposal of steel scrap for 87 of the 115 nuclides, for the same reasons as were discussed for the surficial EDE-critical groups in Section 2.1.2. For the remaining 28 nuclides, the highest surficial effective doses are from the recycling of copper scrap.

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<sup>1</sup> The abbreviation "t" stands for metric tons (tonnes); kilotonnes are abbreviated as "kt," megatonnes as "Mt." Tonnes can also be expressed as megagrams (Mg).

Table 2.1 Normalized effective dose equivalents to critical groups for all materials

Radionuclide	Mass-based ( $\mu\text{Sv/y}$ per Bq/g)				Surficial ( $\mu\text{Sv/y}$ per Bq/cm <sup>2</sup> )			
	Steel	Copper	Aluminum	Concrete	Steel	Copper	Aluminum	Concrete
H-3	1.9e-02	1.0e-04	2.8e-06	6.6e-02	3.8e-03	2.0e-04	3.1e-06	2.4e-04
C-14	3.2e-02	2.4e-04	4.5e-06	1.2e-01	6.3e-03	4.7e-04	5.0e-06	4.1e-04
Na-22	4.2e+01	1.2e+00	2.9e-02	2.4e+02	8.3e+00	2.3e+00	3.2e-02	8.5e-01
P-32	5.7e-02	7.9e-04	2.1e-05	1.1e-01	1.1e-02	1.5e-03	2.4e-05	3.8e-04
S-35	3.7e-04	2.7e-05	8.2e-07	1.6e-03	7.4e-05	5.3e-05	9.2e-07	5.7e-06
Cl-36	1.7e+00	2.1e-03	5.9e-05	1.3e+00	3.4e-01	4.0e-03	6.6e-05	4.7e-03
K-40	3.4e+00	6.5e-02	2.2e-03	1.9e+01	6.7e-01	1.3e-01	2.5e-03	6.7e-02
Ca-41	2.1e-01	1.1e-03	2.9e-05	7.2e-01	4.2e-02	2.2e-03	3.2e-05	2.6e-03
Ca-45	2.0e-03	2.2e-04	3.8e-06	1.1e-02	4.0e-04	4.3e-04	4.3e-06	3.9e-05
Sc-46	3.8e+01	9.3e-01	2.3e-02	1.7e+02	7.4e+00	1.8e+00	2.6e-02	5.9e-01
Cr-51	3.8e-01	8.2e-03	2.4e-04	1.8e+00	7.6e-02	1.6e-02	2.7e-04	6.3e-03
Mn-53	8.8e-04	1.4e-05	6.7e-07	1.5e-03	1.7e-04	2.6e-05	7.4e-07	5.5e-06
Mn-54	1.6e+01	4.3e-01	5.6e-02	8.5e+01	3.2e+00	8.4e-01	6.3e-02	3.0e-01
Fe-55	4.6e-04	4.3e-05	3.1e-06	2.1e-03	9.1e-05	8.4e-05	3.5e-06	7.6e-06
Fe-59	2.1e+01	4.4e-01	1.2e-02	8.8e+01	4.2e+00	8.4e-01	1.4e-02	3.1e-01
Co-56	6.8e+01	1.3e+00	4.8e-02	3.0e+02	1.3e+01	2.5e+00	5.3e-02	1.1e+00
Co-57	1.2e+00	1.5e-02	7.2e-03	8.1e+00	2.4e-01	2.9e-02	8.0e-03	2.9e-02
Co-58	1.7e+01	3.5e-01	1.3e-02	7.5e+01	3.3e+00	6.8e-01	1.4e-02	2.7e-01
Co-60	5.2e+01	1.1e+00	2.6e-01	2.9e+02	1.0e+01	2.2e+00	2.9e-01	1.0e+00
Ni-59	4.6e-04	2.8e-05	2.2e-06	2.1e-03	9.1e-05	5.4e-05	2.5e-06	7.6e-06
Ni-63	4.7e-04	5.4e-05	3.5e-06	2.1e-03	9.4e-05	1.0e-04	3.9e-06	7.4e-06
Zn-65	1.5e+01	2.7e-01	3.1e-02	5.9e+01	3.0e+00	5.3e-01	3.5e-02	2.1e-01
As-73	2.2e-02	1.7e-04	1.8e-05	1.2e-01	4.4e-03	3.2e-04	2.0e-05	4.4e-04
Se-75	5.9e+00	6.5e-02	1.0e-02	2.8e+01	1.2e+00	1.3e-01	1.1e-02	1.0e-01
Sr-85	7.6e+00	2.0e-01	5.1e-03	3.6e+01	1.5e+00	3.9e-01	5.7e-03	1.3e-01
Sr-89	6.3e-02	1.2e-03	2.9e-05	1.4e-01	1.2e-02	2.2e-03	3.3e-05	5.0e-04
Sr-90	5.7e-01	1.3e-02	2.6e-04	1.5e+00	1.2e-01	2.6e-02	2.9e-04	5.2e-03
Y-91	1.4e-01	3.5e-03	7.9e-05	4.3e-01	2.7e-02	6.7e-03	8.8e-05	1.5e-03
Zr-93	9.3e-03	1.7e-03	2.1e-05	9.4e-03	1.8e-03	3.4e-03	2.3e-05	3.3e-05
Zr-95	1.5e+01	4.4e-01	1.1e-02	8.6e+01	3.0e+00	8.6e-01	1.2e-02	3.1e-01
Nb-93m	3.3e-03	6.1e-04	7.3e-06	3.8e-03	6.6e-04	1.2e-03	8.1e-06	1.4e-05
Nb-94	3.0e+01	8.7e-01	2.0e-01	1.7e+02	6.0e+00	1.7e+00	2.2e-01	6.2e-01
Nb-95	1.2e+01	2.8e-01	7.1e-03	5.1e+01	2.4e+00	5.3e-01	7.9e-03	1.8e-01
Mo-93	3.7e-02	6.4e-04	9.0e-06	1.7e-01	7.3e-03	1.2e-03	1.0e-05	6.1e-04
Tc-97	1.9e-01	1.1e-03	3.0e-05	7.1e-01	3.7e-02	2.1e-03	3.3e-05	2.5e-03
Tc-97m	4.5e-03	1.6e-04	4.6e-06	2.7e-02	8.9e-04	3.1e-04	5.1e-06	9.7e-05
Tc-99	1.6e+00	9.5e-03	2.5e-04	6.1e+00	3.2e-01	1.8e-02	2.8e-04	2.2e-02
Ru-103	7.1e+00	1.1e-01	4.5e-03	3.2e+01	1.4e+00	2.2e-01	5.1e-03	1.2e-01
Ru-106	4.2e+00	8.0e-02	1.9e-02	2.2e+01	8.2e-01	1.5e-01	2.2e-02	7.7e-02

Table 2.1 Normalized effective dose equivalents to critical groups for all materials

Radionuclide	Mass-based ( $\mu\text{Sv/y}$ per Bq/g)				Surficial ( $\mu\text{Sv/y}$ per Bq/cm <sup>2</sup> )			
	Steel	Copper	Aluminum	Concrete	Steel	Copper	Aluminum	Concrete
Ag-108m	2.9e+01	5.5e-01	2.4e-01	1.7e+02	5.7e+00	1.1e+00	2.7e-01	6.2e-01
Ag-110m	5.2e+01	9.7e-01	1.7e-01	2.8e+02	1.0e+01	1.9e+00	1.9e-01	9.8e-01
Cd-109	6.5e-02	1.5e-03	2.0e-04	4.8e-01	1.3e-02	2.9e-03	2.2e-04	1.7e-03
Sn-113	3.7e+00	9.1e-02	6.6e-03	2.1e+01	7.4e-01	1.8e-01	7.4e-03	7.4e-02
Sb-124	3.4e+01	5.8e-01	2.0e-02	1.5e+02	6.6e+00	1.1e+00	2.3e-02	5.2e-01
Sb-125	7.1e+00	1.6e-01	4.0e-02	4.3e+01	1.4e+00	3.1e-01	4.5e-02	1.5e-01
Te-123m	1.5e+00	1.3e-02	3.5e-03	9.0e+00	3.0e-01	2.6e-02	3.9e-03	3.2e-02
Te-127m	1.0e-01	1.5e-03	1.3e-04	4.8e-01	2.1e-02	2.9e-03	1.4e-04	1.7e-03
I-125	7.3e-01	1.5e-03	4.8e-05	2.5e-01	1.4e-01	3.0e-03	5.3e-05	8.8e-04
I-129	2.2e+02	4.0e-01	1.2e-02	2.9e+02	4.4e+01	7.8e-01	1.4e-02	1.0e+00
I-131	3.7e+00	3.8e-02	1.2e-03	1.0e+01	7.2e-01	7.1e-02	1.3e-03	3.6e-02
Cs-134	4.4e+01	5.5e-01	2.0e-02	1.6e+02	8.6e+00	1.1e+00	2.3e-02	5.8e-01
Cs-135	8.2e-03	8.6e-05	6.8e-06	2.6e-02	1.7e-03	1.7e-04	7.6e-06	9.3e-05
Cs-137	1.6e+01	2.0e-01	7.4e-03	6.1e+01	3.2e+00	3.9e-01	8.3e-03	2.2e-01
Ba-133	4.9e+00	1.5e-01	4.2e-03	3.5e+01	9.7e-01	3.0e-01	4.7e-03	1.3e-01
Ce-139	1.5e+00	2.9e-02	1.2e-03	9.4e+00	3.0e-01	5.6e-02	1.3e-03	3.4e-02
Ce-141	7.1e-01	9.1e-03	4.4e-04	3.2e+00	1.4e-01	1.8e-02	4.9e-04	1.1e-02
Ce-144	1.0e+00	3.0e-02	7.3e-04	5.3e+00	2.0e-01	5.9e-02	8.1e-04	1.9e-02
Pm-147	4.4e-03	8.2e-04	9.9e-06	5.9e-03	8.6e-04	1.6e-03	1.1e-05	2.1e-05
Sm-151	3.3e-03	6.2e-04	7.2e-06	2.7e-03	6.4e-04	1.2e-03	8.0e-06	9.5e-06
Eu-152	2.2e+01	6.1e-01	1.5e-02	1.2e+02	4.3e+00	1.2e+00	1.7e-02	4.4e-01
Eu-154	2.2e+01	6.0e-01	1.5e-02	1.4e+02	4.3e+00	1.2e+00	1.7e-02	4.9e-01
Eu-155	4.5e-01	6.2e-03	3.4e-04	3.2e+00	8.8e-02	1.2e-02	3.8e-04	1.1e-02
Gd-153	5.9e-01	6.7e-03	4.3e-04	3.9e+00	1.2e-01	1.3e-02	4.7e-04	1.4e-02
Tb-160	2.0e+01	4.9e-01	1.2e-02	8.8e+01	3.9e+00	9.4e-01	1.4e-02	3.1e-01
Tm-170	3.6e-02	1.1e-03	3.1e-05	2.3e-01	7.1e-03	2.1e-03	3.4e-05	8.1e-04
Tm-171	2.7e-03	2.2e-04	4.1e-06	2.0e-02	5.4e-04	4.2e-04	4.6e-06	7.2e-05
Ta-182	2.3e+01	5.9e-01	2.7e-02	1.1e+02	4.6e+00	1.1e+00	3.0e-02	4.0e-01
W-181	1.8e-01	1.5e-03	3.1e-04	1.1e+00	3.6e-02	2.9e-03	3.4e-04	3.9e-03
W-185	2.0e-03	7.6e-05	2.1e-06	9.7e-03	4.0e-04	1.5e-04	2.3e-06	3.4e-05
Os-185	1.4e+01	2.0e-01	1.2e-02	5.6e+01	2.8e+00	3.9e-01	1.3e-02	2.0e-01
Ir-192	1.1e+01	1.9e-01	1.1e-02	5.8e+01	2.2e+00	3.7e-01	1.2e-02	2.1e-01
Tl-204	1.2e-02	1.9e-04	1.0e-04	7.8e-02	2.3e-03	3.7e-04	1.1e-04	2.8e-04
Pb-210	1.2e+01	3.9e-01	3.7e-02	2.5e+01	2.4e+00	7.5e-01	4.2e-02	9.1e-02
Bi-207	4.3e+01	5.5e-01	1.6e-01	1.7e+02	8.5e+00	1.1e+00	1.8e-01	6.0e-01
Po-210	3.3e+00	3.9e-02	3.1e-03	6.3e+00	6.6e-01	7.7e-02	3.5e-03	2.2e-02
Ra-226	3.5e+01	1.1e+00	2.6e-02	2.0e+02	7.0e+00	2.2e+00	2.9e-02	7.2e-01
Ra-228	1.8e+01	7.8e-01	1.5e-02	1.2e+02	3.6e+00	1.5e+00	1.7e-02	4.1e-01

Table 2.1 Normalized effective dose equivalents to critical groups for all materials

Radionuclide	Mass-based ( $\mu\text{Sv/y}$ per Bq/g)				Surficial ( $\mu\text{Sv/y}$ per Bq/cm <sup>2</sup> )			
	Steel	Copper	Aluminum	Concrete	Steel	Copper	Aluminum	Concrete
Ac-227	1.4e+02	2.7e+01	3.2e-01	1.4e+02	2.8e+01	5.3e+01	3.6e-01	5.0e-01
Th-228	4.9e+01	7.6e+00	7.7e-02	1.8e+02	9.7e+00	1.5e+01	8.6e-02	6.5e-01
Th-229	1.9e+02	3.6e+01	5.1e-01	1.3e+02	3.6e+01	6.9e+01	5.6e-01	4.8e-01
Th-230	2.7e+01	5.3e+00	7.6e-02	1.8e+01	5.4e+00	1.0e+01	8.4e-02	6.3e-02
Th-232	1.2e+02	2.4e+01	3.8e-01	8.9e+01	2.4e+01	4.6e+01	4.2e-01	3.2e-01
Pa-231	9.5e+01	1.8e+01	3.1e-01	9.7e+01	1.9e+01	3.4e+01	3.4e-01	3.4e-01
U-232	7.5e+01	1.3e+01	1.5e-01	3.7e+01	1.5e+01	2.6e+01	1.7e-01	1.3e-01
U-233	1.4e+01	2.7e+00	3.1e-02	3.2e+01	2.8e+00	5.3e+00	3.5e-02	1.1e-01
U-234	1.4e+01	2.7e+00	3.1e-02	2.3e+01	2.7e+00	5.2e+00	3.4e-02	8.1e-02
U-235	1.4e+01	2.6e+00	3.0e-02	3.3e+01	2.7e+00	5.0e+00	3.4e-02	1.2e-01
U-236	1.3e+01	2.5e+00	2.9e-02	2.1e+01	2.6e+00	4.9e+00	3.2e-02	7.5e-02
U-238	1.3e+01	2.4e+00	2.8e-02	2.1e+01	2.5e+00	4.7e+00	3.1e-02	7.5e-02
Np-237	3.2e+02	1.1e+01	1.3e-01	1.1e+03	6.2e+01	2.2e+01	1.5e-01	3.8e+00
Pu-236	1.4e+01	2.8e+00	3.4e-02	1.0e+01	2.7e+00	5.4e+00	3.8e-02	3.7e-02
Pu-238	3.1e+01	6.0e+00	9.3e-02	2.9e+01	6.1e+00	1.2e+01	1.0e-01	1.0e-01
Pu-239	3.3e+01	6.4e+00	1.0e-01	3.1e+01	6.6e+00	1.2e+01	1.1e-01	1.1e-01
Pu-240	3.3e+01	6.4e+00	1.0e-01	3.1e+01	6.6e+00	1.2e+01	1.1e-01	1.1e-01
Pu-241	5.8e-01	1.0e-01	2.0e-03	6.1e-01	1.1e-01	2.0e-01	2.2e-03	2.2e-03
Pu-242	3.2e+01	6.1e+00	9.7e-02	3.0e+01	6.2e+00	1.2e+01	1.1e-01	1.1e-01
Pu-244	3.5e+01	6.2e+00	1.0e-01	5.8e+01	6.8e+00	1.2e+01	1.1e-01	2.1e-01
Am-241	4.8e+01	9.1e+00	1.1e-01	3.3e+01	9.4e+00	1.8e+01	1.2e-01	1.2e-01
Am-242m	4.7e+01	9.0e+00	1.0e-01	3.3e+01	9.3e+00	1.8e+01	1.2e-01	1.2e-01
Am-243	4.8e+01	9.1e+00	1.1e-01	4.5e+01	9.5e+00	1.8e+01	1.2e-01	1.6e-01
Cm-242	1.6e+00	3.2e-01	3.8e-03	1.1e+00	3.2e-01	6.3e-01	4.2e-03	3.9e-03
Cm-243	3.3e+01	6.3e+00	7.4e-02	3.0e+01	6.6e+00	1.2e+01	8.2e-02	1.1e-01
Cm-244	2.6e+01	5.1e+00	5.9e-02	1.8e+01	5.2e+00	9.8e+00	6.5e-02	6.4e-02
Cm-245	4.9e+01	9.4e+00	1.1e-01	3.8e+01	9.7e+00	1.8e+01	1.2e-01	1.4e-01
Cm-246	4.8e+01	9.3e+00	1.1e-01	3.3e+01	9.5e+00	1.8e+01	1.2e-01	1.2e-01
Cm-247	4.7e+01	9.2e+00	1.0e-01	5.7e+01	9.3e+00	1.7e+01	1.1e-01	2.0e-01
Cm-248	1.8e+02	3.4e+01	3.9e-01	1.2e+02	3.5e+01	6.6e+01	4.4e-01	4.3e-01
Bk-249	1.5e-01	2.8e-02	3.3e-04	1.0e-01	2.9e-02	5.4e-02	3.6e-04	3.7e-04
Cf-248	5.1e+00	1.0e+00	1.2e-02	3.3e+00	1.0e+00	1.9e+00	1.3e-02	1.2e-02
Cf-249	4.4e+01	8.0e+00	9.6e-02	6.0e+01	8.7e+00	1.6e+01	1.1e-01	2.1e-01
Cf-250	2.2e+01	4.2e+00	4.9e-02	1.6e+01	4.3e+00	8.2e+00	5.5e-02	5.9e-02
Cf-251	4.3e+01	8.1e+00	9.4e-02	4.1e+01	8.4e+00	1.6e+01	1.1e-01	1.5e-01
Cf-252	1.6e+01	3.2e+00	3.7e-02	1.1e+01	3.2e+00	6.1e+00	4.1e-02	3.8e-02
Cf-254	3.3e+02	1.2e+01	2.5e-01	1.4e+03	6.5e+01	2.4e+01	2.7e-01	4.9e+00
Es-254	2.0e+01	1.3e+00	2.1e-02	9.2e+01	4.0e+00	2.5e+00	2.3e-02	3.3e-01

Note: To convert these values to conventional units (mrem/y per pCi/g or mrem/y per pCi/cm<sup>2</sup>), multiply by 0.0037



Table 2.2 Normalized effective doses to critical groups for all materials

Radionuclide	Mass-based ( $\mu\text{Sv/y}$ per Bq/g)				Surficial ( $\mu\text{Sv/y}$ per Bq/cm <sup>2</sup> )			
	Steel	Copper	Aluminum	Concrete	Steel	Copper	Aluminum	Concrete
H-3	2.0e-02	1.1e-04	2.9e-06	6.9e-02	4.0e-03	2.0e-04	3.2e-06	2.5e-04
C-14	3.3e-02	2.5e-04	4.6e-06	1.2e-01	6.5e-03	4.8e-04	5.1e-06	4.2e-04
Na-22	4.2e+01	1.1e+00	2.9e-02	2.2e+02	8.3e+00	2.2e+00	3.2e-02	8.0e-01
P-32	5.6e-02	7.8e-04	2.1e-05	1.1e-01	1.1e-02	1.5e-03	2.3e-05	3.8e-04
S-35	5.5e-04	4.2e-05	1.3e-06	1.9e-03	1.1e-04	8.1e-05	1.5e-06	6.7e-06
Cl-36	2.0e+00	2.3e-03	6.7e-05	1.5e+00	3.9e-01	4.5e-03	7.5e-05	5.3e-03
K-40	3.4e+00	6.5e-02	2.2e-03	1.8e+01	6.7e-01	1.3e-01	2.5e-03	6.4e-02
Ca-41	1.8e-01	9.5e-04	2.4e-05	6.1e-01	3.5e-02	1.9e-03	2.7e-05	2.2e-03
Ca-45	2.1e-03	2.5e-04	4.3e-06	1.0e-02	4.1e-04	4.8e-04	4.8e-06	3.6e-05
Sc-46	3.7e+01	9.1e-01	2.3e-02	1.7e+02	7.3e+00	1.8e+00	2.6e-02	5.9e-01
Cr-51	3.6e-01	7.9e-03	2.4e-04	1.8e+00	7.0e-02	1.5e-02	2.7e-04	6.3e-03
Mn-53	9.0e-04	6.3e-06	6.8e-07	1.6e-03	1.8e-04	1.2e-05	7.6e-07	5.6e-06
Mn-54	1.6e+01	4.2e-01	5.5e-02	8.0e+01	3.1e+00	8.2e-01	6.1e-02	2.8e-01
Fe-55	7.5e-04	6.0e-05	6.3e-06	4.2e-03	1.5e-04	1.2e-04	7.0e-06	1.5e-05
Fe-59	2.1e+01	4.3e-01	1.2e-02	8.9e+01	4.1e+00	8.3e-01	1.3e-02	3.2e-01
Co-56	6.7e+01	1.3e+00	4.7e-02	3.0e+02	1.3e+01	2.5e+00	5.2e-02	1.1e+00
Co-57	1.1e+00	1.5e-02	7.0e-03	7.4e+00	2.2e-01	2.8e-02	7.8e-03	2.6e-02
Co-58	1.7e+01	3.4e-01	1.2e-02	7.6e+01	3.3e+00	6.6e-01	1.4e-02	2.7e-01
Co-60	5.2e+01	1.1e+00	2.5e-01	2.7e+02	1.0e+01	2.1e+00	2.8e-01	9.7e-01
Ni-59	4.3e-04	1.9e-05	2.1e-06	2.2e-03	8.5e-05	3.6e-05	2.4e-06	7.9e-06
Ni-63	3.7e-04	3.4e-05	3.4e-06	2.0e-03	7.3e-05	6.6e-05	3.8e-06	7.0e-06
Zn-65	1.4e+01	2.7e-01	3.0e-02	5.6e+01	2.8e+00	5.2e-01	3.4e-02	2.0e-01
As-73	1.9e-02	1.4e-04	1.6e-05	1.0e-01	3.7e-03	2.7e-04	1.8e-05	3.7e-04
Se-75	5.5e+00	6.5e-02	1.0e-02	2.6e+01	1.1e+00	1.3e-01	1.1e-02	9.4e-02
Sr-85	7.6e+00	2.0e-01	5.1e-03	3.6e+01	1.5e+00	3.8e-01	5.7e-03	1.3e-01
Sr-89	6.2e-02	1.1e-03	2.9e-05	1.8e-01	1.2e-02	2.2e-03	3.2e-05	6.3e-04
Sr-90	4.2e-01	9.4e-03	1.9e-04	1.1e+00	8.8e-02	1.8e-02	2.1e-04	3.8e-03
Y-91	1.3e-01	3.0e-03	7.5e-05	4.5e-01	2.6e-02	5.8e-03	8.4e-05	1.6e-03
Zr-93	2.9e-03	5.3e-04	9.0e-06	4.6e-03	5.7e-04	1.0e-03	1.0e-05	1.6e-05
Zr-95	1.5e+01	4.3e-01	1.1e-02	8.1e+01	2.9e+00	8.4e-01	1.2e-02	2.9e-01
Nb-93m	6.2e-04	8.1e-05	2.7e-06	2.8e-03	1.2e-04	1.6e-04	3.1e-06	9.9e-06
Nb-94	3.0e+01	8.4e-01	1.9e-01	1.6e+02	5.9e+00	1.6e+00	2.1e-01	5.8e-01
Nb-95	1.2e+01	2.7e-01	7.0e-03	5.1e+01	2.4e+00	5.2e-01	7.8e-03	1.8e-01
Mo-93	1.9e-01	1.2e-03	5.2e-05	9.0e-01	3.8e-02	2.4e-03	5.8e-05	3.2e-03
Tc-97	3.3e-01	2.0e-03	5.3e-05	1.3e+00	6.6e-02	3.9e-03	6.0e-05	4.6e-03
Tc-97m	3.6e-03	2.8e-04	6.4e-06	2.8e-02	7.2e-04	5.3e-04	7.1e-06	9.9e-05
Tc-99	3.1e+00	1.9e-02	5.0e-04	1.2e+01	6.2e-01	3.6e-02	5.6e-04	4.3e-02
Ru-103	7.1e+00	1.1e-01	4.5e-03	3.3e+01	1.4e+00	2.2e-01	5.0e-03	1.2e-01
Ru-106	4.1e+00	7.8e-02	1.9e-02	2.1e+01	8.2e-01	1.5e-01	2.1e-02	7.4e-02

Table 2.2 Normalized effective doses to critical groups for all materials

Radionuclide	Mass-based ( $\mu\text{Sv/y}$ per Bq/g)				Surficial ( $\mu\text{Sv/y}$ per Bq/cm <sup>2</sup> )			
	Steel	Copper	Aluminum	Concrete	Steel	Copper	Aluminum	Concrete
Ag-108m	2.9e+01	5.4e-01	2.3e-01	1.6e+02	5.7e+00	1.1e+00	2.6e-01	5.8e-01
Ag-110m	5.2e+01	9.6e-01	1.7e-01	2.6e+02	1.0e+01	1.9e+00	1.9e-01	9.3e-01
Cd-109	5.5e-02	8.0e-04	2.0e-04	3.9e-01	1.1e-02	1.6e-03	2.2e-04	1.4e-03
Sn-113	3.7e+00	8.8e-02	6.4e-03	2.0e+01	7.4e-01	1.7e-01	7.2e-03	7.0e-02
Sb-124	3.3e+01	5.7e-01	2.0e-02	1.5e+02	6.6e+00	1.1e+00	2.2e-02	5.2e-01
Sb-125	7.0e+00	1.5e-01	3.9e-02	4.0e+01	1.4e+00	3.0e-01	4.3e-02	1.4e-01
Te-123m	1.4e+00	1.3e-02	3.4e-03	8.2e+00	2.7e-01	2.6e-02	3.8e-03	2.9e-02
Te-127m	9.7e-02	1.5e-03	1.2e-04	4.6e-01	1.9e-02	2.9e-03	1.4e-04	1.6e-03
I-125	1.0e+00	2.0e-03	6.3e-05	3.1e-01	2.0e-01	3.8e-03	7.0e-05	1.1e-03
I-129	3.3e+02	5.9e-01	1.8e-02	4.3e+02	6.4e+01	1.2e+00	2.0e-02	1.5e+00
I-131	3.4e+00	3.6e-02	1.2e-03	1.0e+01	6.7e-01	6.9e-02	1.3e-03	3.6e-02
Cs-134	4.1e+01	5.4e-01	2.0e-02	1.5e+02	8.0e+00	1.1e+00	2.2e-02	5.5e-01
Cs-135	8.6e-03	8.4e-05	6.6e-06	2.7e-02	1.8e-03	1.6e-04	7.4e-06	9.8e-05
Cs-137	1.5e+01	2.0e-01	7.4e-03	5.7e+01	3.0e+00	3.8e-01	8.2e-03	2.0e-01
Ba-133	4.9e+00	1.5e-01	4.2e-03	3.2e+01	9.6e-01	2.9e-01	4.7e-03	1.2e-01
Ce-139	1.4e+00	2.8e-02	1.2e-03	8.6e+00	2.8e-01	5.4e-02	1.3e-03	3.1e-02
Ce-141	6.5e-01	8.9e-03	4.4e-04	3.2e+00	1.3e-01	1.7e-02	4.9e-04	1.1e-02
Ce-144	9.9e-01	2.5e-02	6.9e-04	5.4e+00	2.0e-01	4.8e-02	7.7e-04	1.9e-02
Pm-147	1.7e-03	2.7e-04	4.7e-06	4.4e-03	3.3e-04	5.2e-04	5.3e-06	1.6e-05
Sm-151	1.1e-03	2.1e-04	3.4e-06	1.7e-03	2.2e-04	4.0e-04	3.8e-06	6.0e-06
Eu-152	2.2e+01	5.9e-01	1.5e-02	1.2e+02	4.3e+00	1.1e+00	1.7e-02	4.2e-01
Eu-154	2.1e+01	5.8e-01	1.5e-02	1.3e+02	4.2e+00	1.1e+00	1.6e-02	4.6e-01
Eu-155	4.0e-01	5.6e-03	3.4e-04	2.9e+00	7.8e-02	1.1e-02	3.8e-04	1.0e-02
Gd-153	5.2e-01	6.4e-03	4.2e-04	3.4e+00	1.0e-01	1.2e-02	4.7e-04	1.2e-02
Tb-160	1.9e+01	4.7e-01	1.2e-02	8.8e+01	3.8e+00	9.2e-01	1.4e-02	3.2e-01
Tm-170	3.4e-02	9.1e-04	3.0e-05	2.1e-01	6.7e-03	1.8e-03	3.4e-05	7.6e-04
Tm-171	2.3e-03	1.0e-04	3.1e-06	1.7e-02	4.5e-04	2.0e-04	3.4e-06	6.1e-05
Ta-182	2.3e+01	5.7e-01	2.6e-02	1.1e+02	4.6e+00	1.1e+00	2.9e-02	3.8e-01
W-181	1.6e-01	1.4e-03	2.9e-04	9.4e-01	3.1e-02	2.7e-03	3.3e-04	3.3e-03
W-185	2.0e-03	7.8e-05	2.1e-06	9.8e-03	4.0e-04	1.5e-04	2.3e-06	3.5e-05
Os-185	1.3e+01	2.0e-01	1.1e-02	5.3e+01	2.6e+00	3.8e-01	1.3e-02	1.9e-01
Ir-192	1.1e+01	1.9e-01	1.0e-02	5.8e+01	2.2e+00	3.6e-01	1.2e-02	2.1e-01
Tl-204	1.2e-02	2.0e-04	9.8e-05	7.8e-02	2.4e-03	3.9e-04	1.1e-04	2.8e-04
Pb-210	6.3e+00	2.4e-01	1.8e-02	1.2e+01	1.2e+00	4.6e-01	2.0e-02	4.3e-02
Bi-207	4.0e+01	5.5e-01	1.5e-01	1.6e+02	7.9e+00	1.1e+00	1.7e-01	5.6e-01
Po-210	2.5e+00	3.7e-02	3.0e-03	3.1e+00	4.9e-01	7.2e-02	3.3e-03	1.1e-02
Ra-226	3.5e+01	1.1e+00	2.7e-02	1.9e+02	6.9e+00	2.1e+00	3.0e-02	6.8e-01
Ra-228	1.9e+01	7.3e-01	1.6e-02	1.1e+02	3.7e+00	1.4e+00	1.8e-02	4.0e-01
Ac-227	2.8e+01	5.1e+00	7.7e-02	5.6e+01	5.4e+00	9.8e+00	8.5e-02	2.0e-01

Table 2.2 Normalized effective doses to critical groups for all materials

Radionuclide	Mass-based ( $\mu\text{Sv/y}$ per Bq/g)				Surficial ( $\mu\text{Sv/y}$ per Bq/cm <sup>2</sup> )			
	Steel	Copper	Aluminum	Concrete	Steel	Copper	Aluminum	Concrete
Th-228	3.7e+01	3.3e+00	4.8e-02	1.7e+02	7.3e+00	6.3e+00	5.3e-02	6.0e-01
Th-229	3.2e+01	4.8e+00	1.0e-01	4.3e+01	6.4e+00	9.2e+00	1.1e-01	1.5e-01
Th-230	1.0e+01	5.5e-01	3.5e-02	7.3e+00	2.0e+00	1.1e+00	3.9e-02	2.6e-02
Th-232	1.1e+01	9.9e-01	3.7e-02	3.3e+01	2.1e+00	1.9e+00	4.1e-02	1.2e-01
Pa-231	3.3e+01	1.4e+00	1.1e-01	2.6e+01	6.6e+00	2.8e+00	1.3e-01	9.4e-02
U-232	1.4e+01	2.0e+00	3.2e-02	2.9e+01	2.7e+00	3.9e+00	3.5e-02	1.0e-01
U-233	5.9e+00	5.2e-01	7.6e-03	2.0e+01	1.2e+00	1.0e+00	8.4e-03	6.9e-02
U-234	4.2e+00	5.1e-01	7.4e-03	1.5e+01	8.1e-01	9.9e-01	8.2e-03	5.2e-02
U-235	5.1e+00	5.1e-01	8.4e-03	1.7e+01	9.9e-01	9.9e-01	9.3e-03	6.0e-02
U-236	3.8e+00	4.7e-01	6.9e-03	1.4e+01	7.5e-01	9.1e-01	7.7e-03	4.8e-02
U-238	3.9e+00	4.4e-01	6.7e-03	1.4e+01	7.7e-01	8.5e-01	7.5e-03	4.9e-02
Np-237	2.9e+01	1.2e+00	2.1e-02	9.9e+01	5.8e+00	2.4e+00	2.3e-02	3.5e-01
Pu-236	4.5e+00	6.3e-01	1.5e-02	3.2e+00	9.0e-01	1.2e+00	1.7e-02	1.2e-02
Pu-238	1.1e+01	8.5e-01	3.7e-02	7.9e+00	2.2e+00	1.7e+00	4.2e-02	2.8e-02
Pu-239	1.2e+01	6.5e-01	4.1e-02	8.5e+00	2.4e+00	1.3e+00	4.6e-02	3.0e-02
Pu-240	1.2e+01	6.5e-01	4.1e-02	8.5e+00	2.4e+00	1.3e+00	4.6e-02	3.0e-02
Pu-241	2.2e-01	9.4e-03	7.4e-04	1.6e-01	4.3e-02	1.8e-02	8.2e-04	5.6e-04
Pu-242	1.1e+01	6.1e-01	3.8e-02	8.2e+00	2.2e+00	1.2e+00	4.3e-02	2.9e-02
Pu-244	1.7e+01	7.5e-01	4.2e-02	3.9e+01	3.4e+00	1.5e+00	4.7e-02	1.4e-01
Am-241	1.1e+01	2.1e+00	3.4e-02	7.5e+00	2.1e+00	4.0e+00	3.8e-02	2.7e-02
Am-242m	1.1e+01	2.1e+00	3.4e-02	8.0e+00	2.1e+00	4.1e+00	3.8e-02	2.8e-02
Am-243	1.2e+01	2.1e+00	3.6e-02	2.0e+01	2.3e+00	4.1e+00	4.0e-02	7.1e-02
Cm-242	1.3e+00	2.5e-01	3.8e-03	7.2e-01	2.5e-01	4.9e-01	4.3e-03	2.6e-03
Cm-243	8.6e+00	1.6e+00	2.6e-02	1.3e+01	1.7e+00	3.0e+00	2.9e-02	4.8e-02
Cm-244	6.6e+00	1.3e+00	2.2e-02	4.3e+00	1.3e+00	2.5e+00	2.4e-02	1.5e-02
Cm-245	1.1e+01	2.1e+00	3.6e-02	1.2e+01	2.2e+00	4.0e+00	4.0e-02	4.4e-02
Cm-246	1.1e+01	2.1e+00	3.5e-02	7.1e+00	2.1e+00	4.0e+00	3.9e-02	2.5e-02
Cm-247	1.4e+01	2.0e+00	3.5e-02	3.4e+01	2.8e+00	4.0e+00	3.9e-02	1.2e-01
Cm-248	3.8e+01	7.2e+00	1.2e-01	2.6e+01	7.4e+00	1.4e+01	1.4e-01	9.1e-02
Bk-249	4.3e-02	7.7e-03	1.3e-04	3.1e-02	8.4e-03	1.5e-02	1.5e-04	1.1e-04
Cf-248	2.2e+00	4.4e-01	6.8e-03	1.3e+00	4.4e-01	8.6e-01	7.6e-03	4.8e-03
Cf-249	2.2e+01	3.8e+00	6.1e-02	3.9e+01	4.3e+00	6.9e+00	6.8e-02	1.4e-01
Cf-250	8.6e+00	1.7e+00	2.8e-02	5.7e+00	1.7e+00	3.2e+00	3.1e-02	2.0e-02
Cf-251	1.9e+01	3.5e+00	5.9e-02	1.9e+01	3.7e+00	6.8e+00	6.6e-02	6.8e-02
Cf-252	5.0e+00	9.7e-01	1.5e-02	3.3e+00	9.8e-01	1.9e+00	1.7e-02	1.2e-02
Cf-254	3.2e+02	8.7e+00	2.2e-01	1.4e+03	6.2e+01	1.7e+01	2.4e-01	4.9e+00
Es-254	1.9e+01	8.9e-01	1.8e-02	8.6e+01	3.8e+00	1.7e+00	2.0e-02	3.1e-01

Note: To convert these values to conventional units (mrem/y per pCi/g or mrem/y per pCi/cm<sup>2</sup>), multiply by 0.0037

### 3 RECYCLING AND DISPOSAL OF STEEL SCRAP

*Assessments have been performed of the potential radiation doses to individuals from the recycling or disposal of iron and steel scrap that could be cleared from nuclear facilities. The assessment addresses 37 scenarios that depict exposures resulting from the handling and processing of cleared scrap and the products of melting and refining this scrap at steel mills and foundries, emission of airborne effluents from these facilities, transportation of scrap and furnace products, the use of these products, the landfill disposal of cleared scrap and furnace by-products, and the infiltration of well water by leachate from landfills and storage piles containing cleared scrap or furnace by-products. The analysis utilizes data on ferrous metal recycling, as currently practiced in the United States, and on contemporary U.S. work practices and living habits.*

*The mean doses to the groups of exposed individuals characterized by 30 of these scenarios are ranked to determine the critical groups for each radionuclide. Seven scenarios—describing exposures to iron and steel products produced from the single furnace heat during one year that contains the maximum fraction of cleared scrap—are not included in the ranking.*

*The critical group for the largest number of radionuclides, accounting for over one-third of the 115 radionuclides in the analysis, consists of workers processing scrap at a scrap yard.*

*Mean values of mass-based normalized EDEs to critical groups range from a high of 330  $\mu\text{Sv/y}$  per Bq/g (1.2 mrem/y per pCi/g) from Cf-254 to a low of  $3.7\text{e-}4$   $\mu\text{Sv/y}$  per Bq/g ( $1.4\text{e-}6$  mrem/y per pCi/g) from S-35. The corresponding surficial EDEs are 65 and  $7.4\text{e-}5$   $\mu\text{Sv/y}$  per Bq/cm<sup>2</sup>, respectively. The critical groups for both nuclides are the scrap yard workers. Mean values of mass-based normalized effective doses range from a high of 330  $\mu\text{Sv/y}$  per Bq/g (1.2 mrem/y per pCi/g) from I-129 to a low of  $3.7\text{e-}4$   $\mu\text{Sv/y}$  per Bq/g ( $1.4\text{e-}6$  mrem/y per pCi/g) from Ni-63. The corresponding surficial effective doses are 64 and  $7.3\text{e-}5$   $\mu\text{Sv/y}$  per Bq/cm<sup>2</sup>, respectively. The critical group for I-129 is the individuals drinking water from wells down gradient from a pile of steel slag, while that for Ni-63 is the scrap yard workers.*

This chapter describes the radiological assessment of the recycling and disposal of iron and steel scrap that could be cleared from NRC- or Agreement State-licensed facilities.<sup>1</sup> The model created for this analysis is based on some of the steps that would most likely be involved in recycling such scrap into consumer or industrial products, or in disposing of this scrap in an industrial or municipal landfill.

#### 3.1 Introduction to Analysis

The assessment of the potential doses from cleared ferrous metal scrap<sup>2</sup> consists of two main parts. The first step is characterizing the flow of cleared scrap through the normal recycling process, beginning with the generation of scrap, through melting and refining, manufacturing, and product use, as well as disposal as an alternative to recycling. This enables the calculation

<sup>1</sup> Throughout this report, the terms "NRC-licensed facility", "licensed facility", "nuclear facility," and "licensee," unless otherwise qualified, refer to NRC- or Agreement State-licensed facilities.

<sup>2</sup> As will be described later in this chapter, the major constituent of the ferrous metal scrap from NRC-licensed facilities consists of carbon steel. In the remainder of this report, the term "steel scrap," unless otherwise qualified, refers to the various types of ferrous metal scrap.

of concentrations of the various radionuclides in the products and by-products of the melting and refining of steel scrap, normalized to an initial unit specific activity (Bq/g) or unit areal activity concentration (Bq/cm<sup>2</sup>).

The second step is the development and analysis of exposure scenarios. The general approach to the development of exposure scenarios is discussed in Section 1.2. The implementation of this approach in the assessment of cleared steel scrap is described in the following sections.

### 3.1.1 Approach to Scenario Development

A number of previous assessments have been conducted to quantify the potential radiation exposures of individual members of the public to the recycling of residually radioactive materials. In general, these assessments have been based on the formulation and evaluation of fairly specific scenarios that describe hypothetical situations in which individuals might be exposed to residual radioactivity of reused or recycled materials. In order to be comprehensive, this approach requires identifying the entire range of potential scenarios and using professional judgment 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 recycling 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.

The specific approach has a number of limitations. 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 separate parameters are required to describe the scenarios. Finally, the data quality requirements for assigned values to these parameters make serious demands on the analytical resources available to this study. Each parameter must be researched, documented, and subjected to quality assurance procedures.

In contrast, a generic approach uses broadly defined scenarios that can represent 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," the other as "a 1000-kg" object—to represent different categories of consumer products.

The generic approach addresses some of the limitations of the specific scenario approach. By representing a range of situations, carefully chosen generic scenarios can address any situation of

interest that falls into that generic category. Furthermore, the number of detailed parameters can be minimized, along with the effort required to derive and defend the value assigned to each parameter.

The approach taken in this analysis is a combination of the specific and generic approaches. A number of 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.

### 3.1.2 Scenarios Characterizing the Recycling and Disposal of Cleared Steel Scrap

A large number of potential exposure scenarios for the recycling and disposal of steel scrap could be postulated. The design bases set for this study require that the scenarios be comprehensive, appropriate, and practical. *Comprehensive* means that the scenarios have to address the radiation exposures of individual members of potential critical groups. The scenarios have to be *appropriate* to actual practices in the recycling and disposal of steel scrap and to conditions of product use. Finally, the number of scenarios has to be *practical*, in that a manageable number of scenarios would encompass the radiation exposures of the critical groups. The situations that could result in higher doses, but that have a low probability of occurrence, or that postulate exposures of a small number of individuals, are excluded. The basis of exclusion is that a key design objective of the analysis is to evaluate the *likely* radiation exposure of the members of each critical group. Unlikely situations, or those that expose at most a handful of individuals, do not meet this criterion.

The approach to the present analysis is similar in some respects to that taken by Charles and Smith (1992), who evaluated the feasibility of different options for managing large volumes of very low-level radioactive waste. The management options included scenarios similar to those selected for the present study, including clearance followed by recycling and/or disposal of scrap metal, slag, and dust in landfills. The exposure scenarios used in their analysis were derived by adopting the various management options. The generic nature of their exposure scenarios is similar to that of some of the scenarios in the present analysis. A summary of scenarios used in previous studies is presented in Table 3.1.

The scenarios listed in Table 3.1 fall into two broad categories: the individuals who are exposed in the course of their occupation—"work-related" scenarios—and persons whose exposures are not related to their occupations—"non-work-related" scenarios.

### 3.2 Flow of Steel Scrap

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

**Table 3.1 Scenarios discussed in previous studies**

Work-related	Non-work-related
<ul style="list-style-type: none"> <li>• Decontamination and dismantling of concrete and steel structures and handling scrap generated during the process</li> <li>• Transport of scrap to recycling or disposal facility</li> <li>• Exposure to scrap piles</li> <li>• Repair of contaminated machinery</li> <li>• Operation of melter and subsequent processing</li> <li>• Building renovation or demolition</li> <li>• Landfill disposal (operation of facility or waste fires)</li> <li>• Reuse of large concrete masses (building renovation)</li> <li>• Reuse of contaminated slag in concrete manufacture, production/manufacture of end products</li> </ul>	<ul style="list-style-type: none"> <li>• Use of end products (i.e. frying pan, steel furniture, automobile, steel reinforcement in houses, large and small objects)</li> <li>• Melting and refining process (airborne effluents)</li> <li>• Slag in roadbeds, foundations of houses, use of contaminated slag in concrete</li> <li>• Landfill and sanitary disposal of waste products or contaminated scrap (leachate, inadvertent intrusion)</li> <li>• Incineration of contaminated scrap</li> <li>• Building occupancy by members of the public</li> <li>• Drinking water that contains radionuclides leached from surface soils</li> <li>• Residential (contaminated soil)</li> <li>• Shallow land disposal</li> <li>• Reuse of large concrete masses (building occupancy)</li> </ul>

Figure 3.1 presents a schematic diagram of the flow of steel scrap, as characterized in the present analysis. This diagram, which is a simplified idealization of the actual process, depicts the sequence of steps which are represented by the exposure scenarios. Intermediate steps, not represented by exposure scenarios, are indicated by dashed lines or boxes. Other steps and processes are discussed in the following sections of this chapter.

The process begins with the release of cleared scrap from an NRC-licensed facility. It is assumed that the scrap is shipped by truck<sup>3</sup> to a scrap yard operated by a scrap metal dealer. The processing performed by this dealer, which can vary with the grade (i.e., type or composition) of scrap, includes shearing or torch-cutting the metal to size, briquetting or crushing thin and lightweight materials (e.g., turnings and borings), and baling.<sup>4</sup> The scrap dealer then ships the

<sup>3</sup> Scrap and products and by-products of steel mills and foundries can also be shipped by rail or waterway.

<sup>4</sup> Ray Turner, The David J. Joseph Company, private communication with Robert Anigstein, SC&A, Inc., March, 2001.

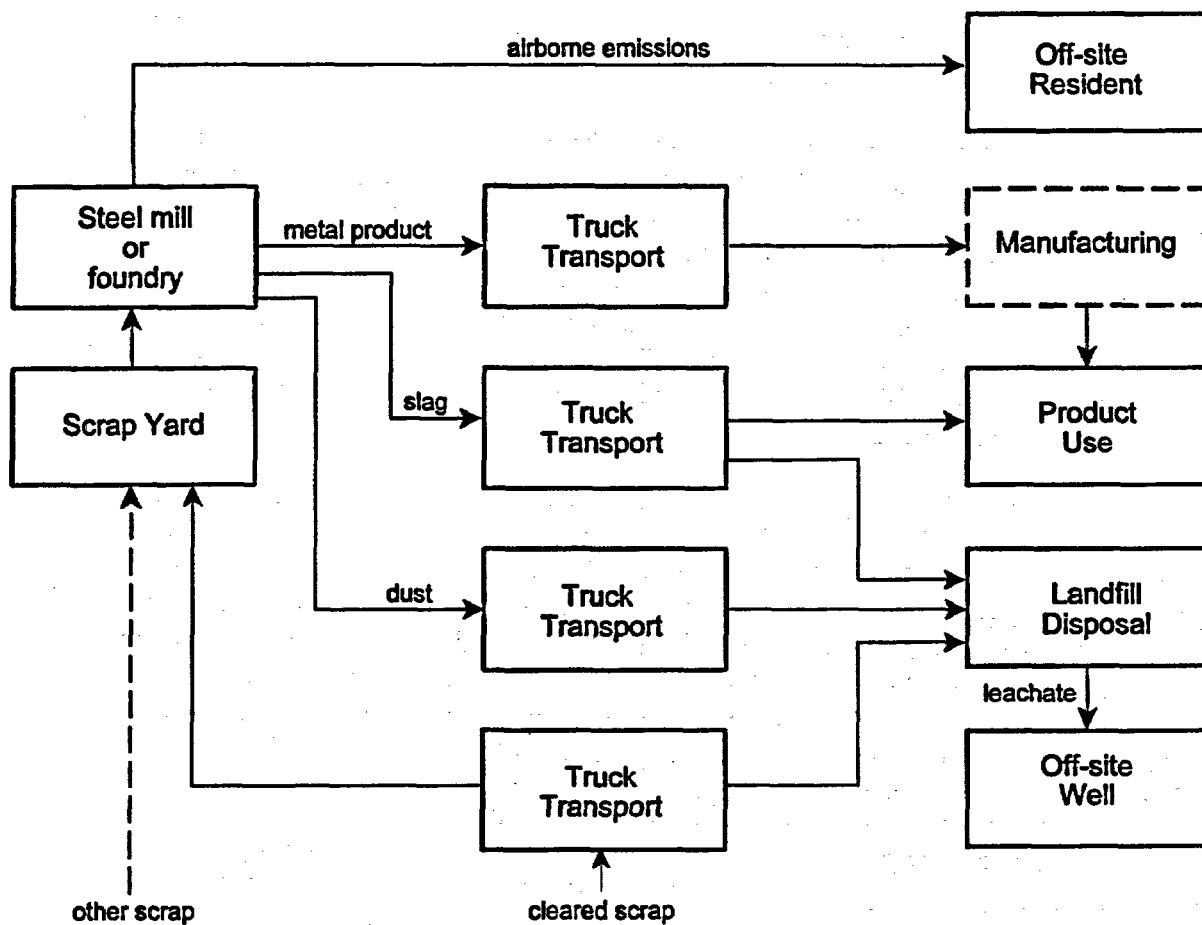


Figure 3.1 Flow of steel scrap

processed scrap to a melt shop,<sup>5</sup> where it may be stored for a time or immediately charged to a furnace.

Alternatively, the licensee or demolition contractor may elect to dispose of the scrap in an industrial or municipal solid waste (MSW) landfill.<sup>6</sup>

The U.S. iron and steel industry comprises three main types of facilities that consume steel scrap: basic oxygen furnaces (BOFs), which are components of integrated steel mills; electric

<sup>5</sup> The generic term "melt shop" is used throughout this chapter to refer to any facility where scrap metal is melted and refined into finished or semi-finished iron or steel products.

<sup>6</sup> Another alternative scenario is the processing of scrap at the nuclear facility. Such processing would most likely be performed by radiation workers whose occupational exposures are controlled under current regulations. This scenario is therefore outside the scope of the present study, which is limited to assessing the radiation exposures of members of the public.



arc furnaces (EAFs) used to make steel; and cupola furnaces, induction furnaces, and EAFs at iron and steel foundries. These facilities are discussed in greater detail later in this chapter.

During melting, the furnace charge separates into three different process streams: offgas, slag, and metal. Each of the process streams undergoes different treatment, use, and final disposal. The offgas includes gases, vapors, or particulates that evolve from the furnace. The vapors may form particulates when cooled. Most of the particulates are collected in baghouse filters or other air pollution control devices (APCDs). The gaseous effluents, as well as a fraction of the particulates that escape the APCD, are dispersed into the atmosphere.<sup>7</sup> Most basic oxygen furnace (BOF) dust and sludge is either landfilled directly or landfilled after recovery of metal values. Small amounts of the dust are recycled directly at the integrated steel mill and small amounts are used in cement.

Electric arc furnace (EAF) baghouse dust is a RCRA-listed<sup>8</sup> waste (K061), containing potentially hazardous elements such as lead, cadmium, and chromium. The disposal of this material must therefore conform to applicable EPA regulations. The dust could be disposed of directly in a RCRA Subpart C (hazardous waste) landfill; the dust could be stabilized by an EPA-approved process and disposed of as delisted waste in an industrial landfill (either on site or at a regional location); the dust could be processed for recovery of valuable metals; or the dust could be incorporated into fertilizer. 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. Processing of EAF dust at a generic disposal or treatment facility is addressed in the present analysis, as is landfill disposal following immobilization.<sup>9</sup> The EAF dust is typically transported in trucks operated by brokers licensed to handle hazardous waste. At either type of facility, the dust is typically unloaded in an enclosed building, where it is immediately placed in a bin and moistened with water for dust control.

Slag is a nonmetallic product resulting from the interaction of flux and impurities in the molten metal. Because slag is lighter than iron, it will float on top of the melt. After slag is removed from the furnace and cooled, it is stored in piles outdoors at the melt shop until it is either used by the mill or transported to a slag processor. Since the slag contains compounds such as calcium oxide, hydration of up to 10% can occur, limiting the use of steel slags, as compared to blast furnace slags. Steel slags can be used in applications such as railroad ballast or unconfined highway base and shoulders, where expansion from hydration will not pose a problem. Some BOF slag is used as an additive in cement kilns (American Iron and Steel Institute, as cited in Florida Steel Homes, Inc. 1998). Typically, steel slags are stored outdoors for six months or more to reduce the free lime content to levels where slag stability is acceptable. This also

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<sup>7</sup> Some small induction furnaces do not use an APCD, resulting in a total release of the offgas to the atmosphere.

<sup>8</sup> RCRA is the abbreviation for the Resource Conservation and Recovery Act, which regulates the land disposal of hazardous wastes.

<sup>9</sup> Processing of EAF dust is not shown in Figure 3.1.

provides adequate time for dicalcium silicate to expand to stable levels (Kalyoncu 2002). Alternatively, the slag is transported by truck<sup>10</sup> for disposal in a landfill.

The iron or steel produced by a melt shop is used in a virtually endless variety of products. The present analysis models exposures to three generic products as well as five specific products made from iron or steel.

### 3.2.1 Sources of Cleared Steel Scrap

The radiological assessment described in this chapter is limited to scrap steel cleared from NRC-licensed facilities. These include commercial nuclear power plants, test and research reactors, other fuel cycle facilities, and by-product material licensees. By far the largest single source of steel scrap cleared from NRC-licensed facilities would be the dismantling of a commercial nuclear power plant (see Section A.7). The scrap cleared during such dismantlement is therefore used as the source term for the present analysis. All commercial nuclear power plants currently licensed to operate in the United States employ light-water reactors which are of two types: boiling water reactors (BWRs) and pressurized water reactors (PWRs). Separate estimates of the masses of steel scrap that would be cleared during dismantlement have been made for the two types of power plants:

- BWR ..... 14,657 – 19,374 t<sup>11</sup>
- PWR ..... 19,754 – 23,592 t

A more detailed discussion of the estimated steel scrap from the Reference BWR is presented in Section A.2.3.5. The corresponding data on the Reference PWR is discussed in Section A.2.4.2.

Of the 104 nuclear power reactors currently licensed to operate in the United States, 35 are BWRs and 69 PWRs (NRC 2000). It is therefore assumed that there is a 33.7% probability that a reactor undergoing dismantlement at a particular time and place would be a BWR and a 66.3% probability that it would be a PWR.

According to a decommissioning analysis performed for the NRC by Pacific Northwest Laboratory (Konzek et al. 1995), the dismantlement of a PWR would take 1.7 years. Based on this information, we assume that the scrap generated during the dismantlement of either a BWR or PWR nuclear power station would be cleared and released at a uniform rate over a 1.7-year period.

As was discussed in Section 1.1, the first step in the assessment is to calculate mass-based normalized doses. For the purpose of that calculation, we assume that all cleared scrap will be

<sup>10</sup> See Footnote 3 on page 3-4.

<sup>11</sup> Throughout this chapter, metric tons (tonnes) are abbreviated as "t." The term "tons" refers to short tons (1 ton = 0.9072 t)

uniformly contaminated by one of the 115 radionuclides that are addressed in the present analysis. Long-lived nuclides with short-lived progeny (i.e., those with half-lives of less than six months) are assumed to be in secular equilibrium with these progenies at the time of clearance. (Radioactive decay chains and progeny ingrowth are discussed in detail in Appendix E.)

### 3.2.1.1 Secondary Recycling

The present analysis does not explicitly address secondary recycling: iron and steel products made from cleared scrap that are in turn recycled at the end of their useful lives. Such secondary recycling could, in theory, lead to a buildup of radioactivity in the metal pool. However, as discussed below, such buildup would not make a significant contribution to the doses to individual members of the various critical groups, which is the objective of the present analysis.

- Many of the radionuclides that would remain in the finished iron or steel products following melting and refining—especially the emitters of strong external radiation (i.e.,  $\gamma$ -rays)—have relatively short half-lives—approximately 5 years or less. Consequently, any buildup over a period of years would be partially offset by radioactive decay.
- It is conceivable (as assumed in the present analysis) that all the ferrous scrap cleared from a single licensed facility (e.g., a commercial nuclear power plant) would be consumed by a single steel mill or foundry. However, the finished steel products made with the recycled scrap would be distributed throughout the United States, as well as abroad. When these products reach the end of their useful lives, they will, in many cases, be recycled in turn. Because of the wide dispersal of these products, the secondary recycling would be distributed throughout the iron and steel industry, both here and abroad.
- Not all of the products made from cleared scrap would be recycled domestically, because: (1) some of the products would be sold abroad, (2) some of the products would be discarded rather than recycled, and (3) some of the scrap generated from the discarded products would be exported.<sup>12</sup>
- The total amount of steel scrap that could be cleared by NRC-licensed facilities over the next 50 years is about 2.4 Mt; therefore, about 48 kt would be cleared in an average year (see Section A.7). Let us assume that: (1) all this scrap is initially recycled and (2) a fraction<sup>13</sup> of the spent products made from this recycled scrap enters the U.S. pool of secondary ferrous metals. Simultaneously, about 51 Mt of virgin metal, in the form of pig iron and direct reduced iron (DRI),<sup>14</sup> is produced each year. Eventually, through recycling, a similar

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<sup>12</sup> For example, about 74 Mt of ferrous scrap were consumed in 2000 and 5.8 Mt were exported (Fenton 2002).

<sup>13</sup> The steel scrap recycle rate for 2000 has been estimated to be 64% (Fenton 2002).

<sup>14</sup> Direct reduced iron is produced by reacting lumps or pellets of iron oxide in a shaft furnace with natural gas to produce metallic iron. Unlike in the blast furnace, reduction occurs in the solid state.

fraction of this metal also enters the secondary metals pool. Thus, the 48 kt of cleared scrap is offset by 51 Mt of virgin metal, a dilution of 1:1,000.

- The buildup from secondary recycling of products made from cleared scrap would thus comprise at most 0.1% of the initial specific activity of this scrap—this assumes no radioactive decay, steady state conditions, and an indefinitely long period of time to achieve equilibrium (i.e., several times the average life of recyclable steel products). By comparison, the average mixing of cleared scrap at a single iron- or steelmaking facility in the present analysis is calculated to be approximately 6%. Consequently, even if radioactive decay were neglected, secondary recycling could contribute, at some future time, an additional 1.6% ( $0.1 + 6 = 0.016$ ) to the radionuclide concentration in finished products, as modeled by the present analysis. Given the uncertainty in the other parameters, this would make an insignificant contribution to the calculated doses to individual members of the potential critical groups.

The potential long-term buildup of radioactivity in the steel pool would thus make no significant impact to individual doses, and is therefore outside the scope of the present analysis.

### 3.2.2 Recycling of Steel Scrap

Three significant sources of ferrous metals are used in the production of steel and cast iron: pig iron, DRI, and scrap. Pig iron is produced in a blast furnace where the primary source of iron units is iron ore supplemented with small amounts of scrap and DRI (Fenton 2002). Feedstock to produce wrought steel products is melted either in an EAF, where the bulk of the furnace charge is scrap, or in a BOF, where about one-fourth of the furnace charge is ferrous scrap and the balance is pig iron. Cast iron and steel are produced in small EAFs, cupolas, or induction furnaces, where the bulk of the furnace charge is scrap.

A total of 74 Mt ( $8.2 \times 10^7$  tons) of iron and steel scrap was consumed in the United States in 2000. Of this total, 15 Mt was consumed during the making of steel in BOFs, 43 Mt was consumed in steelmaking in EAFs, and the balance was consumed in blast furnaces producing pig iron and in furnaces producing iron and steel castings (Fenton 2002).

There are three types of scrap metal used in the steelmaking industry: home, new, and old. *Home scrap* consists of unusable metal produced during the processing or fabrication of steel at the mill into a suitable intermediate product. Even though home scrap is produced at the steel mill or foundry, it is considered a secondary metal, in contrast to processed raw material—i.e., pig iron. *New scrap* (or prompt scrap) is produced during manufacture of end products. New scrap is high-grade metal with very few impurities. *Old scrap* includes obsolete, worn-out or broken products that have been used by consumers or by industry. Approximately 44% of the scrap recycled in 2000 was obsolete or old scrap (USGS 2001). Old scrap is usually lower quality metal, and its chemical composition may not be well known. Scrap metal cleared from a licensed facility that is to be recycled would enter the pool of old scrap.

Scrap is not completely interchangeable among the various types of melting furnaces. BOFs tend to use heavier grades of scrap (e.g., shredded scrap is typically not used), tend to use more prompt scrap, and tend to use higher grades of purchased scrap. However, the types of scrap that would be generated by the dismantling of nuclear power plants (primarily rebar, structural steel, and pipe hangers) would be reasonably interchangeable and are so treated in this analysis.

### 3.2.3 Iron- and Steelmaking

Figure 3.2 shows some of the steps in the melting and refining of steel scrap. It is presented for purposes of illustration, and does not represent all of the steps in the flow of steel scrap that is modeled in the present analysis. Foundry operations are not shown in this figure, but they would be similar to the BOF and EAF illustrated.

Steel is produced either at *integrated* steel mills where molten iron (hot metal), generated in a blast furnace by the reduction of iron ore, is refined into steel in a BOF, or at *non-integrated* mills that use EAFs to melt furnace charges largely comprised of scrap.

Together, integrated and non-integrated mills consumed a total of approximately 59 Mt of steel scrap,<sup>15</sup> and produced a total of 102 Mt of raw steel in 2000 (Fenton 2002, Fenton n/d). This included 92.5 Mt of carbon steel, 2.19 Mt of stainless steel and 7.5 Mt of other alloy steel. Net shipments of steel mill products were 98.9 Mt. In addition, iron and steel foundries consumed 15.2 Mt of scrap and shipped 10.6 Mt of iron and steel castings.

#### 3.2.3.1 Integrated Steel Mills

Integrated steel mills produce pig iron in blast furnaces and refine this pig iron to finished steel in basic oxygen furnaces. The basic oxygen process for steelmaking involves blowing oxygen into the molten steel bath, contained in a refractory-lined vessel, to decrease the amount of oxidizable impurities to desired levels. In 2000, BOFs were used by integrated steel makers to produce 54 Mt of steel in the United States. At that time the integrated steel industry comprised 13 companies operating in 19 locations (Fenton n/d). An earlier survey of BOFs ("1991 Guide to North American Steel Industry" 1991) listed 59 furnaces operated by 16 companies in 26 locations in the United States, while in a more recent report, EPA (2001a) lists 50 BOFs operating at 20 locations. All integrated steel producers operate blast furnaces, which supply about three-fourths of the total metal requirement for the BOFs, and several operate sinter plants, which process waste and by-product materials for recycling into the blast furnaces. A listing of current integrated steel makers and their capabilities is included in Table 3.2.

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<sup>15</sup> The scrap consumed was comprised of 45 Mt of purchased scrap and 14 Mt of home scrap.

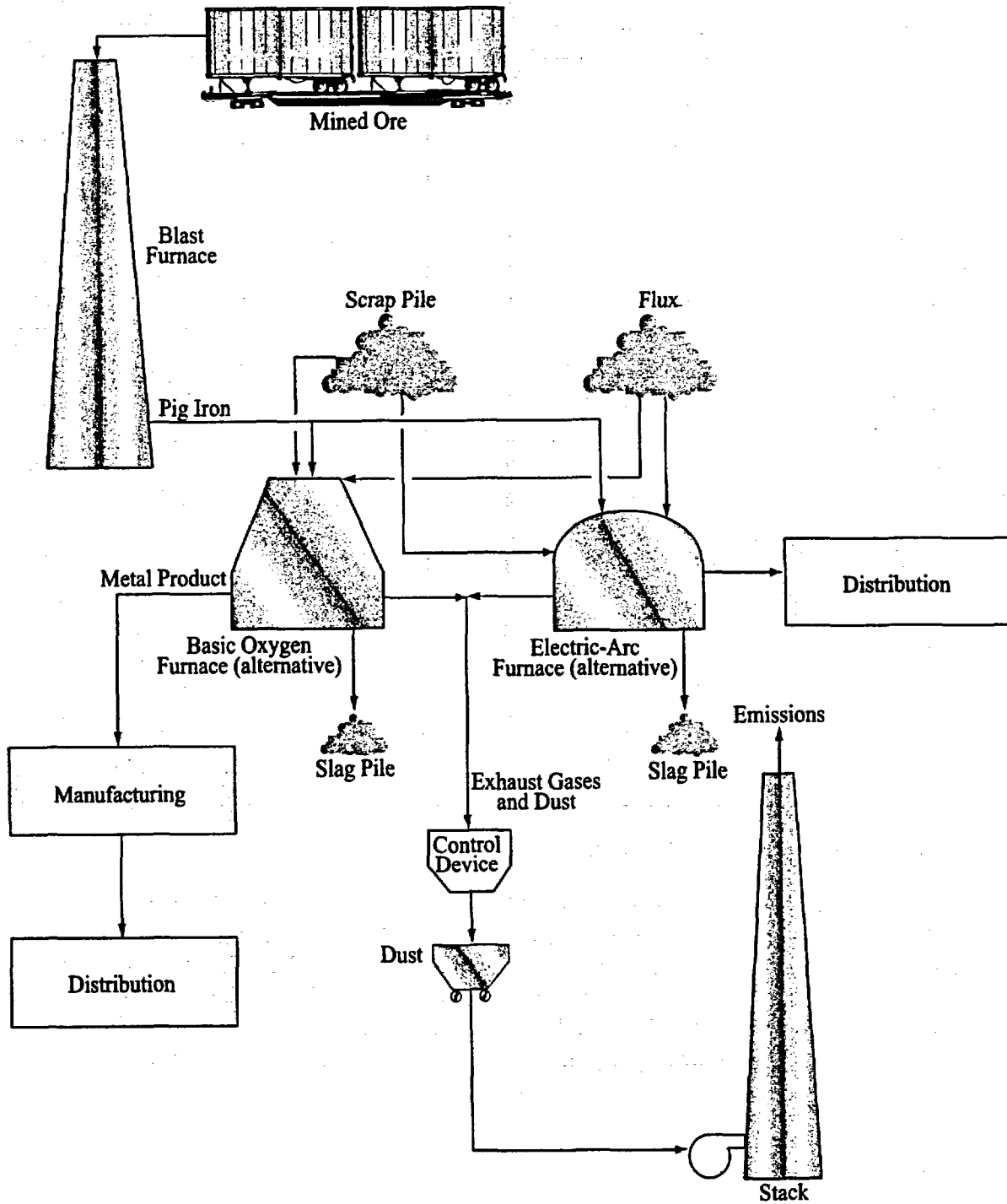


Figure 3.2 Examples of steelmaking processes

Table 3.2 Integrated iron and steel mills

Company	Location	BOF Shops		Blast Furnaces	Sinter Plants	Capacity <sup>a</sup>	
		Vessels	Shops			tons/y	kt/y
Acme Steel	Riverdale, IL	2	1	1		1,290,000	1,170
AK Steel	Ashland, KY	2	1	1		2,168,000	1,967
AK Steel	Middletown, OH	2	1	1	1	2,716,000	2,464
Bethlehem Steel	Burns Harbor, IN	3	1	2	1	5,354,000	4,857
Bethlehem Steel	Sparrows Point, MD	2	1	1	1	4,000,000	3,629
Geneva Steel	Orem, UT	2	1	3	1	2,500,000	2,268
Gulf States Steel	Gadsden, AL	2	1	1		1,300,000	1,179
Inland Steel	East Chicago, IN	4	2	3	1	5,240,000	4,754
LTV Steel	Cleveland, OH	4	2	3		7,720,000	7,004
LTV Steel	East Chicago, IN	2	1	2	1	4,161,000	3,775
National Steel	Granite City, IL	2	1	2		2,575,000	2,336
National Steel	Ecorse, MI	2	1	3		4,100,000	3,720
Rouge Steel	Dearborn, MI	2	1	2		3,309,000	3,002
USX	Braddock, PA	2	1	2		2,760,000	2,504
USX	Fairfield, AL	3	1	1		2,200,000	1,996
USX	Gary, IN	6	2	4	1	6,927,000	6,284
USS/Kobe Steel	Lorain, OH	2	1	2		2,600,000	2,359
WCI Steel	Warren, OH	2	1	1		1,728,000	1,568
	Youngstown, OH				1	—	—
Weirton Steel	Weirton, WV	2	1	2		3,200,000	2,903
	Mingo Junction, OH	2	1	2		2,600,000	2,359
Wheeling-Pittsburgh Steel	Follansbee, WV				1	—	—
<b>Total</b>		<b>50</b>	<b>23</b>	<b>39</b>	<b>9</b>	<b>68,448,000</b>	<b>62,096</b>

Source: EPA 2001a

<sup>a</sup> Production capacity (tons of steel poured per year)

At a typical BOF, a 220-t heat is poured every 45 minutes. BOF shops usually obtain 20% to 35% of the metal charge from scrap (Fruehan 1998).<sup>16</sup> Based on the nominal heat size and the reported annual furnace capacity in the 1991 survey, the average number of heats per year was calculated to be 5,609 with a range of 3,000 to 7,500. The average heat size was calculated to be 215 tons with a range from 80 to 360 tons. Using annual capacities from the more recent EPA report, the average number of heats per year was estimated to be 6,023 with a range from 3,667 to 9,955 (EPA 2001a).

<sup>16</sup> Twenty-six percent to 29% of the charge at Bethlehem Steel's Sparrows Point Plant is scrap and from 38% to 48% of the total scrap charge is home scrap (Timothy W. Miller, Supervisor, Coke, Iron and Steelmaking Research, Bethlehem Steel Corporation, private communication with Kathleen Behling, SC&A, Inc., September 26, 2001). Factors affecting the variability in these parameters include product demand, product mix, and costs of scrap and blast furnace hot metal. Sparrows Point is believed to be fairly typical of the integrated steel industry.

A representative BOF material balance shows that a heat consisting of 878 kg of hot metal, 202 kg of scrap, and 17 kg of iron ore will produce 1,000 kg of steel (Fruehan 1998, Table 9.8). One source estimates that about 24% of the scrap charge is internally generated scrap: home scrap (scrap from current operations that recirculates within the melt shop) plus obsolete scrap from on-site dismantling (SRI 2001). Fenton (2002) quotes 24% as the average fraction of scrap in the furnace charge. If we assume that the small amount of iron ore in the charge is FeO, about 91% of the metal charged would be recovered as raw steel.

During the oxygen blow (used to adjust the melt chemistry), elements such as Cu, Mo, Sn, and Ni cannot be oxidized and are thus not removed from the metal. Elements such as Al, Si, and Zr are fully oxidized and become incorporated in the slag. Elements such as Mn, P, and Cr are distributed between the metal and the slag. Zinc and Pb are mostly removed from the bath as vapor (Fruehan 1998).

After tapping the molten metal, the slag remaining in the furnace is either dumped into a slag pot or is splashed on the walls of the furnace to extend liner life (Fruehan 1998). This slag splashing, which is practiced by 40 to 50% of the North American BOF melt shops, involves 5% to 20% of the slag generated during a heat. However, this temporary coating lasts only one to two heats, so the net effect is that all the slag is removed from the furnace after a few successive heats.<sup>17</sup>

BOF slag is composed of calcium silicates and ferrites combined with fused oxides of iron aluminum, manganese, calcium, and magnesium. A typical slag composition (in wt %), assuming all compounds are present as oxides, is given by Fruehan (1998):

CaO .....	47.9
SiO <sub>2</sub> .....	12.0
MgO .....	6.30
FeO .....	26.4
MnO .....	5.00
P <sub>2</sub> O <sub>5</sub> .....	1.10
Al <sub>2</sub> O <sub>3</sub> .....	1.30

Slag is removed from the furnace, cooled, and processed to recover the high metallic portions (which are rich in iron and manganese). These are used as a source of metallics in sinter plants or as a flux in blast furnaces. The remaining non-ferrous fraction is crushed and sized for reuse within the steel mill, sold as a by-product, or disposed of in a landfill (AISI 1998, Chapter 4). Although some slag may be recycled into the steelmaking operation, internal recycling has been decreasing as the demand for higher quality steel has increased. A steel industry source has estimated that 30% to 40% of the slag is recycled back to the sinter plant and the blast furnace, the balance being landfilled.<sup>17</sup> At some shops, 100% of the slag is landfilled.

<sup>17</sup> Timothy W. Miller, Supervisor, Coke, Iron and Steelmaking Research, Bethlehem Steel Corporation, private communication with Kathleen Behling, SC&A, Inc., September 6, 2001.



The slag output of a BOF ranges from 100 to 440 lb per ton of steel (50 to 220 kg/t), averaging about 240 lb per ton (120 kg/t) (AISI 1998, Chapter 4). The amount of slag varies with the amount of silicon in the hot metal from the blast furnace which feeds the BOF.<sup>17</sup> The average value of 240 lb per ton is in close agreement with the typical value of 200 lb per ton (100 kg/t) quoted by Fruehan (1998, Table 9.8), and is identical to the value quoted elsewhere in that reference (Section 9.7.4.1). Since BOFs produced 54 Mt in 2000, the total amount of slag generated in that year is estimated to be about 6.5 Mt ( 54 Mt steel  $\times$  0.12 = 6.5 Mt).

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. A limited number of BOF shops use electrostatic precipitators (ESP), which produce a "filter cake" containing 7% to 10% moisture. Most shops use venturi scrubbers, which produce sludges containing 40% to 90% moisture. From the venturi scrubbers, the fine particulates entrained in the waste water stream are sent to thickener/flocculation tanks for settling and solids removal. The underflow slurry from the thickener can be dewatered by mechanical filtration (AISI 1998, Chapter 4).

Trace hazardous air pollutants found in the BOF offgas include Cd, Cr, Ni, Pb, Mn, and Zn (Fruehan 1998). A slightly different list was quoted by EPA (2001b) in the proposed NESHAP for integrated iron- and steelmaking. EPA states that hazardous air pollutants emitted as particulate matter include Sb, As, Be, Cd, Cr, Co, Hg, Ni, Mn, Pb and Se, with Mn and Pb being the primary elements of concern. The compositions of fume from a top-blown BOF and bottom-blown BOF (Q-BOP) are listed in Table 3.3.

AISI (1998, Chapter 4) estimates that between 8 and 62 lb of dust and sludge are produced per ton of raw steel (4 – 31 kg/t), with 36 lb per ton (18 kg/t) being the average. Fruehan notes that fugitive emissions from a well-designed filtering system in a BOF shop are 0.158 lb/ton (79 g/t) of steel, which implies 99.4% removal. Jeffery and Vay (1986) cite a value of 45 g/t of steel for a top-blown BOF controlled by an open hood vented to a scrubber (99.7% removal based on uncontrolled emissions of 14.25 kg/t of steel) and 65 g/t for an open hood vented to an ESP (99.5% removal). Atmospheric releases are even lower when controlled by a closed hood vented to a scrubber, being 3.4 g/t of steel (99.98% removal).<sup>18</sup> These authors also cite a value of 28 g/t of steel for a bottom-blown BOF (Q-BOP) controlled by a scrubber (99.8% removal).

Based on a 1988 survey, EPA concluded that 4% of the dust/sludge was recycled at the integrated steel maker, 44% was disposed of, and 52% was sold or sent off site for further metal recovery (AISI 1998, Chapter 4). Any metal recovered would become part of the home scrap or prompt scrap sources of feed. Fruehan (1998, Section 9.3.5.2) describes the growing use of waste oxide recycling to address environmental concerns associated with landfill disposal.

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<sup>18</sup> Based on more recent measurements from three melt shops, EPA (2001a) has replaced this dust release value with a figure of 17.5 g/t or 99.9% removal.

Waste oxide briquettes containing sludges, grit, and mill scale are being used as a coolant ore substitute in some BOFs. As noted above, coolant ore constitutes only about 2% of the total furnace charge. The waste oxides are collected, blended, dried, mixed with lime and binders, and pressed into pillow-shaped briquettes. The briquettes are then cured to remove moisture. A typical waste oxide briquette composition is 35 wt% sludge, 20 wt% grit, and 45 wt% mill scale. Successful exploitation of this technology could reduce the amount of material being landfilled. Fruehan (1998) states that small amounts of dust and sludge are recycled to the sinter plant for metal recovery (this is consistent with AISI 1998, Chapter 4), and that small amounts are sold to the cement industry. The balance is not accounted for by Fruehan, but is presumably landfilled. Limited recycling of dust and sludge is confirmed by AISI 2001 (p.63), where it is noted that less than half the steelmaking dust and sludge is reused.

**Table 3.3 Analysis of top-blown BOF and Q-BOP fume**

Element	Concentration in gas (mg/m <sup>3</sup> at STP)	
	BOF (top-blown)	Q-BOP
Aluminum	MC*	0.43
Antimony	0.006	<0.001
Arsenic	≤0.05	<0.02
Barium	>0.11	0.02
Bismuth	>0.11	0.02
Cadmium	0.077	0.002
Calcium	MC	64
Chromium	0.84	0.26
Copper	0.18	0.1
Iron	>2.7	85.3
Lead	>0.02	0.41
Magnesium	>0.55	2.3
Manganese	>0.11	3.8
Mercury	0.0008	>0.0031
Nickel	0.31	0.18
Phosphorus	MC	0.53
Selenium	0.087	<0.033
Silicon	>1.1	4.2
Strontium	0.016	<0.056
Sulfur	>0.06	7.9
Zinc	MC	0.14

Source: Felton et al. 2000

\* MC = major component (concentration not available)

If the sludge is high in zinc (from melting galvanized steel scrap), it cannot be recycled to the blast furnace. However, it can be recycled to the BOF. A steel industry source estimated that some plants may recycle as much as 15% back to the BOF as coolant ore, but this type of sludge

recycling is practiced at only about one-fourth the integrated steel melt shops.<sup>19</sup> Use of sludge as a filler material is rare.

Since the total amount of scrap in the BOF charge is limited to about 25%, a significant fraction of which is home scrap, the concentrations of 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 (Arthur D. Little 1993).

As indicated in Table 3.2, several of the integrated steel mills have associated sinter plants which accumulate iron units from various process streams and consolidate these iron units with carbon and flux into a form suitable for incorporation as part of the blast furnace feed. Since EPA 2001a, the source document for Table 3.2, was published, the WCI sinter plant has been shut down ("WCI Idles Youngstown Sinter Plant" 2001) leaving only eight plants in operation in the United States. BOF furnace dust and sludge is typically not one of the process streams used as a feed source for the sinter plants due to the presence of zinc, which has a deleterious effect on blast furnace operations (AISI 2001, p. 63). In 2000, 10.6 kt of sinter, accounting for about 15% of total blast furnace feed, was consumed in producing pig iron (Fenton n/d). In assessing the mass balance of raw and recycled materials entering the furnace, the sinter plays a role similar to home scrap.

### 3.2.3.2 Non-Integrated Steel Mills

Non-integrated steel mills mostly employ EAFs and produce carbon steels, stainless steels, tool steels, and other alloy steels. Carbon steel EAF shops are often referred to as mini-mills. AISI (2001) notes: Once relegated to producing inexpensive concrete reinforcing bar, today mini-mills can produce over 80% of all steel products.

In 2000, the non-integrated steel producers used EAFs to produce 47% of total steel production at 120 steelmaking plants (Fenton n/d). The same author estimates that 95.5% of the total EAF production is from scrap (Fenton 2002). It is estimated that about 25% of this scrap is home scrap (SRI 2001). Pig iron and DRI provide the balance of the iron units.

Penton Publishing has recently issued the "North American Mini-Mill/Market Mill EAF Census" (2000) which focuses on furnaces used for melting high-volume carbon steel products. Specialty, alloy, tool, and stainless steel EAFs are not included. A number of nonoperating furnaces are also excluded. The survey lists 94 furnaces, including the average heat size and raw steel annual capacity of each. The number of heats per year can be calculated from this information. For the total population of furnaces, the heats range from 1,538 to 11,765, with an average of 5,634. The average heat size for melting carbon steel, based on the Penton census, is 108 tons, (98 t) with a range from 32 to 365 tons (29 – 331 t).

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<sup>19</sup> Timothy W. Miller, Supervisor, Coke, Iron and Steelmaking Research, Bethlehem Steel Corporation, private communication with Kathleen Behling, SC&A, Inc., September 26, 2001.

A more comprehensive survey of EAF furnaces is published each year by the Iron and Steel Society (I&SS)—e.g., “EAF Roundup” 2001. The survey includes numerous facilities that are not currently operating. The I&SS survey also includes EAFs used for making steel castings, as well as specialty, alloy, tool, and stainless steels, and metal powders and superalloys. EAFs used for these applications tend to be smaller and may operate fewer turns per week. Scrap charges must be more selective to meet stringent and specialized heat chemistries.

The I&SS survey includes more than 200 EAFs. If we eliminate from this population furnaces used for producing metal powders, steel castings, and superalloys,<sup>20</sup> 178 furnaces remain, including furnaces that are not operating or that produce various speciality steels (including stainless steels). Of this total, sufficient data are available on 166 furnaces to calculate the number of heats per year: the average value is 4,405, with a range of 500 to 10,800.

The average value of heats per year from the I&SS survey is about 20% lower than that calculated from the Penton EAF Census. This is not surprising, since the I&SS survey includes a large number of speciality steel melting furnaces that typically operate with lower capacity factors.

The average heat size, based on 178 furnaces, is 97 tons (88 t), with a range of 6 to 370 tons (5.4 – 336 t). The minimum heat size occurs at Champion Steel, a producer of “hard-to-find” grades of tool and high speed steel, while the maximum is at Furnace #7 at Northwestern Steel and Wire (currently in standby).

During refining of the molten steel bath, P, S, Al, Zn, Mn, Cr, and C are typically removed. With the exception of carbon, removal is by partial transfer of these species to the slag phase as oxides (Fruehan 1998). The partition ratio (slag:steel) for phosphorus typically ranges from 5 to 15, and for sulfur from 3 to 5. Manganese is commonly lowered to about 0.06% in the bath (Fruehan 1998). Additional refining may be accomplished in the ladle to which the molten steel from the EAF is transferred. Ladle refining vessels typically use electric arc reheating (AISI 2001).

The fumes generated during the melt-down 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.

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<sup>20</sup> It is appropriate to eliminate these furnaces because EAFs used for steel castings are included with iron and steel foundries, while EAFs producing metal powders and superalloys require special feedstocks.

Dust generation rates have been reported to range from 20 to 40 lb/ton of scrap melted (10 to 20 kg/t) (Fruehan 1998).<sup>21</sup> This is also consistent with an average value of 1.5 t of dust per 100 t of scrap melted cited by Anigstein et al. (2001).

Metals known to volatilize as the scrap heats up include Zn, Pb, Cd, Na, Mn, and Fe. These metals tend to form oxides following volatilization and report to the dust in that form. CaO carryover from lime (added as slag former) also occurs (Fruehan 1998).

Jeffery and Vay (1986) cite a value of 21.5 g/t of carbon steel for atmospheric releases from an EAF using direct shell evacuation plus charging hood vented to a common baghouse. Depending on whether uncontrolled emissions are 19 or 25 kg/t,<sup>22</sup> the removal is 99.88%  $[(19 - 0.0215) \div 19 = 0.9988]$  or 99.91%  $[(25 - 0.0215) \div 25 = 0.9991]$ .

### 3.2.3.3 Iron and Steel Foundries

Iron and steel required for castings are melted in a variety of furnaces, including small EAFs, cupola furnaces, and electric induction furnaces. About 91.5% of the furnace charge in iron foundries is scrap and the balance is mainly pig iron (Fenton 2002, Table 4). Iron and steel foundries account for 20% of ferrous scrap consumption.

Scrap consumption by manufacturers of steel castings and by iron foundries and miscellaneous users in 2000 is summarized below (Fenton 2002, Table 4):

- Electric arc furnace ..... 7.4 Mt
- Cupola furnace ..... 7.4 Mt
- Other (including air furnaces)<sup>23</sup> ..... 2 kt
- Total<sup>24</sup> ..... 15.2 Mt

Of this total, 5.8 Mt, or 38%, was recirculating or home scrap (Fenton 2002, Table 2).

Iron castings are produced in a wide range of sizes. For example, Atchison Casting (2001) reports that it produces parts ranging from a few pounds up to 70,000 pounds (> 32 t). In 1989, about half of all iron castings were used by automotive and truck manufacturers (EPA 1995a, Section 12.10).

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<sup>21</sup> There is some confusion in Fruehan 1998 about the measurement base. In Section 10.4.5 the values are quoted as "9-18 kg (20-40 lbs) per ton of scrap melted," while in Section 10.4.6.2 the values are quoted as "9-18 kg (20-40 lbs) per ton of steel produced" (emphasis added).

<sup>22</sup> Both values are cited by Jeffery and Vay (1986) for uncontrolled emissions from EAFs melting carbon steel.

<sup>23</sup> Excludes data withheld to avoid disclosing company proprietary data.

<sup>24</sup> Includes withheld data on "Other" furnaces.

## Cupola Furnace Melting

The cupola is similar to a small blast furnace, where the iron ore in the charge is replaced by pig iron and steel scrap. A 1998 EPA survey of iron and steel foundries lists furnaces with melt rates ranging from 0.6 to 130 tons per hour (0.5 – 118 t/h)<sup>25</sup> and an average melt rate of 27 tons per hour (24 t/h).<sup>26</sup> Annual iron foundry capacities averaged 118,000 tons (107,000 t) and ranged from 100 to 1,368,000 tons (the latter being a large automotive foundry). The installed capacity, based on the EPA survey, is about twice the cast iron production from cupolas in 1998.

The total number of cupola furnaces has been decreasing over time, with replacement by induction furnaces and electric arc furnaces to maintain industry capacity (Baldwin 1980). Energetics (1999) cites a figure of 144 cupola furnaces. The 1998 EPA survey also lists 144 cupolas including three very low tonnage prototypes.<sup>26</sup> Baldwin (1980) reported that a typical cupola producing a medium-strength cast iron from a cold charge would experience a melting loss of 2% (as a percentage of iron input). Melting losses have been quoted elsewhere as 7% to 10% (Energetics 1999). A melt pouring temperature of 2,300 to 2,350°F (1,530 to 1,560 K) is used for gray iron castings (U.S. Steel 1951).

Baldwin (1980) also documented the quantities of by-product material generated by a ductile iron foundry using a cupola, and a gray and ductile iron foundry using a cupola for primary melting, which duplexes into induction holding furnaces. The amounts of slag produced were 173 and 130 lb/ton (86.5 and 65 kg/t) of metal melted, respectively. According to Energetics (1999), most slag is disposed of in landfills. In certain states, slag may be used in road construction, after sizing and grading. However, the small volume of slag from an average foundry does not allow for economical use of cupola slag in road construction.

Using the results of several studies, EPA (1995a) has compiled emission factors for gray iron foundries with various types of emission control devices used in conjunction with a cupola furnace. These emission factors are summarized in Table 3.4.

The average value for uncontrolled emissions of 6.9 kg/t is based on four literature sources specifying a range from 3.3 to 10 kg/t (Jeffery and Vay 1986, Table 4). Energetics (1999) cites an American Foundry Society survey indicating that average cupola emissions are 13 to 17 pounds of particulates per ton of metal melted (6.5 – 8.5 kg/t), which is in good agreement with Jeffery and Vay (1986). The data in Table 3.4 indicate a baghouse efficiency of 95% and scrubber efficiencies ranging from 42% to 95%. About 86% of all cupola furnaces have some form of air pollution control device (APCD)—typically a fabric filter or a wet scrubber. All large furnaces (i.e., > 40 tons/h [36 t/h]) have an APCD (Energetics 1999).

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<sup>25</sup> This excludes three furnaces with capacities of 0.13, 0.25, and 0.75 tons/h which are presumably prototypes rather than production furnaces.

<sup>26</sup> Jim Maysilles, Metals Group, Emission Standards Division, U.S. Environmental Protection Agency, Research Triangle Park, NC, private communication with Kathleen Behling, SC&A, Inc., September 27, 2001.

### Induction Furnace Melting

A total of 675 facilities responded to a 1996 survey of iron and steel foundries by the EPA's Office of Air Quality Planning and Standards, indicating that 1,202 induction furnaces were available. Less than 5% of the furnaces had melt rate capacities exceeding 10 tons per hour (~9 t/h) (Energetics 1999). Energetics noted that many small furnaces ranging from 2,000- to 15,000-lb (0.9 – 6.8 t) capacity are used by the foundry industry to reduce costs and improve environmental performance. More recently, EPA has documented a total of 748 induction furnaces at iron foundries and 643 induction furnaces at steel foundries.<sup>26</sup> Reported iron foundry melt rates ranged from 0.1 to 42 tons/h (90 kg/h – 38 t/h), with an average of 1.9 tons/h (1.7 t/h). Steel foundry induction furnace melt rates ranged from 0.025 to 8 tons/h (~23 kg/h – ~7 t/h) with an average melt rate of 0.4 tons/h (~360 kg/h). The low end of the range includes numerous very small furnaces which are probably not used for production. The combined annual capacities for iron and steel casting furnaces averaged about 10 kt/y with a range from 4 t/y to 286 kt/y.

**Table 3.4 Particulate emissions for cupola furnaces with various emission control devices**

Control Device	Total Particulates	
	lb/ton <sup>a</sup>	kg/t
Uncontrolled	13.9	7.0
Scrubber <sup>b</sup>	3.1	1.6
Venturi scrubber	3	1.5
Electrostatic precipitator	1.4	0.7
Baghouse	0.7	0.35
Single wet cap	8	4
Impingement scrubber	5	2.5
High energy scrubber	0.8	0.4

Source: EPA 1995a, Table 12.10-3

<sup>a</sup> lb of pollutant/ton of gray iron produced

<sup>b</sup> includes averages for wet cap and other scrubber types not already listed.

Melt losses of 1% to 2% are reported for induction furnaces (Energetics 1999). Slag removal is generally achieved by skimming. Removing slag from induction furnaces is difficult, because the nature of the induction heating process causes the slag to remain relatively cold. Slag volumes must be kept to a minimum and the use of slag/metal reactions for melt refining are limited. Sulfur removal is also limited. These limitations are overcome, to some degree, by using ladle adjustments to achieve desired chemistries in the cast metal. However, because the induction furnace has limited refining capability, considerable care must be taken to control the composition of the scrap metal feed to prevent melt contamination and insure that the desired composition of the cast metal is achieved. Pelletized coke may be added to the melt to adjust its carbon content (Baldwin 1980). Baldwin notes that the amount of slag from a malleable iron foundry using induction-furnace melting is 34.53 pounds of slag per ton of metal melted (15.7 kg/t).

EPA (1995a) lists particulate emission factors for EAFs at gray iron foundries (g of pollutant/Mg [t] of gray iron produced):

- Uncontrolled ..... 500 g/t
- Baghouse ..... 100 g/t

The uncontrolled emissions factor is the rounded off average based on two sources (410 and 500 g/t) (Jeffery and Vay 1986, Table 11). The above data imply that the baghouse efficiency is 78%.

According to Energetics (1999), over 75% of the induction furnaces with a capacity of more than 5 tons/h (> 4.5 t/h) have some type of APCD. But 72% of all induction furnaces had no APCD. The furnaces characterized in the study had melting rate capacities ranging from less than 5 to more than 70 tons/hour (< 4.5 to > 64 t/h). About 87% of the furnaces included in the survey had capacities of less than 5 tons/hour (< 4.5t/h) and about 95% had capacities of less than 10 tons/hour (< 9 t/h).

### 3.2.4 Output of Melting and Refining Processes

The four main outputs of the melting and refining process are dust or sludge that is captured from the offgas, slag which is skimmed or poured off the molten metal, the metal product, and airborne effluent releases—that portion of the offgas which escapes capture by the APCD.<sup>27</sup> These process streams were discussed briefly in Section 3.2—more detailed discussions of significant aspects of these media are presented below.

#### 3.2.4.1 EAF Baghouse Dust

As was stated earlier, EAF baghouse dust is a RCRA-listed waste designated as K061. The K061 regulations have continued to change since originally promulgated in 1988 and remain in a state of flux. These regulations determine how the dust and its by-products can be used or disposed of. The recent history of baghouse dust disposal is summarized in Table 3.5. The 1998 landfill data include 305,000 tons (277,000 t) (from 25 mini-mills) processed by EnviroSAFE Services of Ohio, Inc., a wholly owned subsidiary of EnviroSource Technologies, 55,000 tons (50,000 t) processed by Northwestern Steel and Wire (NWSW), with the balance unidentified. Bagsarian (1999) quotes an EnviroSource executive as stating that dust generation is now 40 to 60 lb per ton (20 to 30 kg/t) for new mini-mills and other upgraded mills.

The temporal trends shown in Table 3.5 are largely driven by the changing regulatory climate at EPA regarding RCRA materials, and to a lesser extent by the success or failure of various treatment technologies. Prior to the RCRA regulations on the land-based disposal of hazardous wastes in August 1990, most K061 wastes were shipped to landfills. Then, throughout the early 1990's, most of the waste was processed in Waelz kilns for metal recovery (HTMR-HRDC in

<sup>27</sup> See Footnote 7 on page 3-6.



Table 3.5). In July 1995, EPA (1995b) ruled that K061 waste could be stabilized and sent to nonhazardous waste landfills if the treated product passed the toxicity characteristic leaching procedure (TCLP). At that time, EPA granted a generator-specific petition from Conversion Systems, Inc. to delist certain solid wastes containing EAF dust that were stabilized by the Super Detox™ process for disposal in RCRA Subpart D landfills. Subsequent to that ruling, there has been a significant shift back to landfill disposal (O'Neil 1998).

**Table 3.5 Disposal of EAF dust (1000 tons/y)**

Disposal Route	1985	1992	1993	1995	1996	1997	1998
Landfill	337	63	82	143	220	365	400
Fertilizer	25	13	25	25	12	12	
Micronutrients	16	17	17	16	16	16	
HTMR-HRDC <sup>a</sup>	55	424	384	351	290	310	330
HTMR-ZN <sup>b</sup>	17	50	82	82	110	125	135
HTMR-Misc. <sup>c</sup>	0	10	14	33	52	61	60
Total	462	560	604	650	700	889	925

Sources: 1985 – 1997 data, EPRI 1998; 1998 data, Bagsarian 1999.

<sup>a</sup> HTMR (High Temperature Metals Recovery) - HRDC (Horsehead Resource Development Co.)

<sup>b</sup> HTMR - ZN (Zinc Nacional)

<sup>c</sup> Includes Laclede, MRT, HRDC-North Star Steel, Inorganic Recycling, International Mill Services (plasma arc process, shut down and dismantled ca. 1996), ZTT (operations terminated August 1997). 1998 data include Northstar - 27,500 tons, Nucor-Hickman - 9,000 tons, Nucor-Yamato - 9,000, and AmeriSteel (formerly with MRT) - 7,400 tons, balance unidentified.

In addition, prior to July 24, 2002, K061-derived fertilizers were not subject to regulation as hazardous wastes pursuant to 40 CFR 266.20(b), which stated that “zinc-containing fertilizers using hazardous waste K061 that are produced for the general public’s use are not presently subject to this regulation.” On that date, EPA (2002) promulgated revised regulations which altered this exemption. Under the new regulations, zinc fertilizers are exempted from the RCRA definition of solid waste, if the fertilizer meets certain limits on the maximum allowable concentrations of As, Cd, Cr, Pb and Hg. Alternatively, the materials are exempted if they meet the applicable treatment standards in 40 CFR 268 Subpart D for each hazardous waste component contained. At the time the new regulation was promulgated, EPA had identified only one fertilizer manufacturer who was processing K061 dust (from one steel mill) into zinc micronutrient fertilizer.

As can be seen from Table 3.5, use of EAF dust in fertilizer and micronutrients accounted for about 3% of the EAF dust disposed of in 1997.

As shown in Table 3.5, over 900,000 tons (820 kt) of EAF dust was disposed of in 1998. The two largest domestic disposal approaches were high temperature metal recovery (HTMR) at Horsehead Resource Development Co. (HRDC) and burial of stabilized, delisted waste in landfills. As noted in Table 3.5, significant quantities are also processed outside the United States (e.g., at Zinc Nacional, SA in Mexico).

HRDC operates three regional Waelz kiln plants located in Palmerton, PA; Chicago; and Rockwood, TN. These plants have a combined capacity of about 450,000 tons/y (~410,000 t/y) (Bosley 1994, Schmitt 1996). In the HRDC process, EAF dust is mixed with coke or coal, together with lime and silica, and fed into a rotary (Waelz) kiln about 120 to 180 ft (37 – 55 m) long and 10 to 12 ft (3 – 4 m) in diameter, operating at about 1,100°C (Arthur D. Little 1993). The Zn and other volatile metals are collected in a baghouse as oxides (i.e., crude zinc oxide, CZO). The baghouse product is sent to a second kiln where the Pb and Cd are fumed off and collected from a baghouse for further treatment. The zinc oxide clinker is shipped to the Zinc Corporation of America where it is processed in an electrothermal furnace (Foster 1991). The clinker is a high quality zinc concentrate containing about 60% Zn.

In the HRDC Waelz kiln process approximately 70% of the baghouse dust feed is converted to "slag".<sup>28, 29</sup> Disposal of this slag is a matter of ongoing regulatory review by the EPA. Anti-skid/deicing applications of the slag are banned under 40 CFR 266.20. Other applications where slag is placed on the land require that the slags meet the treatment standards specified by the RCRA land disposal requirements (Bourdeau 1998).

Over the past several years, HRDC has been developing methods to recover iron and flux units from the Waelz kiln slags so that they can be returned to the steelmaking process (Schmitt 1996). This iron-rich material has properties similar to DRI. Bagsarian (1999) stated that HRDC was recycling 330,000 tons (300 kt) of EAF dust into Quickiron DRI. For example, Auburn Steel is a customer for Quickiron DRI and uses about 700 tons (635 t) per month, which constitutes 2% of its furnace feed.

EPA has granted Envirosource a multi-site delisting for materials produced by the Super Detox™ process (EPA 1995b). After treatment, the stabilized EAF dust can be managed either at an Envirosource facility or at an approved RCRA Subpart D disposal facility (on site at the steel mill or off site). Envirosource originally had two regional facilities: one near Toledo (Envirosafe Services of Ohio, Inc.) and one in southern Idaho.<sup>30</sup> (The Idaho facility was acquired by American Ecology in 2001.) Capacities of these facilities are:

- Ohio—150 tons/h (136 t/h), stabilization capability of over 200,000 tons (180 kt) of waste annually, 2 million tons (1.8 Mt) of permitted landfill capacity
- Idaho—over 100,000 tons (90 kt) per year stabilization capacity, over 2 million tons (1.8 Mt) permitted disposal capacity

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<sup>28</sup> This "slag" is not a fused product as is the case for steel slags, since the kiln operates at a lower temperature than a steelmaking furnace.

<sup>29</sup> David J. Sosinsky, Horsehead Resource Development Company, Palmerton, PA, private communication with William C. Thurber, SC&A, Inc., October 30, 1996.

<sup>30</sup> Although EPA regulations would allow the stabilized dust to be disposed of in a RCRA Subpart D (non-hazardous) landfill, these two facilities conform to the requirements of RCRA Subpart C for hazardous waste disposal.

Based on these capacities and the 1998 landfill data from Bagsarian 1999 (see Table 3.4), it appears that EnviroSAFE is operating near capacity. American Ecology also operated an on-site Super Detox™ stabilization plant at NWSW at Sterling, IL. Stabilized waste was disposed of on site at a landfill previously constructed and operated for steelmaking wastes. NWSW used wet scrubbers rather than baghouses for air pollution control on its EAFs. The company suspended operations in 2001—its assets were offered for sale at public auction in April 2002. In June 2002, a new company, Sterling Steel LLC, announced that it plans to operate a steel rod facility at the NWSW site. It is not clear whether the operations will include an EAF.

At the Super Detox™ processing facilities, 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<sup>3</sup> (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.

About 3% of the EAF dust was used for fertilizer and micronutrient applications in 1997 (see Table 3.5). According to 40 CFR 266.20, which details use of EAF dust in fertilizer, such use 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 (Arthur D. Little 1993) to achieve a reasonable maximum concentration of zinc in fertilizer of 3%. Assuming that the initial concentration of zinc is 20% in the EAF dust and that the final zinc concentration is 3% in enriched fertilizer, 28,000 tons (25 kt) of EAF dust would be added to 159,000 tons (144 kt) of non-enriched fertilizer (additives).<sup>31</sup> 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.

EPA (1999) published a study which evaluated issues relating to heavy metals and other non-nutritive constituents in fertilizers and liming materials. The quantities of cadmium and lead which would be added to soil each year as a result of the use of EAF dust as fertilizer are listed in Table 3.6. These quantities are based on the assumption that zinc constitutes 15% of the dust.

**Table 3.6 Buildup of heavy metals in soil from use of EAF dust as fertilizer**

Metal	Concentration in dust	Annual application rate (kg/ha)		
zinc	15%	5.6	11.2	22.4
cadmium	359 ppm	0.013	0.027	0.054
lead	1.917%	0.716	1.431	2.863

Source: EPA 1999, Table G-5a

Note: quantities of Cd and Pb concomitant to the application of EAF dust to achieve desired additions of Zn

<sup>31</sup> J. Wyett, Frit Fertilizer, personal communication with Mary Anderson, SAIC, February 1995.

The disposition of EAF dust has been an issue for the steel industry for several years; as a result, the EPA's regulatory approach in this area is evolving. Because of the regulatory and liability issues, industry has responded rapidly with new practices for the disposition of EAF dust; these changing practices, however, make the process difficult to analyze. New recycling processes are being developed to remove heavy metals and zinc oxide, producing various by-products 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 most likely continue to evolve.

#### 3.2.4.2 Slag

Unlike EAF dust, steelmaking slag can be reprocessed for commercial use or disposed of in nonhazardous waste landfills without special processing. Some commercial uses of steel slags were discussed on page 3-6.

Based on steel production of 101 Mt in 2000, Kalyoncu (2002) estimated that the expected steel slag production was 13 Mt. This estimate includes material from both BOFs and EAFs with different slag generation rates. Of this, 5.1 Mt was sold or used as follows (Kalyoncu 2002):

- Asphaltic concrete aggregate ..... 0.9 Mt
- Fill ..... 1.0 Mt
- Railroad ballast ..... 0.4 Mt
- Road bases ..... 1.7 Mt
- Other uses (ice control, soil conditioning, misc.) .. 1.1 Mt

Presumably, the unsold balance of about 5.5 Mt is either recycled to a sinter plant or landfilled after recovery of metal values.

Slag is transported from the melt shop to manufacturers or processors by either truck, rail, or waterway. Of the slag sold in 2000, 78% was transported by truck, 6% by rail, and 16% by water. Most slag was transported less than 100 km (Kalyoncu 2002). Truck transport is typically in dump trucks with payloads of up to 25 tons (22.7 t).

#### 3.2.4.3 Metal Products

The line of steel products produced from EAFs and BOFs is not identical, but there is substantial overlap between product lines. In the early stages of commercialization, EAFs tended to produce a limited line of lower quality products such as rebar. Today, however, steel from EAFs can be used in the production of about 80% of the same products as are manufactured from BOF steel (Fruehan 1998). In some cases, a melt shop may produce blooms or slabs for sale to other processors. Both product types follow the flow model presented in Figure 3.1. Metal products are transported from the mill to manufacturers or processors by either truck, rail, or waterway.

Finished steel and cast iron products are used by consumers for innumerable applications, covering the gamut from small objects in contact with the body (stainless steel jewelry), to cookware, appliances and automobiles. One industry trade association has estimated that about two-thirds of the weight of a passenger car is steel and cast iron and, of this, about 45% is recycled metal (SRI 2002). In industrial settings, workers are frequently in close proximity to massive steel objects and structures (e.g, crane operators, machinists, operators of earth-moving machinery, etc.)

#### **3.2.4.4 Miscellaneous By-Products**

There are other by-products from steelmaking in addition to slag and dust. However, these constitute comparatively small amounts of material, and have not been addressed in the main analysis. One such by-product is mill scale, which is formed 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 steel product at a mill, but is more typically between 0.5% and 0.75%. Scale must be removed from finished steel because it results in unwanted characteristics of the 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. Scoping analyses of the potential radiological impacts of mill scale and other miscellaneous by-products, indicate that these products would not constitute significant sources of exposure. A detailed discussion of these analyses is presented in Appendix N.

### **3.3 Mass Fractions and Partitioning Factors**

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

#### **3.3.1 Mass Fractions**

Table 3.7 presents a summary of the data characterizing iron- and steelmaking practices. Not all of these data are directly utilized in the analyses: some are combined with other values to assign values and/or uncertainty distributions to the parameters used in the calculations, while others are presented as background information. Furthermore, there are minor discrepancies between the data collected and the values of some of the parameters used in the analysis, due to rounding or other approximations. The values of the mass flow parameters used in the analysis are listed in Table B.3.

Table 3.7 Key data for development of mass flow parameters

Furnace type:	BOF	EAF	Cupola	Induction
Metal product	carbon steel	carbon, tool, stainless steel	cast iron	cast iron, steel
Fate of dust/sludge	recycling, landfill disposal	metals recovery, fertilizer, disposal in hazardous or industrial landfill	landfill disposal	landfill disposal
Furnace temperature	1873 K	1873 K	1548 K	1823 K
Metal product recovery <sup>a</sup>	91%	90%	90 – 98%	98 – 99%
Scrap in feed <sup>a</sup>	24%	95.5%	91.5%	91.5%
Home scrap <sup>b</sup>	24%	25%	38%	38%
Dust/sludge generation	0.4 – 3.1% <sup>c</sup>	0.1 – 0.2% <sup>d</sup>	0.33 – 1.0% <sup>c</sup>	0.41 – 0.5 <sup>c</sup>
Efficiency of APCD	99.4 – 99.9%	99.88 – 99.91%	95% max.	78% max.
Slag generation	5.0 – 22.0% <sup>c</sup>	12 – 14% <sup>c</sup>	6.5 – 8.6% <sup>d</sup>	1.57% <sup>c</sup>
Size of average heat	195 t	88 t	27 t/h	1.9 t/h
Average number of heats/y per facility	6,023	4,405	n/a	n/a

<sup>a</sup> With respect to total metal in furnace charge

<sup>b</sup> With respect to total scrap in furnace charge

<sup>c</sup> With respect to metal produced

<sup>d</sup> With respect to scrap melted

### 3.3.1.1 Furnace Charge

The fraction of the total furnace charge that is comprised of scrap varies with the melting process. In EAFs the charge is largely scrap. According to the Steel Recycling Institute (SRI 2001), 95.5% of EAF output is from scrap. Fenton (2000) reported that scrap accounted for 24% of BOF steel produced in 2000. Data from the same source indicates that 91.5% of the feed to iron foundries is scrap.

As discussed previously, a significant fraction of the scrap is home scrap. The amount of home scrap depends on the melting process. The Steel Recycling Institute (SRI 2001) has estimated that about 25% of the scrap charged into an EAF is home scrap. The same source estimates that about 24% of the BOF scrap charge is internally generated (e.g., home) scrap. Based on industry data for 1998, compiled by the U.S. Geologic Survey, it can be estimated that about 38% of the scrap used in producing iron and steel castings is home scrap (Fenton 1999, Table 2). Data for 2000 yields the same value within the precision of the listed data (Fenton 2002, Tables 2 and 4).

### 3.3.1.2 Metal Product

Industry data indicate that EAFs typically produce 90 t of steel for every 100 t of scrap used (Lankford et al. 1985), resulting in a mass fraction of 0.9. Anigstein et al. (2001, Section E.7) derive the same value, using an argument based on mass balance. Average metal product recovery for BOFs has been quoted as 91% (Fruehan 1998). These data are used indirectly to convert mass fractions in terms of metal in the furnace charge to mass fractions in terms of metal produced.

For cupola furnaces melting cast iron, recoveries have been variously cited as 98% (Baldwin 1980) and 90% to 93% (Energetics 1999). For induction furnaces melting cast iron, metal recoveries have been quoted to range from 98 to 99% (Energetics 1999). These values are quoted for the purpose of background information—they are not used in the present analysis.

### 3.3.1.3 Baghouse Dust and Sludge

There is reasonable consistency in the literature for dust generation rates from melting of carbon steel at EAF facilities. Brough and Carter (1972) and Venturini (1970) give 15 kg/t as a "measured operating value." Arthur D. Little (1993) presents 15 kg/t of capacity as an industry average of 52 plants responding to their survey. Estimates of the ranges of dust production among various mills are also fairly consistent. Brough and Carter (1972) cite a range of 7.5 to 20 kg/t as a specification for baghouse design; Elert and Wiborgh (1992) cite a range of 10 to 15 kg/t for Swedish EAF steel mills; Szabo and Gerstle (1978) give a range of 12 to 29 kg/t; and Fruehan (1998) quotes a range of 10 to 20 kg/t of scrap melted. A range of 10 to 20 kg of dust generated per tonne of metal charged to the furnace, with a best estimate of 15 kg/t, is adopted for the present analysis.

More limited data are available for BOFs. According to AISI 1998, Chapter 4, BOF dust ranges from 4 to 31 kg/t of raw steel produced, with an average of approximately 18 kg/t. These values are adopted for the present analysis.

Cupola furnaces used to melt cast iron have uncontrolled emissions (i.e., total emissions prior to filtration or other APCD, if any) ranging from 3.3 to 10 kg/t of gray iron produced, with an average of 6.9 kg/t. Uncontrolled emissions from induction furnaces at gray iron foundries are about an order of magnitude lower, with a range of 0.41 to 0.5 kg/t of metal produced and an average value of 0.45 kg/t (Jeffery and Vay 1986).

A fraction of the furnace dust will escape the air pollution control device and be released from the stack together with gaseous products. As cited on page 3-18, EAF baghouse efficiencies range from 99.88% to 99.91%, while the filtering system efficiencies in BOF shops can range from 99.4% to 99.9% (see page 3-14, above). Baghouse efficiencies of 95% for cupola furnaces and 78% for induction furnaces melting cast iron are cited on pp. 3-19 et seq. However, not all furnaces use APCDs.

### 3.3.1.4 Slag

The mass fraction of BOF slag is assigned a range of 50 to 220 kg/t of steel produced, with an average value of 120 kg/t slag, based on AISI 1998, Chapter 4. A major slag marketer estimates that 120 to 140 kg of slag per tonne of steel are produced at an EAF.<sup>32</sup> Based on additional reviews of data for EAF slag generation, a range from 120 to 140 kg/t of steel produced, with a mean value of 130 kg/t, was adopted for the present analysis.

Slag generation rates are lower in cast iron melting than in steel melting. Values of 65 and 86.5 kg/t of metal melted have been cited for cupola furnaces melting gray iron and/or ductile iron (Energetics 1999). For induction furnaces melting malleable iron, a slag generation rate of 15.7 kg/t of metal melted has been cited by Baldwin (1980).

### 3.3.2 Partitioning Factors

An analysis of the redistribution (partitioning) of the residual activities of cleared steel scrap entering a melting furnace is needed to determine the radionuclide concentrations in each of the furnace products mentioned earlier. Since all isotopes of a given element have virtually identical chemical properties, the partitioning of the various radioisotopes can be determined from the partitioning of the stable isotopes of the same elements, or of other radioisotopes for which partitioning data exist. A partitioning factor is defined as the ratio of the total amount of a given element or compound in one of the furnace products to the amount in the scrap metal charged to the furnace.<sup>33</sup>

This section presents the basic assumptions and methodology used in developing the partitioning factors of impurities (including radionuclides) during melting and refining.

#### 3.3.2.1 Basic Assumptions

Many of the elements included in the partitioning studies, with the exception of the actinides, are typically found in steelmaking as components of steel scrap, alloying additions, slag-forming agents, 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. As noted in Appendix J, a typical low carbon steel (SAE 1020) contains  $\leq 0.05\%$  S. A free machining steel—SAE 1118—contains 0.08% to 0.13% S. In general, steelmaking processes and operating conditions have been developed that can maximize the retention of a particular element in the molten steel, depending on the desired result, or,

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<sup>32</sup> Rick West, Sales Manager for International Mill Services, private communication with William C. Thurber, SC&A, Inc., June 25, 1996.

<sup>33</sup> This concept is a generalization of the partition coefficient used in chemistry, but differs from the latter in three significant respects: (1) the partition factor refers to the total amount (not concentration) in the furnace product; (2) it is the ratio of this amount to the original amount in scrap, not the equilibrium concentration; and (3) it includes the volatile fractions as well as the amounts that collect in dust, and is therefore not restricted to liquid phases.



conversely, maximize its removal. The elemental partitioning factors determined for the present analysis are intended to be representative of the expected behavior during melting in a typical domestic EAF or BOF. While some differences might be expected in the partitioning of impurities in these different steelmaking furnaces, sufficient information is not available to quantify these differences. A separate set of partitioning factors was developed for cast iron melting.

It is recognized that there would be variability in the behavior of impurities 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). Details on cesium partitioning are presented in Section J.1.4.7. Other factors that could affect the 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 analysis has some associated uncertainty. In order to address this uncertainty, probability distributions are assigned to the partitioning factors.

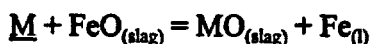
The main components of a typical melt shop that play significant roles in the analysis are the primary melting chamber (the furnace) and the APCD. As stated previously, the latter system typically consists of a fabric baghouse filter, a scrubber, or an electrostatic precipitator. Other components of the melt shop, such as ladles, tundishes, and reheating ovens, are not important to the analysis because no phase changes occur and there is no dilution or concentration of radioactive contaminants. The most common types of steel melting furnaces use a basic slag (Lankford et al. 1985). Other processes, such as the use of different slagging agents, gas sparging, and mixing, can affect partitioning of impurities. However, these processes are not included in the present analysis because their use in iron and steelmaking is extremely variable and their effects are difficult to predict. Such special processes fall outside of mainstream steelmaking.

During melting and refining, impurities can partition to one or both of the liquid components (i.e., the slag and metal phases), or discharge from the furnace in the volatilized gas. Some of the impurities that leave the furnace in the volatilized gas will remain in the vapor phase and some will condense or coalesce into particulates (dust). Impurities found in coarse particulates are captured by the APCD. Some of the fine particles and species in the vapor phase will escape in the airborne effluents exiting the stack. A small fraction of metals and oxides that are refractory or ferrous in nature will be carried over to the dust.

### **3.3.2.2 General Methodology for Determining Partitioning of Impurities**

The distribution of impurities during melting and refining of steel or cast iron is a complex process that can be influenced by numerous chemical and physical factors, including composition of the steel bath, chemistry of the slag, vapor pressure of the particular chemical species, solubility of the element in molten iron, density of the oxide(s), steel-melting temperature, and melting practice (e.g., furnace type and size, melting time, method of carbon adjustment, and method of alloy additions).

The general methodology employed here was to first consider metal/slag reactions based on thermodynamic calculations (i.e., Gibb's free energy) to determine whether an element was likely to partition to the slag or to the melt. To accomplish this, the free energy change for the following general reaction written here between a divalent solute element M (e.g., Co) and iron oxide in the slag was evaluated at 1600°C (1873 K):



where  $\underline{M}$  is the symbol for solute dissolved in liquid iron and  $\text{Fe}_{(\text{m})}$  is iron in the melt. From these calculations, partition ratios describing the distribution of the element between the melt and the slag are developed. The detailed methodology is presented in Section J.1.1 of Appendix J. Elements that form highly stable oxides (e.g., actinides and lanthanides) will tend to partition strongly to the slag. Elements whose oxides are less stable than FeO would tend to remain in the melt (e.g., Co, Ni, Tc).

The vapor pressures of the more volatile elements and their oxides were examined to gain insight into which elements would tend to concentrate in the dust leaving the furnace. Elements such as cadmium, cesium, polonium, and zinc all have normal boiling points well below 1873 K and would be expected to volatilize from the melt and be concentrated in the dust.

These theoretical considerations were supplemented with a review of the steelmaking and nuclear metallurgy literature to obtain industrial and laboratory data on observed partitioning of various elements during steel melting. In some instances, no thermodynamic or literature data were available. In such cases, partitioning is based on chemical analogy with similar elements. For example, the lanthanides, Pm and Gd, are assumed to behave in a manner similar to Ce and Sm, for which data are available.

In some cases, only a single data point is available and so a fixed percentage for the elemental partitioning is assigned to each process stream. If multiple sources of data were available, a range of values representing the combined sources is established. Since, in many cases, thermodynamic and vapor pressure data only indicate tendencies as to how elements partition rather than quantitatively fix the specifics of the distribution among process streams, engineering judgment is employed to quantify these tendencies. The convention is adopted that, if an element tends to remain in the melt, 1% is assumed to be transported to the dust due to physical entrainment associated with the turbulence of the melting and refining process. Similarly, if an element tends to partition to the slag, 5% is assumed to be transferred to the dust. The detailed rationale for these conventions is provided in Section J.1.7.

Table 3.8 lists the ranges of partitioning factors (during steelmaking) of each element that is represented by one or more radioisotopes in the present analysis. Probability distributions, most often employing beta functions, are developed to represent the range of variability and/or uncertainty in these factors, using the methodology described in Section J.5. The parameters that specify each of these distributions are listed in Table B.2. Similar data for cast iron production are presented in Table 3.9.

Table 3.8 Partitioning in steelmaking (%)

Elements	Metal product	Dust	Slag	Volatile
H	5-15	0	0	85-95
C	27-100	0	0	0-73
Na, K	0	40-60	40-60	0
P	9-48	2-4	50-87	0
S	6-25	1-5	74-89	0
Cl, I	0	0-50	0-50	0-100
Ca, Sc, Sr, Y, Zr, Nb, Ba, Ce, Pm, Sm, Eu, Gd, Tb, Tm, Ta, Ra, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es	0	2.5-7.5	92.5-97.5	0
Cr	40-97	1-3	0-59	0
Mn	2-24	3-4	72-95	0
Fe	95.5-98.5	0.5-1.5	1-3	0
Co, Ni, Mo, Tc, Ru, Sn, W, Ir	98.5-99.5	0.5-1.5	0	0
Zn	0-20	80-100	0	0
As	50-90	10-50	0	0
Se, Te, Os, Tl, Pb, Bi, Po	2.5-7.5	92.5-97.5	0	0
Ag	75-99	1-25	0	0
Cd	0	100	0	0
Sb	75-99	1-20	0-5	0
Cs	0	95-100	0-5	0

### 3.4 Mixing of Cleared Scrap

The concentration of each radionuclide in cleared scrap would be reduced by mixing with other materials, including scrap from other sources, prior to melting. Further mixing occurs during the disposal of furnace by-products. The mixing of cleared scrap and of products and by-products of the melting and refining of the scrap are briefly discussed in this section. The type of mixing factor used in each exposure scenario is listed in Table 3.10. A detailed discussion of all mixing factors used in the present analysis is presented in Appendix D.

#### 3.4.1 Processing Scrap at Scrap Yard

It is assumed that all the steel scrap cleared during the dismantlement of a commercial nuclear power plant during one year is processed by a single scrap dealer. The mixing at the scrap yard is modeled by calculating a mixing factor, which is the mass of steel scrap cleared from a nuclear facility in one year, divided by the annual throughput of the scrap yard.

### 3.4.2 Melting and Refining of Scrap

#### 3.4.2.1 Annual-Average Mixing Factors

The mixing of scrap in the furnace is modeled as a multi-step process. The first step consists of selecting the type of furnace which would receive the scrap. For the purpose of the present analysis, furnaces recycling steel scrap are grouped into three classifications, as discussed in Section 3.2. The probability that the cleared scrap would be recycled at any particular furnace is assumed to be proportional to the annual scrap consumption of that furnace. The following probabilities are assigned to the three furnace types:

- BOF ..... 20%
- EAF ..... 58%
- Iron and steel foundries ..... 22%

Table 3.9 Partitioning in cast iron melting (%)

Elements	Metal product	Dust	Slag	Volatile
H	5-15	0	0	85-95
C, Cr, Fe, Co, Ni, Mo, Tc, Ru, Ag, W, Ir	99-100	0-1	0	0
Na, K, Cs	0	50-100	0-50	0
P	9-48	2-4	50-87	0
S	6-25	1-5	74-89	0
Cl, I	0	0-50	0-50	0-100
Ca, Sc, Sr, Y, Zr, Nb, Ba, Ce, Pm, Sm, Eu, Gd, Tb, Tm, Ta, Ra, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es	0	2.5-7.5	92.5-97.5	0
Mn	96-99	0-1	0-4	0
Zn	1-3	97-100	0	0
As	50-90	10-50	0	0
Se	89.5-96.5	3.5-10.5	0	0
Cd, Po	0	100	0	0
Sn	98.5-99.5	0.5-1.5	0	0
Sb	2-6	94-98	0	0
Te	40-60	40-60	0	0
Os	2.5-7.5	92.5-97.5	0	0
Tl, Pb	4-10	90-96	0	0
Bi	3-7	93-97	0	0

Each type of furnace uses a different mix of purchased scrap, home scrap, and virgin metal, as shown in Table 3.7.

As discussed in Section 3.2.3, the annual scrap consumption among furnaces of a given type covers a wide range. In order to determine mixing factors for the range of iron- and steel making furnaces and melt shops in the United States, data were collected and tabulated on the annual

production capacities of 23 BOF shops,<sup>34</sup> 168 EAFs, and 1703 furnaces at iron and steel foundries. The mixing factor is the ratio of the cleared scrap (generated during one year of dismantlement of a nuclear power reactor) to the annual production capacity of given furnace. (Because the mixing is averaged over one year of production, the calculated ratio is called the "annual-average mixing factor.") The furnace, as mentioned earlier, is selected at random from a distribution of furnace sizes, weighted by the number of furnaces in each size category and by the average scrap consumption of the furnaces in that category: a furnace which consumes a large amount of scrap is more likely to be the recipient of a particular batch of scrap than a small furnace.<sup>35</sup>

This process can be visualized by assuming that the scrap cleared in one year remains, for the purpose of the recycling analysis, as one indivisible lot.<sup>36</sup> This lot, however, joins the nationwide flow of scrap and therefore follows the same paths as the rest of the scrap destined for recycling.

### 3.4.2.2 Maximum Single-Heat Mixing Factors

Section 3.4.2.1 discussed the calculation of annual-average mixing factors at furnaces melting steel scrap cleared from a nuclear facility. However, over the course of a year, the proportion of cleared scrap will vary from one furnace heat to another. At a large furnace, for which the annual consumption of purchased scrap is much greater than the amount that would be cleared by a nuclear facility during one year, many heats may contain no cleared material—the mixing factor for such a heat would be zero. Conversely, some heats would contain much more than the annual-average ratio of cleared material. The maximum single-heat mixing factor is the ratio of cleared scrap to the mass of metal poured in the single furnace heat produced during one year that contains the maximum fraction of cleared scrap.

This mixing factor depends on the furnace type. Cupola furnaces producing cast iron can melt a charge consisting of a single grade of scrap. Consequently, it is conceivable—indeed likely—that all the old scrap in at least one heat would consist of cleared material. EAFs, on the other hand, require different grades of scrap. At the beginning of a melt cycle, light shredded scrap is added to facilitate melting and prolong electrode life. As the melt progresses, heavier grades are added. According to a steel industry source, a single EAF heat would include steel

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<sup>34</sup> These facilities typically have two or more furnaces. However, the furnaces operate together and share the same scrap metal supplies.

<sup>35</sup> In the infrequent case that the mass of cleared scrap is greater than the annual scrap consumption of a given furnace, the mixing factor is simply the ratio of purchased scrap to the metal poured.

<sup>36</sup> In the case noted in Footnote 35, the balance of the lot would be consumed by a different furnace.

from 5 to 20 sources.<sup>37</sup> Consequently, a distribution of single-heat mixing factors was constructed and utilized for both EAF and BOF facilities.

### 3.4.2.3 Mixing of Waste in the Landfill

The analyses of the landfill disposal of cleared scrap, slag, or BOF/foundry dust assume that one year's material from a given nuclear power plant or melt shop would be emplaced in a single landfill, commingled with other wastes received by that landfill over the course of a year. The mixing of the disposed scrap or dust is determined by dividing the quantity of such material by the annual volume of all wastes disposed of at a given landfill.

### 3.4.2.4 Mixing of EAF Dust During Processing and Disposal

The analysis assumes that the scrap from only a single nuclear power plant is sent to any given scrap yard, landfill, or melt shop. In most cases, it is assumed that the furnace products of a such a melt shop are disposed of in a landfill or processed for further use at other facilities, none of which receive any other residually radioactive materials. This is a reasonable assumption for most scenarios, since the number of disposal, processing, or recycling facilities in the United States is far greater than the number of nuclear power plants which would undergo dismantlement in any one year. Therefore, the probability that scrap from two or more nuclear power plants would be processed in the same scrap yard, disposed of in the same landfill, recycled in the same melt shop, etc., is very small.

This assumption is not valid for the processing and disposal of EAF dust. As discussed in Section 3.2.4.1, there are only two currently operating facilities that process EAF dust for disposal and subsequently dispose of such dust in on-site landfills. In 1998, there were seven operating HTMR facilities in the United States (see Table 3.5). Since there is no way of predicting which EAF dust disposal option would be selected by a given steel mill, nor which facility the dust would be sent to, it is reasonable to assume that the dust from any given mill would be mixed with the nationwide stream of EAF dust. This stream would, of necessity, include EAF dust from all other steel mills that are simultaneously recycling steel scrap from the dismantlement of other nuclear reactors.

The dilution for the EAF dust processing scenario is calculated as follows:

$$df_r = \frac{f_E m_d n_D}{M_t} \quad 3.1$$

$df_r$  = mixing factor for EAF dust during processing or disposal

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<sup>37</sup> Thomas A. Danjczek, President, Steel Manufacturer's Association, private communication with Robert Anigstein, SC&A, Inc., 1999.

$f_E$  = fraction of steel scrap recycled at EAFs  
= 0.58

$m_d$  = mass of dust generated by EAF (g)

$n_D$  = total number of nuclear plants undergoing dismantlement in a given year

$M_t$  = annual amount of EAF dust generated in United States  
=  $9.25 \times 10^5$  tons ( $8.39 \times 10^{11}$  g) (see Table 3.5)

The number of nuclear plants undergoing dismantlement in any one year is sampled from a distribution, based on the dates of license expirations of NRC-licensed nuclear power reactors listed in NRC 2000, Table 12. The period of dismantlement is assumed to be 1.7 years. Years in which no dismantlement is projected are excluded from consideration.

Additional factors are needed in Equation 3.1 to calculate the mixing factor in the scenario describing the disposal of EAF dust in a hazardous waste landfill:

$$df_r = \frac{df_H F_d f_E m_d n_D}{M_t}$$

$df_H$  = dilution factor for stabilization process  
= 0.77

$F_d$  = fraction of EAF dust in waste stream  
= 0.75<sup>38</sup>

### 3.5 Radionuclide Concentrations During Melting and Refining

#### 3.5.1 Annual-Average Concentrations

Five factors affect the radionuclide concentrations in the furnace products: (1) initial activity concentration (specific activity) in the scrap, (2) mixing of cleared scrap with other metals (purchased scrap from other sources, virgin metal, and home scrap), (3) mass fraction of the given medium (i.e., furnace product), (4) partitioning factor of the element in question, and (5) radioactive decay and progeny ingrowth. For the purposes of calculating the normalized doses, which is the aim of the present analysis, the initial specific activity is assigned a value of unity. Mixing, mass fractions, and partitioning factors are discussed in Sections 3.3 and 3.4. Radioactive decay is addressed in Sections 3.6 and 3.7.

The annual average concentrations, not accounting for radioactive decay and progeny ingrowth, are calculated as follows:

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<sup>38</sup> Greg Ballmer, EnviroSAFE Services of Ohio, Inc., private communication with Kathleen Behling, SC&A, Inc., March 13, 2002.

$$C_{ij} = \frac{C_{is}}{f_{pk}} \left( \frac{1 - f_{hk}}{1 - f_{ip} f_{hk}} \right) \frac{f_{ij}}{f_{jk}} \quad 3.2$$

- $C_{ij}$  = concentration of nuclide  $i$  in medium  $j$  (Bq/g)  
 $C_{is}$  = average concentration of nuclide  $i$  in purchased scrap + virgin metal (Bq/g)  
 $f_{hk}$  = fraction of home scrap used in furnace type  $k$  (BOF, EAF, or "other")  
 $\quad = \frac{g_{hk} f_{hk}}{f_{pk}}$   
 $g_{hk}$  = fraction of scrap in furnace type  $k$  derived from home scrap (see Table B.3)  
 $f_{pk}$  = total fraction of scrap in type  $k$  furnace charge (see Table B.3)  
 $f_{ip}$  = partition factor of nuclide  $i$  in metal product (see Table B.2)  
 $f_{ij}$  = partition factor of nuclide  $i$  in medium  $j$  (see Tables B.2)  
 $f_{pk}$  = mass fraction of metal product in furnace type  $k$ , in relationship to metal charged to furnace (see Table 3.7)  
 $f_{jk}$  = mass fraction of medium  $j$  in furnace type  $k$ , in relationship to the molten metal poured (see Table B.3)

The annual release of volatile nuclides can be calculated as follows:

$$A_{iv} = \frac{C_{io} f_{ia} M_o}{1 - f_{ip} f_{hk}} \quad 3.3$$

- $A_{iv}$  = total activity of nuclide  $i$  volatilized during one year (Bq)  
 $C_{io}$  = concentration of nuclide  $i$  in cleared scrap (Bq/g)  
 $f_{ia}$  = fraction of nuclide  $i$  volatilized from furnace  
 $M_o$  = total mass of cleared scrap charged to furnace in one year (g)

The activity calculated in Equation 3.3 does not include the activity in the dust that is released to the atmosphere. The latter quantity is calculated as follows:

$$A_{id} = C_{id} f_{dk} m_p (1 - \epsilon_k) \quad 3.4$$

- $A_{id}$  = total activity of nuclide  $i$  released in airborne dust during one year (Bq)  
 $C_{id}$  = concentration of nuclide  $i$  in dust (Bq/g)  
 $f_{dk}$  = mass fraction of dust in furnace type  $k$ , in relationship to molten metal poured (see Table B.3)  
 $m_p$  = total mass of metal produced in one year (g)  
 $\quad =$  annual production capacity of particular furnace or melt shop



$\epsilon_k$  = efficiency of APCD for furnace type  $k$

The total mass of slag and dust produced in a year is equal to the annual mass of metal produced multiplied by the mass fraction of slag or dust:

$$m_{jk} = f_{jk} m_p$$

$m_{jk}$  = mass of product  $j$  produced by furnace of type  $k$  during one year (g)

### 3.5.2 Maximum Single-Heat Concentrations

Equations 3.2 – 3.4 are used to calculate the radionuclide concentrations in scenarios in which the source of the activity is averaged over one year's output of the mill. This includes all scenarios where the exposure is to slag or dust, since these materials are processed, handled, and transported in a continuous stream. It also applies to the handling of finished metal at the melt shop, and to the transport of such metal. In all scenarios where the exposure is to a single item (or batch of items) made from such metal, it is conservatively assumed that each of these items was made from the single heat that contained the highest fraction of scrap at a given melt shop over the course of a year.

To calculate the radionuclide concentrations in metal produced from the maximum single heat, Equation 3.2 is modified as follows:

$$S_{ip} = f_{ip} [S_{is}(1 - f_{hk}) + C_{ip} f_{hk}] \quad 3.5$$

$S_{ip}$  = concentration of nuclide  $i$  in metal produced from maximum single heat (Bq/g)

$S_{is}$  = concentration of nuclide  $i$  in purchased scrap + virgin metal in maximum single heat (Bq/g)

$C_{ip}$  = annual-average concentration of nuclide  $i$  in metal (see Equation 3.2) (Bq/g)

Appendix K lists the mean and the 5th, 50th, 90th, and 95th percentile normalized undecayed concentration of each radionuclide in the furnace products of an EAF. The maximum single-heat concentrations in the metal product are calculated according to Equation 3.5, while the annual-average concentrations in the metal product, slag and dust are calculated according to Equation 3.2. The total annual activity released to the atmosphere is the sum of the activities calculated by Equations 3.3 and 3.4. All concentrations and released activities are normalized to unit specific activity in scrap. Appendix K also lists the corresponding data for BOF and cast iron furnaces, respectively.

## 3.6 Exposure Pathways

As was noted in Section 1.6, the exposure pathways included in the present analysis fall into two categories: external and internal.

### 3.6.1 External Exposure

The general methodology of assessing external exposure is similar for all the radiological assessments in the present analysis. This pathway discussed in Section 1.6.1. For the purpose of assessing the dose from external exposure, the exposure scenarios fall into two broad categories:

1. Scenarios where the source of exposure is a steady stream of residually radioactive material.
2. Product use scenarios, where the individual is exposed to the same product during the entire assessment period.

#### 3.6.1.1 External Exposure to a Steady Stream of Material

External exposure to a steady stream of residually radioactive material is assessed as follows:

$$D_{ix} = C_{ij} F_{ix} t_{xy} U_x e^{-\lambda_i t_i} \quad 3.6$$

- $D_{ix}$  = dose from external exposure to nuclide  $i$  during assessment period ( $\mu\text{Sv}$ )
- $C_{ij}$  = average activity concentration of nuclide  $i$  in medium  $j$  (from Equation 3.2) ( $\text{Bq/g}$ )
- $F_{ix}$  = dose coefficient for external exposure to nuclide  $i$  ( $\mu\text{Sv/h per Bq/g}$ )
- $t_{xy}$  = exposure duration during assessment period (h)
- $U_x$  = uncertainty factor
- $\lambda_i$  = radioactive decay rate of nuclide  $i$  ( $\text{d}^{-1}$ )
- $t_i$  = interval from time scrap is cleared until scenario begins

The parameters  $F_{ix}$  and  $U_x$  are defined and discussed in Section 1.6.1. Unique aspects, specific to the individual scenarios, are discussed as part of the description of each scenario. Additional details are presented in Appendix C.

Strictly speaking, Equation 3.6 applies only to nuclides without radioactive progenies (other than the short-lived progeny assumed to be in secular equilibrium with the parent—see Appendix E), or to the parent nuclide of a radioactive decay chain. The dose contribution of progeny that exhibit significant ingrowth before or during the assessment period is explicitly included by modeling this ingrowth by means of the Bateman equations. The reported dose from a nuclide having such progeny includes this contribution. A complete list of both short-lived and longer-lived progenies included in the analysis appears in Table E.1.

The same comment applies to all calculations of radionuclide concentrations in the present analysis.

### 3.6.1.2 External Exposure to Single Product

Doses from external exposure to a single product are calculated as follows:

$$D_{ix} = C_{ij} f_{ix} t_{xy} \left( \frac{e^{-\lambda_1 t_a} - e^{-\lambda_1(t_s + t_a)}}{\lambda_1 t_a} \right) \quad 3.7$$

$D_{ix}$  = dose from external exposure during assessment period ( $\mu\text{Sv}$ )

$t_a$  = assessment period (d)

### 3.6.2 Internal Exposure

Internal exposure comprises two principal pathways: inhalation, and ingestion. A general discussion of the dose assessment of these pathways is presented in Section 1.6.2. A more specific discussion of the inhalation pathway, which is applicable to the assessment of steel scrap—and of other materials presented in Chapters 4 to 6—is presented below, followed by a discussion of inadvertent ingestion of particulate matter (secondary ingestion). Ingestion of residually radioactive food and water, and inadvertent ingestion of soil, are discussed as part of the description of the scenarios that include these pathways.

#### 3.6.2.1 Inhalation Exposure

In some work-related scenarios, some of the material being handled or processed (e.g., metallic particulates, slag, or EAF dust) would be dispersed into the air and inhaled by the exposed individual. The dose due to this exposure pathway is calculated as follows:

$$D_{ih} = C_{ij} F_{ih} R_h t_{iy} \chi_d e^{-\lambda_1 t_a} \quad 3.8$$

$D_{ih}$  = dose from inhalation of radionuclide  $i$  during assessment period ( $\mu\text{Sv}$ )

$F_{ih}$  = dose conversion factor (or dose coefficient) for inhalation of radionuclide  $i$  ( $\mu\text{Sv/Bq}$ )

$R_h$  = inhalation rate ( $\text{m}^3/\text{h}$ )

$t_{iy}$  = duration of internal exposure during assessment period (h)

$\chi_d$  = airborne concentration of dust (mass loading) ( $\text{g}/\text{m}^3$ )

The internal dose conversion factors used to calculate the effective dose equivalent (EDE) and the corresponding dose coefficients used to calculate effective dose are discussed in Section 1.6.2. The specific activities of airborne particulates are assumed to be the same as those of the material from which those particulates are generated, except in scenarios where the composition of the particulates is different than the composition of the originating material. These exceptions are discussed in the descriptions of the scenarios in Section 3.7.

Inhalation exposures also result from the emissions of airborne effluents from furnaces recycling steel scrap. These are described as part of the discussion of that scenario.

### Inhalation Rate

Two methods used to estimate inhalation rates for dose assessments are: (1) the tidal volume and frequency method (ICRP 1975, ICRP 1994, and EPA 1997), and (2) the method using oxygen demand based on metabolic conversion of food nutrients (Layton 1993). Although the latter method 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 EPA and ICRP base their average hourly inhalation rates on the tidal volume (L/breath) and the frequency (breaths/minute) for various activity levels; that is the method adopted for this study.

The inhalation rates in ICRP 1975 and EPA 1997 were reviewed to determine a reasonable range for the present analysis. ICRP 1975 lists an inhalation rate of 20 L/min for an adult man and 19 L/min for an adult woman. In calculating the regional deposition of inhaled aerosols in the Reference Worker, ICRP 1994 assumes inhalation rates for light activity which have a time-weighted average of 1.2 m<sup>3</sup>/h (20 L/min). This value was adopted as both the mean and the most likely value in estimating the inhalation exposures of workers in the present analysis. EPA 1997 (Chapter 5) cites a number of studies performed under a variety of conditions. The study which agrees best with the ICRP model—the field protocols reported by Adams—lists a mean adult inhalation rate of 0.6 m<sup>3</sup>/h for sedentary activities, 1.2 m<sup>3</sup>/h for light activities, and 1.8 m<sup>3</sup>/h for moderate activities. Based on these data, this parameter was assigned a triangular distribution, with a mode of 1.2 m<sup>3</sup>/h and a range of 0.6 – 1.8 m<sup>3</sup>/h.

Although both higher and slightly lower inhalation rates for various activities have been reported, our purpose in assigning values to this parameter is to estimate the inhalation exposures of members of the critical group over the course of one year. An individual experiencing a high inhalation rate during heavy exertion would not maintain such a rate during his entire workday, much less during every workday over the course of a year.

#### 3.6.2.2 Inadvertent (Secondary) Ingestion

Material that is dispersed into the air would also be deposited on accessible surfaces. Secondary ingestion comprises the ingestion of residually radioactive material from contaminated hands and food. Every work-related scenario assessment that includes the inhalation pathway also includes inadvertent secondary ingestion. The dose from this exposure pathway is calculated as follows:

$$D_{ig} = C_i F_{ig} I_s t_{iy} e^{-\lambda_i t_i} \quad 3.9$$

$D_{ig}$  = dose from ingestion of radionuclide  $i$  during the assessment period ( $\mu$ Sv)

$F_{ig}$  = dose conversion factor for ingestion of radionuclide  $i$  ( $\mu$ Sv/Bq)

$I_s$  = secondary ingestion rate (g/h)

The rate of secondary ingestion is a highly uncertain parameter. EPA 1997 presents a detailed discussion of soil and soot ingestion, primarily by children. Estimates of daily ingestion by adults range from 0.56 mg of "housedust" during "typical living space activities" to 480 mg of soil while gardening. Table 4-15 of EPA 1997 cites an adult soil ingestion rate from gardening of 20 mg/h, cited by Sheppard for assessment purposes. This appears to be a reasonable estimate of the maximum hourly rate, averaged over one year of exposure in a work-related scenario, and is the value adopted for the exposure of the "reasonably maximally exposed individual" in the scrap metal recycling assessments by Anigstein et al. (2001). A minimum value of the ingestion rate is zero. This corresponds to the ingestion of workers practicing good industrial hygiene. Some scrap metal processors, for example, prohibit eating or smoking in the workplace.<sup>39</sup> In addition, many workers wear heavy gloves and/or use respiratory protection, both of which would minimize hand-to-mouth transfer. The parameter  $I_s$  was assigned a uniform distribution of 0 – 0.02 g/h.

### 3.7 Dose Assessment of Recycling and Disposal of Steel Scrap

The exposure scenarios for the steel scrap analysis are based on the schematic flow diagram of the recycling and/or disposal of steel scrap presented in Figure 3.1. These scenarios fall into six general categories, corresponding to the six headings shown in boldface type in Table 3.10. The table lists the full descriptive title and short name—or abbreviation—of each individual scenario, the mixing factor for that scenario (as mentioned earlier), and which of the three principal exposure pathways are addressed in the analysis of each scenario. A complete list of parameters characterizing the various scenarios and their values and distributions is presented in Table B.8.

#### 3.7.1 Handling and Processing Scenarios

After clearance of scrap metal from an NRC-licensed facility, scrap and the various products of the melting and refining process (slag, dust, and metal products) would be handled and processed in a number of settings. The handling and processing scenarios analyzed for the present analysis encompass a range of representative activities.

Generic scenarios for industrial workers use a range of values that reflects varying operational practices among scrap yards and melt shops. The duration of exposure is limited to the time that a worker would reasonably spend working with or in close proximity to residually radioactive material. Even though the exposed individual would be primarily engaged in handling scrap or furnace products, for example, he is unlikely to spend each full workday exposed to such materials. Other activities 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 of daily exposure times that often did not span a full workday is assigned to some scenarios to account for these other activities.

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<sup>39</sup> Norb Geiss, The David J. Joseph Company, private communication with Robert Anigstein and William C. Thurber, SC&A, Inc., February 14, 2003.

Table 3.10 Scenario and exposure pathway matrix

Scenario abbreviation	Scenario title	MF <sup>a</sup>	Pathways <sup>b</sup>		
			Ext <sup>c</sup>	Inh	Ing
<b>Handling and Processing</b>					
Scrap yard	Processing steel scrap at scrap yard	SD	1	●	●
Handling slag	Handling slag at steel mill	AA	F1	●	●
Transferring EAF dust	Transferring EAF dust at steel mill	AA	4	●	●
Baghouse maintenance	EAF Baghouse maintenance	AA	10		
Handling metal product	Handling metal product at steel mill or foundry	AA	5	●	●
Processing EAF dust	Processing EAF dust	DP	3	●	●
Processing steel slag	Processing steel slag for road construction	AA	2	●	●
<b>Atmospheric Release</b>					
Airborne emissions	Emission of airborne effluents from furnace	AA	F2	●	●
<b>Transportation</b>					
Scrap truck-driver	Truck driver hauling cleared steel scrap	N	8		
Slag truck-driver	Truck driver hauling slag	AA	9	●	●
EAF dust-bulk trailer	Truck driver hauling EAF dust in dry bulk trailer	AA	11		
EAF dust-dump trailer	Truck driver hauling EAF dust in dump trailer	AA	12	●	●
Metal product-driver	Truck driver hauling steel products	AA	13		
<b>Product Use</b>					
Sailor-operations	Sailor with watch station in operations area	AA	19		
Sailor-deck duty	Sailor with watch station on deck	AA	19		
Building road with slag	Building road using steel slag	AA	F1	●	●
Driving on slag road	Driving on road built with steel slag	AA	F1		
Slag basement	Living in basement built with cement made from slag	AA	7		
Exposure to large mass	Exposure to large metal mass	SH	2		
Exposure to small mass	Exposure to small metal mass	SH	3		
Steel object on body	Small steel object on body	SH	6		
Home with steel studs	Living in home built with steel studs	SH	15		
Driver-automobile	Driver of automobile with cast iron engine block	SH	16		
Driver-diesel engine	Driver of truck with cast iron diesel engine block	SH	17		
Sailor-hull plate	Sailor berthing near steel hull plate	SH	18		
<b>Landfill Disposal</b>					
Scrap disposal-industrial	Handling steel scrap at an industrial landfill	IL	F1		
Scrap disposal-municipal	Handling steel scrap at a municipal landfill	ML	F1		
Dust disposal-industrial	Handling BOF/foundry dust at an industrial landfill	IL	F1		
Dust disposal-municipal	Handling BOF/foundry dust at a municipal landfill	ML	F1		
Slag disposal-industrial	Handling slag at an industrial landfill	IL	F1	●	●
Slag disposal-municipal	Handling slag at a municipal landfill	ML	F1	●	●
EAF dust disposal	Handling EAF dust at a hazardous waste landfill	HL	F1		
<b>Groundwater Infiltrated by Leachate from Landfills or Storage Piles</b>					
Leachate-industrial-scrap	Leachate from industrial landfill-scrap	IL			●
Leachate-municipal-scrap	Leachate from municipal landfill-scrap	ML			●
Leachate-industrial-dust	Leachate from industrial landfill-BOF/foundry dust	IL			●
Leachate-municipal-dust	Leachate from municipal landfill-BOF/foundry dust	ML			●
Leachate-steel slag	Leachate from slag storage pile	AA			●

## Notes to Table 3.10

<sup>a</sup> MF = mixing factor (see text—additional details in Appendix D): AA = annual average, DP = EAF dust processing, HL = hazardous waste landfill, IL = industrial landfill, ML = municipal landfill, N = no mixing, SD = scrap dealer, SH = maximum single heat

<sup>b</sup> Ext = external, Inh = inhalation, Ing = ingestion

<sup>c</sup> External exposure dose coefficients (details in Appendix C):

- 1 Scrap pile
- 2 Slag pile
- 3 Dust pile
- 4 Baghouse
- 5 Large metal object
- 6 Small metal object
- 7 Small object next to body
- 8 Scrap truck
- 9 Slag truck
- 10 Worker atop dust truck
- 11 Dust in dry bulk trailer
- 12 Dust in dump trailer: (a) driver's seat, (b) sleeper
- 13 Truck with I-beams
- 14 Cement basement
- 15 House with steel studs
- 16 Auto—cast iron engine block
- 17 Diesel truck: (a) driver's seat, (b) sleeper
- 18 Hull plate: (a) bunk, (b) lounge area
- 19 Steel ship: (a) berthing, (b) mess and lounge, © operations, (d) deck
- F1 Soil contaminated to an infinite depth (Eckerman and Ryman 1993)
- F2 Contaminated ground surface (Eckerman and Ryman 1993)

### 3.7.1.1 Processing Steel Scrap at a Scrap Yard

Following clearance from an NRC-licensed facility, scrap metal would be transported to a scrap yard, where it would be unloaded, processed, and prepared for shipment to a melter. The scrap processing scenario describes the exposure of a scrap yard worker while shearing or torch-cutting the metal, briquetting or crushing thin and lightweight materials, and baling. The daily duration of external and internal exposure is assigned a range of 4 – 6 h, based on information furnished to SC&A personnel during visits to two scrap yards processing ferrous metal scrap. This individual is assumed to work 250 days per year.

The source of external exposure is a 3,500-ton (3,175 t) pile of steel scrap, at an average distance of 2 m from the worker. (The size is based on the sizes of ferrous metal scrap piles observed by SC&A personnel during a visit to a large scrap yard.)

The airborne concentration of dust that is the source of inhalation exposure was modeled on the basis of data collected by the U.S. Occupational Safety & Health Administration (OSHA) at the site of the World Trade Center in New York. As described by OSHA (2002a):

OSHA has taken a total of 1331 samples (excluding bulk and blank samples) to monitor worker exposures to dusts, fumes, oxides, and other compounds of metals such as antimony,

beryllium, chromium, cobalt, copper, iron, lead, manganese, mercury, molybdenum, nickel, vanadium, zinc, cadmium, magnesium, and arsenic. To minimize the length of the "WTC OSHA Heavy Metal Monitoring Data tables" only the samples that showed detected results for these metals are listed.

Of particular interest to the present assessment are 515 measurements of iron oxide concentrations based on samples collected by personal monitors worn by various workers (OSHA 2002 b – 2002 e). Each sample spanned a period which appears to correspond to the daily duration of exposure, ranging from 30 min to 9.5 h, with a mean duration of 5.84 h. Because the present radiological assessment assumes that all existing health and safety regulations would be adhered to, we deleted 24 measurements that showed average daily concentrations in excess of the OSHA limit of 10 mg/m<sup>3</sup>, leaving a data base of 491 average daily concentrations. Since the scrap yard worker is assumed to work 250 days a year, we created a random sample of 250 of these concentrations. The average of these 250 values represents an average annual concentration. This annual average was calculated 10,000 times—once for each realization of the scrap yard worker's dose assessment.

The measurements of iron oxide reflect the fact that the iron or steel being processed oxidizes upon being suspended as an aerosol. However, the residual radioactivity of such dust originates in the metal. The iron oxide is assumed to be Fe<sub>2</sub>O<sub>3</sub>, which contains 69.94% Fe by weight. Consequently, in calculating the inhalation dose to the scrap yard worker, a factor of 0.6994 was inserted into Equations 3.8 and 3.9 to adjust for the Fe content of the dust.

### 3.7.1.2 Handling Slag at Steel Mill

The exposed individual in the slag handling scenario is a worker at a steel mill who transfers slag using a front-end loader. The slag is spread over a large, flat area—the vehicle is either on top or at the edge of the pile. Because, as is discussed on page 3-42, this worker performs other duties, as well as being away from the slag pile while transferring the load to a waiting transport vehicle, the daily exposure duration is assigned a uniform distribution of 2 – 6 h. This individual is assumed to work 250 days per year.

The dose from external exposure is calculated as follows:

$$D_{ix} = C_{ig} F_{ix} S_{vx} t_{dy} t_{xd} U_x e^{-\lambda t} \quad 3.10$$

- $C_{ig}$  = average activity concentration of nuclide  $i$  in slag (Bq/g)
- $F_{ix}$  = dose coefficient for external exposure to nuclide  $i$  ( $\mu$ Sv/h per Bq/g) from Federal Guidance Report (FGR) 12: soil contaminated to an infinite depth (Eckerman and Ryman 1993)
- $S_{vx}$  = vehicle shielding factor

The vehicle shielding factor,  $S_{vx}$ , accounts for the shielding afforded by the loader. 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. Based on calculated transmission factors, this parameter is assigned a triangular distribution with a range of 0.3 – 0.7 and a mode of 0.5.

The uncertainty factor,  $U_x$ , is used to account for different locations of the worker with respect to the slag. If he is on top of the slag, he is exposed to an effectively infinite slab of slag, which conforms to the exposure conditions modeled in FGR 12, so  $U_x = 1$ . When he is loading slag from the edge of the large, flat pile, he is exposed to one-half of an infinite slab, so  $U_x = 0.5$ . Therefore,  $U_x$  is assigned a uniform distribution of 0.5 – 1.

The airborne concentration of the principal components of steel slags, such as those listed on page 3-13, are subject to the same OSHA protective exposure limit (PEL) as nuisance dust, which is 5 mg/m<sup>3</sup> for respirable particles. Because the limit is a time-weighted average (TWA) that applies to any given 8-hour shift, the annual average concentration would be significantly less than this limit. In the present analysis, the annual average airborne dust concentration is modeled as a truncated lognormal distribution, with a range of zero to 5 mg/m<sup>3</sup> and a mean of 2.5 mg/m<sup>3</sup>.

### 3.7.1.3 Transferring EAF Dust at Steel Mill

The EAF dust transfer scenario describes a steel mill worker transferring EAF dust from a hopper underneath the baghouse to a dry-bulk trailer in preparation for shipment. The worker stands on top of the trailer while the dust is being loaded via an overhead chute or conveyor belt.

External exposure is from the dust in the trailer, which is realistically modeled, based on engineering drawings and other information from The Heil Co., the manufacturer of one of the trailers known to be used for transporting EAF dust.<sup>40</sup> Because some dust would become airborne during this transfer, the dust concentration is modeled by the same distribution used in the slag-handling scenario.

The actual transfer takes from 30 minutes to one hour. The annual exposure duration depends on the number of truckloads of dust generated by the steel mill in one year, which is calculated as follows:

$$n_L = \frac{M_d}{m_L}$$

$n_L$  = number of truckloads required to haul away EAF dust generated in one year

$M_d$  = mass of dust generated by given steel mill in one year (t)

$m_L$  = mass of load (t)

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<sup>40</sup> David Fellows, The Heil Co., Mid West Region, Delafield, WI, private communication with Robert Anigstein, SC&A, Inc., September 15, 1993.

The dose from external exposure is calculated by means of Equation 3.6, while that from internal exposure is by means of Equations 3.8 and 3.9, with

$$t_{xy} = t_{iy} = n_L t_{tr} \quad 3.11$$

#### 3.7.1.4 EAF Baghouse Maintenance

Steel mill workers are occasionally assigned to spend a day repairing or changing the baghouse filters. Such a worker typically spends four to six hours<sup>41</sup> in the midst of the suspended filters in the dust-laden atmosphere of the baghouse, wearing a respirator equipped with a full facepiece. While performing such maintenance, the worker would be exposed to external radiation from the residual dust that is retained in the filters after they are emptied. At a typical facility, this procedure is carried out an average of seven times per year (Anigstein et al. 2001, Section 5.4.4). Because different workers may be assigned this task over the course of a year, the exposure may take place as little as one day a year, or as much as 10 days a year if one worker is always assigned this duty. (This work is sometimes performed by outside contractors—the same individual might then visit the same mill several times a year).

The use of the respirator, as well as SCBA and supplied air, as needed, precludes any significant internal exposures, which are therefore not addressed in this scenario.

#### 3.7.1.5 Handling Metal Product at Steel Mill or Foundry

The metal handling scenario addresses the potential exposure of an individual performing a variety of tasks at a steel mill or foundry. Even though merely handling the metal products will not generate airborne dust, other processing activities ongoing at the melt shop (melting, pouring molten steel, water-cooling steel, etc.) would cause metal dust to be suspended in the air.

External exposure is to a 200-kg mass of metal at an average distance of 2 m. The airborne dust concentration is modeled by the same distribution used in the slag-handling scenario described in Section 3.7.1.2. Because the particulate matter would most likely be in the form of iron oxide, a factor of 0.6994 was inserted into Equations 3.8 and 3.9 to adjust for the Fe content of the material being inhaled or ingested. Due to the generic nature of the scenario, the exposure duration has a range of 4 – 8 h/day.

#### 3.7.1.6 Processing EAF Dust

The EAF dust processing scenario addresses a worker at a processing facility working near a pile of EAF dust. The same scenario would represent workers at an HTMR facility (e.g., HRDC). The source of external exposure is an 8,000-ton (7.26 kt) pile of EAF dust, at an average distance of 2 m. The size of the pile is estimated by assuming that the Envirosource facility in Ohio, which has an annual capacity of 200,000 tons (180 kt), as noted in Section 3.2.4.1, would have a

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<sup>41</sup> Rest periods necessitated by work in a confined area and the need to don and remove protective clothing restrict the amount of time the worker can spend on this task.

backlog of about two weeks of material. The airborne dust concentration is modeled by the same distribution used in the slag-handling scenario described in Section 3.7.1.2. The exposure duration has a range of 2 – 6 h/d and occurs 250 d/y.

A mixing factor specific to this scenario is described in Section 3.4.2.4.

### **3.7.1.7 Processing Steel Slag for Road Construction**

The slag processing scenario addresses the exposure of a worker at a processing facility working near a slag pile. The same types of activities that occur at a facility processing EAF dust would occur here. The source material is limited to steel slags, since foundries usually do not generate enough slag for commercial use to be economically viable.

The source of external exposure is a 20-kt pile of steel slag. The size, rounded to one significant figure, is based on the requirements of the State of Ohio Department of Transportation (1998). To be acceptable for embankments, BOF slag must be aged for a minimum of six months, in stockpiles that contain no more than 23 kt. (Ohio does not have a specification for EAF slag.) The airborne dust concentration is modeled by the same distribution used in the slag-handling scenario described in Section 3.7.1.2. The exposure duration has a range of 2 – 6 h/d and occurs 250 d/y.

### **3.7.2 Emission of Airborne Effluents from Furnace**

When cleared scrap is melted and refined, nearby residents would be potentially exposed to airborne radioactive effluents released from the furnace. The airborne emissions scenario takes place near a steel mill or foundry that is recycling scrap metal cleared from a nuclear facility. The exposed individual lives near the melt shop year round and his diet includes a certain fraction of home-produced fruits, vegetables, milk and meat.

This scenario includes the exposure pathways illustrated in Figure 3.3.

The airborne effluent emissions are either gaseous or are particulates that escape the air pollution control system at the melt shop. Average air pollution control efficiencies range from 78% for induction furnaces to 99.9% for EAFs. However, some smaller cupola furnaces, and most small induction furnaces, do not employ APCDs (see Section 3.3.1.3).

To simplify the notation, the expressions for radioactive decay are not explicitly incorporated in the expressions for radionuclide or activity concentrations in the following discussion of this scenario. However, radioactive decay from the time of clearance is accounted for in the calculations.

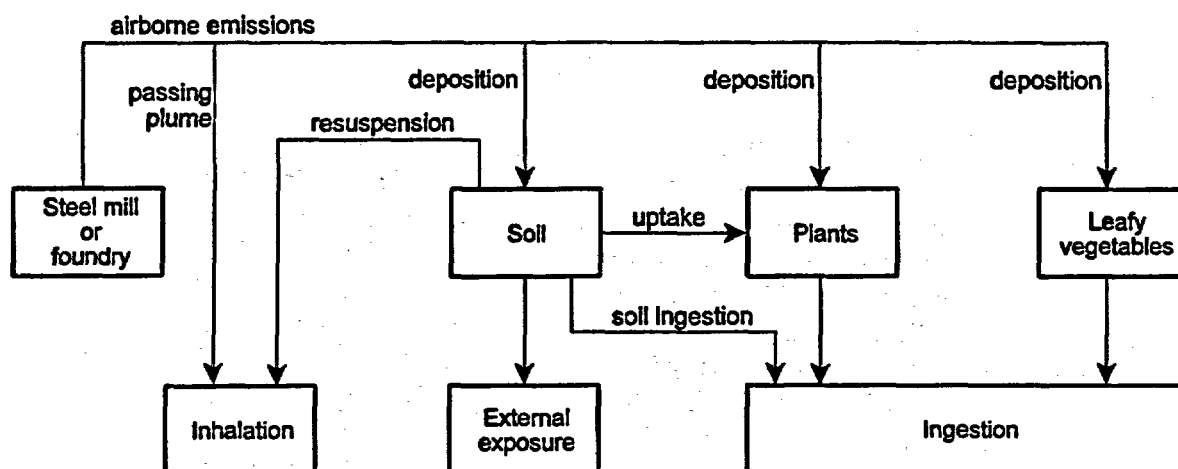


Figure 3.3 Schematic diagram of airborne emissions scenario

### 3.7.2.1 Atmospheric Dispersion Term

The effluent emissions from the melt shop form a plume that undergoes dispersion due to the turbulence of the atmosphere as it is transported downwind from the facility. The downwind concentrations of such gaseous effluent emissions are usually estimated by means of one of several Gaussian dispersion models. These concentrations are used to assess the exposures of the nearby residents.

The sector-averaged Gaussian plume model assumes that *within* each sector the pollutant concentration will not vary with the angular coordinate (i.e., the direction) of the receptor with respect to the emission source. For a release rate that is steady during the course of a year, the average concentration of a given atmospheric pollutant at a given distance from the emission point in a given sector is calculated according to the following equation:

$$\overline{\chi_k(x)} = \frac{2.032 Q}{x} \sum_{ij} \frac{f_{ijk} e^{-\frac{1}{2} \left( \frac{h_e}{\sigma_{zj}(x)} \right)^2}}{u_i \sigma_{zj}(x)} \quad 3.12$$

$\overline{\chi_k(x)}$  = average radionuclide concentration at distance  $x$  in sector  $k$  (Bq/m<sup>3</sup>)

$Q$  = radionuclide release rate (Bq/s)

$f_{ijk}$  = joint frequency of Pasquill stability class  $j$  and wind speed  $i$  in sector  $k$

$h_e$  = effective release height (m)

$\sigma_{zj}(x)$  = vertical standard deviation of plume for stability class  $j$  at distance  $x$  (m)

$x$  = distance to receptor (m)

$u_i$  = mean speed of wind-speed range  $i$  in sector  $k$  (m/s)

The ratio of the radionuclide concentration to the release rate is known as the sector-averaged atmospheric dispersion factor,  $(\overline{\chi/Q})_k$ , or, more commonly,  $\chi/Q$ .

An examination of the available STAR (STability ARray) data obtained from the Department of Energy<sup>42</sup> showed that complete data, including all seven atmospheric stability classes, were available for only 54 locations in the contiguous 48 states. These data, comprising locations in 25 different states, are assumed to be representative of conditions nationwide. The methodology for calculating dispersion factors in the present analysis is similar to that prescribed by the NRC meteorology branch for licensees to follow in performing their own off-site impact analyses. This methodology is described in Regulatory Guide 1.111 (NRC 1977) and embodied in the computer code XOQDOQ (Sagendorf et al. 1982). The analysis is designed to determine the annual-average atmospheric dispersion factor ( $\chi/Q$ ), as well as the annual-average ground deposition factor ( $D/Q$ ), for each wind sector at each of the above-mentioned 54 locations.

This approach evaluates each of the 16 wind sectors and selects the sector where the atmospheric and ground concentrations would be the highest on an annual-average basis. For each of these 16 sectors, the analysis used each of the 42 calculated  $\chi/Q$ 's (6 windspeed classes  $\times$  7 stability classes), weighted by the frequency of occurrence, to calculate the annual-average dispersion factor for that sector. The exposed individual is assumed to live 1 km from the emission source in the compass sector having the highest annual-average  $\chi/Q$  for the given location. The 54 sets of dispersion and deposition coefficients are then used to construct a probability distribution for use with the Monte Carlo analysis of the scenario.

Equation 3.12 applies if the release point is higher than twice the height of adjacent structures. Regulatory Guide 1.111, Regulatory Position 2. b, "Releases Other than Elevated," states that releases from points less than the height of adjacent buildings should be treated as ground-level releases. For releases at an intermediate height (higher than adjacent structures, but less than twice the height), detailed information regarding the exit velocity of the plume is required. If the exit velocity is unknown, a ground level release is to be assumed. Since detailed information on exit velocities that would be representative of the over 1,000 iron- and steelmaking facilities covered by our analysis are not available, ground-level releases were assumed for the purpose of these calculations.

For ground level releases, the atmospheric dispersion factor is calculated as follows:

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<sup>42</sup> Barry Parks, U.S. Department of Energy, private communication with Robert Anigstein, SC&A, Inc., April 10, 2002.

$$\chi/Q = \frac{2.032 f_D(x)}{x} \sum_{ij} \frac{f_{ijk}}{u_i \Sigma_{zj}(x)}$$

3.13

$$\Sigma_{zj}(x) = \left( \sigma_{zj}^2(x) + \frac{D_z^2}{2} \right)^{1/2}$$

$$\leq \sqrt{3} \sigma_{zj}(x)$$

$\Sigma_{zj}(x)$  = vertical standard deviation of plume at distance  $x$ , with correction for additional dispersion within building wake cavity (m)

$f_D(x)$  = plume depletion factor at distance  $x$

$D_z$  = maximum adjacent building height either up- or downwind from release point

The algorithm for calculating the plume depletion factor is taken from a listing of the code XOQDOQ (Sagendorf et al. 1982). At a distance of 1 km from a ground-level release, it has a value of 0.9. This value can be confirmed by referring to Regulatory Guide 1.111 (NRC 1977, Figure 3).

Because of the variety of iron- and steelmaking facilities being modeled,  $D_z$  was assigned a uniform distribution of 15 to 50 m. These values were assigned on the basis of personal observations made during visits to several steel mills by SC&A staff members, an examination of photographs taken during these visits, and engineering judgment.

The methodology described above applies to gaseous releases. The concentrations of elemental radioiodines and particulates are depleted by fallout as the plume travels from the release point to the receptor location. This plume depletion effect is modeled by including the plume depletion factor,  $f_D(x)$ , in Equation 3.13. For gaseous releases,  $f_D(x) = 1$ .

### 3.7.2.2 Ground-Surface Concentration Resulting from Atmospheric Releases

The ground deposition rates of elemental radioiodines and particulates were calculated as a function of distance, in a manner similar to that used for the  $\chi/Q$  calculation described above.

$$D(x) = \frac{\pi f_D(x) f_p(x) Q}{8x} \sum_{ij} f_{ijk}$$

$D(x)$  = deposition rate of radionuclide at distance  $x$  (Bq/(s·m<sup>2</sup>))

$f_p(x)$  = relative deposition rate at distance  $x$  (m<sup>-1</sup>)

These ground deposition rates enable the calculation of annual-average areal concentrations of deposited radionuclides. These concentrations also include the activity that is weathered off plants. Therefore the total deposition rate was used in the calculation.

$$C_g(x) = D(x) \left( \frac{1 - e^{-\lambda t_b}}{\lambda} \right)$$

$C_g(x)$  = ground-surface radionuclide concentration at distance  $x$  (Bq/m<sup>2</sup>)

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

$\lambda$  = radioactive decay constant (d<sup>-1</sup>)

The volumetric radionuclide concentration in the soil is calculated as follows:

$$C_{s(0)}(x) = \frac{C_g(x)}{d_1 \rho_s}$$

$C_{s(0)}(x)$  = soil radionuclide concentration at distance  $x$  at time of scenario (Bq/g)

$d_1$  = thickness of surface soil layer (m)

$\rho_s$  = average density of soil in surface layer (g/m<sup>3</sup>)

### 3.7.2.3 Concentration in Edible Parts of Plants

The radionuclide concentration in the edible parts of plants at the time of harvest is described by Equation 3.14. 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 3.15 and 3.16, respectively.

$$C_v = D \left[ \frac{r \left( 1 - e^{-\lambda_e t_{pv}} \right)}{Y_v \lambda_e} + \frac{B_{iv} \left( 1 - e^{-\lambda_j t_b} \right)}{\lambda_j P} \right] \quad 3.14$$

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

$r$  = the fraction of total material being deposited that is intercepted by crops

- $\lambda_e$  = effective weathering and decay constant at harvest ( $d^{-1}$ )  
 =  $\lambda_j + \lambda_w$   
 $\lambda_j$  = radioactive decay constant of nuclide  $j$  ( $d^{-1}$ )  
 $\lambda_w$  = weathering constant ( $d^{-1}$ )  
 $t_{v}$  = time period that crops  $v$  are exposed to contamination during 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  $v$  (dimensionless)  
 $P$  = areal soil density (kg/ $m^2$ )

The areal soil density ( $P$ ) is the product of the bulk density of soil and the mixing depth of the soil layer. The bulk density,  $1.6 \text{ g/cm}^3$ , is taken from FGR 12 (Eckerman and Ryman 1993), while the thickness of the soil layer is the plow depth: 0.15 m. Values for most environmental and biotic transport of radionuclides were fixed and were taken from Kennedy and Strenge (1992).

The concentration of C-14 in plants is calculated as follows:

$$C_{v,C-14} = \frac{f_{v,C} \chi_{C-14}}{\chi_C} \quad 3.15$$

- $C_{v,C-14}$  = concentration of C-14 in edible part of plant  $v$  (Bq/g wet-weight plant)  
 $f_{v,C}$  = fraction of total plant mass that is stable carbon  
 = 0.11  
 $\chi_{C-14}$  = concentration of C-14 (as  $^{14}\text{CO}_2$ ) in air at receptor location (Bq/ $m^3$ )  
 $\chi_C$  = concentration of stable carbon (as  $\text{CO}_2$ ) in the atmosphere  
 =  $0.16 \text{ g/m}^3$

The concentration of H-3 in plants due to airborne effluent emissions is calculated as follows:

$$C_{v,H-3} = \frac{f_{H_2O} \Gamma_{H-3} \chi_{H-3}}{H} \quad 3.16$$

- $C_{v,H-3}$  = concentration of H-3 in edible part of plant  $v$  (Bq/g wet-weight plant)  
 $f_{H_2O}$  = fraction of total plant mass that is water  
 = 0.75  
 $\Gamma_{H-3}$  = ratio of tritium concentration in plant water to tritium concentration in atmospheric water  
 = 0.5  
 $\chi_{H-3}$  = concentration of H-3 (as THO) in air at receptor location (Bq/ $m^3$ )



$H$  = absolute humidity of the atmosphere at receptor ( $\text{g}/\text{m}^3$ )

Till and Meyer (1983) state that atmospheric humidity varies greatly from one location to another in the United States. A map in that reference divides the continental United States into five regions, each with a different range of absolute humidity. The values range from a low of  $3.5 \text{ g}/\text{m}^3$  in the Rocky Mountain region to a high of  $16.2 \text{ g}/\text{m}^3$  along the Gulf Coast (Till and Meyer 1983, Figure 9.1). The areas of these five regions were used to derive a frequency distribution of the mean absolute humidity in each region, which is listed in Table 3.11.

**Table 3.11 Absolute Humidity in Continental United States**

Percentage of U.S.	Average absolute humidity ( $\text{g}/\text{m}^3$ )
40%	4.9
20%	6.6
20%	8.4
15%	10.7
5%	13.8
Weighted average	7.3

A triangular distribution was assigned to this parameter, with a range of  $3 \text{ g}/\text{m}^3$  to  $16 \text{ g}/\text{m}^3$  and a mode of  $7 \text{ g}/\text{m}^3$ , based on the extreme values cited in Till and Meyer's map, and the mean value from the distribution in Table 3.11, rounded to one significant figure.

Plants for human consumption are assumed to have a holdup period before being consumed. The radionuclide concentration in plants at the end of the holdup period is calculated as follows:

$$C_{v,h} = C_v e^{-\lambda t_h}$$

$C_{v,h}$  = radionuclide concentration in edible part of plant  $v$  for human consumption at the end of the holdup period ( $\text{Bq}/\text{g}$  wet-weight plant)

$\lambda$  = radioactive decay constant ( $\text{d}^{-1}$ )

$t_h$  = holdup period between harvesting and consumption (d)

#### 3.7.2.4 Dose Calculation

The source of external exposure is the surficial activity concentration on the soil as a result of deposition from the plume. The exposed individual is assumed to spend certain amounts of time indoors, outdoors, and at other locations away from the source of exposure. The dose from external exposure is calculated as follows:

$$D_{ix} = C_{is} F_{ix} (S_{sx} t_{id} + t_{od})$$

$C_{is}$  = areal activity concentration of nuclide  $i$  on ground surface (Bq/m<sup>2</sup>)

$F_{ix}$  = dose coefficient for external exposure to nuclide  $i$  on contaminated ground surface (μSv/h per Bq/g) (from FGR 12)

$S_{sx}$  = indoor shielding factor

$t_{id}$  = time spent indoors during assessment period (h)

$t_{od}$  = time spent outdoors during assessment period (h)

Values for the parameter  $S_{sx}$  were developed from the values used in Kennedy and Strenge (1992), because they represented reasonable values for a residence.

Doses from the inhalation of effluents in the passing plume and inhalation of suspended particles of soil are calculated as follows:

$$D_{ih} = (A_{ip} + A_{ir}) F_{ih}$$

$A_{ip}$  = activity of nuclide  $i$  inhaled directly from passing plume during assessment period (Bq)

$A_{ir}$  = activity of nuclide  $i$  inhaled due to resuspension of soil during assessment period (Bq)

The activity inhaled directly from the passing plume is calculated as follows:

$$A_{ip} = (R_{hs} R_{so} t_s + R_{hod} t_{od}) \chi_i$$

$R_{hs}$  = breathing rate for indoor activities (m<sup>3</sup>/h)

$R_{so}$  = ratio of indoor to outdoor radionuclide concentrations

$R_{hod}$  = breathing rate for normal activities outdoors (m<sup>3</sup>/h)

$\chi_i$  = average concentration of radionuclide  $i$  in ambient air from passing plume, from Equation 3.12 (Bq/m<sup>3</sup>)

$R_{so}$  is assigned a value of 0.40, based on Alzona et al. (1978), who estimated that the dust level inside a building is about 40% of that outdoors—conditions within a plume are similar to those resulting from suspended soil.

The activity inhaled as a result of resuspension of the soil at a residence is calculated by Equation 3.17. 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, 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).

$$A_{ir} = \left[ R_{hdd} t_{dd} \chi_{dd} + R_{hod} (t_{od} - t_{dd}) \chi_{do} + R_{hs} t_s (\chi_s + F_r P_d) \right] \frac{C_{is}}{\rho_s d_s} \quad 3.17$$

$R_{hdd}$  = breathing rate for dusty activities outdoors ( $m^3/h$ )

$t_{dd}$  = time spent on dusty activities outdoors (h)

$\chi_{dd}$  = concentration of resuspended soil in ambient air during dusty activities outdoors ( $g/m^3$ )

$\chi_{do}$  = concentration of resuspended soil during normal activities outdoors ( $g/m^3$ )

$\chi_s$  = concentration of resuspended soil blown indoors ( $g/m^3$ )

$F_r$  = indoor resuspension factor ( $m^{-1}$ )

$P_d$  = indoor dust-loading on floors ( $g/m^2$ )

$C_{is}$  = ground surface concentration of radionuclide  $i$  ( $Bq/m^2$ )

$\rho_s$  = average density of soil in surface layer ( $g/m^3$ )

$d_s$  = thickness of soil layer available for resuspension (resuspension layer) (m)

The thickness of the soil layer that is available for suspension,  $d_s$ , is used to calculate the ambient radionuclide concentrations due to resuspension. The types of human activities that could cause resuspension are walking or driving on packed dirt or roadways. A value of 1 cm (0.01 m) is used for  $d_s$ , based on the assumption that the particles that are deposited on the soil during an atmospheric release would not be mixed deeper into the soil under normal conditions.

Food pathways comprise plant products grown at the receptor location, milk produced by a cow that consumes forage grown on the same location, meat from animals raised on site, and secondary (inadvertent) ingestion of surface soil on site. The calculation of doses via this pathway involves the following assumptions:

- 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 food crops and forage is not included.
- The concentration of C-14 and H-3 in the edible parts of the plant due to atmospheric release is calculated separately, using different equations.
- The harvested crops and animal products for human consumption are retained during a holdup period before being consumed. Radioactive decay during the holdup 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.

The dose from ingestion of contaminated plants and soil is calculated as follows:

$$D_{if} = \left[ f_{hv} (C_{il} U_l + C_{iv} U_v) + f_{hf} C_{if} U_f + f_{hm} C_{im} U_m + f_{hk} C_{ik} U_k + C_{is} U_s \right] F_{ig}$$

$f_{hv}$  = home-produced fraction of all vegetables (dimensionless)

$C_{il}$  = concentration of radionuclide  $i$  in edible part of leafy vegetables (Bq/kg wet-weight)

$U_l$  = human consumption rate of leafy vegetables (kg/y wet-weight)

$C_{iv}$  = concentration of radionuclide  $i$  in edible part of non-leafy vegetables (Bq/kg wet-weight)

$U_v$  = human consumption rate of non-leafy vegetables (kg/y wet-weight)

$f_{hf}$  = home-produced fraction of fruit (dimensionless)

$C_{if}$  = concentration of radionuclide  $i$  in edible part of fruit (Bq/kg wet-weight)

$U_f$  = human consumption rate of fruit (kg/y wet-weight)

$f_{hm}$  = home-produced fraction of meat (dimensionless)

$C_{im}$  = concentration of radionuclide  $i$  in meat (Bq/kg wet-weight)

$U_m$  = human consumption rate of meat (kg/y wet-weight)

$f_{hk}$  = home-produced fraction of milk (dimensionless)

$C_{ik}$  = concentration of radionuclide  $i$  in milk (Bq/kg wet-weight)

$U_k$  = human consumption rate of milk (L/y)

$C_{is}$  = concentration of radionuclide  $i$  in soil (Bq/g dry-weight soil)

$U_s$  = human consumption rate of soil (g dry-weight soil/y)

The total annual intakes of milk, meat, fruit, leafy vegetables and other vegetables were based on data in the "Exposure Factors Handbook" (EPA 1997). The home-produced fraction of each of these foods was represented by a triangular distribution constructed from data on different population groups listed in EPA 1997. The lower limit of the distribution represents the average "central city" resident, the mode represents "nonmetropolitan" populations, while the maximum represents "households who farm."

The soil ingestion pathway also includes uncertainty, incorporated in the modeling via the parameter for consumption rate of soil,  $U_s$ . The range used is based on an extensive recent review of human ingestion of soil (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.”

### 3.7.3 Transportation Scenarios

Several stages of the flow diagram depicted in Figure 3.1 involve transportation. Scrap metal cleared from NRC-licensed facilities must be transported from a nuclear facility to the scrap yard or landfill site, and the metal products and by-products must be transported from a melt shop to manufacturers, processors, users, or disposal sites. Although these can occur by truck, rail, air (for some highly specialized metal products), or waterway, truck transportation is ubiquitous for most materials. Truck transportation also presents the highest potential doses to individuals because of long exposure times and small distances between the material and the driver. The potential critical group in each of the five transportation scenarios listed in Table 3.10 comprises truck drivers hauling cleared steel scrap or the products or by-products of the melting and refining of such scrap.

#### 3.7.3.1 Truck Driver Hauling Cleared Steel Scrap

This scenario describes the transportation of cleared scrap metal from the nuclear facility. As described in Section 3.2, the scrap metal can either be transported to a scrap dealer if it is destined for recycling, or to a waste disposal facility if the licensee or contractor so chooses. No internal exposures of drivers from surficial or volumetric contamination of the scrap are expected. According to a DOE handbook on airborne releases: No significant impacts [i.e., suspension] are anticipated for material that will undergo plastic deformation (e.g., metal, plastics, wood) during free-fall or upon impact with a hard, unyielding surface (DOE 1994).

The external exposure is from a 20-t truckload of cleared scrap. The exposure duration is based on information from the San Onofre Nuclear Generating Station (SONGS), which is currently undergoing decommissioning. A representative of SONGS stated that when scrap haulers come to the site, they arrive in a convoy of six to eight trucks, as opposed to one driver going back and forth, to remove the materials. They take the scrap to a location that is about 1 to 1½ hours from the site.<sup>43</sup> The analysis assumes that the same group of drivers would perform this work during the course of a year. The number of hours of exposure per year is therefore calculated as follows:

$$t_{xy} = \frac{M_0 t_t}{m_L N_d}$$

$M_0$  = mass of steel scrap cleared in one year (t)

$t_t$  = time per trip (h)

<sup>43</sup> Eric Goldin, San Onofre Nuclear Generating Station, private communication with Kathleen Behling, SC&A, Inc., February 21, 2002.

$N_d$  = number of drivers

### 3.7.3.2 Truck Driver Hauling Slag

Slag is typically transported from a steel mill or foundry to a slag processor by drivers employed by the processor. According to Kalyoncu (2002): "Most ferrous slag was transported less than 100 kilometers; trucks were the most economical means of transportation for such distances." Because the slag is transported in open dump trucks or dump trailers and the driver is present to operate the mechanism that unloads the trailer, internal exposures from airborne and deposited slag dust would occur during the loading and unloading of the truck.

The external exposure is from the 20-t truckload of slag during the time the driver is in the cab of the truck.

The airborne concentrations of respirable dust during loading and unloading were calculated from measurements of an EPA-sponsored study performed by the Midwest Research Institute (MRI) (Bohn et al. 1978, Tables B-3 and B-4). MRI performed six measurements of airborne dust concentrations generated by the load-out of processed slag into 35-ton (32-t) capacity dump trucks using a 10 yd<sup>3</sup> (7.6 m<sup>3</sup>) front-end loader. The data included measurements taken both upwind and downwind of the operation. Reported data included the total dust concentrations and the fractions with AMAD < 30 μm and < 5 μm.<sup>44</sup> In the present analysis, the concentrations of particles with AMAD < 10 μm were calculated by first subtracting the upwind (background) concentrations from the downwind measurements and then performing a log-log interpolation between the 30 μm and 5 μm values. A lognormal distribution was then derived, based on the mean and standard deviation of these results.

The hours of external exposure per year in driver's seat are calculated as follows:

$$t_{xyd} = \frac{M_g \bar{t}_w X}{m_L t_{dw} v}$$

$$\leq 52 t_w$$

$t_{xyd}$  = duration of external exposure in driver's seat (h/y)

$M_g$  = mass of slag generated in one year (t)

$X$  = distance traveled (mi)

$\bar{t}_w$  = average time in driver's seat hauling one-way load (h/w)

<sup>44</sup> AMAD is the acronym for Activity Median Aerodynamic Diameter, "[which] is the diameter of a unit density sphere with the same terminal settling velocity in air as that of an aerosol particle whose activity is the median of the entire aerosol." (Eckerman et al. 1988).

$\overline{t_{dw}}$  = average time driving with one-way load (h/w)

$v$  = average speed (mph)

$t_w$  = time in driver's seat hauling one-way load (h/w)

The time in the driver's seat is based on data on Type 2 (regional) drivers summarized in Table 3.12.

**Table 3.12 Weekly hours of Type 2 drivers**

	Average	Minimum	Maximum
On duty <sup>a</sup>	55	38	70
Driving <sup>a</sup>	49	30	65
In driver's seat <sup>b</sup>	51	32.7	66.7
Hauling one-way load <sup>c</sup>	26.5	17.7	34.2

<sup>a</sup> American Trucking Association 2000

<sup>b</sup> Estimated—see text

<sup>c</sup> One-way driving time is calculated by subtracting ½ of the time spent driving from the time in the driver's seat.

We estimate the time spent in the driver's seat on the basis of information from a representative of the American Trucking Association.<sup>45</sup> According to this source, examples of time behind the wheel include sitting at weighing stations, inspection station (typically between state borders), whether the driver loads or unloads his haul (meaning that if he does not help in the unloading, he may wait in vehicle), completing his daily logbook, etc. As much as one-third or more of the total "on-duty driving time" could be spent in the cab but not driving.

The time spent in the driver's seat is estimated by first subtracting the time spent driving from the total on-duty time, then adding one-third of this difference to the driving time. These data are assumed to represent averages over 52 weeks per year. The time spent in the driver's seat is estimated by first subtracting the time spent driving from the total on-duty time, then adding one-third of this difference to the driving time.

The duration of internal exposure is calculated as follows:

$$t_{iy} = n_t t_{it}$$

$t_{iy}$  = duration of internal exposure (h/y)

$n_t$  = number of trips per year

$t_{it}$  = time spent loading and unloading (h/trip)

<sup>45</sup> Fletcher Hall, American Trucking Association, private communication with Kathleen Behling, SC&A, Inc., April 8, 2002.

The number of trips per year is calculated as follows:

$$n_t = \frac{M_g}{m_L} \leq \frac{52 t_{dw} v}{X}$$

$t_{dw}$  = time in driver's seat hauling one-way load (h/w)

### 3.7.3.3 Transportation of EAF Dust

Three types of truck trailers are commonly used to transport EAF dust to a treatment and/or disposal facility. Two of these are explicitly addressed in the present analysis.

- Dry bulk trailer, which is a fully enclosed container that is unloaded pneumatically. The driver of the tractor hauling the trailer would not usually be exposed to any airborne or deposited dust—the trailer would not normally be attached to the tractor during the transfer of dust from the baghouse into the trailer. Therefore, only external exposure is included in this scenario.
- Dump trucks or dump trailers—open conveyances covered with tarpaulins. In such cases, drivers may be exposed to airborne or deposited dust during loading and unloading.
- Roll-off containers carried on truck-trailers. This scenario was not analyzed, since the exposures to drivers of such vehicles would be similar to or be bounded by the dump trailer scenario.

Drivers hauling EAF dust would work for a licensed hazardous waste hauler or disposal firm. It is therefore plausible that some drivers would carry this material year-round.

#### Truck Driver Hauling EAF Dust in a Dry Bulk Trailer

The external exposure of the driver is from the 20-t truckload of dust during transportation. The exposure duration is calculated in the same way as in the case of the driver hauling slag:

$$t_{xyd} = \frac{M_d \bar{t}_w X}{m_L \bar{t}_{dw} v} \leq 52 t_w$$

$M_d$  = mass of EAF dust captured in the baghouse in one year (t)

Because of the limited number of treatment and disposal facilities for EAF baghouse dust, as discussed in Section 3.2.4.1, such dust is likely to be transported over long distances. Therefore,



the drivers would fall into the "Type 1" category.<sup>46</sup> The weekly hours of Type 1 drivers are shown in Table 3.13.

The distance traveled is assigned a triangular distribution. The minimum distance—65 mi (~100 km)—is based on the transport of baghouse dust from a steel mill visited by SC&A staff members to a nearby processing facility. The average distance—1,000 mi (~1,600 km), used as the mode of the distribution—is based on information from a source in the steel recycling industry.<sup>47</sup> The maximum—2,000 mi (~3,200 km)—is based on the maximum likely driving distance from a U.S. steel mill to a domestic processing or disposal facility.

**Table 3.13 Weekly hours of Type 1 drivers**

	Average	Minimum	Maximum
On duty <sup>a</sup>	58	47	76
Driving <sup>a</sup>	52	38	67
In driver's seat <sup>b</sup>	54	41	70
Hauling one-way load <sup>c</sup>	28	22	36.5

<sup>a</sup> American Trucking Association 2000

<sup>b</sup> Estimated—see text

<sup>c</sup> One-way driving time is calculated by subtracting ½ of the time spent driving from the time in the driver's seat.

Based on an engineering drawing of a tractor-trailer combination furnished by The Heil Co., a manufacturer of dry bulk trailers, the tractor hauling the trailer is assumed to be equipped with a day cab (i.e., no sleeping compartment).<sup>48</sup>

### Truck Driver Hauling EAF Dust in a Dump Trailer

This scenario differs from the preceding one in two significant respects. First, the driver is assumed to drive a truck equipped with a sleeping compartment. Second, he is assumed to remain with his vehicle during loading and unloading, and to be exposed to airborne dust generated during the transfer.

The number of days of exposure in the sleeper is calculated as follows:

<sup>46</sup> According to FMCSA 2000, these are long-haul drivers who "... are away from their normal work reporting location and home for more than three days at a time; in total, they are away from home for a large part of the year."

<sup>47</sup> Ray Turner, The David J. Joseph Company, private communication with Robert Anigstein, SC&A, Inc., February 28, 2001.

<sup>48</sup> See Footnote 40 on page 3-46.

$$t'_{ys} = \frac{M_d X}{m_L t_{md} v}$$

$$\leq \frac{52 t_{dw}}{t_{md}}$$

$t'_{ys}$  = days of exposure per year in sleeper

$t_{md}$  = maximum permitted driving time without an 8-h rest period  
= 10 h

The hours per night spent in the truck's sleeper berth are based on a survey of long-distance drivers commissioned by the Federal Highway Administration (FHWA 1999). These data, which are listed in Table 3.14, were used to construct a cumulative distribution function for this parameter.

Table 3.14 Hours spent in truck sleeper berth

Uniform range:	2 - 3	4 - 5	6 - 7	8 - 9	10 - 12
Number of drivers	1	11	97	183	14
Percent	0.33%	3.59%	31.70%	59.80%	4.58%

Source: FHWA (1999)

The airborne dust concentration during the loading and unloading of the dump truck is assigned the same distribution as is used in the analysis of the driver hauling slag. The duration of internal exposure is also calculated in the same manner as that of the slag hauler, with the changes appropriate to the transportation of EAF dust (i.e., distances traveled, annual production of by-product, etc.)

### 3.7.3.4 Truck Driver Hauling Steel Products

Drivers hauling heavy loads, such as steel I-beams, in mountainous terrain, such as the area surrounding Pittsburgh, PA, are skilled and specialized in this work, and are likely to be employed full time carrying such cargo. The only exposure pathway is external exposure to the 20-t load of steel products. The hours of external exposure per year are calculated as follows:

$$t_{xy} = \frac{M_p \bar{t}_w X}{m_L \bar{t}_{dw} v}$$

$$\leq 52 t_w$$

$M_p$  = mass of metal produced in one year (t)

The distance traveled is represented by a beta distribution, with a mean value (276 mi [444 km]) based on the average distance for shipment of "Base metal in primary or semifinished forms and in finished basic shapes" (Bureau of the Census 1999). The minimum value is based on engineering judgment—50 mi (~80 km) results in an average exposure time of 1 hour. Although shorter trips are possible, the time spent loading and unloading would make it unlikely that a driver would spend less than ~1 hour per load. The maximum distance is estimated to be 2,000 mi (3,200 km).<sup>49</sup>

### 3.7.4 Product Use Scenarios—Annual-Average Mixing

The first five product use scenarios listed in Table 3.10 involve large batches of material: steel used to make the hull, decks, and bulkheads of a ship; and slag used in a roadbed or as an ingredient in portland cement. The radiological assessments of the groups described by these scenarios are based on annual average mixing of cleared scrap with materials from other sources. In the remaining seven product use scenarios, the assessments are based on the maximum single-heat mixing factors, as discussed in Section 3.4.2.2.

#### 3.7.4.1 Steel Ships

Two scenarios listed in Table 3.10 address the exposures of sailors serving aboard a naval vessel. All of the steel plates on the ship are assumed to be made from steel produced in a furnace—either a BOF or an EAF—that uses cleared scrap as part of its metal feed. This is a plausible assumption, given that a shipyard normally contracts a single supplier for its steel plates.<sup>50</sup>

There are a number of reasons for selecting these scenarios for the present analysis. One is that the ship is a very large metal object that, as stated above, is likely to be made primarily of steel produced at a single melt shop. Unlike the case with most other work-related scenarios, the ship scenarios provide an opportunity for 24-hour per day exposures during most of the year. In addition, there is an active shipbuilding industry in the United States.

The last observation is based in part on the list of major shipbuilding contracts of U.S. shipyards compiled by Colton & Company (1996). Out of a total of 302 vessels under contract at the end of 1996, 146 had been ordered by U.S. Government agencies. The total tonnage of the vessels ordered by the Government was listed as 928,692 light tons<sup>51</sup> (842.5 kt). Since steel is the preponderant material used in the construction of large vessels, this represents a small but significant market segment for steel products. (The total tonnage of vessels under commercial

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<sup>49</sup> See Footnote 47 on page 3-62.

<sup>50</sup> Technical staff, Carderock Division, Naval Surface Warfare Center, private communication with SC&A project staff, January 30, 2003.

<sup>51</sup> "Light tons" refers to the weight or displacement of the fully outfitted vessel, but without fuel or cargo.

contracts was not listed.) The Government vessels range in size from 55 2-ton surf boats ordered by the Coast Guard, to two 75,000-ton aircraft carriers.

The assessment of these exposure scenarios is intended to encompass the range of exposures of crew members of maritime vessels, both civilian and military, as well as of other individuals occupying large metal structures. In the interest of a realistic analysis, however, we selected a specific model ship with specific crew assignments and duties. The model is based on the U.S. Navy AOE-6 (Supply) class fast combat support ship, the Navy's largest combat logistics ship. However, the model is not intended to, and does not, exactly replicate the AOE-6 class.

AOE-6 class general characteristics (Sharpe 1999):

- Length ..... 754 feet (230 m)
- Beam ..... 107 feet (32.6 m)
- Displacement ..... 48,800 tons (44.3 kt) (full load); 19,700 tons (17.9 kt) (light)
- Crew ..... 40 officers, 627 enlisted

The scenarios assess the exposures of two individuals. They are both enlisted personnel who sleep in a large berthing area just below the main deck and use the crew messing (dining) and lounge areas on top of the main deck. One sailor stands watch in the operations area on the fourth level in the forward superstructure, while the other is involved in underway replenishment (UNREP) operations and stands watch on the main deck during such operations. While not standing watch, both sailors are involved in maintenance and training in or near their respective watch stations.

External exposures to both sailors are from the steel plates in the hull, decks, and bulkheads. Since there would be no significant abrasion of the steel during the time the sailors are aboard, internal exposures are not addressed.

The exposure duration of all crew members is governed in part by the ship's optempo—the fraction of time the ship is at sea. For fiscal year 1997, the latest for which data are available, the projected average optempo of all U.S. Naval vessels on active duty was 55% (Department of the Navy 2001). The optempo in the present analysis is assigned a triangular distribution, with a range of 45 – 65%, and a mean of 55%. Crewmen would take their annual leave while the ship is in port. The time on leave is represented by a triangular distribution, with a range of 14 – 28 days and an average of 21 days.

### Sailor with Watch Station in Operations Area

Area-average exposure rates are calculated for the four areas occupied by the operations watchstander in this idealized model. Because the rate calculated by MCNP code already takes into consideration the variation in position within each occupied area, the uncertainty parameter,  $U_x$ , in Equation 3.7, is assigned a fixed value,  $U_x = 1$ . The sources of exposure in each of these areas are approximately 30 separate parts of the hull, decks, and bulkheads which comprise the structure of the ship. Machinery and steel frame members (girders, stanchions, and stringers)

would most likely not come from the same melt shop as the steel plates; therefore, they are not assumed to be made from cleared scrap. The interior compartments contain cargo, fuel, engines, furniture, bedding, etc., none of which are assumed to consist of cleared materials. As a practical matter, photon radiation (x-rays and  $\gamma$ -rays) from all but the nearest components would be considerably attenuated. Nevertheless, the model ship was analyzed as a single entity, eliminating the need for subjective judgment as to which components to evaluate for which receptor location, in light of the fact that the MCNP code<sup>52</sup> models the contribution from radiation scattered by air, water, and surrounding objects.

This sailor would spend 72 hours per week in the main crew berthing area (sleeping, relaxing, and performing housekeeping duties and personal functions) while the ship is at sea. He would spend 66 hours per week in the operations area, 24 hours in the messing and lounge areas, and six hours on the main deck for recreational purposes. While the ship is in port, except for the days away from the ship on leave or in training, the sailor would spend part of his off-duty hours ashore on liberty. However, he would sleep and take some of his meals aboard the ship. Because of the watch and duty cycle, it is convenient to distribute the time in port over a 28-day period. During such a cycle, he would spend 248.5 hours in berthing, 56 hours in lounge and mess, 189 hours in the operations area, and the rest of his time ashore.

#### **Sailor with Watch Station on Deck**

The UNREP watchstander would occupy three of the same locations as the operations watchstander: berthing, mess and lounge, and the main deck, which is his watch and duty station. Because of different duty assignments, the distribution of time at these locations is somewhat different. He would spend 89 hours per week in the berthing area, 53 hours on the main deck, and 26 hours in mess and lounge. In port, when not away on leave or training, he would spend 252 hours per 28-day cycle in berthing, 179 hours on deck, 56 hours in mess and lounge, and the remaining time on liberty.

#### **3.7.4.2 Road Built with Steel Slag**

Steel slag is used as road fill and may also be used as an aggregate in asphaltic cement used as pavement. Two scenarios describe the exposures of individuals to slag used for this purpose. The first addresses the exposure of road construction workers, while the second addresses motorists driving over such a road after it is completed. In both cases, slag constitutes the entire road base as well as 80% of the pavement.

#### **Building Road Using Steel Slag**

Road construction workers using steel slag as the underlayer of a roadbed would be subject to external exposure to the slag, as well as being subject to internal exposure from slag dust. Since such a worker would be exposed to a large expanse of a thick, flat layer of slag, the external

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<sup>52</sup> See Section 1.6.1 for a description of the code.

exposure is modeled by means of the dose coefficients for soil contaminated to an infinite depth from FGR 12 (Eckerman and Ryman 1993).

The uncertainty factor,  $U_x$ , is used to account for different locations of the worker with respect to the slag in the road base. If he is on top of the road base, away from the edges, he is exposed to an effectively infinite slab of road base, which conforms to the exposure conditions modeled in FGR 12, so  $U_x = 1$ . When he is at the edge of the road, he is exposed to one-half of an infinite slab, so  $U_x = 0.5$ . Therefore,  $U_x$  is assigned a uniform distribution of 0.5 – 1.

The airborne concentration of slag dust is assigned the same distribution as in the slag-handling scenario described in Section 3.7.1.2.

The exposure duration would depend on the amount of slag produced by a given furnace in one year, and on the rate of road construction. (However, it is unlikely to exceed 250 days in one year, the period of assessment in the present analysis.) R.S. Means 2000, a standard reference for contractors, states that a road construction crew laying down a 1-foot-deep ( $\approx 30$ -cm) pavement base of 1½-inch diameter ( $\approx 4$ -cm) crushed stone has a production rate of 3,800 yd<sup>2</sup> (3,177 m<sup>2</sup>) per day. A crew laying down 4-inch-thick ( $\approx 10$ -cm) asphaltic concrete has a rate of 4,140 yd<sup>2</sup> (3,462 m<sup>2</sup>) per day. Assuming that the same crew lays down both the pavement base and concrete, the area of road produced in a day can be determined as follows:

$$\dot{A} = R_b r_b + R_c (1 - r_b) \quad 3.18$$

- $\dot{A}$  = Rate of road production (m<sup>2</sup>/d)  
 $R_b$  = Production rate of road base  
 = 3,177 m<sup>2</sup>/d  
 $r_b$  = fraction of day spent laying down road base  
 $R_c$  = Production rate of concrete pavement  
 = 3,462 m<sup>2</sup>/d

Solving the second Equation 3.18 for  $r_b$ , we find

$$r_b = \frac{R_c}{R_b + R_c}$$

Substituting this expression in the first Equation 3.18, we obtain

$$\begin{aligned} \dot{A} &= \frac{R_b R_c}{R_b + R_c} \\ &= 1,657 \text{ m}^2/\text{d} \end{aligned}$$

The quantity of slag used per day can now be readily determined:

$$\dot{m}_g = \dot{A}(d_c f_c + d_b) \rho_g$$

$\dot{m}_g$  = rate of slag utilization  
= 1,279 t/d

$d_c$  = thickness of concrete  
= 0.102 m

$f_c$  = fraction of slag in asphaltic concrete  
= 0.8

$d_b$  = thickness of road base  
= 0.305 m

$\rho_g$  = bulk density of slag  
= 2 g/cm<sup>3</sup>

The exposure duration is calculated as follows:

$$t_{ys} = \frac{M_g}{\dot{m}_g} \leq 250$$

$t_{ys}$  = exposure duration (d/y)

$M_g$  = total mass of steel slag (EAF or BOF) generated in one year (t)

As depicted in this scenario, the workers also perform other duties, such as maintenance of equipment and training. It is very unlikely for any worker to spend all of his 8-hour shift exposed to the slag in the road base. However, it is likely that he would spend over one-half of his time so employed.<sup>53</sup> Consequently, the exposure duration is assigned a uniform distribution of 5 – 7 h/d.

### Driving on Road Built with Steel Slag

The second of the slag road scenarios addresses the exposure of a commuter driving over the road constructed in the previous scenario. In the completed road, the source of exposure is the pavement, which is made of asphaltic concrete containing 80% slag which was used as aggregate. Although the layer underlying the pavement is assumed to be made entirely of slag, any direct radiation from this layer would be strongly attenuated by the pavement and would not make a significant contribution to the external exposure of the motorist.

<sup>53</sup> A description of a representative position is found in "Road Maintenance Worker" (2000).

Since the slag is either contained within or under a solid mass, no slag dust would be dispersed into the air while the driver is on the road, thus eliminating the source of internal exposure.

The exposure duration is based, in part, on EPA 1997, Table 15-121, which lists a distribution of time spent traveling in a car per 24-hour period. The percentiles for all respondents are shown in Table 3.15, below.

Table 3.15 Time spent traveling in a car (min/d)

%ile	0	5	25	50	75	90	95	98	99	100
Time	1	10	34	63	110	175	240	345	450	1280

Source: EPA 1997, Table 15-121

The exposure duration is also a function of the length of the segment of the road that can be built with one year's production of slag:

$$L = \frac{a}{w}$$

L = length of road built from one year's slag production of EAF or BOF (m)

a = area of road built from one year's slag production of EAF or BOF (m<sup>2</sup>)

$$a = \frac{M_g}{(d_c f_c + d_b) \rho}$$

w = width of typical U.S. highway  
 = 2 lane × 12 ft wide (FHWA 2001)  
 = 7.315 m

Assuming that a person commutes to and from work on the same stretch of road, 250 days per year,

$$t_{xs} = \frac{2L}{v} \leq \frac{t_c}{60}$$

t<sub>xs</sub> = exposure duration (h/d)

v = average travel speed driving to work  
 = 33.6 mph (data for 1995 [NPTS 1997, Figure 11])  
 = 5.41 × 10<sup>4</sup> m/h

t<sub>c</sub> = time spent in car (see Table 3.15) (min/d)

The dose from external exposure to direct radiation from residual activity in the slag is calculated as follows:



$$D_{ix} = C_{ig} f_g F_{ix} t_{xs} t_{ys} \left( \frac{e^{-\lambda_1 t_1} - e^{-\lambda_1(t_1 + t_2)}}{\lambda_1 t_2} \right) \quad 3.19$$

- $C_{ig}$  = concentration of nuclide  $i$  in slag (uncorrected for decay) (Bq/g)  
 $f_g$  = fraction of slag in concrete  
 $F_{ix}$  = FGR 12 dose coefficient for nuclide  $i$  in soil contaminated to infinite depth ( $\mu\text{Sv/h}$  per Bq/g)  
 $t_{xs}$  = exposure duration (d)

### 3.7.4.3 Living in Basement Built with Cement Made from Slag

Texas Industries, Inc. (TXI) holds a patent on the CemStar process, which uses 5% to 15% steel slag in producing the clinker that goes into portland cement.<sup>54</sup> Cement, in turn, constitutes 10% of concrete, the remaining ingredients being aggregate (80%), water, and sand. Assuming that the average amount of slag in cement made with this material is 10%, the resulting concrete would have an average slag content of 1%.

If slag generated at a steel mill recycling cleared scrap was used in producing portland cement, and if that cement in turn was used to make concrete for constructing the floor and outside walls of a basement, a person occupying that basement would be subject to external exposure to residual radioactivity of the slag.<sup>55</sup> The exposed individual in this scenario spends variable amounts of time each day in such a basement. Since the walls and floor would be covered and/or painted, there would be no particulate matter generated from the concrete. Consequently, there would be no opportunity for internal exposure via inhalation or ingestion.

The exposure duration is modeled as a triangular distribution, with a range of 4 – 16 h/d and a mode of 16 h/d. The lower end of this range was chosen to encompass work-related occupancy of a concrete structure. A most likely value was chosen to represent a residential setting; this was also used as the maximum value in the parameter range. The exposure takes place 350 days per year. The dose is calculated by Equation 3.19, using the parameters appropriate to the present scenario.

### 3.7.5 Product Use Scenarios—Maximum Single-Heat Mixing Factor

In seven product use scenarios, the assessments are based on the maximum single-heat mixing factors, as discussed in Section 3.4.2.2. In each case, since the source of exposure is an iron or steel product in domestic or commercial use, the only pathway is external exposure to the object

<sup>54</sup> Jamie Rogers, Texas Industries, Inc., private communication with William C. Thurber, SC&A, Inc., April, 1997.

<sup>55</sup> As was mentioned on page 3-6, steel slags are not suitable for use as aggregate in concrete used in construction.

in question. Since there would be no release of residually radioactive material from the object, there would be no opportunity for internal exposure.

The first three of these scenarios portray exposures to generic metal objects. These 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 the body), rather than specific scenarios (e.g., a person wearing a belt buckle or using a frying pan). The scenario "exposure to large metal mass," for example, represents such exposure situations as individuals using large consumer products (e.g., a refrigerator) made from recycled steel scrap.

These scenarios incorporate uncertainty into exposure duration via the parameter for hours per day, while the value for days per year is held constant. Exposure times for the generic large and small metal mass scenarios were developed to include those individuals who spend a large fraction of their workday or residential time near these objects (e.g., machine tools, office furniture, and household appliances or furniture). The daily exposure durations are represented by a triangular distribution with a range of 2 – 8 h and a mode of 4 h. The exposures occur 350 days per year. The most likely value is one-half of a typical workday. A range of 2 – 8 h/d would cover a variety of potential exposure situations in both residential and occupational settings.

The other four scenarios depict realistic exposures to specific products. Although some simplification of these models is necessary, these assessments are as realistic as practicable within the scope of the present analysis.

#### **3.7.5.1 Exposure to Large Metal Mass**

The large metal mass scenario assesses the external exposure to a large generic object that is constructed of iron or steel made from recycled steel scrap. The source of exposure is a 200-kg hollow metal cylinder at an average distance of 2 m.

#### **3.7.5.2 Exposure to Small Metal Mass**

The small metal mass scenario assesses the external exposure to a small generic object that is constructed of iron or steel made from recycled steel scrap. This generic object represents a wide range of small to medium-sized home appliances. The source of exposure is a 12-kg hollow metal sphere at an average distance of 2 m.

#### **3.7.5.3 Small Steel Object on Body**

The small steel object scenario assesses the external exposure to a small generic steel object that is worn or carried in close contact with the body. It has a mass of 45 g and can represent a wide variety of objects: pendants or other pieces of large jewelry, belt buckles, pocket knives, etc. The exposure duration is represented by a triangular distribution with a range of 2.86 – 16 h/d and a mode of 5 h/d. The exposures occur 350 days per year. The exposure duration has a wide range because of the variety of potential sources of exposure.

#### 3.7.5.4 Living in Home Built with Steel Studs

Steel framing components are commonly used in home construction—the American Iron and Steel Institute (AISI 1998, Chapter 4) estimated that the number of full-steel home starts in the United States has doubled from 40,000 in 1994 to 95,000 in 1997 and was projected to reach 325,000 by the year 2000.

The exposure geometry depicts an individual inside a small house in which the conventional 2-by-4 wood frame is replaced by steel studs. It is plausible that such a house would be constructed with steel components made from a single roll of sheet metal, which was rolled from a bloom cast from a single furnace heat.

The exposure duration is represented by a triangular distribution with a range of 4 – 16 h/d, and a mode of 8 h/d. The exposures occur 350 days per year. The range of exposure durations is designed to encompass both residential and work-related exposures.

#### 3.7.5.5 Driver of Automobile with Cast Iron Engine Block

The automotive industry is a large consumer of steel made from recycled scrap—approximately 32% of a typical U.S. automobile is made from recycled steel (SRI 2001). In the exposure assessment of the driver of an automobile, it is assumed that one component is made from the single furnace heat with the largest likely fraction of cleared scrap. The most massive object that could be made from a single furnace heat is a cast iron engine block, which is the source of external exposure in this scenario.

The exposed individual is the owner/operator of a taxicab. The exposure duration is based on the rules that govern the working hours of such individuals and on their actual work practices. Such rules are exemplified by the regulations of the Taxi and Limousine Commission of the City of New York, which stipulate that an owner/driver must work a minimum number of 9 hours per day for 210 days per year before he is allowed to lease his cab to another driver.<sup>56</sup> This provides an estimate of the lower limit of the annual exposure duration. The upper limit is based on the regulatory limit of 12 hours of driving in any 24-hour period—the driver is assumed to take a one-half hour break during each day, reducing his daily exposure to 11.5 hours. He might work as much as six days a week, 50 weeks a year, for a total of 300 days.<sup>57</sup> The exposure duration is assigned a uniform distribution spanning this range of hours per year.

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<sup>56</sup> The high price of taxi medallions, which are required to operate a “yellow cab,” one that is licensed to pick up passengers on the street and at airports, etc., mandates that the owner would maximize his income.

<sup>57</sup> Allan Fromberg, Assistant Commissioner for Public Affairs, New York City Taxi & Limousine Commission, private communication with Robert Anigstein, SC&A, Inc., March 19, 1998.

### 3.7.5.6 Driver of Truck with Cast Iron Diesel Engine Block

The diesel engine scenario is intended to represent exposures to large pieces of industrial equipment made of cast iron. The selected component is a cast iron diesel engine block on a Class 8 truck<sup>58</sup> used for long distance hauling. This scenario encompasses other exposure scenarios where the source material is cast iron. The exposed individual is the owner-operator of such a truck. Hence, he would be driving the same truck for an entire year and, in addition to time spent on duty in the driver's seat, would spend additional time in the sleeping compartment. Although there are other possible scenarios where the source term would be an even more massive cast iron component, the greater distance between the exposed individual and the source, and the shorter average annual exposure duration, would most likely lead to smaller exposures. Furthermore, the truck driver represents a sufficiently large number of individuals to fall within the scope of the present analysis.

The exposure duration in the driver's seat is based on the weekly hours of Type 1 drivers listed in Table 3.13. These data are assumed to represent averages over 52 weeks per year. The hours per night in the sleeper are the same as those of the truck driver hauling EAF dust in a dump trailer, described on page 3-63. The number of days of exposure in the sleeper is calculated as follows:

$$t'_{ys} = \frac{52 t'_{dw}}{t_{md}}$$

$t'_{dw}$  = time in driver's seat (h/week)

### 3.7.5.7 Sailor Berthing near Steel Hull Plate

Because sailors spend considerable periods of time aboard ship and may be assigned sleeping quarters which are located immediately adjacent to the ship's hull, the exposure of a sailor to a hull plate made from cleared scrap was selected to represent exposures to large steel plates. Although the sailor might be an enlisted man on a naval vessel or a member of the merchant marine, the former was selected for the present analysis.

This scenario differs from the steel ship scenarios described in Section 3.7.4.1 in that the exposure is to a single hull plate made from the single furnace heat having the maximum likely fraction of cleared scrap. Separate exposure geometries are defined for the sailor occupying his bunk and for being in the adjacent lounge area. The exposure duration in both locations is based on information on practices of the U.S. Navy; however, since this scenario is intended to span the range of exposures on a variety of vessels, both military and civilian, the exposure duration is more generic than in the scenarios described in Section 3.7.4.1.

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<sup>58</sup> The U.S. Department of Transportation defines Class 8 trucks as those with a gross vehicle weight (GVW)—including cargo—greater than 30,000 lb (~13.6 t).

According to the Department of the Navy (1998, p. C-3), naval enlisted personnel afloat in wartime have 87 hours off duty per week, including 56 hours allotted to sleeping. According to a former naval officer,<sup>59</sup> the maximum time per week a sailor would spend in his bunk would comprise 56 hours sleeping, three hours Sunday free time, and one-half of the 14 hours per week allotted to "free time," for a total of 66 hours per week, or an average of 9.4 hours per day. At a minimum, a sailor would sleep seven hours per night and spend the rest of his free time away from his bunk. In addition, a sailor would spend from ½ to 1½ hours of his free time in the lounge area. Uniform distributions spanning the cited ranges were assigned to the daily occupancy of the two locations.

A sailor might spend as much as six months of a year away from his ship, which includes training and leaves, leaving six months on board. At a minimum, a sailor will be away on leave for 30 days, leaving 335 days on board. A most likely scenario is 300 days per year on board ship. A triangular distribution, with these three values comprising the minimum, maximum and mode, was assigned to the days per year during which exposures would occur.

### 3.7.6 Landfill Disposal Worker Scenarios

Scrap metal and by-products of melting and refining may be disposed of in a landfill. Landfills used for waste disposal include industrial or construction and demolition (C&D) landfills, MSW landfills, and hazardous waste landfills. MSW landfills, except for previously existing landfills operating under a "grandfather" exemption, are regulated under RCRA Subpart D. Industrial and C&D landfills may comply with Subpart D regulations, but EPA does not require them to do so. (In the present report, the term "industrial landfill" includes C&D landfills.) Except for different annual volumes of waste—industrial landfills are typically (but not always) smaller than MSW landfills—these two landfill categories are treated the same way in the analysis. (The waste streams affect the mixing factors for these scenarios.)

Hazardous waste landfills fall under RCRA Subpart C. According to current practices, as discussed in Section 3.2.4.1, EAF dust placed in a Subpart C landfill is stabilized and placed in drums or other containers prior to disposal.

Seven scenarios assess the exposures of workers at landfills. As depicted in these scenarios, the workers operate equipment on top of the landfill and are exposed to the materials being disposed of. Their activities can include moving the waste with a front-end loader using a piece of machinery, such as a bulldozer, to compact the material in the landfill. These workers also perform other duties, such as maintenance of equipment and training and administrative functions. It is very unlikely for any worker to spend all of his 8-hour shift exposed to the waste. However, it is likely that he would spend over one-half of his time so employed.<sup>60</sup>

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<sup>59</sup> Cdr. John Harrop, USN (ret.), private communication with Robert Anigstein, SC&A, Inc., February 2002.

<sup>60</sup> A description of a representative position is found in "Landfill Equipment Operator" (2002).

Consequently, the exposure duration is assigned a uniform distribution of 5 – 7 h/d, and occurs during 250 days per year.

In all seven cases, external exposure is assessed in the same manner as in the slag handling scenario described in Section 3.7.1.2. In the present cases, however, the individual is not assumed to spend a significant amount of time at the edge of the landfill. Consequently, the exposure geometry resembles that of the semi-infinite slab, so the uncertainty parameter in Equation 3.6 has a fixed value,  $U_x = 1$ .

#### **3.7.6.1 Handling Steel Scrap at an Industrial or MSW Landfill**

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 release of residually radioactive particulate matter from the scrap, and consequently no mechanism for internal exposure of landfill workers disposing of such scrap. (See the discussion of the scrap transportation scenario in Section 3.7.3.1). Therefore, the only exposure pathway is the external exposure to the scrap deposited in the landfill.

#### **3.7.6.2 Handling BOF or Foundry Dust at an Industrial or an MSW Landfill**

As described in Section 3.2.3.1, the offgas from a BOF that is captured by an APCD is turned into a sludge or "filter cake." Although, in the present study, we apply the generic term "dust" to all material that is captured by an APCD, in the case of the BOFs, such material would retain enough moisture to prevent the formation of any significant amount of airborne particulate matter. Consequently, there would be little opportunity for internal exposure of workers disposing of this material in a landfill. The internal exposure to radionuclides in foundry dust would be bounded by the internal exposure in the EAF dust processing scenario, and is not separately assessed in this scenario. The only pathway that is assessed in this scenario is external exposure to the dust deposited in the landfill.

#### **3.7.6.3 Handling Slag at an Industrial or an MSW Landfill**

Unlike scrap metal and BOF dust, slag would be likely to generate airborne dust as it is being deposited in a landfill, giving rise to internal exposure pathways, which are included in the assessment of this scenario. The concentration of airborne dust is represented by the same distribution as is adopted for the slag handling scenario described in Section 3.7.1.2.

#### **3.7.6.4 Handling EAF Dust at a Hazardous Waste Landfill**

Since EAF baghouse dust would be stabilized and packed in containers prior to disposal in a hazardous waste landfill, there would be no opportunity for internal exposure of the landfill workers. The only pathway that is assessed in this scenario is external exposure to the dust deposited in the landfill. A mixing factor specific to this scenario is described in Section 3.4.2.4.

### 3.7.7 Consumption of Groundwater Infiltrated by Leachate

Leachate from industrial or MSW landfills, or from a slag storage pile, could infiltrate nearby wells used as sources of drinking water. Assessments are performed of the exposures of individuals that obtain their drinking water from wells that are down gradient from landfills used to dispose of cleared scrap, or BOF or foundry dust. These individuals are characterized by four exposure scenarios, according to the disposed material and the type of landfill: (1) cleared scrap disposed of in an industrial landfill, (2) scrap disposed of in an MSW landfill, (3) BOF and foundry dust disposed of in an industrial landfill, and (4) the same dust disposed of in an MSW landfill. A fifth scenario characterizes an individual drinking from a well that is down gradient from a pile of stored slag.

The only pathway addressed by these scenarios is the consumption of drinking water from the contaminated well. The only other plausible pathways—the use of well water in the production of homegrown foods—would not have a significant impact on the dose. According to EPA 1997, Table 13-71, homegrown produce accounts for less than 10% of the fruits and vegetables consumed in the United States, and even smaller fractions of other foods. A scoping analysis using an earlier version of the RESRAD computer program code (ANL 1996) showed that doses from the groundwater pathway were dominated by the consumption of drinking water, the consumption of foods produced on site making a negligible contribution.

#### 3.7.7.1 Leachate from Landfills Used for the Disposal of Steel Scrap or BOF/Foundry Dust

Leaching of residual activities on cleared scrap, or in BOF or foundry dust, could begin immediately after the metal or dust is emplaced in an industrial or MSW landfill. The leaching of the activities and their subsequent transport through the soil underlying the landfill to an aquifer and then to a nearby well used to supply household water is based on the model underlying the RESRAD computer code, described by Yu et al. (2001). Although the RESRAD model addresses the transport of radionuclides to a well either in or on the boundary of the contaminated zone, Yu et al. (1993, Appendix K) also describe a simple methodology for estimating off-site doses, which is used in the present analysis. The mathematical description of the model used to calculate the leaching of the activities from the landfill is presented below. The values assigned to the parameters used with this model are presented in Table 3.16, which follows the description of the model.

Because of the time required for transport of radionuclides to an underground source of drinking water, the maximum dose could occur many years after the emplacement of the wastes, depending on the radionuclide in question and on the hydrogeology of the site. The present analysis limits the period of assessment to 1,000 years from the time of release.

#### Travel Time Through the Vadose (Unsaturated) Zone

The travel time through the vadose (unsaturated) zone of the  $i$ -th chemical element was determined by means of Equation E.21 of Yu et al. 2001:

$$\Delta t_{v_i} = \frac{\Delta z R_{d_{i,v}} p_{ev} R_s}{I}$$

$$R_{d_{i,v}} = 1 + \frac{\rho_v K_{d_{i,v}}}{p_{tv} R_{sv}} \quad 3.20$$

$$R_{sv} = \left( \frac{I}{K_{sv}} \right)^{\frac{1}{2b+3}} \leq 1$$

- $\Delta t_{v_i}$  = travel time of  $i$ -th element through the vadose zone (y)  
 $\Delta z$  = thickness of vadose zone (m)  
 $R_{d_{i,v}}$  = retardation factor of  $i$ -th element (in vadose zone)  
 $p_{ev}$  = effective porosity of vadose zone  
 $R_s$  = saturation ratio  
 $I$  = infiltration rate (m/y)  
 $\rho_v$  = bulk soil density of vadose zone (g/cm<sup>3</sup>)  
 $K_{d_{i,v}}$  = soil-water distribution coefficient for  $i$ -th element in vadose zone (cm<sup>3</sup>/g)  
 $p_{tv}$  = total porosity of vadose zone  
 $K_{sv}$  = saturated hydraulic conductivity of vadose zone (m/y)  
 $b$  = soil-specific exponential parameter

In the subsequent discussion, the subscript  $i$  has been dropped to simplify the notation.

The fractional leach rate is calculated by Equation 3.21, which is based on Equation E.3 of Yu et al. 2001.

$$\mu = \frac{I}{d_L p_{tc} R_{dc} R_{sc}} \quad 3.21$$

- $\mu$  = fractional leach rate (y<sup>-1</sup>)  
 $d_L$  = thickness of contaminated zone (m)

The subscript "c" refers to the contaminated zone (i.e., landfill). The parameters  $p_{tc}$ ,  $R_{dc}$ , and  $R_{sc}$  are analogous to the corresponding parameters  $p_{tv}$ ,  $R_{dv}$ , and  $R_{sv}$  of the vadose zone.

The concentration in the pore water percolating through the soil is given by:



$$\begin{aligned}
 C_p(t) &= \frac{C_o d_L \mu \rho_c e^{-\mu(t-t_s)}}{I} \\
 &= \frac{C_o \rho_c e^{-\mu(t-t_s)}}{P_{tc} R_{dc} R_{sc}}
 \end{aligned}
 \tag{3.22}$$

$C_p(t)$  = concentration of nuclide in pore water at time  $t$  (Bq/cm<sup>3</sup>)

$C_o$  = initial specific activity of nuclide in landfill (Bq/g)

$t$  = time from clearance (y)

$t_s$  = time of emplacement of wastes (= time scenario begins)

### Transport to Well

Yu et al. (2001) present a simple model that describes the transport of the radionuclides through the soil to the aquifer and thence to a drinking-water well down gradient from the source. The transport of the activities from the surface to the aquifer is described above. Once the contaminated water reaches the aquifer, it moves along a trajectory which is described by a vector sum of the vertical flow rate (the infiltration rate) and the horizontal flow rate. Figure 3.4 shows how the contaminated water moving downward through a volume element of width  $dx$ , at a distance  $x$  from the well, is deflected in the horizontal direction until it intercepts the well.

The travel time in the aquifer is represented by

$$\begin{aligned}
 t_a(x) &= \frac{P_{ca} R_{da} x}{J K_{sa}} \\
 R_{da} &= 1 + \frac{\rho_a K_{da}}{P_{ta}}
 \end{aligned}
 \tag{3.23}$$

$t_a(x)$  = travel time of nuclide  $i$  through a distance  $x$  (y)

$x$  = distance from source element to well (m)

$J$  = hydraulic gradient

The subscript "a" refers to the aquifer. These parameters are analogous to the corresponding parameters of the vadose zone.

Dilution of the pore water is modeled by Equation 3.24, derived by differentiating the first of Equations E.27 of Yu et al. 2001:

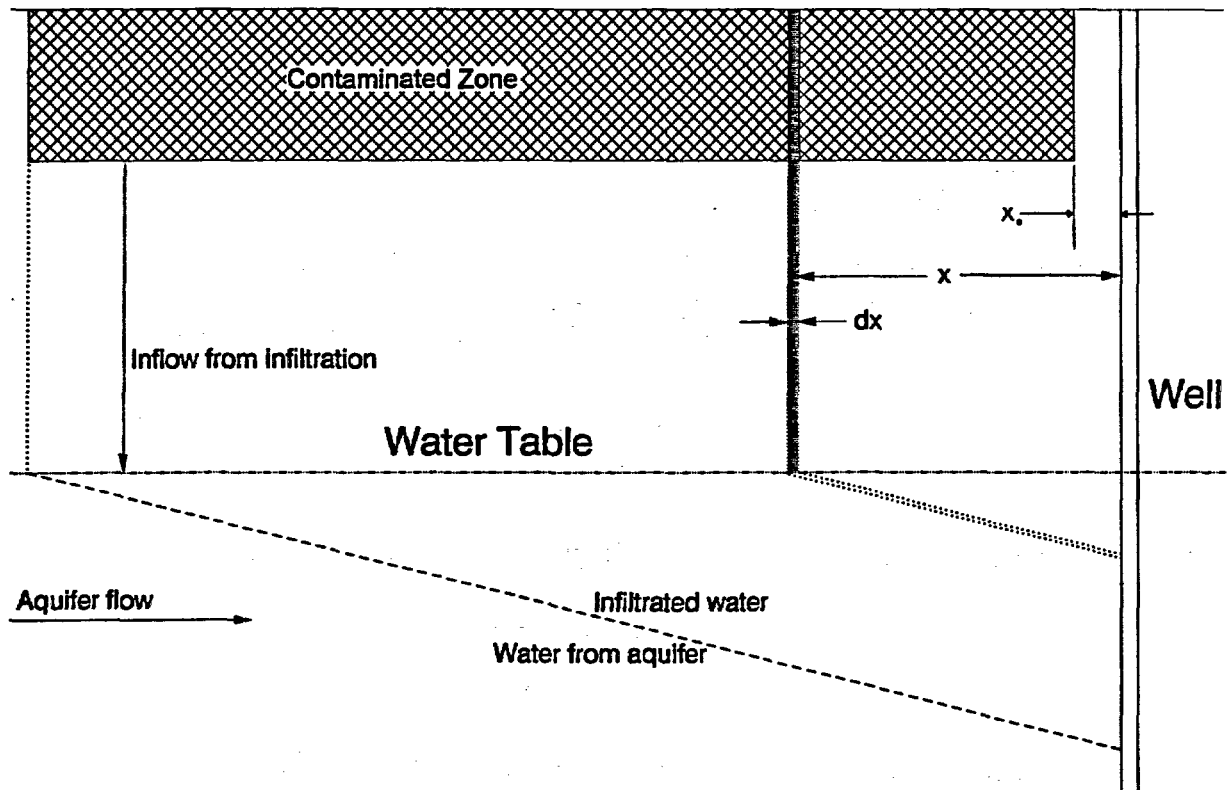


Figure 3.4 Transport of Leachate from Landfill to Well

$$df = \frac{I}{\delta_w J K_{ra}} dx \quad 3.24$$

$df$  = incremental dilution factor (concentration in pore water + concentration in well) of element  $dx$

$\delta_w$  = screened depth of well (m)

The contribution of element  $dx$  to the concentration of a nuclide in the well water is given by the following expression:

$$\begin{aligned} dC_w(\tau) &= C_p(\tau) df \\ &= \frac{C_o d_L \mu \rho_c e^{-\mu \tau}}{\delta_w J K_{ra}} dx \end{aligned} \quad 3.25$$

$dC_w(\tau)$  = increment of concentration of nuclide in well at time  $\tau$  (Bq/cm<sup>3</sup>)

$$\begin{aligned}
 \tau &= t - t_0 - t_a(\xi) \quad (y) \\
 &\geq 0 \\
 t_0 &= t_a(x_0) + \Delta t_v + t_r \quad (y) \\
 x_0 &= \text{distance from landfill boundary to well (m)} \\
 t_a(\xi) &= \text{travel time in aquifer of nuclide through length } \xi \quad (y) \\
 \xi &= x - x_0 \quad (m)
 \end{aligned}$$

The first of Equations 3.25 follows directly from the definition of  $df$  given above, while the second was derived by substituting the expressions in Equations 3.22 and 3.24 for  $C_p(t)$  and  $df$ , respectively. Differentiating the first line of Equation 3.23 with respect to  $x$ , and solving for  $dx$ ,

$$dx = \frac{J K_{sa}}{P_{ca} R_{da}} dt_a$$

At a fixed time  $t$ ,  $\partial\tau = -dt_a$ . Substituting these expressions in Equation 3.25, we obtain

$$\partial C_w(\tau) = -\frac{C_0 d_L \mu \rho_c e^{-\mu\tau}}{\delta_w P_{ca} R_{da}} \partial\tau$$

The concentration of nuclide in well at time  $t$  is obtained by integrating the above expression over the range of travel times in the aquifer, and introducing radioactive decay, which has been omitted up to now for the sake of clarity:

$$\begin{aligned}
 C_w(t) &= \frac{C_0 d_L \rho_c \left(1 - e^{-\mu(t-t_0)}\right) e^{-\lambda t}}{\delta_w P_{ca} R_{da}} && (t_0 \leq t \leq t_0 + t_a(l)) \quad 3.26 \\
 &\leq \frac{A C_0 I \rho_c \left(1 - e^{-\mu(t-t_0)}\right) e^{-\lambda t}}{P_{tc} R_{dc} R_{sc} U_w}
 \end{aligned}$$

At later times,

$$\begin{aligned}
 C_w(t) &= \frac{C_0 d_L \rho_c \left(e^{-\mu(t-t_0-t_a(0))} - e^{-\mu(t-t_0)}\right) e^{-\lambda t}}{\delta_w P_{ca} R_{da}} && (t \geq t_0 + t_a(l)) \quad 3.27 \\
 &\leq \frac{A C_0 I \rho_c \left(e^{-\mu(t-t_0-t_a(0))} - e^{-\mu(t-t_0)}\right) e^{-\lambda t}}{P_{tc} R_{dc} R_{sc} U_w}
 \end{aligned}$$

$A$  = active area of landfill ( $m^2$ )

$$= \frac{M_w T_w}{d_L \rho_w}$$

$M_w$  = annual mass flow of waste (t/y)

$T_w$  = time period for emplacement of wastes  
= 1.7 y

$U_w$  = pumping rate of well ( $m^3/y$ )

$t_s(l)$  = travel time in aquifer of nuclide through length  $l$  (y)

$$l = l_0 (m)$$

$$\leq \frac{\delta_w J K_{sa}}{I} - x_0$$

$l_0$  = length of landfill parallel to aquifer flow (m)

The concentration will increase with time as more and more of the leachate from the further portions of the landfill reaches the well. For short-lived radionuclides, however, the increase is offset by radioactive decay. The time of maximum concentration (in the absence of progeny ingrowth) can be found by setting the derivative of  $C_w(t)$  to 0.

$$0 = \frac{d}{dt} \left[ \left( 1 - e^{-\mu(t-t_0)} \right) e^{-\lambda t} \right] \quad 3.28$$

$$= \left[ \lambda \left( 1 - e^{-\mu(t-t_0)} \right) - \mu \left( e^{-\mu(t-t_0)} \right) \right] e^{-\lambda t}$$

Solving Equation 3.28,

$$t_m = t_0 + \frac{\ln \left( \frac{\lambda + \mu}{\lambda} \right)}{\mu}$$

$$\leq t_s(l) + t_0$$

$t_m$  = time of maximum concentration from clearance (y)  
 $\leq 1,000$  y

In the case of radionuclides with radioactive progenies, an iterative process is required to find the time of peak dose, which is delivered by both the parent nuclide and by the progeny that has grown in during the travel time from the contaminated zone to the well. To simplify the expression, progeny ingrowth is not shown in Equations 3.26 and 3.27. Such ingrowth is explicitly modeled by use of the Bateman Equations, as described in Appendix E.

## Dose Assessment

The dose from drinking water from the well is calculated as follows:

$$D_{iw} = \overline{C_{w_i}} F_{ig} I_w$$

$D_{iw}$  = Dose from drinking water from well during year of peak dose ( $\mu\text{Sv/y}$ )

$\overline{C_{w_i}}$  = average concentration of radionuclide  $i$  in well during peak year ( $\text{Bq/cm}^3$ )

$I_w$  = annual consumption of water ( $\text{cm}^3/\text{y}$ )

The radionuclide concentrations in the well water are calculated according to Equations 3.26 and 3.27. The consumption rate of tap water,  $I_w$ , was assigned a truncated lognormal distribution, based on data in EPA 1997. The logarithmic mean and standard deviation are taken from EPA 1997, Table 3-11. The upper bound of the distribution is based on the maximum reported value of  $4,730 \text{ cm}^3/\text{d}$ , while the lower bound is  $196 \text{ cm}^3/\text{d}$ . The latter value was calculated by assuming that the logarithms would be symmetrically distributed about the mean of  $963 \text{ cm}^3/\text{d}$ .

## Landfill Parameters

The primary source of parameter values for the landfill groundwater scenarios is an EPA report that lists input parameters to be used in groundwater modeling for the evaluation of industrial landfills (EPA 2001c). These values, along with additional data sources, are listed in Table 3.16.

### 3.7.7.2 Leachate from Slag Storage Pile

Similar to the leaching of residual activities from materials emplaced in a landfill, residually radioactive constituents of steel slag in a storage pile could leach and infiltrate a drinking-water well that is down gradient from the pile. A study, based on a search of available literature, was performed to enable the calculation of leach rates of various radionuclides. In addition, EPA sponsored an experimental study at the Brookhaven National Laboratory (BNL) to determine the leach rates of constituents of various steel and iron slags. Details of these studies are presented by Anigstein et al. (2001, Appendix I). Some of the information obtained from both studies is presented in this section, followed by the development of a model of the leaching of radionuclides which partition to the slag.

Table 3.16 Landfill parameters

	Symbol	Units	Source
<b>Contaminated zone</b>			
Infiltration Rate (single liner)	$l$	m/y	EPA 2001c
Depth	$d_L$	m	EPA 2001c
Waste density	$\rho_w$	g/cm <sup>3</sup>	EPA 2001c
Density of zone	$\rho_c$	g/cm <sup>3</sup>	$f_w \rho_w + (1 - f_w) \rho_v$ <sup>a</sup>
Fraction of waste in landfill volume	$f_w$	—	Dehmel et al. 1994
Total porosity	$p_{tc}$	— = $p_{tv}$	
Hydraulic conductivity	$K_{sc}$	m/y = $5 K_{sv}$ <sup>b</sup>	
Soil-specific exponential parameter	$b_c$	—	values for sand (Yu et al. 2000, Attachment C, p. 3-16)
Soil-water distribution coefficient	$K_{dc}$	cm <sup>3</sup> /g	= $0.2 K_{dv}$ <sup>c</sup>
Length parallel to aquifer flow	$l_o$	m	= $2 \sqrt{\frac{A}{\pi}}$
Area	$A$	m <sup>2</sup>	calculated
<b>Vadose zone</b>			
Saturated hydraulic conductivity	$K_{sv}$	m/y	EPA 2001c
Total porosity	$p_{tv}$	—	EPA 2001c
Thickness	$\Delta z_v$	m	EPA 2001c
Bulk density	$\rho_v$	g/cm <sup>3</sup>	EPA 2001c
Soil-water distribution coefficient	$K_{dv}$	cm <sup>3</sup> /g	Yu et al. (2000, Attachment C, pp. 3-30/31) <sup>d</sup>
Soil-specific exponential parameter	$b_v$	— = $b_c$	
Effective porosity	$p_{ev}$	—	generic soil type (Yu et al. 2000, Attachment C, p. 3-9)
<b>Aquifer</b>			
Effective porosity	$p_{ea}$	—	EPA 2001c
Bulk density	$\rho_a$	g/cm <sup>3</sup>	EPA 2001c
Saturated hydraulic conductivity	$K_{sa}$	m/y	EPA 2001c
Hydraulic gradient	$J$	—	EPA 2001c
Depth of well below water table	$d_w$	m	EPA 2001c
Soil-water distribution coefficient	$K_{da}$	cm <sup>3</sup> /g	= $K_{dv}$
Total porosity	$p_{ta}$	—	Yu et al. (2000, Attachment C, p. 3-6) value for sand Minimum = RESRAD default value (Yu et al. 2001)
Well pumping rate	$U_w$	m <sup>3</sup> /a	Maximum (rounded) from Yu et al. (2000, Attachment C, p. 3-39)
Distance to well	$x_o$	m	EPA 2001c

<sup>a</sup> Assumes uniform mixing of waste with daily soil cover

$$b \quad \frac{1}{K_{sc}} = \frac{f_w}{K_{sw}} + \frac{(1 - f_w)}{K_{sv}} \text{ assume } K_{sw} \gg K_{sv}$$

$$c \quad K_{dc} = f_w K_{dv} + (1 - f_w) K_{dv} \text{ assume } K_{dw} \ll K_{dv}$$

<sup>d</sup> See Appendix B for additional data sources

### Slag Cement Leaching Studies

The American Nuclear Society has developed and formalized detailed procedures for measuring the leachability of solidified low-level radioactive wastes (ANS 1986). This procedure involves testing of controlled-geometry specimens in demineralized water at 17.5°C to 27.5°C to determine releases over successive intervals of time. Mass transport is assumed to be controlled by a diffusion process. When the fraction leached from a uniform sample is less than 20% of the initial activity, the leaching behavior can be approximated by that of a semi-infinite medium where the "effective diffusivity" is given by the following equation:

$$D_i = \pi T_n \left( \frac{a_{in} V}{A_{io} \Delta_{nt} S} \right)^2 \quad 3.29$$

$D_i$  = effective diffusivity of nuclide  $i$  (cm<sup>2</sup>/d)

$T_n$  = mean time of the leaching interval  $n$  (d)

$$= \left( \frac{t_n^{1/2} + t_{n-1}^{1/2}}{2} \right)^2$$

$a_{in}$  = activity of nuclide  $i$  released during time interval  $n$  (Bq)

$V$  = sample volume (cm<sup>3</sup>)

$A_{io}$  = initial activity of nuclide  $i$  in sample (Bq)

$\Delta_{nt}$  = duration of  $n$ -th leaching interval (d)

$$= t_n - t_{n-1}$$

$S$  = surface area of sample (cm<sup>2</sup>)

When the cumulative fraction leached,  $\frac{\sum_n a_{in}}{A_{io}}$ , is greater than 0.2, Equation 3.29 must be

corrected for specimen geometry.

Using a model and procedures similar to those described in ANS 1986, Japanese investigators have determined the fractional leaching of Sr-90, Co-60, Cs-137, and H-3 from cement/slag composites in deionized water and synthetic sea water (Matsuzuru and Ito 1977; Matsuzuru et al. 1977, 1979). The duration of the leaching tests was about 100 days. The radionuclides were incorporated into the cement via a sodium sulfate solution. Leaching data were analyzed using a plane source diffusion model to derive the expression:

$$f_i = \frac{2S}{V} \sqrt{\frac{D_i t}{\pi}} \quad 3.30$$

$f_i$  = fraction of nuclide  $i$  leached in  $t$  days.

Equation 3.30 can be rewritten as

$$f_i = \left[ \frac{2S}{V} \sqrt{\frac{D_i}{\pi}} \right] t^{1/2} \quad 3.31$$

$$= m_i t^{1/2}$$

where the expression in the square brackets is represented by  $m_i$ , the slope of the line obtained by plotting  $f_i$  vs.  $t^{1/2}$ .

Once  $m_i$  is determined, Equations 3.31 can be solved for  $D_i$ :

$$D_i = \pi \left( \frac{m_i V}{2S} \right)^2 \quad 3.32$$

Since the actual leaching process involves an initial rapid leaching rate of a few days' duration ( $\sim 7$  d for Sr-90 and  $\sim 2$  d for Co-60), followed by a longer-term linear relation between  $f_i$  and  $t^{1/2}$ , the experimental data are fitted to an equation of the form

$$f_i = m_i t^{1/2} + \alpha_i \quad 3.33$$

Equation 3-30 can also be used to determine the value of  $f_i$  for various geometries, as follows:

$$f_{i2} = f_{i1} \left( \frac{S_2 V_1}{S_1 V_2} \right) \quad 3.34$$

where subscripts 1 and 2 refer to geometries 1 and 2, respectively.

Because of certain limitations and problems, such as the initial leach rate, Matsuzuru and Ito (1977) defined  $L$ , the leaching coefficient, with the same mathematical form as  $D$  in Equation 3.32. Values of  $L$  for Sr-90 leached from slag cements ranged from  $1.2 \times 10^{-7}$  to  $1.7 \times 10^{-7}$  cm<sup>2</sup>/day for both deionized water and synthetic sea water at 25°C. Using average values of  $L_S$  for samples cured for seven days prior to testing in deionized water, and assuming a right circular cylinder,  $h = 2r$ ,  $V = 70$  cm<sup>3</sup>, we have derived values for  $m_S$  and  $\alpha_S$  in Equation 3.33, which are listed in Table 3.17. The leachability of Cs-137 was reported to be about ten times that of Sr-90; it is therefore assumed that  $m_{Cs} = 10 m_S$  and  $\alpha_{Cs} = 10 \alpha_S$ . Equation 3.34 is then used to derive values that describe leaching from slag particles that are also right circular cylinders, but only 1 cm in diameter—a more typical size for EAF slags. The chromium data is based on particles that passed through a 9.5 mm mesh. The calculated value



cited in the section "Other Slag Leaching Studies," below, therefore constitutes an upper bound to  $m_{Cr}$  for a 1-cm right circular cylinder, listed in Table 3.17.

**Table 3.17 Leaching parameter values**

Element	$m (d^{-3/4})$		$\alpha$	
	$r = 2.233 \text{ cm}^a$	$r = 0.5 \text{ cm}$	$r = 2.233 \text{ cm}$	$r = 0.5 \text{ cm}$
Sr	5.8e-04	2.59e-03	4.97e-03	2.22e-02
Cs	5.8e-03	2.59e-02	4.97e-02	2.22e-01
Cr <sup>b</sup>	c	6.9e-06	0	0

<sup>a</sup> Corresponds to 70 cm<sup>3</sup> right circular cylinder ( $h = 2r$ )

<sup>b</sup> Cr is used as a surrogate for Nb, Np, Pa and U—see discussion below.

<sup>c</sup> Not applicable, see text.

The strontium data are replaced by the data obtained from BNL, described below.

#### Data from Brookhaven National Laboratory

Results from leaching experiments on EAF slags performed at BNL indicate that the leaching of strontium was governed by diffusion (Fuhrmann and Schoonen 1997). The diffusion coefficients determined from tests on three monolithic samples of EAF slag are listed in Table 3.18. To calculate the value of  $m_{Sr}$  for a monolithic cylinder, we first invert Equation 3.32:

$$m_i = \frac{2S}{V} \sqrt{\frac{D_i}{\pi}} = \frac{12}{r} \sqrt{\frac{D_i}{\pi}}$$

$$S = 2\pi(r^2 + hr) = 6\pi r^2 \quad (h = 2r)$$

$$V = \pi r^3$$

$$m_{Sr} = 1.54 \times 10^{-2} d^{-3/4}$$

$$D_{Sr} = 1.51 \times 10^{-11} \text{ cm}^2/\text{s} \text{ (mean of values in Table 3.18)}$$

$$= 1.30 \times 10^{-6} \text{ cm}^2/\text{d}$$

$$r = 0.5 \text{ cm}$$

**Table 3.18 Diffusion coefficients for EAF slag monolithic samples**

Slag Sample	Diffusion Coefficient (cm <sup>2</sup> /s)
AS-1	1.4e-11
AS-2	2.5e-11
AS-3	6.2e-12

Source: Anigstein et al. 2001 (Appendix I-1)

Since Fuhrmann and Schoonen did not report any initial releases that were not diffusion-controlled,  $\alpha_{Sr}$  is set equal to zero. These data are used to model the Sr-90 leaching from the slag in the present analysis.

### Other Slag Leaching Studies

Researchers at Australia's Commonwealth Scientific and Industrial Research Organisation incorporated the toxic elements As, Sb, Cd, Zn and Cr into slags of various types by melting them at 1300°C, and subsequently leached the slags according to the EPA TCLP protocol (Jahanshahi et al. 1994). Three of the slags, while not identical to EAF slags, are useful for developing preliminary modeling parameters. Unfortunately, of the five elements studied, only Cr is expected to be found in the slag in any significant quantity. However, in the absence of element-specific leaching data, Cr can be considered as a surrogate for the stable oxides expected in slags. Assuming that the fraction leached is proportional to  $t^{1/2}$ , this fraction can be expressed by Equation 3.33, where the upper limit of  $m_{Cr}$  is about  $6.9 \times 10^{-6} d^{1/2}$ , based on Cr in the one of the slags tested.

### Leach Rate

The leach rate from slag is calculated by Equation 3.33, using the BNL data for strontium and the parameter values for 1-cm diameter particles listed in Table 3.17 for other elements.

Information from a slag processor indicates that the processor may size and stockpile slag over six warm-weather months for winter use such as anti-skid road sanding.<sup>61</sup> As mentioned in Section 3.7.1.7, the State of Ohio Department of Transportation (1998) requires that slag used for embankments must be aged for a minimum of six months in stockpiles that contain no more than 23,000 t. The slag is thus assumed to have a turnover rate of twice a year and to contain six months' of slag production from a given steel mill, but not more than 23,000 t. The slag is assumed to be continuously dumped onto a 1-meter high pile and to be removed at the same rate. The new slag is mixed uniformly with the old slag—the slag that is removed is thus a representative sample of this mixture.

To model the age-dependent leach rate, we must first determine the age distribution of the individual particles in the pile. If there is a constant number,  $N$ , of particles in the pile, the number of particles added or removed during time  $dt$  is

$$dn = \lambda_r N dt$$

$\lambda_r$  = removal rate constant

---

<sup>61</sup> Rick West, Sales Manager for International Mill Services, private communication with William C. Thurber, SC&A, Inc., August 22, 1996.

Assume that  $v_0$  particles are added to the pile at some initial time ( $t = 0$ ). After time  $t$ , the number of these particles left in the pile is given by

$$v(t) = v_0 e^{-\lambda t}$$

By definition, this is the number of particles older than  $t$ . The number of particles with ages between  $t$  and  $t + dt$  is obtained by differentiating the above expression with respect to  $t$  and changing the sign:

$$dv = \lambda v_0 e^{-\lambda t} dt$$

Since this expression is independent of the initial time, it can be generalized to all the particles in the pile:

$$\frac{dn}{N} = \lambda e^{-\lambda t} dt \quad 3.35$$

$dn$  = number of particles in pile with ages between  $t$  and  $t + dt$

$N$  = total number of particles in pile

The time-dependent leach rate is derived by differentiating  $f_i$  in Equation 3.33 with respect to time:

$$df_i = \frac{m_i t^{-1/2}}{2} dt$$

Multiplying the above expression by the age distribution function of Equation 3.35 yields the leach rate of particles with ages between  $t$  and  $t + dt$ . Integrating that expression with respect to time yields

$$f'_i(t) = \frac{m_i \lambda}{2} \int_0^t \tau^{-1/2} e^{-\lambda \tau} d\tau \quad (0 < t \leq T) \quad 3.36$$

$f'_i(t)$  = leach rate of nuclide  $i$  in slag pile at time  $t$

$t$  = time since the first residually radioactive slag was placed in pile

$\tau$  = variable of integration

$T$  = period during which pile receives residually radioactive steel slag

The integral expression does not have an analytical solution but must be evaluated numerically. Equation 3.36 applies to the period during which the storage pile receives residually radioactive slag. After this time, no new contaminated particles are being added to the pile. The general

relationship remains the same, but the leaching is now from particles with ages between  $t$  and  $t - T$ .

$$f'_i(t) = \frac{m_i \lambda_i}{2} \int_{t-T}^t \tau^{-1/2} e^{-\lambda_i \tau} d\tau \quad (t > T) \quad 3.37$$

The elapsed time since the pile began receiving residually radioactive slag is represented by  $t$ , which is thus the age of the oldest radioactive particle in the pile, while  $t - T$  is the time since the pile stopped receiving such slag, and thus the age of the newest particle.

The expression for the radionuclide concentration in the pore water percolating through the soil (in the absence of radioactive decay) is analogous to that for the landfill scenario in Equation 3.25:

$$C_{ip}(t) = \frac{C_{ig} d_g f'_i(t) \rho_g}{I} \quad 3.38$$

$C_{ip}(t)$  = concentration of nuclide  $i$  in pore water at time  $t$  (Bq/cm<sup>3</sup>)

$C_{ig}$  = initial specific activity of nuclide  $i$  in slag (Bq/g)

$d_g$  = thickness of slag layer (m)

$\rho_g$  = density of slag (g/cm<sup>3</sup>)

The contribution of element  $dx$  to the concentration of radionuclide  $i$  in the well is given by the following expression:

$$\begin{aligned} dC_{w,i}(\tau) &= C_{ip}(\tau) df \\ &= \frac{C_{ig} d_g f'_i(\tau) \rho_g}{\delta_w J K_r} dx \\ &= \frac{C_{ig} d_g f'_i(\tau) \rho_g}{\delta_w p'_c R'_d} d\tau \end{aligned} \quad 3.39$$

where all the parameters have been defined previously.

The first of Equations 3.39 follows directly from the definition of  $df$  following Equation 3.24, the second was derived by substituting the expressions in Equations 3.38 and 3.24 for  $C_{ip}(t)$  and  $df$ , respectively, while the third was derived by differentiating the first line of Equation 3.23, solving for  $dx$ , and substituting. The concentration of radionuclide  $i$  in the well at time  $\tau$  is obtained by integrating the last line of Equation 3.39 and introducing radioactive decay, which has been omitted up to now for the sake of clarity:

$$C_{w_1}(t) = \frac{C_{ig} d_g f_U \rho_g e^{-\lambda_1 t}}{\delta_w P_{ca} R_{d,1a}} \int_{t_1}^{t-t_0} f_1'(\tau) d\tau \quad 3.40$$

$$t_1 = 0 \quad (t_0 \leq t \leq t_0 + t_{a_1}(I))$$

$$t_1 = t - t_0 - t_{a_1}(I) \quad (t > t_0 + t_{a_1}(I))$$

$f_U$  = dilution factor for water usage

$$= \frac{d_w J K_a \sqrt{\pi A}}{2 U_w} \leq 1$$

$A$  = area of slag pile ( $m^2$ )

$$= \frac{V_g}{d_g}$$

$V_g$  = slag volume ( $m^3$ )

$$= \frac{0.5 m_s}{\rho_g}$$

$$\leq \frac{m_p}{\rho_g}$$

$m_s$  = one year's slag production (t)

$m_p$  = maximum mass of slag pile (t)

As was the case with the landfill scenarios, the concentration will increase with time as more and more of the leachate from the further portions of the slag pile reaches the well. For short-lived nuclides, however, the increase is again offset by radioactive decay. An iterative process is required to find the time of peak dose, which is delivered by both the parent nuclide and any radioactive progenies that have grown in during the travel time from the slag pile to the well.

The dose from drinking water from the well is calculated in the same way as in the landfill leachate scenarios, described on page 3-82. The radionuclide concentration in the well water is calculated according to Equation 3.40.

### 3.7.8 Scenario Timing

This section presents the basic assumptions used in defining the time periods for each of the recycling scenarios. The timing is based on data on the U.S. ferrous metals industries, supplemented by engineering judgment.

### 3.7.8.1 Scrap Transportation

- The scrap transportation scenario occurs two to six days after the scrap is cleared. This includes time to schedule a truck, perform minimal sizing operations, bring the truck to the site, load the truck, and ship the scrap to a scrap dealer or landfill.

### 3.7.8.2 Scrap Yard

- The scrap yard scenario begins two days after the scrap is loaded on the truck, allowing time for transport, unloading, and conveying the scrap to the processing location in the scrap yard. Typically, steel scrap is shredded or size-reduced and shipped out within one week.<sup>62</sup> Adding this time period to that of the transportation scenario, and allowing a minimum of one day for the actual transport of the scrap, the processing of a particular batch of scrap could begin as early as three days after the scrap is cleared and might occur as late as 17 days after clearance.

### 3.7.8.3 Melting and Refining, and Processing

- A former steel industry executive noted that the amount of time that scrap metal would be held at a steel mill will vary, based on scrap metal prices and business conditions, but that an EAF shop might keep three weeks of inventory on hand.<sup>63</sup> For a BOF shop, the scrap might be on hand for about two weeks. (BOF shops tend to use more factory bundles of scrap, which are typically auctioned monthly.) In either case, the melt shop's objective is to keep its raw materials inventory to a minimum. If continuous cast ingot from an EAF is rolled for inventory rather than to order, the product might remain at the mill an average of two weeks before being shipped. An exception could be large structural members, where setup time for the rolling mill might dictate producing greater amounts of material during a run. The inventory of some structurals might exceed four weeks. (Structurals are typically produced by EAF shops rather than BOF shops.) On the other hand, for customers such as General Motors, with a strong commitment to just-in-time (JIT) inventories, material may ship the same day as it is rolled. (Typically, the automotive companies use sheet steel produced from BOFs.)

Another source of inventory information is visits to steel mills made by SC&A staff in 1996. One EAF shop purchased all of its steel scrap through one broker and generally used a JIT approach. Trucks and rail cars provided pre-identified grades of scrap to facilitate furnace charging. Rail cars were processed in two or three days. Truck shipments might remain on

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<sup>62</sup> Michael A. Mattia, Director, Risk Management, Institute for Scrap Recycling Industries, private communication with Kathleen Behling, SC&A, Inc., October 19, 2001.

<sup>63</sup> Gordon Geiger, College of Engineering and Mines, University of Arizona, Tucson AZ, private communication with William C. Thurber, SC&A, Inc., September 17, 2001.

site for up to one month. The facility also had a large off-site scrap storage area where steel purchased in response to low scrap prices was stockpiled for longer periods.

Based on this information, it is assumed that scrap steel remains at an EAF shop for zero to 30 days before it is melted. Comparable values for a BOF shop are zero to 14 days. The semi-finished steel is assumed to remain for zero to 14 days at a BOF shop and zero to 28 days at an EAF shop. Cast iron producers are assumed to have schedules similar to those of EAFs.

- Releases of airborne effluent emissions from a steel mill occur at the time the scrap is melt-refined (see above).
- Following initial processing, iron and steel products undergo further processing before use; this secondary processing, plus storage and handling, is assumed to take 22 days.

#### 3.7.8.4 Use of Iron and Steel Products

- Distribution of generic manufactured items is assumed to take seven days; distribution of an automobile is assumed to take seven to 90 days.
- Generic manufactured items (i.e., large metal mass, small metal mass, small metal object worn on the body) are assumed to be put into use immediately after distribution.
- Construction of a simple house made with steel studs is assumed to take three to six months after distribution.
- Shipyards generally procure steel plate as needed, and do not stockpile large quantities. Thus, the storage time in a yard is short, on the order of days. A naval supply ship may take 18 months from keel laying to delivery. Steel plate is used almost immediately, but since the ship is built from the keel up, a few months may pass before the steel plate to be used in a berthing compartment arrives at the shipyard.<sup>64</sup>

Once delivered, the crew will man the ship, and begin living on the ship. However, a shakedown period of several months is typically required before the ship is in a full operational status. Thus, the steel plates will be formed (poured and rolled) about 18 months before the sailor begins berthing in the berthing compartment (Anigstein et al. 2001, Appendix H-2).

The three scenarios involving sailors on ships are assumed to begin 18 months after the steel is produced at an EAF or a BOF shop.

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<sup>64</sup> Capt. A. Mancini, U.S. Naval Sea Systems Command, private communication with John Harrop, SC&A, Inc., May 19, 1999.

### 3.7.8.5 Slag Use and Disposal

- Steel slag and baghouse dust are produced at the time melting and refining occurs.
- Steel slag that is sold for subsequent use is processed at the mill 2 – 4 days after it is generated and leaves the mill in another 2 days. Slag is assumed to be used six months after distribution. Slag that is to be disposed of in a landfill is held at the mill for 7 days, at which time it is transported to a disposal facility. The slag is assumed to be disposed of immediately following handling at a sanitary landfill.
- A road constructed with steel slag is open for use one day after the end of construction activities.

### 3.7.8.6 Dust Processing and Disposal

- EAF baghouse dust is transported within three days after production. Handling and processing of the dust takes four days, at which time the dust is disposed of in a hazardous waste landfill.
- BOF dust is sent to a landfill seven days after it is produced. Storage and handling take four days, at which time the dust is disposed of in a landfill.

## 3.8 Calculation of Surficial Normalized Doses

In most cases, the residual activity of the cleared scrap would reside on or near the surface. However, the radiation exposure of an individual to large batches of this material, which would consist of many individual components of differing sizes and shapes, can be approximated by assuming an average uniform distribution of the activity in the entire mass of the metal. All of the scenarios discussed in this chapter treat the residual activities as distributed throughout the mass of scrap or furnace product. Thus, whether the radiation source is a pile of assorted scrap, or the residually radioactive metal products or non-metallic by-products of the melting and refining process, expressing the radionuclide concentrations as specific activities, in Bq/g, is more meaningful in the present analysis.

Specific activities are related to areal activity concentrations by the following relationship:

$$C_{ij} = S_{ij} \sigma_j$$

$C_{ij}$  = specific activity of nuclide  $i$  in component  $j$  (Bq/g)

$S_{ij}$  = areal activity concentration of nuclide  $i$  in component  $j$  (Bq/cm<sup>2</sup>)



$$\begin{aligned}\sigma_j &= \text{mass-to-surface ratio of component } j \text{ (g/cm}^2\text{)} \\ &= \frac{m_j}{a_j} \\ m_j &= \text{mass of component } j \text{ (g)} \\ a_j &= \text{exposed surface area of component } j \text{ (cm}^2\text{)}\end{aligned}$$

A mass-based normalized dose is defined as the dose to an exposed individual, normalized to a unit specific activity of a given radionuclide *in the scrap* at the time of clearance. This specific activity is an average value: the total activity of a given nuclide divided by the total mass of scrap being cleared. The exposure of this individual may be to scrap or to any of the products or by-products generated during the recycling of the scrap—the normalized dose expressed is in terms of the specific activity of the cleared scrap.

The surficial normalized dose is the dose to an individual exposed under the same conditions from a radionuclide that was uniformly distributed over one surface of the scrap at the time of clearance. This is likewise an average value: the total activity of a given nuclide divided by the exposed surface area of scrap being cleared. For scrap that is in the form of sheets, plates, or piping, it is assumed that the residual activity resided on only one surface. A surficial normalized dose for each scenario is derived by dividing the mass-based normalized dose by the mass thickness (mass-to-surface ratio) of steel scrap likely to be cleared from BWR or PWR commercial nuclear power plants undergoing dismantlement.

$$D_{i(s)} = \frac{D_{i(m)}}{\bar{\sigma}}$$

$$\begin{aligned}D_{i(s)} &= \text{surficial normalized dose from radionuclide } i \\ D_{i(m)} &= \text{mass-based normalized dose from radionuclide } i \\ \bar{\sigma} &= \text{average mass-to-surface ratio of carbon steel components likely to be cleared from a BWR or PWR (g/cm}^2\text{)}\end{aligned}$$

### 3.8.1 Mass-to-Surface Ratio

The mass-to-surface ratios of the various steel components of nuclear power reactors are evaluated in order to create a frequency distribution for use in calculating the surficial normalized doses. This evaluation, which is discussed in greater detail in Section A.6.1, consists of examining the steel components of the Reference BWR and the Reference PWR. Three general types of BWR components—rebar, structural steel, and pipe hangers—are judged to be likely candidates for clearance. Each of these types comprises components which span a wide range of sizes. Each size has a different mass-to-surface ratio. Four types of PWR components—the three BWR types plus piping—are judged to be candidates for clearance. The average mass-to-surface ratio of cleared steel components was calculated as follows:

$$\bar{\sigma} = \frac{\sum m_j}{\sum a_j}$$

Since the mix of cleared components will vary over the 1.7-year period of dismantlement, probability distributions of average mass-to-surface ratios of scrap cleared during a 12-month period were constructed for both PWRs and BWRs. These values, specific to the reactor type randomly selected during the Monte Carlo probabilistic analyses, were used to calculate the surficial normalized doses.

### 3.9 Dose Assessments of Recycling and Disposal of Steel Scrap

As discussed in previous sections of this chapter, the radiological assessment of the clearance of steel scrap from NRC-licensed facilities compares the radiation exposures of various groups to each of 115 radionuclides and their progenies in 30 exposure scenarios. The exposures of additional groups are assessed in seven scenarios involving exposures to iron and steel products made from the single furnace heat during one year that contains the maximum fraction of cleared scrap. These groups are not included in the ranking to determine the critical group for each radionuclide.

#### 3.9.1 Calculation of Effective Dose Equivalents (EDEs)

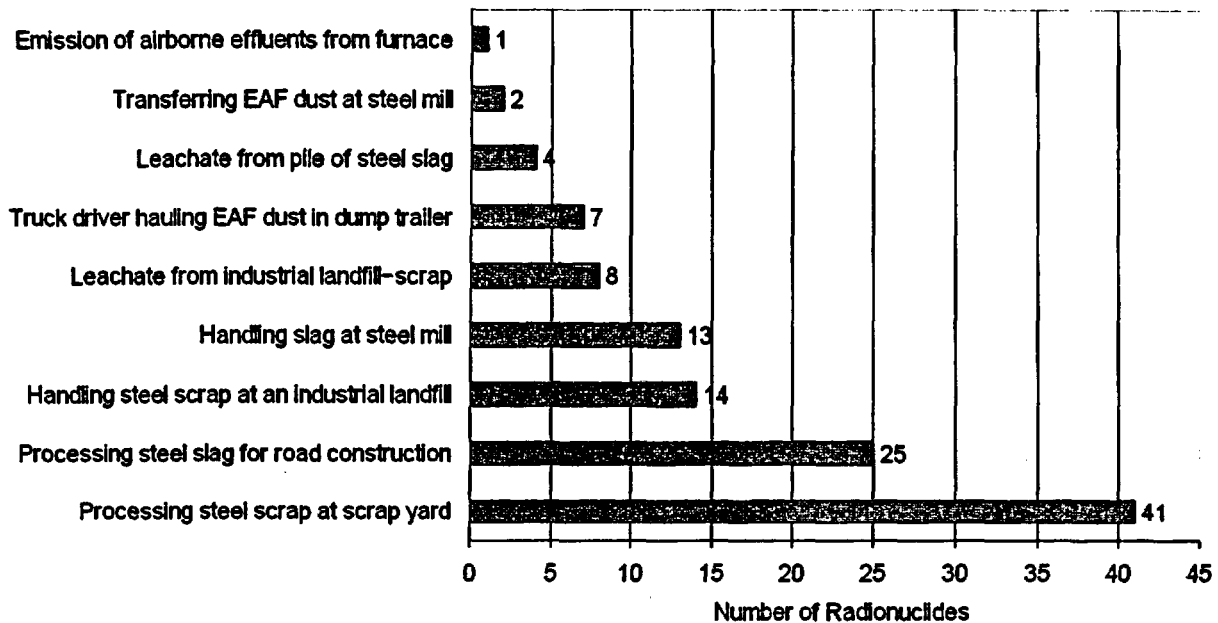
The groups described by nine of these scenarios receive the highest mean normalized EDEs from one year of exposure to cleared steel scrap from all 115 nuclides, one scenario constituting the EDE-critical group for 41 nuclides.<sup>65</sup> Table 3.21 lists the mean and the 5th, 50th, and 95th percentile mass-based normalized EDEs from each radionuclide to its respective critical group, while Table 3.22 lists the corresponding surficial EDEs. Figure 3.5 lists the scenarios describing the EDE-critical groups and displays the number of radionuclides for which each scenario constitutes the critical group. The mean and the 5th, 50th, 90th, and 95th percentile normalized EDEs from all 115 nuclides for all 30 scenarios are tabulated in Appendix F-1. The corresponding statistics for the seven single-heat scenarios are tabulated in Appendix M-1.

The scenario giving rise to a critical group for the greatest number of radionuclides models workers handling and processing scrap metal at a scrap yard. There are several reasons for this. First, the scenario occurs during the first two weeks following clearance. Consequently, a short-lived radionuclide such as P-32, with a 14-day half-life, would not have undergone a great amount of decay. Second, this scenario occurs prior to the scrap being melted and refined; therefore, none of the residual radioactive contaminants would have been removed by partitioning or volatilization, as could happen once the scrap is melted. Finally, the scrap yard workers spend much of their workday in close proximity to large quantities of scrap, and are

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<sup>65</sup> As discussed in Chapter 1, the group which receives the highest mean normalized EDE from a given radionuclide is defined as the EDE-critical group for that nuclide.

exposed to direct, penetrating radiation from  $\gamma$ -emitting nuclides, as well as to the inhalation and secondary ingestion of the metallic oxide dust generated during the cutting and sizing operations.



**Figure 3.5 Scenarios giving rise to EDE-critical groups for steel**

In the case of the drinking water scenarios, many realizations of the Monte Carlo uncertainty analyses result in zero doses from some radionuclides. Depending on the particular set of parameters sampled, the contaminant could miss the well entirely or fail to reach it within 1,000 years or within 20 half-lives of the radionuclide in question, whichever is the shorter time. For the six radionuclides listed in Table 3.19, the mean normalized EDE in the critical group is higher than the 90th percentile EDE. The critical group for five of these nuclides comprises individuals drinking water from wells down gradient from an industrial landfill containing cleared steel scrap. The critical group for the sixth nuclide—Sr-90—comprises individuals drinking water from wells down gradient from a slag storage pile. The group with the highest EDE for which the mean does not exceed the 90th percentile might be considered as an alternate critical group for that nuclide. These potential alternate critical groups are listed in Table 3.19.

### 3.9.2 Calculation of Effective Doses

The groups described by the same nine scenarios characterizing the EDE-critical groups receive the highest mean normalized effective doses from one year of exposure to cleared steel scrap from all 115 nuclides, the workers handling and processing steel scrap at a scrap yard constituting the critical group for 59 nuclides. Table 3.23 lists the mean and the 5th, 50th, and 95th percentile mass-based normalized effective doses from each radionuclide to its respective critical group, while Table 3.24 lists the corresponding surficial effective doses. Figure 3.6 lists the scenarios describing the effective dose-critical groups and displays the number of radionuclides for which each scenario constitutes the critical group. The mean and the 5th, 50th,

90th, and 95th percentile normalized effective doses from all 115 nuclides for all 30 scenarios are tabulated in Appendix F-2. The factors leading to the highest effective doses in these scenarios are similar to those giving rise to the EDE-critical groups discussed in Section 3.9.1.

**Table 3.19 Normalized mass-based EDEs from selected nuclides ( $\mu\text{Sv/y}$  per Bq/g)**

Nuclide <sup>a</sup>	Critical group			Potential alternate critical group <sup>b</sup>		
	Mean	90 <sup>th</sup> %-ile	Scenario	Mean	90 <sup>th</sup> %-ile	Scenario
C-14	3.2e-02	0.0e+00	Leachate-industrial-scrap	1.1e-03	3.1e-03	Scrap yard
Mn-53	8.8e-04	0.0e+00	Leachate-industrial-scrap	8.4e-05	2.2e-04	Scrap yard
Sr-90	5.7e-01	6.4e-05	Leachate-steel slag	2.7e-01	7.1e-01	Scrap yard
Mo-93	3.7e-02	0.0e+00	Leachate-industrial-scrap	2.7e-03	7.1e-03	Scrap yard
Cs-135	8.2e-03	0.0e+00	Leachate-industrial-scrap	8.0e-03	3.1e-02	Airborne emissions
Np-237	3.2e+02	5.1e+01	Leachate-industrial-scrap	6.0e+01	1.2e+02	Processing steel slag

<sup>a</sup> Nuclides from which mean normalized EDE exceeds 90th percentile EDE

<sup>b</sup> Group with maximum mean EDE which does not exceed 90th percentile EDE to *that* group

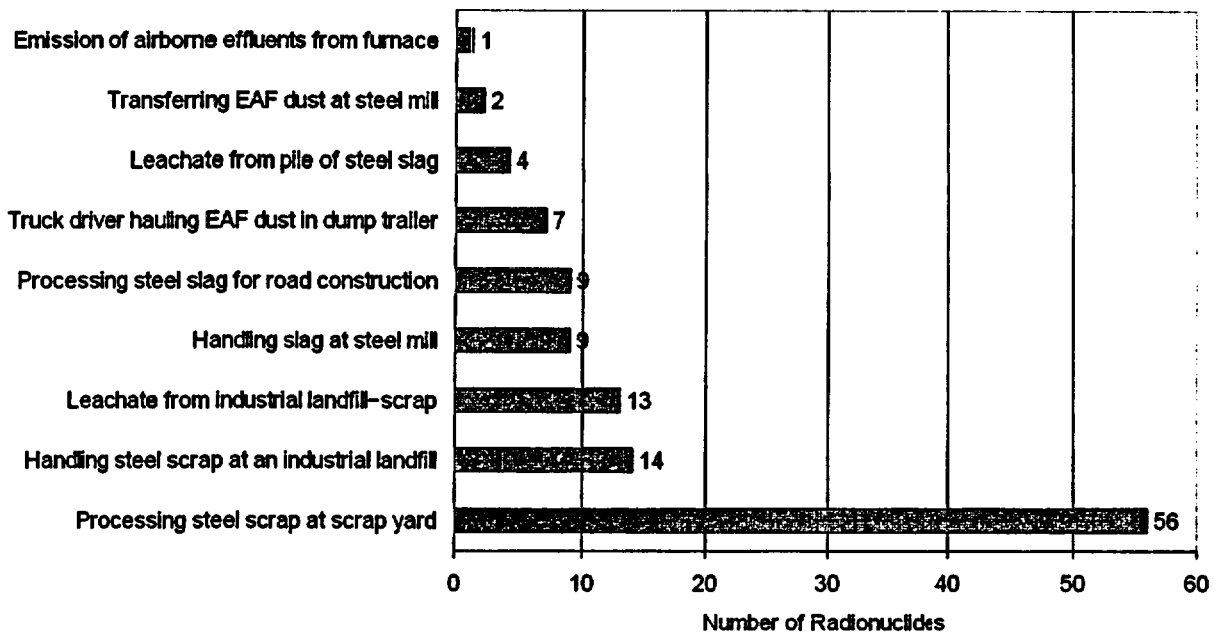
The corresponding statistics for the seven single-heat scenarios are tabulated in Appendix M-2. For the 11 radionuclides listed in Table 3.20, the mean normalized effective dose in the critical group is higher than the 90th percentile effective dose. The critical group for ten of these nuclides comprises persons drinking water from wells down gradient from an industrial landfill containing cleared steel scrap. The critical group for the 11th nuclide—Sr-90—comprises persons drinking water from wells down gradient from a slag storage pile. The group with the highest effective dose for which the mean does not exceed the 90th percentile might be considered as an alternate critical group for that nuclide. These potential alternate critical groups are listed in Table 3.20.

**Table 3.20 Normalized mass-based effective doses from selected nuclides ( $\mu\text{Sv/y}$  per Bq/g)**

Nuclide <sup>a</sup>	Critical group			Potential alternate critical group <sup>b</sup>		
	Mean	90 <sup>th</sup> %-ile	Scenario	Mean	90 <sup>th</sup> %-ile	Scenario
C-14	3.3e-02	0.0e+00	Leachate industrial scrap	1.2e-03	3.2e-03	Scrap yard
Mn-53	9.0e-04	0.0e+00	Leachate industrial scrap	6.5e-05	1.7e-04	Scrap yard
Sr-90	4.2e-01	4.8e-05	Leachate steel slag	2.4e-01	6.3e-01	Scrap yard
Mo-93	1.9e-01	0.0e+00	Leachate industrial scrap	5.2e-03	1.4e-02	Scrap yard
Cs-135	8.6e-03	0.0e+00	Leachate industrial scrap	8.2e-03	3.1e-02	Airborne emissions
U-233	5.9e+00	0.0e+00	Leachate industrial scrap	2.7e+00	5.4e+00	Processing steel slag
U-234	4.2e+00	0.0e+00	Leachate industrial scrap	2.6e+00	5.3e+00	Processing steel slag
U-235	5.1e+00	0.0e+00	Leachate industrial scrap	3.4e+00	6.7e+00	Processing steel slag
U-236	3.8e+00	0.0e+00	Leachate industrial scrap	2.4e+00	4.9e+00	Processing steel slag
U-238	3.9e+00	0.0e+00	Leachate industrial scrap	2.5e+00	4.9e+00	Processing steel slag
Np-237	2.9e+01	4.8e+00	Leachate industrial scrap	7.9e+00	2.1e+01	Scrap yard

<sup>a</sup> Nuclides from which mean normalized effective dose exceeds 90th percentile effective dose

<sup>b</sup> Group with maximum mean effective dose which does not exceed 90th percentile effective dose to *that* group



**Figure 3.6 Scenarios giving rise to effective dose-critical groups for steel**

**Table 3.21 Normalized mass-based effective dose equivalents to critical groups for steel**

Radionuclide	$\mu\text{Sv/y per Bq/g}$				mrem/y per pCi/g				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
H-3	1.9e-02	0.0e+00	1.4e-05	7.3e-02	7.2e-05	0.0e+00	5.0e-08	2.7e-04	Leachate-Industrial-scrap
C-14	3.2e-02	0.0e+00	0.0e+00	4.8e-02	1.2e-04	0.0e+00	0.0e+00	1.8e-04	Leachate-Industrial-scrap
Na-22	4.2e+01	4.2e+00	2.1e+01	1.6e+02	1.6e-01	1.5e-02	7.9e-02	5.8e-01	Scrap yard
P-32	5.7e-02	5.5e-03	2.9e-02	2.1e-01	2.1e-04	2.0e-05	1.1e-04	7.7e-04	Scrap yard
S-35	3.7e-04	3.9e-05	1.9e-04	1.4e-03	1.4e-06	1.4e-07	7.1e-07	5.1e-06	Scrap yard
Cl-36	1.7e+00	0.0e+00	0.0e+00	7.3e+00	6.4e-03	0.0e+00	0.0e+00	2.7e-02	Leachate-steel slag
K-40	3.4e+00	3.4e-01	1.7e+00	1.3e+01	1.3e-02	1.2e-03	6.4e-03	4.6e-02	Scrap yard
Ca-41	2.1e-01	0.0e+00	0.0e+00	8.9e-01	7.8e-04	0.0e+00	0.0e+00	3.3e-03	Leachate-steel slag
Ca-45	2.0e-03	1.8e-04	1.0e-03	7.7e-03	7.5e-06	6.7e-07	3.8e-06	2.8e-05	Scrap yard
Sc-46	3.8e+01	3.7e+00	1.9e+01	1.4e+02	1.4e-01	1.4e-02	7.0e-02	5.2e-01	Scrap yard
Cr-51	3.8e-01	2.1e-02	1.7e-01	1.6e+00	1.4e-03	7.6e-05	6.1e-04	5.9e-03	Scrap disposal-Industrial
Mn-53	8.8e-04	0.0e+00	0.0e+00	0.0e+00	3.2e-06	0.0e+00	0.0e+00	0.0e+00	Leachate-Industrial-scrap
Mn-54	1.6e+01	1.6e+00	8.1e+00	5.9e+01	5.9e-02	5.9e-03	3.0e-02	2.2e-01	Scrap yard
Fe-55	4.6e-04	4.4e-05	2.3e-04	1.7e-03	1.7e-06	1.6e-07	8.6e-07	6.3e-06	Scrap yard
Fe-59	2.1e+01	2.1e+00	1.1e+01	7.8e+01	7.8e-02	7.7e-03	4.0e-02	2.9e-01	Scrap yard
Co-56	6.8e+01	6.7e+00	3.4e+01	2.5e+02	2.5e-01	2.5e-02	1.3e-01	9.3e-01	Scrap yard
Co-57	1.2e+00	6.5e-02	5.3e-01	5.1e+00	4.5e-03	2.4e-04	1.9e-03	1.9e-02	Scrap disposal-Industrial
Co-58	1.7e+01	1.7e+00	8.6e+00	6.3e+01	6.3e-02	6.2e-03	3.2e-02	2.3e-01	Scrap yard
Co-60	5.2e+01	5.2e+00	2.7e+01	1.9e+02	1.9e-01	1.9e-02	9.8e-02	7.2e-01	Scrap yard
Ni-59	4.6e-04	5.2e-05	2.4e-04	1.6e-03	1.7e-06	1.9e-07	8.8e-07	6.1e-06	Scrap yard
Ni-63	4.7e-04	4.7e-05	2.4e-04	1.7e-03	1.8e-06	1.7e-07	9.0e-07	6.4e-06	Scrap yard
Zn-65	1.5e+01	4.5e+00	1.0e+01	4.7e+01	5.6e-02	1.6e-02	3.8e-02	1.7e-01	EAF dust-dump trailer
As-73	2.2e-02	1.2e-03	9.6e-03	9.3e-02	8.2e-05	4.4e-06	3.6e-05	3.4e-04	Scrap disposal-Industrial
Se-75	5.9e+00	1.7e+00	4.0e+00	1.8e+01	2.2e-02	6.3e-03	1.5e-02	6.8e-02	EAF dust-dump trailer
Sr-85	7.6e+00	7.5e-01	3.9e+00	2.8e+01	2.8e-02	2.8e-03	1.4e-02	1.0e-01	Scrap yard
Sr-89	6.3e-02	6.4e-03	3.2e-02	2.3e-01	2.3e-04	2.4e-05	1.2e-04	8.6e-04	Scrap yard
Sr-90	5.7e-01	0.0e+00	0.0e+00	1.5e-01	2.1e-03	0.0e+00	0.0e+00	5.5e-04	Leachate-steel slag
Y-91	1.4e-01	1.4e-02	6.9e-02	5.0e-01	5.0e-04	5.1e-05	2.6e-04	1.9e-03	Scrap yard
Zr-93	9.3e-03	1.2e-03	5.1e-03	2.8e-02	3.4e-05	4.3e-06	1.9e-05	1.0e-04	Processing steel slag
Zr-95	1.5e+01	1.5e+00	7.6e+00	5.5e+01	5.6e-02	5.5e-03	2.8e-02	2.0e-01	Scrap yard
Nb-93m	3.3e-03	4.1e-04	1.9e-03	1.0e-02	1.2e-05	1.5e-06	6.9e-06	3.8e-05	Handling slag
Nb-94	3.0e+01	3.0e+00	1.5e+01	1.1e+02	1.1e-01	1.1e-02	5.7e-02	4.1e-01	Scrap yard
Nb-95	1.2e+01	1.2e+00	6.1e+00	4.5e+01	4.5e-02	4.4e-03	2.3e-02	1.7e-01	Scrap yard
Mo-93	3.7e-02	0.0e+00	0.0e+00	4.2e-02	1.4e-04	0.0e+00	0.0e+00	1.6e-04	Leachate-Industrial-scrap
Tc-97	1.9e-01	0.0e+00	0.0e+00	8.1e-01	6.9e-04	0.0e+00	0.0e+00	3.9e-03	Leachate-Industrial-scrap
Tc-97m	4.5e-03	2.4e-04	2.0e-03	1.9e-02	1.7e-05	9.0e-07	7.2e-06	7.0e-05	Scrap disposal-Industrial
Tc-99	1.6e+00	0.0e+00	0.0e+00	6.9e+00	5.9e-03	0.0e+00	0.0e+00	2.6e-02	Leachate-Industrial-scrap
Ru-103	7.1e+00	7.0e-01	3.6e+00	2.6e+01	2.6e-02	2.6e-03	1.3e-02	9.8e-02	Scrap yard
Ru-106	4.2e+00	4.2e-01	2.1e+00	1.5e+01	1.5e-02	1.5e-03	7.8e-03	5.7e-02	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 3.21 Normalized mass-based effective dose equivalents to critical groups for steel

Radionuclide	$\mu\text{Sv/y}$ per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ag-108m	2.9e+01	2.9e+00	1.5e+01	1.1e+02	1.1e-01	1.1e-02	5.4e-02	3.9e-01	Scrap yard
Ag-110m	5.2e+01	5.2e+00	2.6e+01	1.9e+02	1.9e-01	1.9e-02	9.8e-02	7.1e-01	Scrap yard
Cd-109	6.5e-02	3.5e-03	2.8e-02	2.7e-01	2.4e-04	1.3e-05	1.0e-04	1.0e-03	Scrap disposal-industrial
Sn-113	3.7e+00	3.7e-01	1.9e+00	1.4e+01	1.4e-02	1.4e-03	7.0e-03	5.1e-02	Scrap yard
Sb-124	3.4e+01	3.3e+00	1.7e+01	1.2e+02	1.2e-01	1.2e-02	6.3e-02	4.6e-01	Scrap yard
Sb-125	7.1e+00	7.1e-01	3.6e+00	2.6e+01	2.6e-02	2.6e-03	1.3e-02	9.7e-02	Scrap yard
Te-123m	1.5e+00	8.1e-02	6.5e-01	6.3e+00	5.6e-03	3.0e-04	2.4e-03	2.3e-02	Scrap disposal-industrial
Te-127m	1.0e-01	3.0e-02	7.1e-02	3.2e-01	3.9e-04	1.1e-04	2.6e-04	1.2e-03	EAF dust-dump trailer
I-125	7.3e-01	2.1e-01	6.3e-01	1.6e+00	2.7e-03	8.0e-04	2.3e-03	5.9e-03	Airborne emissions
I-129	2.2e+02	0.0e+00	0.0e+00	7.7e+02	8.2e-01	0.0e+00	0.0e+00	2.9e+00	Leachate-steel slag
I-131	3.7e+00	1.9e-01	1.6e+00	1.5e+01	1.4e-02	7.0e-04	5.8e-03	5.7e-02	Scrap disposal-industrial
Cs-134	4.4e+01	1.3e+01	3.0e+01	1.3e+02	1.6e-01	4.9e-02	1.1e-01	5.0e-01	EAF dust-dump trailer
Cs-135	8.2e-03	0.0e+00	0.0e+00	0.0e+00	3.0e-05	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
Cs-137	1.6e+01	4.9e+00	1.1e+01	5.0e+01	6.0e-02	1.8e-02	4.1e-02	1.9e-01	EAF dust-dump trailer
Ba-133	4.9e+00	4.9e-01	2.5e+00	1.8e+01	1.8e-02	1.8e-03	9.1e-03	6.7e-02	Scrap yard
Ce-139	1.5e+00	8.2e-02	6.6e-01	6.4e+00	5.7e-03	3.0e-04	2.5e-03	2.4e-02	Scrap disposal-industrial
Ce-141	7.1e-01	3.8e-02	3.1e-01	3.0e+00	2.6e-03	1.4e-04	1.1e-03	1.1e-02	Scrap disposal-industrial
Ce-144	1.0e+00	1.0e-01	5.1e-01	3.7e+00	3.7e-03	3.8e-04	1.9e-03	1.4e-02	Scrap yard
Pm-147	4.4e-03	5.3e-04	2.4e-03	1.3e-02	1.6e-05	2.0e-06	9.0e-06	4.9e-05	Handling slag
Sm-151	3.3e-03	4.0e-04	1.8e-03	9.9e-03	1.2e-05	1.5e-06	6.6e-06	3.7e-05	Processing steel slag
Eu-152	2.2e+01	2.2e+00	1.1e+01	8.1e+01	8.1e-02	8.1e-03	4.1e-02	3.0e-01	Scrap yard
Eu-154	2.2e+01	2.1e+00	1.1e+01	8.0e+01	8.0e-02	7.9e-03	4.0e-02	2.9e-01	Scrap yard
Eu-155	4.5e-01	2.4e-02	1.9e-01	1.9e+00	1.7e-03	8.9e-05	7.2e-04	6.9e-03	Scrap disposal-industrial
Gd-153	5.9e-01	3.2e-02	2.6e-01	2.5e+00	2.2e-03	1.2e-04	9.5e-04	9.1e-03	Scrap disposal-industrial
Tb-160	2.0e+01	1.9e+00	1.0e+01	7.3e+01	7.3e-02	7.2e-03	3.7e-02	2.7e-01	Scrap yard
Tm-170	3.6e-02	1.9e-03	1.6e-02	1.5e-01	1.3e-04	7.1e-06	5.7e-05	5.5e-04	Scrap disposal-industrial
Tm-171	2.7e-03	1.5e-04	1.2e-03	1.1e-02	1.0e-05	5.4e-07	4.4e-06	4.2e-05	Scrap disposal-industrial
Ta-182	2.3e+01	2.3e+00	1.2e+01	8.6e+01	8.6e-02	8.5e-03	4.4e-02	3.2e-01	Scrap yard
W-181	1.8e-01	9.8e-03	7.9e-02	7.6e-01	6.8e-04	3.6e-05	2.9e-04	2.8e-03	Scrap disposal-industrial
W-185	2.0e-03	2.2e-04	1.0e-03	7.3e-03	7.5e-06	8.1e-07	3.8e-06	2.7e-05	Scrap yard
Os-185	1.4e+01	4.1e+00	9.6e+00	4.4e+01	5.3e-02	1.5e-02	3.5e-02	1.6e-01	EAF dust-dump trailer
Ir-192	1.1e+01	1.1e+00	5.7e+00	4.2e+01	4.1e-02	4.1e-03	2.1e-02	1.5e-01	Scrap yard
Ti-204	1.2e-02	1.2e-03	6.0e-03	4.2e-02	4.3e-05	4.5e-06	2.2e-05	1.6e-04	Scrap yard
Pb-210	1.2e+01	5.1e+00	1.2e+01	2.2e+01	4.5e-02	1.9e-02	4.3e-02	8.0e-02	Transferring EAF dust
Bi-207	4.3e+01	1.3e+01	2.9e+01	1.3e+02	1.6e-01	4.8e-02	1.1e-01	4.9e-01	EAF dust-dump trailer
Po-210	3.3e+00	1.5e+00	3.2e+00	5.8e+00	1.2e-02	5.6e-03	1.2e-02	2.1e-02	Transferring EAF dust
Ra-226	3.5e+01	3.6e+00	1.8e+01	1.3e+02	1.3e-01	1.3e-02	6.6e-02	4.8e-01	Scrap yard
Ra-228	1.8e+01	1.8e+00	9.1e+00	6.6e+01	6.7e-02	6.8e-03	3.4e-02	2.4e-01	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 3.21 Normalized mass-based effective dose equivalents to critical groups for steel

Radionuclide	$\mu\text{Sv/y}$ per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ac-227	1.4e+02	1.7e+01	8.0e+01	4.4e+02	5.3e-01	6.4e-02	3.0e-01	1.6e+00	Handling slag
Th-228	4.9e+01	6.4e+00	2.8e+01	1.5e+02	1.8e-01	2.4e-02	1.0e-01	5.5e-01	Handling slag
Th-229	1.9e+02	2.3e+01	1.0e+02	5.6e+02	6.9e-01	8.5e-02	3.8e-01	2.1e+00	Processing steel slag
Th-230	2.7e+01	3.4e+00	1.5e+01	8.4e+01	1.0e-01	1.2e-02	5.6e-02	3.1e-01	Processing steel slag
Th-232	1.2e+02	1.5e+01	6.7e+01	3.7e+02	4.5e-01	5.5e-02	2.5e-01	1.4e+00	Processing steel slag
Pa-231	9.5e+01	1.2e+01	5.2e+01	2.9e+02	3.5e-01	4.3e-02	1.9e-01	1.1e+00	Processing steel slag
U-232	7.5e+01	9.1e+00	4.1e+01	2.3e+02	2.8e-01	3.4e-02	1.5e-01	8.5e-01	Processing steel slag
U-233	1.4e+01	1.7e+00	7.7e+00	4.3e+01	5.2e-02	6.4e-03	2.9e-02	1.6e-01	Processing steel slag
U-234	1.4e+01	1.7e+00	7.6e+00	4.2e+01	5.1e-02	6.3e-03	2.8e-02	1.5e-01	Processing steel slag
U-235	1.4e+01	1.7e+00	7.7e+00	4.2e+01	5.1e-02	6.2e-03	2.9e-02	1.6e-01	Handling slag
U-236	1.3e+01	1.6e+00	7.2e+00	4.0e+01	4.8e-02	5.9e-03	2.6e-02	1.5e-01	Processing steel slag
U-238	1.3e+01	1.6e+00	6.9e+00	3.8e+01	4.7e-02	5.8e-03	2.6e-02	1.4e-01	Processing steel slag
Np-237	3.2e+02	0.0e+00	0.0e+00	5.1e+02	1.2e+00	0.0e+00	0.0e+00	2.3e+00	Leachate-industrial-scrap
Pu-236	1.4e+01	1.6e+00	7.5e+00	4.2e+01	5.0e-02	6.1e-03	2.8e-02	1.5e-01	Handling slag
Pu-238	3.1e+01	3.8e+00	1.7e+01	9.4e+01	1.2e-01	1.4e-02	6.3e-02	3.5e-01	Processing steel slag
Pu-239	3.3e+01	4.1e+00	1.8e+01	1.0e+02	1.2e-01	1.5e-02	6.8e-02	3.8e-01	Processing steel slag
Pu-240	3.3e+01	4.1e+00	1.8e+01	1.0e+02	1.2e-01	1.5e-02	6.8e-02	3.8e-01	Processing steel slag
Pu-241	5.8e-01	6.7e-02	3.0e-01	2.1e+00	2.1e-03	2.5e-04	1.1e-03	7.7e-03	Scrap yard
Pu-242	3.2e+01	3.9e+00	1.7e+01	9.7e+01	1.2e-01	1.4e-02	6.4e-02	3.6e-01	Processing steel slag
Pu-244	3.5e+01	4.4e+00	1.9e+01	1.1e+02	1.3e-01	1.6e-02	7.1e-02	3.9e-01	Processing steel slag
Am-241	4.8e+01	5.8e+00	2.6e+01	1.4e+02	1.8e-01	2.2e-02	9.7e-02	5.3e-01	Processing steel slag
Am-242m	4.7e+01	5.8e+00	2.6e+01	1.4e+02	1.7e-01	2.1e-02	9.6e-02	5.3e-01	Processing steel slag
Am-243	4.8e+01	6.0e+00	2.7e+01	1.5e+02	1.8e-01	2.2e-02	9.8e-02	5.4e-01	Processing steel slag
Cm-242	1.6e+00	2.0e-01	8.9e-01	4.9e+00	6.0e-03	7.4e-04	3.3e-03	1.8e-02	Handling slag
Cm-243	3.3e+01	4.0e+00	1.9e+01	1.0e+02	1.2e-01	1.5e-02	6.9e-02	3.8e-01	Handling slag
Cm-244	2.6e+01	3.1e+00	1.5e+01	8.1e+01	9.7e-02	1.2e-02	5.4e-02	3.0e-01	Handling slag
Cm-245	4.9e+01	6.1e+00	2.7e+01	1.5e+02	1.8e-01	2.2e-02	1.0e-01	5.5e-01	Processing steel slag
Cm-246	4.8e+01	6.0e+00	2.6e+01	1.5e+02	1.8e-01	2.2e-02	9.8e-02	5.4e-01	Processing steel slag
Cm-247	4.7e+01	5.9e+00	2.6e+01	1.4e+02	1.7e-01	2.2e-02	9.7e-02	5.3e-01	Processing steel slag
Cm-248	1.8e+02	2.2e+01	9.7e+01	5.4e+02	6.6e-01	8.1e-02	3.6e-01	2.0e+00	Processing steel slag
Bk-249	1.5e-01	1.7e-02	8.0e-02	4.4e-01	5.4e-04	6.5e-05	3.0e-04	1.6e-03	Handling slag
Cf-248	5.1e+00	6.2e-01	2.8e+00	1.6e+01	1.9e-02	2.3e-03	1.0e-02	5.7e-02	Handling slag
Cf-249	4.4e+01	5.6e+00	2.4e+01	1.3e+02	1.6e-01	2.1e-02	9.0e-02	5.0e-01	Processing steel slag
Cf-250	2.2e+01	2.6e+00	1.2e+01	6.6e+01	8.1e-02	9.8e-03	4.5e-02	2.5e-01	Handling slag
Cf-251	4.3e+01	5.3e+00	2.4e+01	1.3e+02	1.6e-01	2.0e-02	8.7e-02	4.8e-01	Processing steel slag
Cf-252	1.6e+01	2.0e+00	9.0e+00	4.9e+01	6.0e-02	7.3e-03	3.3e-02	1.8e-01	Handling slag
Cf-254	3.3e+02	3.3e+01	1.7e+02	1.2e+03	1.2e+00	1.2e-01	6.2e-01	4.5e+00	Scrap yard
Es-254	2.0e+01	2.2e+00	1.0e+01	7.5e+01	7.6e-02	8.0e-03	3.9e-02	2.8e-01	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval



**Table 3.22 Normalized surficial effective dose equivalents to critical groups for steel**

Radionuclide	$\mu\text{Sv/y per Bq/cm}^2$				mrem/y per pCi/cm <sup>2</sup>				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
H-3	3.8e-03	0.0e+00	2.7e-06	1.4e-02	1.4e-05	0.0e+00	9.9e-09	5.2e-05	Leachate-industrial-scrap
C-14	6.3e-03	0.0e+00	0.0e+00	9.5e-03	2.3e-05	0.0e+00	0.0e+00	3.5e-05	Leachate-industrial-scrap
Na-22	8.3e+00	8.4e-01	4.2e+00	3.0e+01	3.1e-02	3.1e-03	1.6e-02	1.1e-01	Scrap yard
P-32	1.1e-02	1.1e-03	5.6e-03	4.1e-02	4.1e-05	4.1e-06	2.1e-05	1.5e-04	Scrap yard
S-35	7.4e-05	7.7e-06	3.8e-05	2.7e-04	2.7e-07	2.9e-08	1.4e-07	1.0e-06	Scrap yard
Cl-36	3.4e-01	0.0e+00	0.0e+00	1.5e+00	1.3e-03	0.0e+00	0.0e+00	5.4e-03	Leachate-steel slag
K-40	6.7e-01	6.8e-02	3.4e-01	2.4e+00	2.5e-03	2.5e-04	1.3e-03	9.0e-03	Scrap yard
Ca-41	4.2e-02	0.0e+00	0.0e+00	1.8e-01	1.5e-04	0.0e+00	0.0e+00	6.5e-04	Leachate-steel slag
Ca-45	4.0e-04	3.6e-05	2.0e-04	1.5e-03	1.5e-06	1.3e-07	7.5e-07	5.6e-06	Scrap yard
Sc-46	7.4e+00	7.4e-01	3.8e+00	2.7e+01	2.8e-02	2.8e-03	1.4e-02	1.0e-01	Scrap yard
Cr-51	7.6e-02	4.2e-03	3.3e-02	3.2e-01	2.8e-04	1.5e-05	1.2e-04	1.2e-03	Scrap disposal-industrial
Mn-53	1.7e-04	0.0e+00	0.0e+00	0.0e+00	6.4e-07	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
Mn-54	3.2e+00	3.2e-01	1.6e+00	1.2e+01	1.2e-02	1.2e-03	5.9e-03	4.3e-02	Scrap yard
Fe-55	9.1e-05	8.8e-06	4.6e-05	3.4e-04	3.4e-07	3.2e-08	1.7e-07	1.2e-06	Scrap yard
Fe-59	4.2e+00	4.1e-01	2.1e+00	1.5e+01	1.5e-02	1.5e-03	7.8e-03	5.7e-02	Scrap yard
Co-56	1.3e+01	1.3e+00	6.8e+00	4.9e+01	5.0e-02	5.0e-03	2.5e-02	1.8e-01	Scrap yard
Co-57	2.4e-01	1.3e-02	1.0e-01	1.0e+00	8.9e-04	4.9e-05	3.9e-04	3.7e-03	Scrap disposal-industrial
Co-58	3.3e+00	3.3e-01	1.7e+00	1.2e+01	1.2e-02	1.2e-03	6.2e-03	4.5e-02	Scrap yard
Co-60	1.0e+01	1.0e+00	5.2e+00	3.8e+01	3.8e-02	3.9e-03	1.9e-02	1.4e-01	Scrap yard
Ni-59	9.1e-05	1.0e-05	4.7e-05	3.3e-04	3.4e-07	3.8e-08	1.7e-07	1.2e-06	Scrap yard
Ni-63	9.4e-05	9.5e-06	4.8e-05	3.5e-04	3.5e-07	3.5e-08	1.8e-07	1.3e-06	Scrap yard
Zn-65	3.0e+00	9.0e-01	2.0e+00	8.8e+00	1.1e-02	3.3e-03	7.5e-03	3.3e-02	EAF dust-dump trailer
As-73	4.4e-03	2.4e-04	1.9e-03	1.8e-02	1.6e-05	9.0e-07	7.1e-06	6.8e-05	Scrap disposal-industrial
Se-75	1.2e+00	3.5e-01	7.9e-01	3.4e+00	4.3e-03	1.3e-03	2.9e-03	1.3e-02	EAF dust-dump trailer
Sr-85	1.5e+00	1.5e-01	7.6e-01	5.5e+00	5.6e-03	5.6e-04	2.8e-03	2.0e-02	Scrap yard
Sr-89	1.2e-02	1.3e-03	6.3e-03	4.5e-02	4.6e-05	4.7e-06	2.3e-05	1.7e-04	Scrap yard
Sr-90	1.2e-01	0.0e+00	0.0e+00	2.9e-02	4.4e-04	0.0e+00	0.0e+00	1.1e-04	Leachate-steel slag
Y-91	2.7e-02	2.7e-03	1.4e-02	9.8e-02	9.9e-05	1.0e-05	5.0e-05	3.6e-04	Scrap yard
Zr-93	1.8e-03	2.3e-04	1.0e-03	5.6e-03	6.8e-06	8.3e-07	3.8e-06	2.1e-05	Processing steel slag
Zr-95	3.0e+00	3.0e-01	1.5e+00	1.1e+01	1.1e-02	1.1e-03	5.5e-03	4.0e-02	Scrap yard
Nb-93m	6.6e-04	8.2e-05	3.7e-04	2.0e-03	2.4e-06	3.0e-07	1.4e-06	7.4e-06	Handling slag
Nb-94	6.0e+00	6.0e-01	3.0e+00	2.2e+01	2.2e-02	2.2e-03	1.1e-02	8.0e-02	Scrap yard
Nb-95	2.4e+00	2.4e-01	1.2e+00	8.8e+00	8.9e-03	8.7e-04	4.5e-03	3.3e-02	Scrap yard
Mo-93	7.3e-03	0.0e+00	0.0e+00	8.2e-03	2.7e-05	0.0e+00	0.0e+00	3.0e-05	Leachate-industrial-scrap
Tc-97	3.7e-02	0.0e+00	0.0e+00	1.6e-01	1.4e-04	0.0e+00	0.0e+00	6.0e-04	Leachate-industrial-scrap
Tc-97m	8.9e-04	4.9e-05	3.9e-04	3.7e-03	3.3e-06	1.8e-07	1.4e-06	1.4e-05	Scrap disposal-industrial
Tc-99	3.2e-01	0.0e+00	0.0e+00	1.4e+00	1.2e-03	0.0e+00	0.0e+00	5.1e-03	Leachate-industrial-scrap
Ru-103	1.4e+00	1.4e-01	7.1e-01	5.2e+00	5.2e-03	5.1e-04	2.6e-03	1.9e-02	Scrap yard
Ru-106	8.2e-01	8.3e-02	4.2e-01	3.0e+00	3.1e-03	3.1e-04	1.5e-03	1.1e-02	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 3.22 Normalized surficial effective dose equivalents to critical groups for steel

Radionuclide	$\mu\text{Sv/y per Bq/cm}^2$				mrem/y per $\text{pCi/cm}^2$				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ag-108m	5.7e+00	5.8e-01	2.9e+00	2.1e+01	2.1e-02	2.1e-03	1.1e-02	7.7e-02	Scrap yard
Ag-110m	1.0e+01	1.0e+00	5.2e+00	3.8e+01	3.8e-02	3.8e-03	1.9e-02	1.4e-01	Scrap yard
Cd-109	1.3e-02	7.1e-04	5.5e-03	5.3e-02	4.7e-05	2.6e-06	2.0e-05	2.0e-04	Scrap disposal-Industrial
Sn-113	7.4e-01	7.5e-02	3.7e-01	2.7e+00	2.7e-03	2.8e-04	1.4e-03	1.0e-02	Scrap yard
Sb-124	6.6e+00	6.6e-01	3.3e+00	2.4e+01	2.5e-02	2.4e-03	1.2e-02	9.0e-02	Scrap yard
Sb-125	1.4e+00	1.4e-01	7.1e-01	5.1e+00	5.2e-03	5.2e-04	2.6e-03	1.9e-02	Scrap yard
Te-123m	3.0e-01	1.6e-02	1.3e-01	1.2e+00	1.1e-03	6.1e-05	4.8e-04	4.6e-03	Scrap disposal-Industrial
Te-127m	2.1e-02	6.1e-03	1.4e-02	6.0e-02	7.6e-05	2.3e-05	5.2e-05	2.2e-04	EAF dust-dump trailer
I-125	1.4e-01	4.3e-02	1.2e-01	3.1e-01	5.3e-04	1.6e-04	4.6e-04	1.2e-03	Airborne emissions
I-129	4.4e+01	0.0e+00	0.0e+00	1.5e+02	1.6e-01	0.0e+00	0.0e+00	5.7e-01	Leachate-steel slag
I-131	7.2e-01	3.9e-02	3.1e-01	3.0e+00	2.7e-03	1.4e-04	1.1e-03	1.1e-02	Scrap disposal-Industrial
Cs-134	8.6e+00	2.6e+00	5.8e+00	2.6e+01	3.2e-02	9.6e-03	2.2e-02	9.5e-02	EAF dust-dump trailer
Cs-135	1.7e-03	0.0e+00	0.0e+00	0.0e+00	6.3e-06	0.0e+00	0.0e+00	0.0e+00	Leachate-Industrial-scrap
Cs-137	3.2e+00	9.7e-01	2.2e+00	9.6e+00	1.2e-02	3.6e-03	8.1e-03	3.5e-02	EAF dust-dump trailer
Ba-133	9.7e-01	9.7e-02	4.9e-01	3.5e+00	3.6e-03	3.6e-04	1.8e-03	1.3e-02	Scrap yard
Ce-139	3.0e-01	1.7e-02	1.3e-01	1.3e+00	1.1e-03	6.2e-05	4.9e-04	4.7e-03	Scrap disposal-Industrial
Ce-141	1.4e-01	7.7e-03	6.1e-02	5.8e-01	5.2e-04	2.9e-05	2.3e-04	2.2e-03	Scrap disposal-Industrial
Ce-144	2.0e-01	2.0e-02	1.0e-01	7.3e-01	7.4e-04	7.6e-05	3.8e-04	2.7e-03	Scrap yard
Pm-147	8.6e-04	1.1e-04	4.8e-04	2.6e-03	3.2e-06	4.0e-07	1.8e-06	9.7e-06	Handling slag
Sm-151	6.4e-04	7.9e-05	3.6e-04	2.0e-03	2.4e-06	2.9e-07	1.3e-06	7.3e-06	Processing steel slag
Eu-152	4.3e+00	4.4e-01	2.2e+00	1.6e+01	1.6e-02	1.5e-03	8.1e-03	5.9e-02	Scrap yard
Eu-154	4.3e+00	4.3e-01	2.2e+00	1.6e+01	1.6e-02	1.6e-03	8.0e-03	5.8e-02	Scrap yard
Eu-155	8.8e-02	4.9e-03	3.8e-02	3.7e-01	3.3e-04	1.8e-05	1.4e-04	1.4e-03	Scrap disposal-Industrial
Gd-153	1.2e-01	6.5e-03	5.1e-02	4.9e-01	4.3e-04	2.4e-05	1.9e-04	1.8e-03	Scrap disposal-Industrial
Tb-160	3.9e+00	3.9e-01	2.0e+00	1.4e+01	1.4e-02	1.4e-03	7.2e-03	5.3e-02	Scrap yard
Tm-170	7.1e-03	3.9e-04	3.1e-03	2.9e-02	2.6e-05	1.4e-06	1.1e-05	1.1e-04	Scrap disposal-Industrial
Tm-171	5.4e-04	3.0e-05	2.3e-04	2.3e-03	2.0e-06	1.1e-07	8.6e-07	8.3e-06	Scrap disposal-Industrial
Ta-182	4.6e+00	4.6e-01	2.3e+00	1.7e+01	1.7e-02	1.7e-03	8.6e-03	6.2e-02	Scrap yard
W-181	3.6e-02	2.0e-03	1.6e-02	1.5e-01	1.3e-04	7.4e-06	5.8e-05	5.6e-04	Scrap disposal-Industrial
W-185	4.0e-04	4.3e-05	2.0e-04	1.4e-03	1.5e-06	1.6e-07	7.5e-07	5.4e-06	Scrap yard
Os-185	2.8e+00	8.3e-01	1.9e+00	8.2e+00	1.0e-02	3.1e-03	7.0e-03	3.0e-02	EAF dust-dump trailer
Ir-192	2.2e+00	2.2e-01	1.1e+00	8.1e+00	8.2e-03	8.2e-04	4.1e-03	3.0e-02	Scrap yard
Tl-204	2.3e-03	2.4e-04	1.2e-03	8.4e-03	8.5e-06	9.0e-07	4.3e-06	3.1e-05	Scrap yard
Pb-210	2.4e+00	1.0e+00	2.3e+00	4.2e+00	8.9e-03	3.7e-03	8.5e-03	1.6e-02	Transferring EAF dust
Bi-207	8.5e+00	2.6e+00	5.8e+00	2.5e+01	3.1e-02	8.5e-03	2.1e-02	9.4e-02	EAF dust-dump trailer
Po-210	6.6e-01	3.0e-01	6.3e-01	1.1e+00	2.4e-03	1.1e-03	2.3e-03	4.2e-03	Transferring EAF dust
Ra-226	7.0e+00	7.2e-01	3.5e+00	2.5e+01	2.6e-02	2.7e-03	1.3e-02	9.4e-02	Scrap yard
Ra-228	3.6e+00	3.7e-01	1.8e+00	1.3e+01	1.3e-02	1.4e-03	6.7e-03	4.8e-02	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

**Table 3.22 Normalized surficial effective dose equivalents to critical groups for steel**

Radionuclide	$\mu\text{Sv/y per Bq/cm}^2$				mrem/y per $\text{pCi/cm}^2$				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ac-227	2.8e+01	3.5e+00	1.6e+01	8.7e+01	1.0e-01	1.3e-02	5.8e-02	3.2e-01	Processing steel slag
Th-228	9.7e+00	1.3e+00	5.8e+00	2.9e+01	3.6e-02	4.7e-03	2.1e-02	1.1e-01	Handling slag
Th-229	3.6e+01	4.5e+00	2.0e+01	1.1e+02	1.3e-01	1.7e-02	7.4e-02	4.1e-01	Processing steel slag
Th-230	5.4e+00	6.6e-01	3.0e+00	1.7e+01	2.0e-02	2.5e-03	1.1e-02	6.1e-02	Processing steel slag
Th-232	2.4e+01	2.9e+00	1.3e+01	7.3e+01	8.8e-02	1.1e-02	4.9e-02	2.7e-01	Processing steel slag
Pa-231	1.9e+01	2.3e+00	1.0e+01	5.7e+01	6.9e-02	8.5e-03	3.8e-02	2.1e-01	Processing steel slag
U-232	1.5e+01	1.8e+00	8.0e+00	4.5e+01	5.4e-02	6.6e-03	3.0e-02	1.7e-01	Processing steel slag
U-233	2.8e+00	3.4e-01	1.5e+00	8.6e+00	1.0e-02	1.2e-03	5.7e-03	3.2e-02	Processing steel slag
U-234	2.7e+00	3.3e-01	1.5e+00	8.4e+00	1.0e-02	1.2e-03	5.5e-03	3.1e-02	Processing steel slag
U-235	2.7e+00	3.4e-01	1.5e+00	8.2e+00	1.0e-02	1.3e-03	5.6e-03	3.0e-02	Handling slag
U-236	2.6e+00	3.1e-01	1.4e+00	7.9e+00	9.5e-03	1.2e-03	5.2e-03	2.9e-02	Processing steel slag
U-238	2.5e+00	3.0e-01	1.4e+00	7.6e+00	9.2e-03	1.1e-03	5.1e-03	2.8e-02	Processing steel slag
Np-237	6.2e+01	0.0e+00	0.0e+00	1.2e+02	2.3e-01	0.0e+00	0.0e+00	4.6e-01	Leachate-industrial-scrap
Pu-238	2.7e+00	3.3e-01	1.5e+00	8.2e+00	9.9e-03	1.2e-03	5.5e-03	3.0e-02	Handling slag
Pu-238	6.1e+00	7.5e-01	3.4e+00	1.9e+01	2.3e-02	2.8e-03	1.3e-02	7.0e-02	Processing steel slag
Pu-239	6.6e+00	8.1e-01	3.6e+00	2.0e+01	2.4e-02	3.0e-03	1.3e-02	7.5e-02	Processing steel slag
Pu-240	6.6e+00	8.1e-01	3.6e+00	2.0e+01	2.4e-02	3.0e-03	1.3e-02	7.5e-02	Processing steel slag
Pu-241	1.1e-01	1.3e-02	6.0e-02	4.1e-01	4.2e-04	4.9e-05	2.2e-04	1.5e-03	Scrap yard
Pu-242	6.2e+00	7.7e-01	3.5e+00	1.9e+01	2.3e-02	2.8e-03	1.3e-02	7.1e-02	Processing steel slag
Pu-244	6.8e+00	8.6e-01	3.8e+00	2.1e+01	2.5e-02	3.2e-03	1.4e-02	7.6e-02	Processing steel slag
Am-241	9.4e+00	1.2e+00	5.2e+00	2.9e+01	3.5e-02	4.3e-03	1.9e-02	1.1e-01	Processing steel slag
Am-242m	9.3e+00	1.1e+00	5.1e+00	2.9e+01	3.4e-02	4.2e-03	1.9e-02	1.1e-01	Processing steel slag
Am-243	9.5e+00	1.2e+00	5.3e+00	2.9e+01	3.5e-02	4.3e-03	1.9e-02	1.1e-01	Processing steel slag
Cm-242	3.2e-01	4.0e-02	1.8e-01	9.7e-01	1.2e-03	1.5e-04	6.6e-04	3.6e-03	Handling slag
Cm-243	6.6e+00	8.1e-01	3.7e+00	2.0e+01	2.4e-02	3.0e-03	1.4e-02	7.4e-02	Handling slag
Cm-244	5.2e+00	6.3e-01	2.9e+00	1.6e+01	1.9e-02	2.3e-03	1.1e-02	5.9e-02	Handling slag
Cm-245	9.7e+00	1.2e+00	5.4e+00	3.0e+01	3.6e-02	4.4e-03	2.0e-02	1.1e-01	Processing steel slag
Cm-246	9.5e+00	1.2e+00	5.3e+00	2.9e+01	3.5e-02	4.3e-03	2.0e-02	1.1e-01	Processing steel slag
Cm-247	9.3e+00	1.2e+00	5.2e+00	2.8e+01	3.4e-02	4.3e-03	1.9e-02	1.1e-01	Processing steel slag
Cm-248	3.5e+01	4.3e+00	1.9e+01	1.1e+02	1.3e-01	1.6e-02	7.2e-02	3.9e-01	Processing steel slag
Bk-249	2.9e-02	3.5e-03	1.6e-02	8.7e-02	1.1e-04	1.3e-05	5.9e-05	3.2e-04	Handling slag
Cf-248	1.0e+00	1.2e-01	5.6e-01	3.1e+00	3.7e-03	4.6e-04	2.1e-03	1.1e-02	Handling slag
Cf-249	8.7e+00	1.1e+00	4.9e+00	2.6e+01	3.2e-02	4.0e-03	1.8e-02	9.8e-02	Processing steel slag
Cf-250	4.3e+00	5.3e-01	2.4e+00	1.3e+01	1.6e-02	2.0e-03	8.9e-03	4.9e-02	Handling slag
Cf-251	8.4e+00	1.0e+00	4.7e+00	2.6e+01	3.1e-02	3.8e-03	1.7e-02	9.5e-02	Processing steel slag
Cf-252	3.2e+00	3.9e-01	1.8e+00	9.8e+00	1.2e-02	1.4e-03	6.6e-03	3.6e-02	Handling slag
Cf-254	6.5e+01	6.7e+00	3.3e+01	2.4e+02	2.4e-01	2.5e-02	1.2e-01	8.8e-01	Scrap yard
Es-254	4.0e+00	4.3e-01	2.1e+00	1.5e+01	1.5e-02	1.6e-03	7.6e-03	5.5e-02	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 3.23 Normalized mass-based effective doses to critical groups for steel

Radionuclide	$\mu\text{Sv/y}$ per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
H-3	2.0e-02	0.0e+00	1.4e-05	7.6e-02	7.4e-05	0.0e+00	5.2e-08	2.8e-04	Leachate-industrial-scrap
C-14	3.3e-02	0.0e+00	0.0e+00	4.9e-02	1.2e-04	0.0e+00	0.0e+00	1.8e-04	Leachate-industrial-scrap
Na-22	4.2e+01	4.2e+00	2.1e+01	1.6e+02	1.6e-01	1.5e-02	7.9e-02	5.7e-01	Scrap yard
P-32	5.6e-02	5.4e-03	2.8e-02	2.1e-01	2.1e-04	2.0e-05	1.0e-04	7.6e-04	Scrap yard
S-35	5.5e-04	6.0e-05	2.8e-04	2.0e-03	2.0e-06	2.2e-07	1.0e-06	7.3e-06	Scrap yard
Cl-36	2.0e+00	0.0e+00	0.0e+00	8.3e+00	7.3e-03	0.0e+00	0.0e+00	3.1e-02	Leachate-steel slag
K-40	3.4e+00	3.4e-01	1.7e+00	1.2e+01	1.2e-02	1.2e-03	6.3e-03	4.6e-02	Scrap yard
Ca-41	1.8e-01	0.0e+00	0.0e+00	7.5e-01	6.6e-04	0.0e+00	0.0e+00	2.8e-03	Leachate-steel slag
Ca-45	2.1e-03	2.0e-04	1.1e-03	7.7e-03	7.7e-06	7.5e-07	3.9e-06	2.9e-05	Scrap yard
Sc-46	3.7e+01	3.7e+00	1.9e+01	1.4e+02	1.4e-01	1.4e-02	7.0e-02	5.1e-01	Scrap yard
Cr-51	3.6e-01	1.9e-02	1.5e-01	1.5e+00	1.3e-03	7.1e-05	5.7e-04	5.5e-03	Scrap disposal-industrial
Mn-53	8.0e-04	0.0e+00	0.0e+00	0.0e+00	3.3e-06	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
Mn-54	1.6e+01	1.6e+00	8.0e+00	5.8e+01	5.8e-02	5.8e-03	3.0e-02	2.2e-01	Scrap yard
Fe-55	7.5e-04	6.1e-05	3.7e-04	2.9e-03	2.8e-06	2.3e-07	1.4e-06	1.1e-05	Scrap yard
Fe-59	2.1e+01	2.1e+00	1.1e+01	7.7e+01	7.7e-02	7.6e-03	3.9e-02	2.9e-01	Scrap yard
Co-56	6.7e+01	6.7e+00	3.4e+01	2.5e+02	2.5e-01	2.5e-02	1.3e-01	9.3e-01	Scrap yard
Co-57	1.1e+00	6.0e-02	4.8e-01	4.6e+00	4.1e-03	2.2e-04	1.8e-03	1.7e-02	Scrap disposal-industrial
Co-58	1.7e+01	1.7e+00	8.5e+00	6.2e+01	6.2e-02	6.1e-03	3.1e-02	2.3e-01	Scrap yard
Co-60	5.2e+01	5.1e+00	2.6e+01	1.9e+02	1.9e-01	1.9e-02	9.7e-02	7.1e-01	Scrap yard
Ni-59	4.3e-04	4.8e-05	2.2e-04	1.5e-03	1.6e-06	1.8e-07	8.1e-07	5.7e-06	Scrap yard
Ni-63	3.7e-04	3.2e-05	1.8e-04	1.4e-03	1.4e-06	1.2e-07	6.8e-07	5.2e-06	Scrap yard
Zn-65	1.4e+01	4.2e+00	9.6e+00	4.4e+01	5.2e-02	1.5e-02	3.6e-02	1.6e-01	EAF dust-dump trailer
As-73	1.9e-02	1.0e-03	8.1e-03	7.8e-02	6.9e-05	3.7e-06	3.0e-05	2.9e-04	Scrap disposal-industrial
Se-75	5.5e+00	1.6e+00	3.7e+00	1.7e+01	2.0e-02	5.8e-03	1.4e-02	6.3e-02	EAF dust-dump trailer
Sr-85	7.6e+00	7.5e-01	3.8e+00	2.8e+01	2.8e-02	2.8e-03	1.4e-02	1.0e-01	Scrap yard
Sr-89	6.2e-02	6.3e-03	3.2e-02	2.3e-01	2.3e-04	2.3e-05	1.2e-04	8.5e-04	Scrap yard
Sr-90	4.2e-01	0.0e+00	0.0e+00	1.1e-01	1.6e-03	0.0e+00	0.0e+00	4.1e-04	Leachate-steel slag
Y-91	1.3e-01	1.3e-02	6.8e-02	4.9e-01	4.9e-04	5.0e-05	2.5e-04	1.8e-03	Scrap yard
Zr-93	2.9e-03	3.6e-04	1.6e-03	8.8e-03	1.1e-05	1.3e-06	5.9e-06	3.3e-05	Processing steel slag
Zr-95	1.5e+01	1.5e+00	7.5e+00	5.5e+01	5.5e-02	5.5e-03	2.8e-02	2.0e-01	Scrap yard
Nb-93m	6.2e-04	7.0e-05	3.2e-04	2.2e-03	2.3e-06	2.6e-07	1.2e-06	8.2e-06	Scrap yard
Nb-94	3.0e+01	3.0e+00	1.5e+01	1.1e+02	1.1e-01	1.1e-02	5.6e-02	4.1e-01	Scrap yard
Nb-95	1.2e+01	1.2e+00	6.1e+00	4.4e+01	4.4e-02	4.3e-03	2.2e-02	1.6e-01	Scrap yard
Mo-93	1.9e-01	0.0e+00	0.0e+00	2.2e-01	7.1e-04	0.0e+00	0.0e+00	8.2e-04	Leachate-industrial-scrap
Tc-97	3.3e-01	0.0e+00	0.0e+00	1.5e+00	1.2e-03	0.0e+00	0.0e+00	5.4e-03	Leachate-industrial-scrap
Tc-97m	3.6e-03	2.0e-04	1.6e-03	1.5e-02	1.3e-05	7.2e-07	5.8e-06	5.6e-05	Scrap disposal-industrial
Tc-99	3.1e+00	0.0e+00	0.0e+00	1.4e+01	1.2e-02	0.0e+00	0.0e+00	5.1e-02	Leachate-industrial-scrap
Ru-103	7.1e+00	7.0e-01	3.6e+00	2.6e+01	2.6e-02	2.6e-03	1.3e-02	9.7e-02	Scrap yard
Ru-106	4.1e+00	4.1e-01	2.1e+00	1.5e+01	1.5e-02	1.5e-03	7.7e-03	5.6e-02	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

**Table 3.23 Normalized mass-based effective doses to critical groups for steel**

Radionuclide	$\mu\text{Sv/y per Bq/g}$				mrem/y per pCi/g				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ag-108m	2.9e+01	2.8e+00	1.5e+01	1.1e+02	1.1e-01	1.1e-02	5.4e-02	3.9e-01	Scrap yard
Ag-110m	5.2e+01	5.1e+00	2.6e+01	1.9e+02	1.9e-01	1.9e-02	9.7e-02	7.1e-01	Scrap yard
Cd-109	5.5e-02	3.0e-03	2.4e-02	2.3e-01	2.0e-04	1.1e-05	8.8e-05	8.4e-04	Scrap disposal-industrial
Sn-113	3.7e+00	3.7e-01	1.9e+00	1.4e+01	1.4e-02	1.4e-03	7.0e-03	5.1e-02	Scrap yard
Sb-124	3.3e+01	3.3e+00	1.7e+01	1.2e+02	1.2e-01	1.2e-02	6.2e-02	4.6e-01	Scrap yard
Sb-125	7.0e+00	7.0e-01	3.6e+00	2.6e+01	2.6e-02	2.6e-03	1.3e-02	9.6e-02	Scrap yard
Te-123m	1.4e+00	7.4e-02	5.9e-01	5.7e+00	5.1e-03	2.7e-04	2.2e-03	2.1e-02	Scrap disposal-industrial
Te-127m	9.7e-02	2.8e-02	6.6e-02	3.0e-01	3.6e-04	1.0e-04	2.5e-04	1.1e-03	EAF dust-dump trailer
I-125	1.0e+00	3.0e-01	8.9e-01	2.3e+00	3.8e-03	1.1e-03	3.3e-03	8.4e-03	Airborne emissions
I-129	3.3e+02	0.0e+00	0.0e+00	1.1e+03	1.2e+00	0.0e+00	0.0e+00	4.2e+00	Leachate-steel slag
I-131	3.4e+00	1.8e-01	1.4e+00	1.4e+01	1.3e-02	6.5e-04	5.4e-03	5.3e-02	Scrap disposal-industrial
Cs-134	4.1e+01	1.2e+01	2.8e+01	1.3e+02	1.5e-01	4.6e-02	1.0e-01	4.6e-01	EAF dust-dump trailer
Cs-135	8.6e-03	0.0e+00	0.0e+00	0.0e+00	3.2e-05	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
Cs-137	1.5e+01	4.6e+00	1.0e+01	4.7e+01	5.6e-02	1.7e-02	3.8e-02	1.7e-01	EAF dust-dump trailer
Ba-133	4.9e+00	4.8e-01	2.5e+00	1.8e+01	1.8e-02	1.8e-03	9.1e-03	6.6e-02	Scrap yard
Ce-139	1.4e+00	7.5e-02	6.0e-01	5.8e+00	5.2e-03	2.8e-04	2.2e-03	2.2e-02	Scrap disposal-industrial
Ce-141	6.5e-01	3.5e-02	2.8e-01	2.7e+00	2.4e-03	1.3e-04	1.0e-03	1.0e-02	Scrap disposal-industrial
Ce-144	9.9e-01	1.0e-01	5.0e-01	3.7e+00	3.7e-03	3.7e-04	1.9e-03	1.4e-02	Scrap yard
Pm-147	1.7e-03	1.9e-04	8.8e-04	6.0e-03	6.2e-06	7.2e-07	3.2e-06	2.2e-05	Scrap yard
Sm-151	1.1e-03	1.4e-04	6.2e-04	3.4e-03	4.2e-06	5.2e-07	2.3e-06	1.3e-05	Processing steel slag
Eu-152	2.2e+01	2.2e+00	1.1e+01	8.0e+01	8.0e-02	8.0e-03	4.1e-02	3.0e-01	Scrap yard
Eu-154	2.1e+01	2.1e+00	1.1e+01	7.9e+01	7.9e-02	7.9e-03	4.0e-02	2.9e-01	Scrap yard
Eu-155	4.0e-01	2.1e-02	1.7e-01	1.7e+00	1.5e-03	7.9e-05	6.4e-04	6.1e-03	Scrap disposal-industrial
Gd-153	5.2e-01	2.8e-02	2.2e-01	2.1e+00	1.9e-03	1.0e-04	8.3e-04	7.9e-03	Scrap disposal-industrial
Tb-160	1.9e+01	1.9e+00	9.9e+00	7.2e+01	7.2e-02	7.1e-03	3.6e-02	2.7e-01	Scrap yard
Tm-170	3.4e-02	1.8e-03	1.5e-02	1.4e-01	1.3e-04	6.7e-06	5.4e-05	5.2e-04	Scrap disposal-industrial
Tm-171	2.3e-03	1.2e-04	1.0e-03	9.6e-03	8.5e-06	4.6e-07	3.7e-06	3.5e-05	Scrap disposal-industrial
Ta-182	2.3e+01	2.3e+00	1.2e+01	8.5e+01	8.5e-02	8.4e-03	4.3e-02	3.2e-01	Scrap yard
W-181	1.6e-01	8.4e-03	6.8e-02	6.5e-01	5.8e-04	3.1e-05	2.5e-04	2.4e-03	Scrap disposal-industrial
W-185	2.0e-03	2.2e-04	1.0e-03	7.3e-03	7.5e-06	8.0e-07	3.8e-06	2.7e-05	Scrap yard
Os-185	1.3e+01	3.8e+00	8.9e+00	4.1e+01	4.9e-02	1.4e-02	3.3e-02	1.5e-01	EAF dust-dump trailer
Ir-192	1.1e+01	1.1e+00	5.6e+00	4.1e+01	4.1e-02	4.1e-03	2.1e-02	1.5e-01	Scrap yard
Ti-204	1.2e-02	1.3e-03	6.3e-03	4.4e-02	4.5e-05	4.8e-06	2.3e-05	1.6e-04	Scrap yard
Pb-210	6.3e+00	2.7e+00	5.9e+00	1.1e+01	2.3e-02	1.0e-02	2.2e-02	4.1e-02	Transferring EAF dust
Bi-207	4.0e+01	1.2e+01	2.7e+01	1.2e+02	1.5e-01	4.5e-02	1.0e-01	4.6e-01	EAF dust-dump trailer
Po-210	2.5e+00	1.2e+00	2.4e+00	4.2e+00	9.2e-03	4.5e-03	8.7e-03	1.6e-02	Transferring EAF dust
Ra-226	3.5e+01	3.6e+00	1.8e+01	1.3e+02	1.3e-01	1.3e-02	6.6e-02	4.8e-01	Scrap yard
Ra-228	1.9e+01	1.9e+00	9.5e+00	6.8e+01	6.9e-02	7.2e-03	3.5e-02	2.5e-01	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 3.23 Normalized mass-based effective doses to critical groups for steel

Radionuclide	$\mu\text{Sv/y per Bq/g}$				mrem/y per pCi/g				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ac-227	2.8e+01	3.5e+00	1.5e+01	8.4e+01	1.0e-01	1.3e-02	5.7e-02	3.1e-01	Processing steel slag
Th-228	3.7e+01	4.1e+00	1.9e+01	1.3e+02	1.4e-01	1.5e-02	7.1e-02	4.9e-01	Scrap yard
Th-229	3.2e+01	3.6e+00	1.7e+01	1.1e+02	1.2e-01	1.4e-02	6.2e-02	4.2e-01	Scrap yard
Th-230	1.0e+01	1.2e+00	5.3e+00	3.6e+01	3.8e-02	4.4e-03	2.0e-02	1.3e-01	Scrap yard
Th-232	1.1e+01	1.2e+00	5.6e+00	3.8e+01	4.0e-02	4.6e-03	2.1e-02	1.4e-01	Scrap yard
Pa-231	3.3e+01	3.9e+00	1.8e+01	1.2e+02	1.2e-01	1.4e-02	6.5e-02	4.4e-01	Scrap yard
U-232	1.4e+01	1.7e+00	7.4e+00	4.1e+01	5.0e-02	6.1e-03	2.7e-02	1.5e-01	Processing steel slag
U-233	5.9e+00	0.0e+00	0.0e+00	0.0e+00	2.2e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
U-234	4.2e+00	0.0e+00	0.0e+00	0.0e+00	1.5e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
U-235	5.1e+00	0.0e+00	0.0e+00	0.0e+00	1.9e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
U-236	3.8e+00	0.0e+00	0.0e+00	0.0e+00	1.4e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
U-238	3.9e+00	0.0e+00	0.0e+00	0.0e+00	1.5e-02	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
Np-237	2.9e+01	0.0e+00	0.0e+00	5.7e+01	1.1e-01	0.0e+00	0.0e+00	2.1e-01	Leachate-industrial-scrap
Pu-236	4.5e+00	5.3e-01	2.4e+00	1.6e+01	1.7e-02	1.9e-03	8.8e-03	6.0e-02	Scrap yard
Pu-238	1.1e+01	1.3e+00	5.7e+00	3.9e+01	4.0e-02	4.7e-03	2.1e-02	1.4e-01	Scrap yard
Pu-239	1.2e+01	1.4e+00	6.3e+00	4.3e+01	4.4e-02	5.1e-03	2.3e-02	1.6e-01	Scrap yard
Pu-240	1.2e+01	1.4e+00	6.3e+00	4.3e+01	4.4e-02	5.1e-03	2.3e-02	1.6e-01	Scrap yard
Pu-241	2.2e-01	2.5e-02	1.1e-01	7.7e-01	8.0e-04	9.3e-05	4.2e-04	2.9e-03	Scrap yard
Pu-242	1.1e+01	1.3e+00	5.9e+00	4.0e+01	4.1e-02	4.8e-03	2.2e-02	1.5e-01	Scrap yard
Pu-244	1.7e+01	2.0e+00	8.9e+00	6.1e+01	6.3e-02	7.6e-03	3.3e-02	2.3e-01	Scrap yard
Am-241	1.1e+01	1.3e+00	5.9e+00	3.2e+01	4.0e-02	4.9e-03	2.2e-02	1.2e-01	Processing steel slag
Am-242m	1.1e+01	1.3e+00	5.9e+00	3.3e+01	4.0e-02	4.9e-03	2.2e-02	1.2e-01	Processing steel slag
Am-243	1.2e+01	1.5e+00	6.6e+00	3.6e+01	4.4e-02	5.4e-03	2.4e-02	1.3e-01	Handling slag
Cm-242	1.3e+00	1.6e-01	6.9e-01	3.8e+00	4.6e-03	5.8e-04	2.6e-03	1.4e-02	Handling slag
Cm-243	8.6e+00	1.1e+00	4.8e+00	2.6e+01	3.2e-02	3.9e-03	1.8e-02	9.7e-02	Handling slag
Cm-244	6.6e+00	7.9e-01	3.7e+00	2.0e+01	2.5e-02	2.9e-03	1.4e-02	7.5e-02	Handling slag
Cm-245	1.1e+01	1.3e+00	6.2e+00	3.4e+01	4.1e-02	5.0e-03	2.3e-02	1.3e-01	Handling slag
Cm-246	1.1e+01	1.3e+00	5.8e+00	3.3e+01	4.0e-02	4.9e-03	2.2e-02	1.2e-01	Processing steel slag
Cm-247	1.4e+01	1.7e+00	7.3e+00	5.0e+01	5.2e-02	6.2e-03	2.7e-02	1.8e-01	Scrap yard
Cm-248	3.8e+01	4.6e+00	2.1e+01	1.1e+02	1.4e-01	1.7e-02	7.6e-02	4.2e-01	Processing steel slag
Bk-249	4.3e-02	5.3e-03	2.3e-02	1.3e-01	1.6e-04	2.0e-05	8.6e-05	4.8e-04	Processing steel slag
Cf-248	2.2e+00	2.7e-01	1.2e+00	6.8e+00	8.3e-03	1.0e-03	4.6e-03	2.5e-02	Handling slag
Cf-249	2.2e+01	2.6e+00	1.1e+01	7.7e+01	8.0e-02	9.5e-03	4.2e-02	2.8e-01	Scrap yard
Cf-250	8.6e+00	1.0e+00	4.8e+00	2.6e+01	3.2e-02	3.8e-03	1.8e-02	9.6e-02	Handling slag
Cf-251	1.9e+01	2.3e+00	1.0e+01	5.7e+01	7.0e-02	8.4e-03	3.9e-02	2.1e-01	Handling slag
Cf-252	5.0e+00	6.0e-01	2.8e+00	1.5e+01	1.8e-02	2.2e-03	1.0e-02	5.6e-02	Handling slag
Cf-254	3.2e+02	3.2e+01	1.6e+02	1.2e+03	1.2e+00	1.2e-01	5.9e-01	4.3e+00	Scrap yard
Es-254	1.9e+01	2.0e+00	9.9e+00	7.1e+01	7.2e-02	7.5e-03	3.7e-02	2.6e-01	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

**Table 3.24 Normalized surficial effective doses to critical groups for steel**

Radionuclide	$\mu\text{Sv/y per Bq/cm}^2$				mrem/y per pCi/cm <sup>2</sup>				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
H-3	4.0e-03	0.0e+00	2.8e-06	1.5e-02	1.5e-05	0.0e+00	1.0e-08	5.5e-05	Leachate-industrial-scrap
C-14	6.5e-03	0.0e+00	0.0e+00	9.8e-03	2.4e-05	0.0e+00	0.0e+00	3.6e-05	Leachate-industrial-scrap
Na-22	8.3e+00	8.4e-01	4.2e+00	3.0e+01	3.1e-02	3.1e-03	1.6e-02	1.1e-01	Scrap yard
P-32	1.1e-02	1.1e-03	5.6e-03	4.1e-02	4.1e-05	4.0e-06	2.1e-05	1.5e-04	Scrap yard
S-35	1.1e-04	1.2e-05	5.6e-05	3.9e-04	4.0e-07	4.4e-08	2.1e-07	1.5e-06	Scrap yard
Cl-36	3.9e-01	0.0e+00	0.0e+00	1.7e+00	1.4e-03	0.0e+00	0.0e+00	6.1e-03	Leachate-steel slag
K-40	6.7e-01	6.7e-02	3.4e-01	2.4e+00	2.5e-03	2.5e-04	1.2e-03	9.0e-03	Scrap yard
Ca-41	3.5e-02	0.0e+00	0.0e+00	1.5e-01	1.3e-04	0.0e+00	0.0e+00	5.5e-04	Leachate-steel slag
Ca-45	4.1e-04	4.1e-05	2.1e-04	1.5e-03	1.5e-06	1.5e-07	7.8e-07	5.7e-06	Scrap yard
Sc-46	7.3e+00	7.3e-01	3.7e+00	2.7e+01	2.7e-02	2.7e-03	1.4e-02	9.9e-02	Scrap yard
Cr-51	7.0e-02	3.9e-03	3.1e-02	2.9e-01	2.6e-04	1.4e-05	1.1e-04	1.1e-03	Scrap disposal-industrial
Mn-53	1.8e-04	0.0e+00	0.0e+00	0.0e+00	6.5e-07	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
Mn-54	3.1e+00	3.1e-01	1.6e+00	1.1e+01	1.2e-02	1.2e-03	5.8e-03	4.2e-02	Scrap yard
Fe-55	1.5e-04	1.2e-05	7.3e-05	5.7e-04	5.5e-07	4.5e-08	2.7e-07	2.1e-06	Scrap yard
Fe-59	4.1e+00	4.1e-01	2.1e+00	1.5e+01	1.5e-02	1.5e-03	7.7e-03	5.6e-02	Scrap yard
Co-58	1.3e+01	1.3e+00	6.7e+00	4.9e+01	4.9e-02	4.9e-03	2.5e-02	1.8e-01	Scrap yard
Co-57	2.2e-01	1.2e-02	9.5e-02	9.1e-01	8.1e-04	4.5e-05	3.5e-04	3.4e-03	Scrap disposal-industrial
Co-58	3.3e+00	3.3e-01	1.7e+00	1.2e+01	1.2e-02	1.2e-03	6.2e-03	4.5e-02	Scrap yard
Co-60	1.0e+01	1.0e+00	5.2e+00	3.7e+01	3.8e-02	3.8e-03	1.9e-02	1.4e-01	Scrap yard
Ni-59	8.5e-05	9.4e-06	4.3e-05	3.1e-04	3.1e-07	3.5e-08	1.6e-07	1.1e-06	Scrap yard
Ni-63	7.3e-05	6.4e-06	3.6e-05	2.8e-04	2.7e-07	2.4e-08	1.3e-07	1.0e-06	Scrap yard
Zn-65	2.8e+00	8.5e-01	1.9e+00	8.2e+00	1.0e-02	3.1e-03	7.0e-03	3.0e-02	EAF dust-dump trailer
As-73	3.7e-03	2.0e-04	1.6e-03	1.5e-02	1.4e-05	7.5e-07	5.9e-06	5.7e-05	Scrap disposal-industrial
Se-75	1.1e+00	3.2e-01	7.3e-01	3.1e+00	4.0e-03	1.2e-03	2.7e-03	1.2e-02	EAF dust-dump trailer
Sr-85	1.5e+00	1.5e-01	7.5e-01	5.5e+00	5.5e-03	5.5e-04	2.8e-03	2.0e-02	Scrap yard
Sr-89	1.2e-02	1.3e-03	6.2e-03	4.5e-02	4.6e-05	4.7e-06	2.3e-05	1.7e-04	Scrap yard
Sr-90	8.8e-02	0.0e+00	0.0e+00	2.2e-02	3.2e-04	0.0e+00	0.0e+00	8.0e-05	Leachate-steel slag
Y-91	2.6e-02	2.7e-03	1.3e-02	9.6e-02	9.8e-05	9.9e-06	4.9e-05	3.6e-04	Scrap yard
Zr-93	5.7e-04	7.0e-05	3.2e-04	1.7e-03	2.1e-06	2.6e-07	1.2e-06	6.5e-06	Processing steel slag
Zr-95	2.9e+00	3.0e-01	1.5e+00	1.1e+01	1.1e-02	1.1e-03	5.5e-03	3.9e-02	Scrap yard
Nb-93m	1.2e-04	1.4e-05	6.4e-05	4.5e-04	4.5e-07	5.1e-08	2.3e-07	1.7e-06	Scrap yard
Nb-94	5.9e+00	6.0e-01	3.0e+00	2.2e+01	2.2e-02	2.2e-03	1.1e-02	8.0e-02	Scrap yard
Nb-95	2.4e+00	2.3e-01	1.2e+00	8.7e+00	8.8e-03	8.6e-04	4.4e-03	3.2e-02	Scrap yard
Mo-93	3.8e-02	0.0e+00	0.0e+00	4.3e-02	1.4e-04	0.0e+00	0.0e+00	1.6e-04	Leachate-industrial-scrap
Tc-97	6.6e-02	0.0e+00	0.0e+00	2.9e-01	2.5e-04	0.0e+00	0.0e+00	1.1e-03	Leachate-industrial-scrap
Tc-97m	7.2e-04	4.0e-05	3.1e-04	3.0e-03	2.7e-06	1.5e-07	1.2e-06	1.1e-05	Scrap disposal-industrial
Tc-99	6.2e-01	0.0e+00	0.0e+00	2.7e+00	2.3e-03	0.0e+00	0.0e+00	1.0e-02	Leachate-industrial-scrap
Ru-103	1.4e+00	1.4e-01	7.0e-01	5.1e+00	5.2e-03	5.1e-04	2.6e-03	1.9e-02	Scrap yard
Ru-106	8.2e-01	8.2e-02	4.1e-01	3.0e+00	3.0e-03	3.0e-04	1.5e-03	1.1e-02	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 3.24 Normalized surficial effective doses to critical groups for steel

Radionuclide	$\mu\text{Sv/y per Bq/cm}^2$				$\text{mrem/y per pCi/cm}^2$				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ag-108m	5.7e+00	5.7e-01	2.9e+00	2.1e+01	2.1e-02	2.1e-03	1.1e-02	7.6e-02	Scrap yard
Ag-110m	1.0e+01	1.0e+00	5.2e+00	3.7e+01	3.8e-02	3.8e-03	1.9e-02	1.4e-01	Scrap yard
Cd-109	1.1e-02	6.0e-04	4.7e-03	4.5e-02	4.0e-05	2.2e-06	1.7e-05	1.7e-04	Scrap disposal-industrial
Sn-113	7.4e-01	7.4e-02	3.7e-01	2.7e+00	2.7e-03	2.7e-04	1.4e-03	1.0e-02	Scrap yard
Sb-124	6.6e+00	6.6e-01	3.3e+00	2.4e+01	2.4e-02	2.4e-03	1.2e-02	9.0e-02	Scrap yard
Sb-125	1.4e+00	1.4e-01	7.0e-01	5.1e+00	5.2e-03	5.2e-04	2.6e-03	1.9e-02	Scrap yard
Te-123m	2.7e-01	1.5e-02	1.2e-01	1.1e+00	1.0e-03	5.5e-05	4.4e-04	4.2e-03	Scrap disposal-industrial
Te-127m	1.9e-02	5.7e-03	1.3e-02	5.5e-02	7.1e-05	2.1e-05	4.8e-05	2.0e-04	EAF dust-dump trailer
I-125	2.0e-01	6.0e-02	1.8e-01	4.4e-01	7.6e-04	2.2e-04	6.5e-04	1.6e-03	Airborne emissions
I-129	6.4e+01	0.0e+00	0.0e+00	2.3e+02	2.4e-01	0.0e+00	0.0e+00	8.4e-01	Leachate-steel slag
I-131	6.7e-01	3.6e-02	2.9e-01	2.8e+00	2.5e-03	1.3e-04	1.1e-03	1.0e-02	Scrap disposal-industrial
Cs-134	8.0e+00	2.4e+00	5.5e+00	2.4e+01	3.0e-02	9.0e-03	2.0e-02	8.9e-02	EAF dust-dump trailer
Cs-135	1.8e-03	0.0e+00	0.0e+00	0.0e+00	6.6e-06	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
Cs-137	3.0e+00	9.0e-01	2.0e+00	8.9e+00	1.1e-02	3.3e-03	7.5e-03	3.3e-02	EAF dust-dump trailer
Ba-133	9.6e-01	9.7e-02	4.9e-01	3.5e+00	3.6e-03	3.6e-04	1.8e-03	1.3e-02	Scrap yard
Ce-139	2.8e-01	1.5e-02	1.2e-01	1.1e+00	1.0e-03	5.6e-05	4.4e-04	4.3e-03	Scrap disposal-industrial
Ce-141	1.3e-01	7.0e-03	5.6e-02	5.3e-01	4.7e-04	2.6e-05	2.1e-04	2.0e-03	Scrap disposal-industrial
Ce-144	2.0e-01	2.0e-02	1.0e-01	7.2e-01	7.3e-04	7.4e-05	3.7e-04	2.7e-03	Scrap yard
Pm-147	3.3e-04	3.9e-05	1.7e-04	1.2e-03	1.2e-06	1.4e-07	6.4e-07	4.5e-06	Scrap yard
Sm-151	2.2e-04	2.7e-05	1.2e-04	6.8e-04	8.2e-07	1.0e-07	4.5e-07	2.5e-06	Processing steel slag
Eu-152	4.3e+00	4.3e-01	2.2e+00	1.6e+01	1.6e-02	1.6e-03	8.0e-03	5.8e-02	Scrap yard
Eu-154	4.2e+00	4.3e-01	2.1e+00	1.5e+01	1.6e-02	1.6e-03	7.9e-03	5.7e-02	Scrap yard
Eu-155	7.8e-02	4.3e-03	3.4e-02	3.3e-01	2.9e-04	1.6e-05	1.3e-04	1.2e-03	Scrap disposal-industrial
Gd-153	1.0e-01	5.6e-03	4.4e-02	4.3e-01	3.8e-04	2.1e-05	1.6e-04	1.6e-03	Scrap disposal-industrial
Tb-160	3.8e+00	3.8e-01	1.9e+00	1.4e+01	1.4e-02	1.4e-03	7.2e-03	5.2e-02	Scrap yard
Tm-170	6.7e-03	3.7e-04	2.9e-03	2.8e-02	2.5e-05	1.4e-06	1.1e-05	1.0e-04	Scrap disposal-industrial
Tm-171	4.5e-04	2.5e-05	2.0e-04	1.9e-03	1.7e-06	9.3e-08	7.3e-07	7.0e-06	Scrap disposal-industrial
Ta-182	4.6e+00	4.6e-01	2.3e+00	1.7e+01	1.7e-02	1.7e-03	8.5e-03	6.2e-02	Scrap yard
W-181	3.1e-02	1.7e-03	1.3e-02	1.3e-01	1.1e-04	6.3e-06	5.0e-05	4.8e-04	Scrap disposal-industrial
W-185	4.0e-04	4.3e-05	2.0e-04	1.4e-03	1.5e-06	1.6e-07	7.5e-07	5.3e-06	Scrap yard
Os-185	2.6e+00	7.7e-01	1.8e+00	7.7e+00	9.7e-03	2.9e-03	6.5e-03	2.8e-02	EAF dust-dump trailer
Ir-192	2.2e+00	2.2e-01	1.1e+00	8.1e+00	8.2e-03	8.2e-04	4.1e-03	3.0e-02	Scrap yard
Tl-204	2.4e-03	2.6e-04	1.2e-03	8.8e-03	8.9e-06	9.6e-07	4.5e-06	3.2e-05	Scrap yard
Pb-210	1.2e+00	5.4e-01	1.2e+00	2.1e+00	4.6e-03	2.0e-03	4.3e-03	7.9e-03	Transferring EAF dust
Bi-207	7.9e+00	2.4e+00	5.4e+00	2.4e+01	2.9e-02	8.9e-03	2.0e-02	8.7e-02	EAF dust-dump trailer
Po-210	4.9e-01	2.5e-01	4.5e-01	8.2e-01	1.8e-03	9.1e-04	1.7e-03	3.0e-03	Transferring EAF dust
Ra-226	6.9e+00	7.1e-01	3.5e+00	2.5e+01	2.6e-02	2.6e-03	1.3e-02	9.4e-02	Scrap yard
Ra-228	3.7e+00	3.9e-01	1.9e+00	1.3e+01	1.4e-02	1.4e-03	6.9e-03	5.0e-02	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval



Table 3.24 Normalized surficial effective doses to critical groups for steel

Radionuclide	$\mu\text{Sv/y per Bq/cm}^2$				mrem/y per $\text{pCi/cm}^2$				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ac-227	5.4e+00	6.8e-01	3.0e+00	1.6e+01	2.0e-02	2.5e-03	1.1e-02	6.1e-02	Processing steel slag
Th-228	7.3e+00	8.2e-01	3.7e+00	2.7e+01	2.7e-02	3.0e-03	1.4e-02	9.8e-02	Scrap yard
Th-229	6.4e+00	7.5e-01	3.3e+00	2.3e+01	2.4e-02	2.8e-03	1.2e-02	8.5e-02	Scrap yard
Th-230	2.0e+00	2.3e-01	1.0e+00	7.2e+00	7.4e-03	8.7e-04	3.9e-03	2.7e-02	Scrap yard
Th-232	2.1e+00	2.5e-01	1.1e+00	7.6e+00	7.8e-03	9.2e-04	4.1e-03	2.8e-02	Scrap yard
Pa-231	6.6e+00	7.8e-01	3.5e+00	2.4e+01	2.5e-02	2.9e-03	1.3e-02	8.8e-02	Scrap yard
U-232	2.7e+00	3.2e-01	1.5e+00	8.1e+00	9.8e-03	1.2e-03	5.4e-03	3.0e-02	Processing steel slag
U-233	1.2e+00	0.0e+00	0.0e+00	0.0e+00	4.3e-03	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
U-234	8.1e-01	0.0e+00	0.0e+00	0.0e+00	3.0e-03	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
U-235	9.9e-01	0.0e+00	0.0e+00	0.0e+00	3.7e-03	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
U-236	7.5e-01	0.0e+00	0.0e+00	0.0e+00	2.8e-03	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
U-238	7.7e-01	0.0e+00	0.0e+00	0.0e+00	2.8e-03	0.0e+00	0.0e+00	0.0e+00	Leachate-industrial-scrap
Np-237	5.8e+00	0.0e+00	0.0e+00	1.1e+01	2.1e-02	0.0e+00	0.0e+00	4.2e-02	Leachate-industrial-scrap
Pu-236	9.0e-01	1.0e-01	4.7e-01	3.2e+00	3.3e-03	3.9e-04	1.7e-03	1.2e-02	Scrap yard
Pu-238	2.2e+00	2.5e-01	1.1e+00	7.8e+00	8.0e-03	9.3e-04	4.2e-03	2.9e-02	Scrap yard
Pu-239	2.4e+00	2.7e-01	1.2e+00	8.5e+00	8.7e-03	1.0e-03	4.5e-03	3.1e-02	Scrap yard
Pu-240	2.4e+00	2.7e-01	1.2e+00	8.5e+00	8.7e-03	1.0e-03	4.5e-03	3.1e-02	Scrap yard
Pu-241	4.3e-02	5.0e-03	2.2e-02	1.5e-01	1.6e-04	1.8e-05	8.2e-05	5.7e-04	Scrap yard
Pu-242	2.2e+00	2.6e-01	1.2e+00	8.0e+00	8.2e-03	9.5e-04	4.3e-03	3.0e-02	Scrap yard
Pu-244	3.4e+00	4.0e-01	1.8e+00	1.2e+01	1.3e-02	1.5e-03	6.5e-03	4.4e-02	Scrap yard
Am-241	2.1e+00	2.6e-01	1.2e+00	6.5e+00	7.8e-03	9.6e-04	4.3e-03	2.4e-02	Processing steel slag
Am-242m	2.1e+00	2.6e-01	1.2e+00	6.5e+00	7.8e-03	9.6e-04	4.3e-03	2.4e-02	Processing steel slag
Am-243	2.3e+00	2.9e-01	1.3e+00	7.0e+00	8.6e-03	1.1e-03	4.8e-03	2.6e-02	Handling slag
Cm-242	2.5e-01	3.1e-02	1.4e-01	7.5e-01	9.1e-04	1.2e-04	5.1e-04	2.8e-03	Handling slag
Cm-243	1.7e+00	2.1e-01	9.5e-01	5.1e+00	6.3e-03	7.8e-04	3.5e-03	1.9e-02	Handling slag
Cm-244	1.3e+00	1.6e-01	7.3e-01	4.0e+00	4.8e-03	5.9e-04	2.7e-03	1.5e-02	Handling slag
Cm-245	2.2e+00	2.7e-01	1.2e+00	6.6e+00	8.1e-03	9.9e-04	4.5e-03	2.5e-02	Processing steel slag
Cm-246	2.1e+00	2.6e-01	1.2e+00	6.4e+00	7.8e-03	9.5e-04	4.3e-03	2.4e-02	Processing steel slag
Cm-247	2.8e+00	3.3e-01	1.4e+00	9.8e+00	1.0e-02	1.2e-03	5.3e-03	3.8e-02	Scrap yard
Cm-248	7.4e+00	9.1e-01	4.1e+00	2.3e+01	2.7e-02	3.4e-03	1.5e-02	8.4e-02	Processing steel slag
Bk-249	8.4e-03	1.0e-03	4.6e-03	2.6e-02	3.1e-05	3.8e-06	1.7e-05	9.5e-05	Processing steel slag
Cf-248	4.4e-01	5.4e-02	2.5e-01	1.4e+00	1.6e-03	2.0e-04	9.1e-04	5.0e-03	Handling slag
Cf-249	4.3e+00	5.1e-01	2.2e+00	1.5e+01	1.6e-02	1.9e-03	8.3e-03	5.6e-02	Scrap yard
Cf-250	1.7e+00	2.1e-01	9.4e-01	5.2e+00	6.3e-03	7.6e-04	3.5e-03	1.9e-02	Handling slag
Cf-251	3.7e+00	4.6e-01	2.1e+00	1.1e+01	1.4e-02	1.7e-03	7.6e-03	4.2e-02	Processing steel slag
Cf-252	9.8e-01	1.2e-01	5.4e-01	3.0e+00	3.6e-03	4.4e-04	2.0e-03	1.1e-02	Handling slag
Cf-254	6.2e+01	6.3e+00	3.1e+01	2.3e+02	2.3e-01	2.3e-02	1.2e-01	8.5e-01	Scrap yard
Es-254	3.8e+00	4.0e-01	1.9e+00	1.4e+01	1.4e-02	1.5e-03	7.2e-03	5.2e-02	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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## 4 RECYCLING AND DISPOSAL OF COPPER SCRAP

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

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

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

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

### 4.1 Introduction to Analysis

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

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

### 4.2 Flow of Copper Scrap

This section presents an overview of the recycling of copper scrap in the United States. Its purpose is: (1) to serve as an information source for the radiological assessment, and (2) to

present a context for those aspects of the recycling and disposal of copper scrap that are addressed by this assessment. It thus includes some data which are not directly utilized in our study.

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

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

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

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

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

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<sup>1</sup> Scrap and refinery products can also be shipped by rail or waterway.

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

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

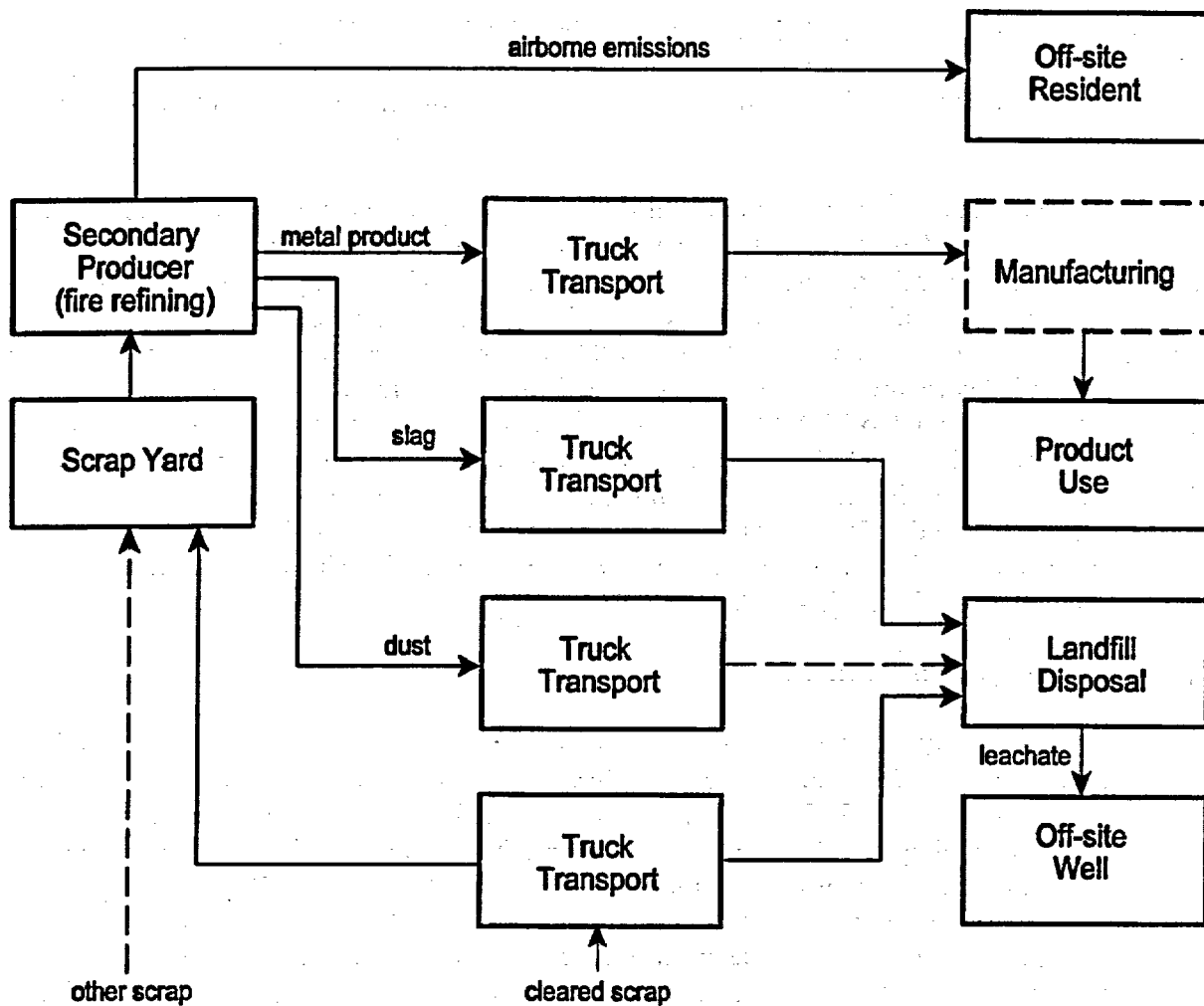


Figure 4.1 Flow of copper scrap

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

#### 4.2.1 Sources of Material

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

total copper inventory yields a balance of 62 t of material that would be a potential candidate for clearance. Much of this scrap would be high quality unalloyed copper from copper wire, cable, and bus bar. It is assumed that this relatively small quantity of scrap would be cleared during a single year.<sup>4</sup>

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

#### 4.2.2 Recycling of Copper Scrap

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

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

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

<sup>5</sup> American Wire Gauge, also known as Brown & Sharpe gauge.

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

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

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

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

**Table 4.1 Copper recovered from copper-base scrap in 2000**

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

Source: Edelstein 2002, Table 6.

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

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

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

Source: Edelstein 2002, Table 7.

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

<sup>a</sup> Fraction of total of each column

<sup>b</sup> Amounts of electrolytically refined and fire-refined scrap based on source of material at smelter level.

<sup>c</sup> Includes copper sulfate and other copper compounds.

<sup>d</sup> Total new scrap and total old scrap as fraction of total scrap

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

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

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

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

<sup>a</sup> From Table 4.2

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

**Table 4.4 Unalloyed copper products made from scrap in 2000**

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

Source: Edelstein (2002, Table 8)

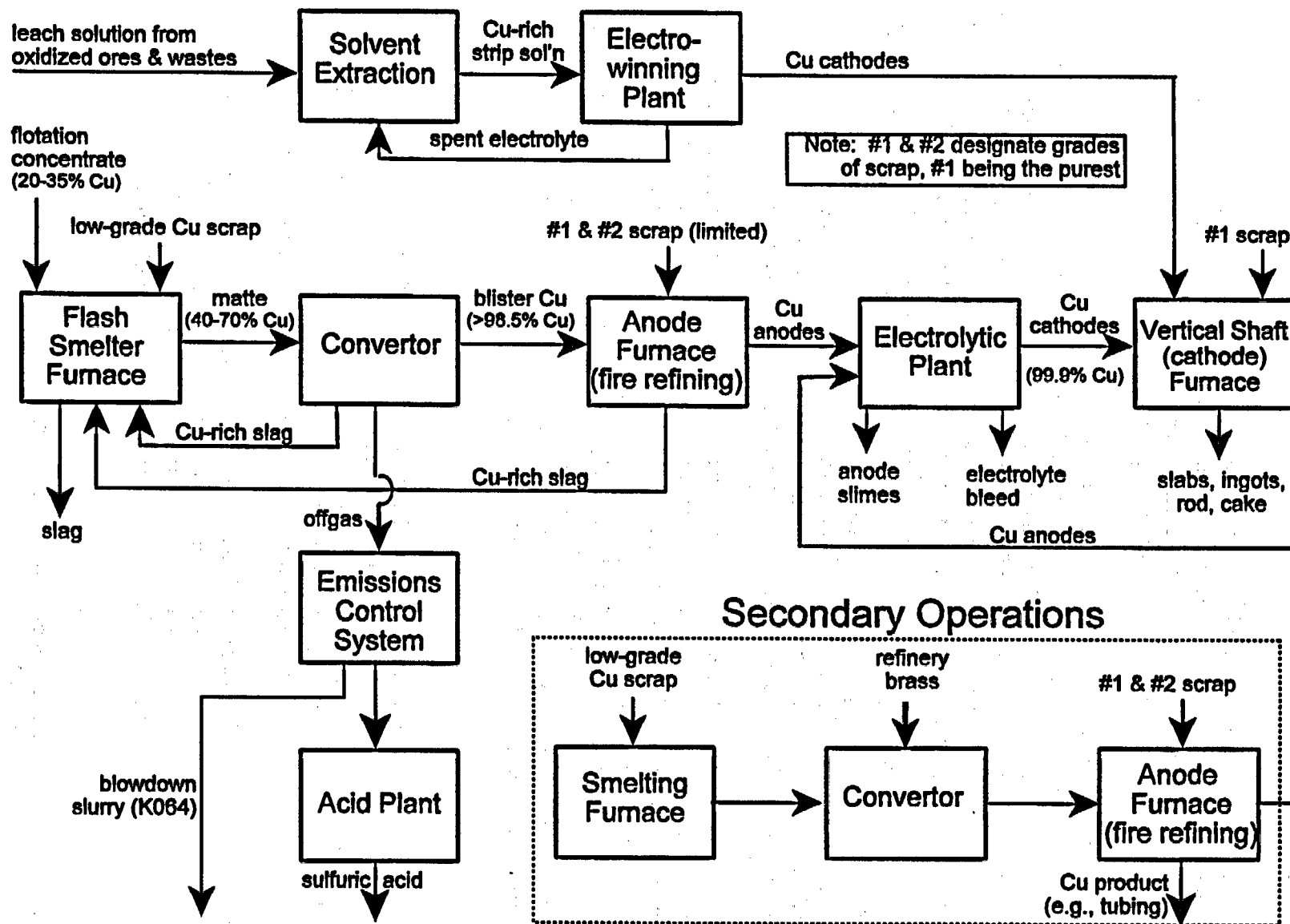


Figure 4.2 Operations in the primary and secondary production of copper



### 4.2.3 Copper Refining

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

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

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

#### 4.2.3.1 Fire Refining

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

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

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<sup>7</sup> A reverberatory furnace used to produce anodes for electrorefining may be referred to as an “anode furnace,” as in the flow diagram depicted in Figure 4.2.

chemical analyses are taken from samples to screen for impurities. Typically, scrap inventories equal one or two days of consumption, but on some occasions may reach five days. The scrap is charged into a 180-t reverberatory furnace, melted, and blown with air or oxygen to oxidize impurities.<sup>8</sup> The oxide slag is skimmed from the melt. The melt is then covered with charcoal and "poled" to remove oxygen. In the poling process, green hardwood logs are thrust into the molten copper bath, where the hydrocarbons react with the oxygen to form CO/CO<sub>2</sub>. The molten copper is then laundered. In this process, the copper flows under charcoal into a ladle which is covered with a carbon-based product. The laundering removes additional oxygen from the melt. Final deoxidation is promoted by the addition of phosphorus; the melt is then cast into billets for subsequent fabrication into tubing.<sup>9</sup> About 30% of the copper in the billets is recycled as home scrap.

At Reading Tube, slag is skimmed from the furnace through a door at one end, using steel rakes which are about 3 – 4 m long. Two operators work together with a single rake to skim the slag into a box beneath the furnace door. Slagging takes about two hours, during which time the operators are about 2.5 m from the furnace wall. The steel slag boxes are about 1 m square and 0.3 m deep. One of the furnace operators transports the filled slag box via forklift truck to a temporary storage area, where it is dumped onto the floor. When the slag has cooled, it is broken up with a "thumper" (air hammer) and metallic copper is culled from the slag by hand. The culled slag is moved with a front-end loader to an outside storage bin. This slag, which contains 30% to 35% copper, is sold to an outside processor for recovery of additional copper content. Offgas from the furnace passes through an after-burner to convert CO to CO<sub>2</sub> and to destroy any hydrocarbons; it is then exhausted through a stack. Stack emissions are monitored for total particulates, opacity, and SO<sub>2</sub>.

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

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

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

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

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

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

### 4.2.3.2 Electrolytic Refining

The final stage in copper purification employs an electrolytic refining<sup>10</sup> process that yields copper which may contain less than 40 ppm of metallic impurities (Ramachandran and Wildman 1987). During electrorefining, copper anodes and pure copper cathode starter sheets are suspended in a  $\text{CuSO}_4\text{-H}_2\text{SO}_4\text{-H}_2\text{O}$  electrolyte, through which an electrical current is passed at a potential of about 0.25 Vdc. The process requires 10 to 14 days to produce a cathode weighing about 150 kg. During electrolysis, the copper dissolves from the anode and deposits on the cathode. Impurities such as Au, Ag, and other precious metals, as well as Pb, Se, and Te, all of which are carried over from copper ore, collect in the anode slimes.<sup>11</sup> These anode slimes are collected and sent to a precious metals refinery (Davenport 1986). Other elements, such as Fe, Ni, and Zn, dissolve in the electrolyte<sup>12</sup> and are removed from the copper electrolysis cells in a bleed stream. The bleed stream is sent to "liberator" cells, where the solution is again electrolyzed and soluble copper is plated out on insoluble lead anodes. The bleed stream is then treated for  $\text{NiSO}_4$  recovery by concentrating the solution in evaporator vessels, where  $\text{NiSO}_4$  crystals precipitate. The remaining liquor is called "black acid." Both the  $\text{NiSO}_4$  and the black acid may be salable products (Kusik and Kenahan 1978).

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

The Amarillo Copper Refinery of ASARCO, Incorporated, the reference electrolytic refinery for the present analysis, has an annual production of 420 kt of electrolytically refined copper. Fire refining is conducted in a 320-t reverberatory furnace with an annual output of 114 kt of anodes. The normal furnace feed is 81% blister copper from primary producers and 19% No. 2 copper scrap (Ramachandran and Wildman 1987). The combined output from the reverberatory furnace and the anode scrap-melting furnace, a total of 240 kt/y, together with 245 kt/y of purchased anodes, is electrorefined. About 63 kt of spent anodes are recycled to the anode melting furnace. Sulfuric acid recovered from the electrolyte bleed circuit is most likely used for electrolyte makeup; accordingly, it is returned to the process. The nickel sulfate, containing 5%  $\text{H}_2\text{SO}_4$  and 3%  $\text{H}_2\text{O}$ , is sold to nickel producers for metal recovery. The nickel sulfate also contains contaminants, such as iron and zinc.

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<sup>10</sup> The terms "electrolytic refining" and "electrorefining" are used interchangeably.

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

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

### 4.2.3.3 Brass and Bronze Smelting

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

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

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

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

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

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

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

#### 4.2.4 Product Use

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

##### 4.2.4.1 Metal Products

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

- Building construction (building wire, plumbing and heating, air conditioning and commercial refrigeration, builders hardware, architectural) . . . . . 3,740 (1,696 kt)
- Electrical and electronic products (power utilities, telecommunications, business electronics, lighting and wiring devices) . . . . . 2,636 (1,196 kt)
- Industrial machinery and equipment (in-plant equipment, industrial valves and fittings, non-electrical instruments, off-highway vehicles, heat exchangers) . . . . . 1,010 (458 kt)
- Transportation equipment (automotive, truck and bus, marine, railroad, aircraft and aerospace) . . . . . 1,095 (497 kt)
- Consumer and general products (appliances, cord sets, military and commercial ordnance, consumer electronics, fasteners and closures, coinage, utensils and cutlery, miscellaneous) . . . . . 1,070 (485 kt)

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

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

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

<sup>14</sup> The total metal content includes, in addition to copper, any alloying elements such as zinc in brass or tin in bronze.

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

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

#### Wire mill products:

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

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

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

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

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

#### 4.2.4.2 Refinery By-products

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

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

### 4.3 Mass Fractions and Partitioning Factors for Refining Operations

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

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

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

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

#### 4.3.1 Mass Fractions

##### 4.3.1.1 Fire Refining

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

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<sup>15</sup> See Footnote 9 on page 4-9.

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

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

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

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

For the purpose of the present analysis, the quantity of metallic copper produced from one furnace heat was calculated by subtracting the amounts of chemically bound copper in the slag and in the dust (i.e., the amount of copper in the form of CuO), from the amount of metal in the furnace charge. Gößling (2001) cites a value of 45.04% Cu<sub>2</sub>O in slag from a fire-refining anode furnace at a primary copper smelter, which corresponds to a Cu content of 40.00%. This is in agreement with the estimate for the Reading facility; however, it should be noted that Gößling describes a somewhat different process. The dust is assumed to contain 75% Cu, in the form of CuO. The calculation results in yields of 97.9% – 99.2%.

#### 4.3.1.2 Electrolytic Refining

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

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

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<sup>16</sup> "PM-10" is the acronym for particulate matter with AMAD  $\leq$  10  $\mu$ m.

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



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

### 4.3.2 Partitioning Factors

#### 4.3.2.1 Fire Refining

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

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

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

#### 4.3.2.2 Electrolytic Refining

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

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

Partitioning factors for electrorefining are presented in Table 4.6.

## 4.4 Mixing of Cleared Scrap

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

Table 4.5 Partitioning in fire refining of copper (%)

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

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

#### 4.4.1 Processing Copper Scrap at Scrap Yard

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

#### 4.4.2 Secondary Fire Refining

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

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

Table 4.6 Partitioning in electrorefining of copper (%)

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

#### 4.5 Radionuclide Concentrations in Various Media

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

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

<sup>18</sup> Because of the skewness of this distribution, the standard error of the mean is a more meaningful metric than the coefficient of variation.

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

## 4.6 Dose Assessment of Copper Recycling and Disposal Scenarios

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

### 4.6.1 Inhalation and Inadvertent Ingestion of Copper Dusts

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

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

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

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

**Table 4.7 Scenario and exposure pathway matrix**

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

<sup>a</sup> CA = corresponding analysis: Fe = steel, mod = modified from corresponding steel analysis

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

<sup>c</sup> Exposure pathways: Ext = external, Inh = inhalation, Ing = ingestion of food, water, or soil; inadvertent ingestion

<sup>d</sup> External exposure dose factors:

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

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

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

#### 4.6.3 Handling Copper Slag at Fire Refinery

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

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

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

#### 4.6.4 Atmospheric Releases During Fire refining

The only significant difference in the atmospheric release scenario for the fire refining of copper scrap and the comparable scenario for melt-refining of steel scrap is the period of buildup of radionuclides in the soil at the receptor location. In the steel scenario, it was assumed that the activity would build up over a period of 1.7 years, the assumed period of time during which steel scrap would be cleared from a commercial nuclear power plant undergoing dismantlement. Because of the large number of steelmaking facilities which consume iron and steel scrap, it is

unlikely that a single melt shop would be recycling scrap from more than one nuclear power reactor. However, the secondary copper industry includes only four fire refineries. Consequently, there is a high likelihood that, if copper cleared from the nuclear plants is destined for recycling, the same refinery would be recycling such scrap in different years. The buildup time was calculated as follows:

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

- $t_b$  = buildup time of activity in soil (d)
- $f_{fr}$  = fraction of Cu scrap consumed by fire-refining furnaces
- $m_{Cu}$  = mass of Cu scrap cleared during dismantlement of one reactor
- $m_{fr}$  = annual capacity of given fire-refining facility
- $n_d$  = days per year
- $N_R$  = number of reactors scheduled for dismantlement
- $m_0$  = mass of cleared Cu scrap processed by given fire-refining facility in one year
- $M_{fr}$  = combined capacity of all U.S. fire-refining facilities

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

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

#### 4.6.5 Transportation Scenarios

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

average speed of all trips made by a given driver is represented by a triangular distribution with a range of 40 to 60 mph (64 – 97 km/h), and a mode of 50 mph. These speeds are based on engineering judgement and are intended to span the range of average highway speeds throughout the United States.

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

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

#### 4.6.6 Drinking Tapwater from Copper Pipes

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

##### 4.6.6.1 Exposure Pathways

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

##### 4.6.6.2 Detailed Description

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

$$D_{iw} = C_{Cu} C_{ip} F_{ig} I_w t_{ys} \left( \frac{e^{-\lambda_1 t_1} - e^{-\lambda_1(t_1 + t_2)}}{\lambda_1 t_2} \right) \quad 4.2$$



- $D_{iw}$  = dose from ingestion of radionuclide  $i$  in tapwater during assessment period ( $\mu\text{Sv}$ )  
 $C_{Cu}$  = concentration of copper in tapwater (g/mL)  
 $C_{ip}$  = undecayed specific activity of radionuclide  $i$  in copper product (see Equation 3.2) (Bq/g)  
 $F_{ig}$  = dose conversion factor for ingestion of radionuclide  $i$  ( $\mu\text{Sv/Bq}$ )  
 $I_w$  = daily consumption of tapwater (mL/d)  
 $t_{ys}$  = exposure duration (d)  
 $t_s$  = time from clearance of material to the time the scenario begins (d)  
 $\lambda_i$  = radioactive decay rate of nuclide  $i$  ( $\text{d}^{-1}$ )  
 $t_a$  = assessment period

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

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

#### 4.6.6.3 Concentration of Copper in Tapwater

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

#### 4.6.7 Well Water Infiltrated by Leachate from Landfills Containing Copper Slag

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

#### 4.6.8 Electrolytic Refineries

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

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

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

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

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

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

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

#### **4.6.9 Brass Mills**

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

#### **4.6.10 Scenario Timing**

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

##### **4.6.10.1 Scrap Transport and Handling**

- Cleared scrap is transported to a scrap dealer or to a landfill. Transportation takes two to six days from the time of clearance.
- The scrap is disposed of in a landfill one to seven days after arrival.
- The scrap is processed and remains at the scrap dealer for a period of one to 30 days after it arrives.

##### **4.6.10.2 Refining and Processing**

- The fire-refining process and associated operations at the secondary producer take place one to five days after the scrap is shipped from the scrap dealer.
- Airborne effluent releases from the reverberatory furnace occur at the time the scrap is melted and refined.
- Slag and dust are produced at the time the scrap is refined.

##### **4.6.10.3 Transportation of Products of Fire Refining**

- Transport of fire-refined copper occurs three to 30 days after production.
- Dust from the reverberatory furnace is collected monthly and may be sent to a third party for metal recovery. Transportation is assumed to take place 30 to 60 days after the dust is generated.

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

#### 4.6.10.4 Use of Copper Products

- Manufactured items are put into use 10 to 60 days after the refined copper is shipped from the secondary producer. As noted in Section 4.2.2, the average life of copper products is 20 years.
- Copper pipes are installed and put into service between 10 and 270 days after shipment from the secondary producer. This range encompasses replacement plumbing, which might be installed and used as soon as 10 days after shipment, and pipes installed in a new building under construction, which might not be used until nine months later. The average service life of copper pipes is 35 years (Henstock 1997).

### 4.7 Dose Assessments of Recycling and Disposal of Copper Scrap

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

#### 4.7.1 Calculation of Effective Dose Equivalents (EDEs)

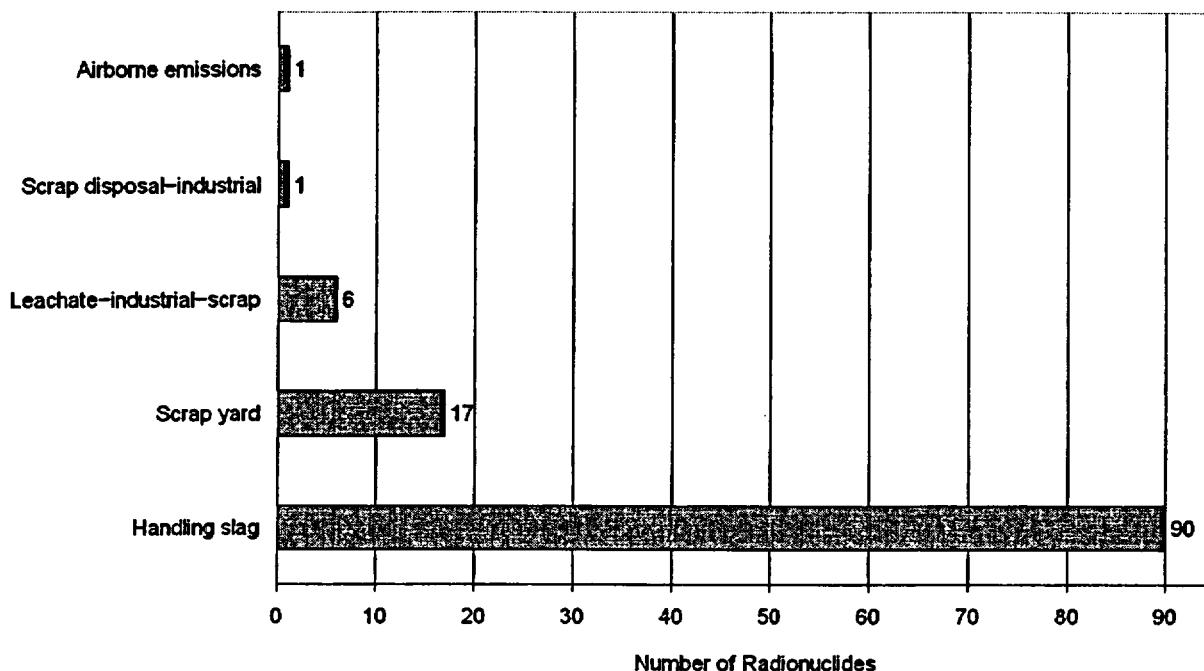
The groups described by five of these scenarios receive the highest mean normalized EDEs from one year of exposure to cleared copper scrap from all 115 nuclides, one scenario constituting the EDE-critical group for 90 nuclides.<sup>21</sup> Table 4.9 lists the mean and the 5th, 50th, and 95th percentile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

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

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

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



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

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

**4.7.2 Calculation of Effective Doses**

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

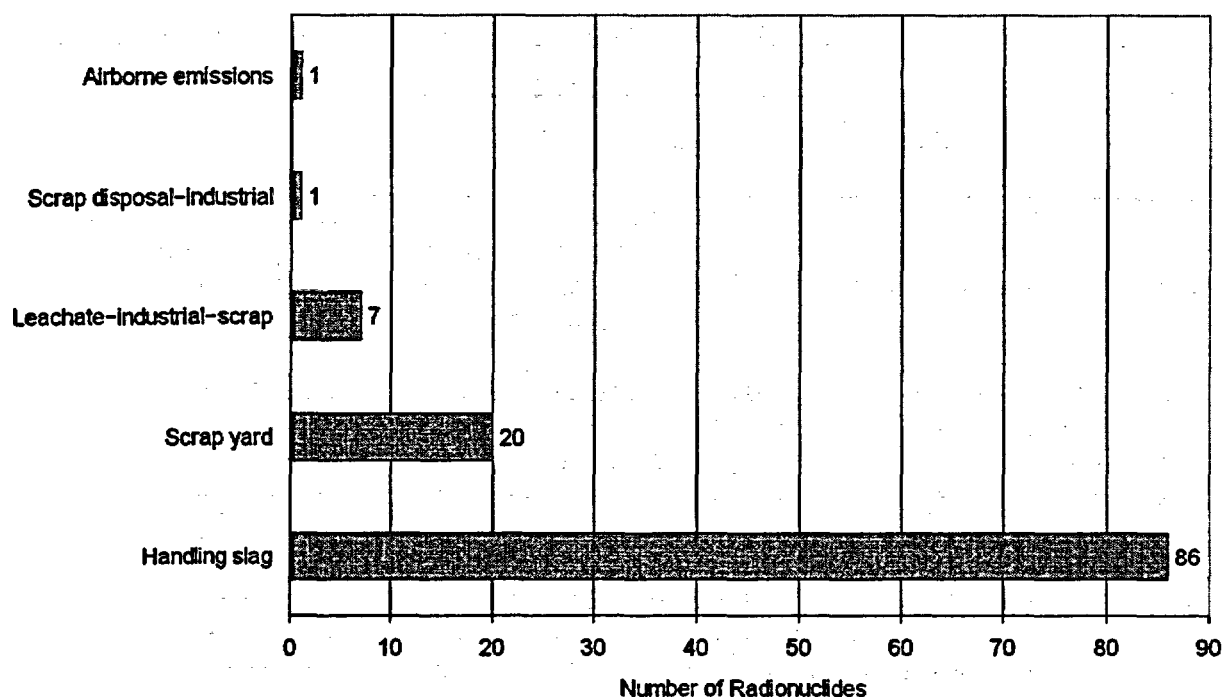


Figure 4.4 Scenarios giving rise to effective-dose critical groups for copper

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

Table 4.8 Mass-based normalized effective dose from Mo-93 ( $\mu\text{Sv/y}$  per Bq/g)

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

<sup>a</sup> Nuclide for which mean normalized effective dose exceeds 90th percentile effective dose

<sup>b</sup> Critical group = persons living down gradient from an industrial landfill used for the disposal of cleared copper scrap

<sup>c</sup> Group with maximum mean effective dose which does not exceed 90th percentile effective dose to that group

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval



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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

Radionuclide	$\mu\text{Sv/y per Bq/g}$				mrem/y per pCi/g				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ac-227	5.1e+00	1.6e+00	4.1e+00	1.2e+01	1.9e-02	5.8e-03	1.5e-02	4.4e-02	Handling slag
Th-228	3.3e+00	1.1e+00	2.7e+00	7.4e+00	1.2e-02	4.1e-03	9.8e-03	2.7e-02	Handling slag
Th-229	4.8e+00	1.5e+00	3.8e+00	1.1e+01	1.8e-02	5.4e-03	1.4e-02	4.1e-02	Handling slag
Th-230	5.5e-01	1.7e-01	4.4e-01	1.3e+00	2.0e-03	6.2e-04	1.6e-03	4.8e-03	Handling slag
Th-232	9.9e-01	3.0e-01	7.9e-01	2.3e+00	3.7e-03	1.1e-03	2.9e-03	8.6e-03	Handling slag
Pa-231	1.4e+00	3.9e-01	9.0e-01	4.4e+00	5.3e-03	1.4e-03	3.3e-03	1.6e-02	Scrap yard
U-232	2.0e+00	6.2e-01	1.6e+00	4.8e+00	7.5e-03	2.3e-03	6.0e-03	1.8e-02	Handling slag
U-233	5.2e-01	1.6e-01	4.1e-01	1.2e+00	1.9e-03	5.8e-04	1.5e-03	4.5e-03	Handling slag
U-234	5.1e-01	1.5e-01	4.1e-01	1.2e+00	1.9e-03	5.7e-04	1.5e-03	4.5e-03	Handling slag
U-235	5.1e-01	1.6e-01	4.1e-01	1.2e+00	1.9e-03	6.0e-04	1.5e-03	4.4e-03	Handling slag
U-236	4.7e-01	1.4e-01	3.8e-01	1.1e+00	1.7e-03	5.3e-04	1.4e-03	4.1e-03	Handling slag
U-238	4.4e-01	1.4e-01	3.5e-01	1.0e+00	1.6e-03	5.0e-04	1.3e-03	3.8e-03	Handling slag
Np-237	1.2e+00	3.9e-01	9.8e-01	2.8e+00	4.5e-03	1.4e-03	3.6e-03	1.1e-02	Handling slag
Pu-236	6.3e-01	2.0e-01	5.0e-01	1.5e+00	2.3e-03	7.2e-04	1.9e-03	5.5e-03	Handling slag
Pu-238	8.5e-01	2.6e-01	8.8e-01	2.0e+00	3.2e-03	9.7e-04	2.5e-03	7.4e-03	Handling slag
Pu-239	6.5e-01	2.0e-01	5.2e-01	1.5e+00	2.4e-03	7.5e-04	1.9e-03	5.7e-03	Handling slag
Pu-240	6.5e-01	2.0e-01	5.2e-01	1.5e+00	2.4e-03	7.5e-04	1.9e-03	5.7e-03	Handling slag
Pu-241	9.4e-03	2.5e-03	5.9e-03	2.8e-02	3.5e-05	9.3e-06	2.2e-05	1.1e-04	Scrap yard
Pu-242	6.1e-01	1.9e-01	4.9e-01	1.4e+00	2.2e-03	7.0e-04	1.8e-03	5.3e-03	Handling slag
Pu-244	7.5e-01	2.6e-01	6.1e-01	1.7e+00	2.8e-03	9.5e-04	2.3e-03	6.3e-03	Handling slag
Am-241	2.1e+00	6.3e-01	1.6e+00	4.8e+00	7.6e-03	2.3e-03	6.1e-03	1.8e-02	Handling slag
Am-242m	2.1e+00	6.5e-01	1.7e+00	5.0e+00	7.9e-03	2.4e-03	6.3e-03	1.9e-02	Handling slag
Am-243	2.1e+00	6.5e-01	1.7e+00	4.9e+00	7.8e-03	2.4e-03	6.2e-03	1.8e-02	Handling slag
Cm-242	2.5e-01	7.7e-02	2.0e-01	6.0e-01	9.4e-04	2.9e-04	7.5e-04	2.2e-03	Handling slag
Cm-243	1.6e+00	4.8e-01	1.2e+00	3.6e+00	5.7e-03	1.8e-03	4.6e-03	1.3e-02	Handling slag
Cm-244	1.3e+00	3.9e-01	1.0e+00	3.0e+00	4.8e-03	1.5e-03	3.8e-03	1.1e-02	Handling slag
Cm-245	2.1e+00	6.3e-01	1.6e+00	4.9e+00	7.6e-03	2.3e-03	6.1e-03	1.8e-02	Handling slag
Cm-246	2.1e+00	6.3e-01	1.6e+00	4.8e+00	7.6e-03	2.3e-03	6.1e-03	1.8e-02	Handling slag
Cm-247	2.0e+00	6.5e-01	1.6e+00	4.8e+00	7.6e-03	2.4e-03	6.1e-03	1.8e-02	Handling slag
Cm-248	7.2e+00	2.2e+00	5.8e+00	1.7e+01	2.7e-02	8.2e-03	2.1e-02	6.3e-02	Handling slag
Bk-249	7.7e-03	2.4e-03	6.1e-03	1.8e-02	2.8e-05	8.7e-06	2.3e-05	6.7e-05	Handling slag
Cf-248	4.4e-01	1.3e-01	3.5e-01	1.0e+00	1.6e-03	5.0e-04	1.3e-03	3.9e-03	Handling slag
Cf-249	3.6e+00	1.1e+00	2.9e+00	8.3e+00	1.3e-02	4.1e-03	1.1e-02	3.1e-02	Handling slag
Cf-250	1.7e+00	5.1e-01	1.3e+00	3.9e+00	6.2e-03	1.9e-03	4.9e-03	1.5e-02	Handling slag
Cf-251	3.5e+00	1.1e+00	2.8e+00	8.3e+00	1.3e-02	4.0e-03	1.0e-02	3.1e-02	Handling slag
Cf-252	9.7e-01	3.0e-01	7.7e-01	2.3e+00	3.6e-03	1.1e-03	2.9e-03	8.5e-03	Handling slag
Cf-254	8.7e+00	3.1e+00	7.2e+00	1.9e+01	3.2e-02	1.1e-02	2.7e-02	7.1e-02	Handling slag
Es-254	8.9e-01	3.3e-01	7.4e-01	1.9e+00	3.3e-03	1.2e-03	2.7e-03	7.2e-03	Handling slag

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 4.12 Normalized surficial effective doses to critical groups for copper

Radionuclide	$\mu\text{Sv/y per Bq/cm}^2$				mrem/y per pCi/cm <sup>2</sup>				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
H-3	2.0e-04	0.0e+00	1.5e-07	8.5e-04	7.6e-07	0.0e+00	5.6e-10	3.1e-06	Leachate-industrial-scrap
C-14	4.8e-04	1.5e-04	3.6e-04	1.2e-03	1.8e-06	5.4e-07	1.3e-06	4.6e-06	Airborne emissions
Na-22	2.2e+00	7.6e-01	1.8e+00	4.9e+00	8.2e-03	2.8e-03	6.8e-03	1.8e-02	Handling slag
P-32	1.5e-03	2.3e-04	8.9e-04	4.9e-03	5.6e-06	8.7e-07	3.3e-06	1.8e-05	Scrap yard
S-35	8.1e-05	1.7e-05	6.0e-05	2.2e-04	3.0e-07	6.2e-08	2.2e-07	8.0e-07	Handling slag
Cl-36	4.5e-03	0.0e+00	0.0e+00	1.8e-02	1.7e-05	0.0e+00	0.0e+00	6.6e-05	Leachate-industrial-scrap
K-40	1.3e-01	2.7e-02	7.9e-02	3.7e-01	4.6e-04	9.8e-05	2.9e-04	1.4e-03	Scrap yard
Ca-41	1.9e-03	0.0e+00	0.0e+00	7.8e-03	6.9e-06	0.0e+00	0.0e+00	2.9e-05	Leachate-industrial-scrap
Ca-45	4.8e-04	1.4e-04	3.8e-04	1.1e-03	1.8e-06	5.3e-07	1.4e-06	4.1e-06	Handling slag
Sc-46	1.8e+00	6.0e-01	1.5e+00	3.9e+00	6.5e-03	2.2e-03	5.4e-03	1.5e-02	Handling slag
Cr-51	1.5e-02	4.5e-03	1.2e-02	3.7e-02	5.7e-05	1.7e-05	4.5e-05	1.4e-04	Handling slag
Mn-53	1.2e-05	3.0e-06	9.5e-06	3.0e-05	4.5e-08	1.1e-08	3.5e-08	1.1e-07	Handling slag
Mn-54	8.2e-01	2.8e-01	6.8e-01	1.8e+00	3.0e-03	1.0e-03	2.5e-03	6.7e-03	Handling slag
Fe-55	1.2e-04	2.7e-05	8.9e-05	2.9e-04	4.3e-07	1.0e-07	3.3e-07	1.1e-06	Handling slag
Fe-59	8.3e-01	2.7e-01	6.7e-01	1.9e+00	3.1e-03	9.9e-04	2.5e-03	6.9e-03	Handling slag
Co-56	2.5e+00	7.9e-01	2.0e+00	5.5e+00	9.1e-03	2.9e-03	7.4e-03	2.0e-02	Handling slag
Co-57	2.8e-02	9.3e-03	2.3e-02	6.3e-02	1.0e-04	3.4e-05	8.5e-05	2.3e-04	Handling slag
Co-58	6.6e-01	2.1e-01	5.4e-01	1.5e+00	2.5e-03	7.9e-04	2.0e-03	5.6e-03	Handling slag
Co-60	2.1e+00	7.0e-01	1.8e+00	4.8e+00	7.9e-03	2.6e-03	6.5e-03	1.8e-02	Handling slag
Ni-59	3.6e-05	1.1e-05	2.9e-05	8.4e-05	1.3e-07	4.2e-08	1.1e-07	3.1e-07	Handling slag
Ni-63	6.6e-05	1.8e-05	5.1e-05	1.6e-04	2.4e-07	6.6e-08	1.9e-07	5.9e-07	Handling slag
Zn-65	5.2e-01	1.8e-01	4.3e-01	1.1e+00	1.9e-03	6.5e-04	1.6e-03	4.2e-03	Handling slag
As-73	2.7e-04	1.0e-05	8.3e-05	9.4e-04	1.0e-06	3.8e-08	3.1e-07	3.5e-06	Scrap disposal-industrial
Se-75	1.3e-01	2.6e-02	7.9e-02	3.7e-01	4.6e-04	9.7e-05	2.9e-04	1.4e-03	Scrap yard
Br-85	3.8e-01	1.3e-01	3.1e-01	8.6e-01	1.4e-03	4.7e-04	1.2e-03	3.2e-03	Handling slag
Sr-89	2.2e-03	7.0e-04	1.8e-03	5.1e-03	8.0e-06	2.6e-06	6.5e-06	1.9e-05	Handling slag
Sr-90	1.8e-02	5.6e-03	1.4e-02	4.2e-02	6.7e-05	2.1e-05	5.3e-05	1.6e-04	Handling slag
Y-91	5.8e-03	2.0e-03	4.7e-03	1.3e-02	2.1e-05	7.2e-06	1.7e-05	4.8e-05	Handling slag
Zr-93	1.0e-03	3.2e-04	8.2e-04	2.4e-03	3.8e-06	1.2e-06	3.0e-06	9.0e-06	Handling slag
Zr-95	8.4e-01	2.9e-01	6.9e-01	1.9e+00	3.1e-03	1.1e-03	2.6e-03	6.9e-03	Handling slag
Nb-93m	1.6e-04	4.9e-05	1.3e-04	3.7e-04	5.8e-07	1.8e-07	4.7e-07	1.4e-06	Handling slag
Nb-94	1.6e+00	5.6e-01	1.3e+00	3.6e+00	6.0e-03	2.1e-03	5.0e-03	1.3e-02	Handling slag
Nb-95	5.2e-01	1.6e-01	4.2e-01	1.2e+00	1.9e-03	6.0e-04	1.5e-03	4.5e-03	Handling slag
Mo-93	2.4e-03	0.0e+00	0.0e+00	2.7e-03	8.8e-06	0.0e+00	0.0e+00	1.0e-05	Leachate-industrial-scrap
Tc-97	3.9e-03	0.0e+00	0.0e+00	1.6e-02	1.4e-05	0.0e+00	0.0e+00	5.8e-05	Leachate-industrial-scrap
Tc-97m	5.3e-04	1.7e-04	4.3e-04	1.2e-03	2.0e-06	6.2e-07	1.6e-06	4.6e-06	Handling slag
Tc-99	3.6e-02	0.0e+00	0.0e+00	1.5e-01	1.3e-04	0.0e+00	0.0e+00	5.4e-04	Leachate-industrial-scrap
Ru-103	2.2e-01	4.4e-02	1.4e-01	6.7e-01	8.1e-04	1.6e-04	5.1e-04	2.5e-03	Scrap yard
Ru-106	1.5e-01	3.2e-02	9.6e-02	4.5e-01	5.6e-04	1.2e-04	3.5e-04	1.7e-03	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval



Table 4.12 Normalized surficial effective doses to critical groups for copper

Radionuclide	$\mu\text{Sv/y per Bq/cm}^2$				mrem/y per pCi/cm <sup>2</sup>				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ag-108m	1.1e+00	2.2e-01	6.7e-01	3.1e+00	3.9e-03	8.2e-04	2.5e-03	1.2e-02	Scrap yard
Ag-110m	1.9e+00	3.9e-01	1.2e+00	5.5e+00	6.9e-03	1.5e-03	4.4e-03	2.0e-02	Scrap yard
Cd-109	1.6e-03	5.2e-04	1.3e-03	3.5e-03	5.8e-06	1.9e-06	4.7e-06	1.3e-05	Handling slag
Sn-113	1.7e-01	5.8e-02	1.4e-01	3.8e-01	6.3e-04	2.2e-04	5.2e-04	1.4e-03	Handling slag
Sb-124	1.1e+00	2.3e-01	7.0e-01	3.3e+00	4.1e-03	8.5e-04	2.6e-03	1.2e-02	Scrap yard
Sb-125	3.0e-01	9.7e-02	2.4e-01	6.8e-01	1.1e-03	3.8e-04	8.9e-04	2.5e-03	Handling slag
Te-123m	2.6e-02	5.4e-03	1.6e-02	7.7e-02	9.6e-05	2.0e-05	6.0e-05	2.8e-04	Scrap yard
Te-127m	2.9e-03	6.5e-04	1.8e-03	8.6e-03	1.1e-05	2.4e-06	6.7e-06	3.2e-05	Scrap yard
I-125	3.8e-03	7.8e-04	2.8e-03	9.9e-03	1.4e-05	2.9e-06	1.0e-05	3.6e-05	Handling slag
I-129	1.2e+00	0.0e+00	0.0e+00	4.0e+00	4.3e-03	0.0e+00	0.0e+00	1.5e-02	Leachate-industrial-scrap
I-131	6.9e-02	6.7e-03	4.0e-02	2.3e-01	2.6e-04	2.5e-05	1.5e-04	8.5e-04	Handling slag
Cs-134	1.1e+00	2.2e-01	6.7e-01	3.1e+00	3.9e-03	8.2e-04	2.5e-03	1.1e-02	Scrap yard
Cs-135	1.6e-04	2.2e-05	1.0e-04	5.1e-04	6.0e-07	8.0e-08	3.8e-07	1.9e-06	Scrap yard
Cs-137	3.8e-01	8.1e-02	2.4e-01	1.1e+00	1.4e-03	3.0e-04	8.9e-04	4.2e-03	Scrap yard
Ba-133	2.9e-01	9.9e-02	2.4e-01	6.3e-01	1.1e-03	3.6e-04	8.8e-04	2.3e-03	Handling slag
Ce-139	5.4e-02	1.9e-02	4.5e-02	1.2e-01	2.0e-04	6.9e-05	1.7e-04	4.4e-04	Handling slag
Ce-141	1.7e-02	5.3e-03	1.4e-02	4.0e-02	6.4e-05	2.0e-05	5.1e-05	1.5e-04	Handling slag
Ce-144	4.8e-02	1.7e-02	4.0e-02	1.0e-01	1.8e-04	6.2e-05	1.5e-04	3.9e-04	Handling slag
Pm-147	5.2e-04	1.7e-04	4.2e-04	1.2e-03	1.9e-06	6.1e-07	1.6e-06	4.5e-06	Handling slag
Sm-151	4.0e-04	1.2e-04	3.2e-04	9.5e-04	1.5e-06	4.6e-07	1.2e-06	3.5e-06	Handling slag
Eu-152	1.1e+00	3.9e-01	9.5e-01	2.5e+00	4.2e-03	1.5e-03	3.5e-03	9.3e-03	Handling slag
Eu-154	1.1e+00	3.8e-01	9.3e-01	2.5e+00	4.2e-03	1.4e-03	3.4e-03	9.1e-03	Handling slag
Eu-155	1.1e-02	3.8e-03	8.9e-03	2.4e-02	4.0e-05	1.4e-05	3.3e-05	8.7e-05	Handling slag
Gd-153	1.2e-02	4.3e-03	1.0e-02	2.7e-02	4.6e-05	1.6e-05	3.8e-05	1.0e-04	Handling slag
Tb-160	9.2e-01	3.1e-01	7.5e-01	2.1e+00	3.4e-03	1.1e-03	2.8e-03	7.6e-03	Handling slag
Tm-170	1.8e-03	6.1e-04	1.4e-03	3.9e-03	6.5e-06	2.3e-06	5.3e-06	1.4e-05	Handling slag
Tm-171	2.0e-04	6.6e-05	1.6e-04	4.4e-04	7.2e-07	2.4e-07	5.9e-07	1.6e-06	Handling slag
Ta-182	1.1e+00	3.8e-01	9.1e-01	2.5e+00	4.1e-03	1.4e-03	3.4e-03	9.1e-03	Handling slag
W-181	2.7e-03	9.2e-04	2.2e-03	6.0e-03	9.9e-06	3.4e-06	8.2e-06	2.2e-05	Handling slag
W-185	1.5e-04	3.8e-05	1.2e-04	3.8e-04	5.6e-07	1.4e-07	4.3e-07	1.4e-06	Handling slag
Os-185	3.8e-01	8.0e-02	2.4e-01	1.1e+00	1.4e-03	2.9e-04	8.9e-04	4.2e-03	Scrap yard
Ir-192	3.6e-01	7.6e-02	2.3e-01	1.1e+00	1.3e-03	2.8e-04	8.5e-04	4.1e-03	Scrap yard
Tl-204	3.9e-04	9.7e-05	2.5e-04	1.2e-03	1.4e-06	3.6e-07	9.2e-07	4.4e-06	Scrap yard
Pb-210	4.6e-01	8.0e-02	3.5e-01	1.2e+00	1.7e-03	3.0e-04	1.3e-03	4.5e-03	Handling slag
Bi-207	1.1e+00	2.2e-01	6.7e-01	3.1e+00	3.9e-03	8.3e-04	2.5e-03	1.2e-02	Scrap yard
Po-210	7.2e-02	2.0e-02	4.5e-02	2.2e-01	2.7e-04	7.3e-05	1.7e-04	8.2e-04	Scrap yard
Ra-226	2.1e+00	7.7e-01	1.8e+00	4.7e+00	7.9e-03	2.8e-03	6.6e-03	1.7e-02	Handling slag
Ra-228	1.4e+00	5.0e-01	1.2e+00	3.1e+00	5.2e-03	1.9e-03	4.3e-03	1.2e-02	Handling slag

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 4.12 Normalized surficial effective doses to critical groups for copper

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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## 5 RECYCLING AND DISPOSAL OF ALUMINUM SCRAP

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

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

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

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

### 5.1 Introduction to Analysis

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

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

## 5.2 Flow of Aluminum Scrap

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

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

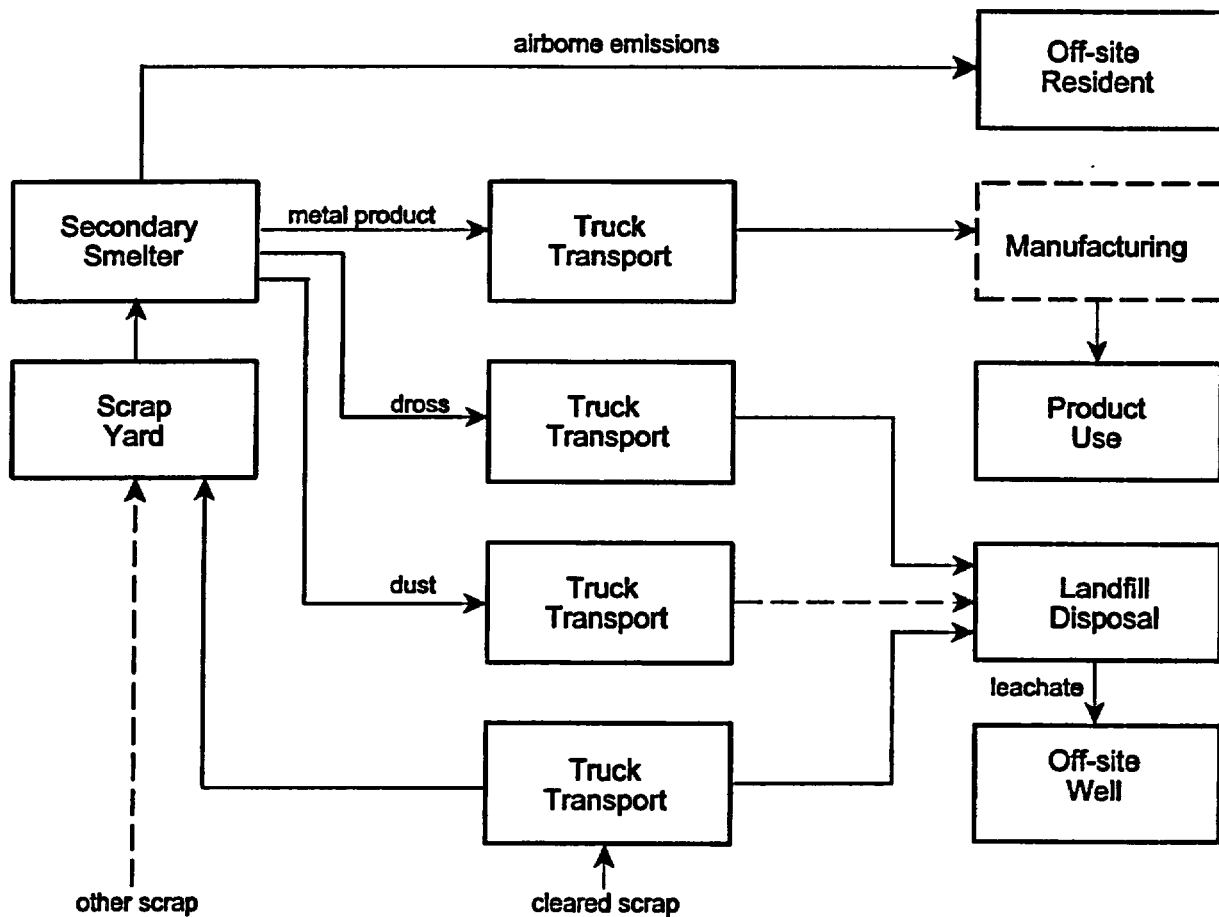


Figure 5.1 Flow of aluminum scrap

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

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

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

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

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

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

### 5.2.1 Sources of Material

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

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<sup>1</sup> Scrap and smelter products can also be shipped by rail or waterway.

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

<sup>3</sup> Alternate types of processing facilities are discussed in Section 5.2.2.

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

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

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

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

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

<sup>a</sup> Sizes listed for 5052-H32 aluminum flat sheet, a common alloy (Cygnet [r/d])

<sup>b</sup> Calculated, assuming density = 2.7 g/cm<sup>3</sup>

### 5.2.2 Recycling of Aluminum Scrap

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



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

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

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

### 5.2.3 Secondary Smelters

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

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

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

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

<sup>7</sup> This total probably includes plants dedicated to UBC remelting.

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

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

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

Source: Plunkert 2002, unless otherwise noted

Notes: Includes imported scrap

Total metal content, scrap = 93.3% Al

Most data rounded to no more than three significant figures, may not add to totals shown.

<sup>a</sup> Old scrap includes sweated pig<sup>8</sup>

<sup>b</sup> Calculated from ratio of old scrap to new scrap consumed

<sup>c</sup> Aluminum Association 2001

<sup>d</sup> Includes 88,000 t of UBC scrap toll-treated for primary producers

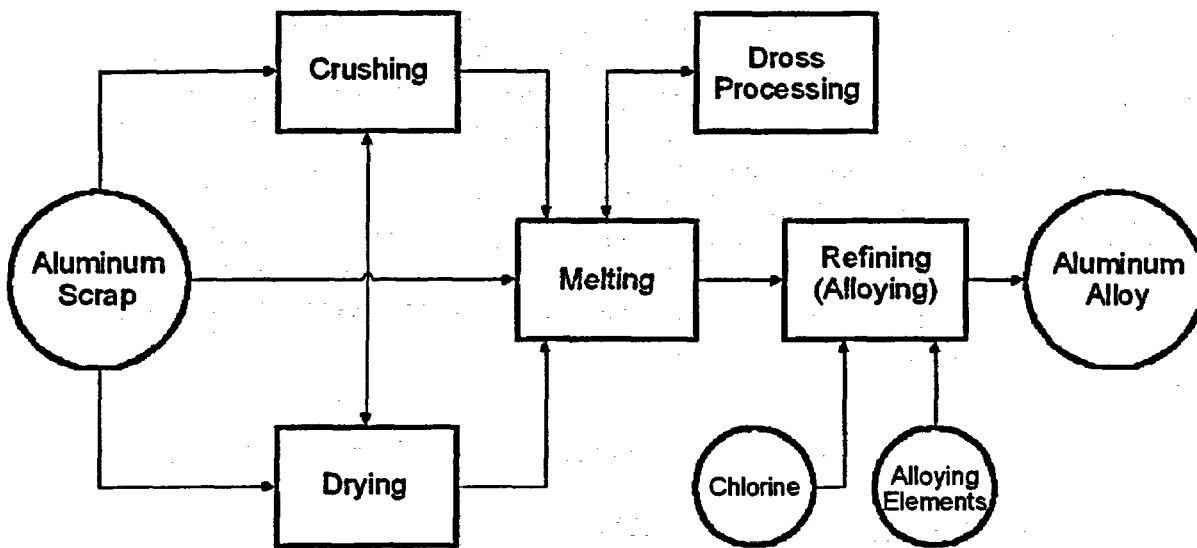
<sup>e</sup> Figures in bold italics derived by present authors from published data

<sup>f</sup> Adjusted by multiplying "totals" by factor of 1.073 to estimate full industry coverage ( $4223 \div 3936 = 1.073$ )<sup>9</sup>

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

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

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



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

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

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

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

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

<sup>10</sup> Saltcake is a general term for the residues of dross processing in rotary furnaces or by other means.

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

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

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

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

#### 5.2.4 Product Use

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

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

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

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

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

**Table 5.3 Product net shipments by major market in 2001**

Market	Total aluminum			Ingot		
	10 <sup>6</sup> lb	kt	Fraction	10 <sup>6</sup> lb	kt	Fraction
Building & construction	2,895	1,313	13.5%	79	36	1.3%
Transportation	6,646	3,015	30.9%	4,052	1,838	68.8%
Consumer durables	1,444	655	6.7%	336	152	5.7%
Electrical	1,361	617	6.3%	185	84	3.1%
Machinery & equipment	1,299	589	6.0%	509	231	8.6%
Containers & packaging	4,851	2,200	22.6%	–	0	0.0%
Other	545	247	2.5%	255	116	4.3%
Domestic total	19,041	8,637	88.7%	5,416	2,457	92.0%
Exports	2,435	1,105	11.3%	470	213	8.0%
Grand total	21,476	9,742	100.0%	5,886	2,670	100.0%

Source: Aluminum Association 2002

### 5.3 Mass Fractions and Partitioning Factors for Smelter Operations

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

#### 5.3.1 Mass Fractions

The melting cycle for a typical reverberatory furnace consists of charging scrap into the forewell of the furnace, blending and mixing alloying materials, adding fluxing salts, removing

magnesium (“demagging”),<sup>12</sup> removing gases, skimming off the dross, and pouring. A heel consisting of 20% to 40% of the furnace capacity is generally left in the furnace to shorten the melting cycle.<sup>13</sup> Scrap is charged to the furnace, either with a front-end loader or a belt conveyor, over a 16- to 18-hour period. Demagging and gas removal require two to four hours, and tapping requires an additional three to four hours, resulting in a total cycle of about 24 hours.

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

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

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<sup>12</sup> Demagging is accomplished by injecting chlorine gas or another gaseous halogen into the melt.

<sup>13</sup> Patricia Plunkert, U.S. Bureau of Mines, private communication with William C. Thurber, SC&A, Inc., September 20, 1995.

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

<sup>15</sup> Jim Bopp, Alchem Aluminum, private communication with Mary Anderson, SAIC, May 23, 1997.

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

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

These mass fractions are summarized in Table 5.4.

**Table 5.4 Comparison of mass fractions in secondary aluminum smelting**

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

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

### 5.3.1.1 Adopted Values

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

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

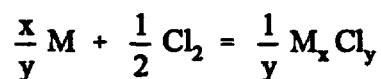
The fraction of dust released to the atmosphere is assigned a normal distribution, with a mean of  $6.5 \times 10^{-4}$  and a standard deviation of  $1.5 \times 10^{-4}$ , based on the data reported in EPA 1995b. Although these emissions are expected to go down as a result of the limits mandated by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

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

### 5.3.2 Partitioning Factors

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

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



M = metal dissolved in liquid aluminum

x = number of atoms of M in chloride salt

y = number of atoms of Cl in chloride salt

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



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

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

Table 5.5 Partitioning of contaminants in aluminum smelting (%)

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

## 5.4 Mixing of Cleared Scrap

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

### 5.4.1 Transport of Aluminum Scrap

Because of the small quantity of aluminum scrap that would be generated during the dismantlement of a commercial nuclear power plant, it is assumed that all of this scrap would be shipped off site as a single truck-load. It is further assumed that the cleared scrap in the truck would be mixed with aluminum scrap from nonimpacted areas of the plant, or from other sources. The mass of cleared scrap, which is represented by a uniform probability distribution

with a range of 1.2 to 2.0 t, is mixed into a 20-t load of scrap. The resulting mixing factors have a range of 0.06 – 0.1.

#### **5.4.2 Processing Aluminum Scrap at Scrap Yard**

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

#### **5.4.3 Secondary Smelter Operations**

##### **5.4.3.1 Annual-Average Mixing Factors**

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

##### **5.4.3.2 Single-Heat Mixing Factors**

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

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<sup>17</sup> Gary Huddleston, environmental manager, Wabash Alloys LLC, private communication with Robert Anigstein, SC&A, Inc., January, 2003.

## 5.5 Radionuclide Concentrations in Various Media

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

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

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

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

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

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

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

$f_{mc}$  = single-heat mixing factor

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

$m_{Al}$  = mass of aluminum scrap cleared from a single nuclear power plant

$M_f$  = capacity of reverberatory furnace (details in Appendix D)

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

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

## 5.6 Aluminum Recycling and Disposal Scenarios

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

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

### 5.6.1 Inhalation of Aluminum Dusts

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

### 5.6.2 Handling Dross at Secondary Smelter

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

### 5.6.3 Use of Aluminum Cooking Ware

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

#### 5.6.3.1 External Exposure

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

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

Table 5.6 Scenario and exposure pathway matrix

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

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

<sup>b</sup> CA = corresponding analysis: Fe = steel, Cu = copper

<sup>c</sup> Exposure pathways: Ext = external, Inh = inhalation, Ing = ingestion of food, water, or soil; inadvertent ingestion

<sup>d</sup> External exposure dose factors:

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

### 5.6.3.2 Ingestion Exposure

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

$$D_{ic} = C_{ip} F_{ig} m_{Al} t_{ys} \left( \frac{e^{-\lambda_i t_1} - e^{-\lambda_i(t_1 + t_2)}}{\lambda_i t_2} \right) \quad 5.1$$

$D_{ic}$  = dose from ingestion of radionuclide  $i$  in cooking ware during assessment period ( $\mu\text{Sv}$ )

$C_{ip}$  = undecayed specific activity of radionuclide  $i$  in metal product<sup>19</sup> (Bq/g)

$F_{ig}$  = dose conversion factor for ingestion of radionuclide  $i$  ( $\mu\text{Sv/Bq}$ )

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

$t_{ys}$  = exposure duration (d)

$t_1$  = time from clearance of material to the time the scenario begins (d)

$\lambda_i$  = radioactive decay rate of nuclide  $i$  ( $\text{d}^{-1}$ )

$t_2$  = period of assessment

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

### 5.6.4 Scenario Timing

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

#### 5.6.4.1 Scrap Transport and Handling

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

<sup>19</sup> An exact expression for this quantity is presented in Section 3.5.2.

- Disposal in a landfill occurs three to 13 days after clearance.
- The scrap is processed and remains at the scrap dealer for a period of one to 30 days after it arrives.

#### 5.6.4.2 Refining and Processing

- The operations at the secondary smelter take place one to 15 days after the scrap is shipped from the scrap dealer.
- Atmospheric releases from the furnace occur at the time the scrap is smelted.
- Dross and dust are produced at the time the scrap is smelted.

#### 5.6.4.3 Transportation of Smelter Products

- The metal is assumed to be transported three to 30 days after it is produced.<sup>20</sup>
- Dross and dust from the reverberatory furnace are collected periodically and sent to a third party for metal recovery. Transportation is assumed to take place 30 to 60 days after the dust and dross are generated.

#### 5.6.4.4 Use of Aluminum Products

- Manufactured items are put into use 10 to 60 days after the aluminum is shipped from the secondary smelter.
- Generic aluminum products are assumed to have a useful life of 30 years. There are two specific aluminum products in the present analysis: an aluminum engine block and an aluminum cooking pot. The engine block is assumed to be in a taxicab which is driven by its owner an average of about 2,500 hours per year. In addition, it may be leased to other drivers when the owner is off duty. Due to heavy use, the engine is assumed to have a service life of three years.<sup>21</sup> An aluminum pot is assumed to have a service life of 20 years.

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

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

## 5.7 Dose Assessments of Recycling and Disposal of Aluminum Scrap

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

### 5.7.1 Calculation of Effective Dose Equivalents (EDEs)

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

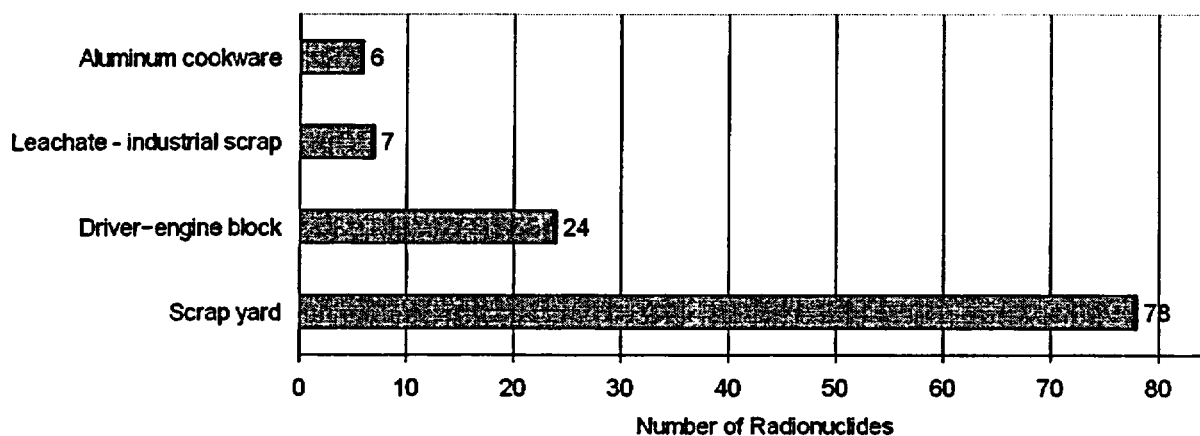


Figure 5.3 Scenarios giving rise to EDE-critical groups for aluminum

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

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

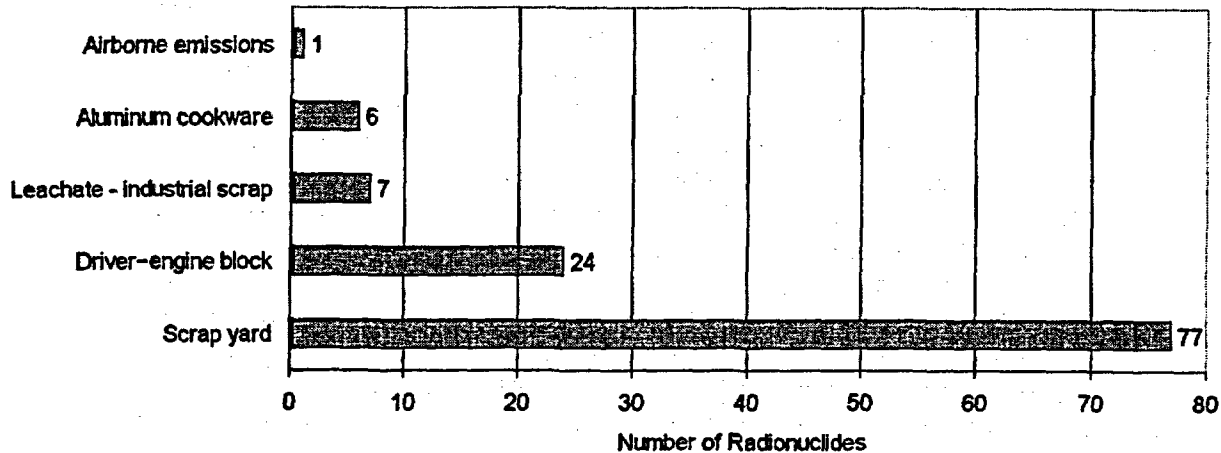
<sup>22</sup> As discussed in Chapter 1, the group which receives the highest mean normalized EDE from a given radionuclide is defined as the EDE-critical group for that nuclide.



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

### 5.7.2 Calculation of Effective Doses

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



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

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

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

Radionuclide	$\mu\text{Sv/y}$ per $\text{Bq}/\text{cm}^2$				mrem/y per $\text{pCi}/\text{cm}^2$				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
H-3	3.1e-06	0.0e+00	2.9e-09	1.1e-05	1.1e-08	0.0e+00	1.1e-11	4.2e-08	Leachate-industrial-scrap
C-14	5.0e-06	0.0e+00	0.0e+00	9.2e-06	1.8e-08	0.0e+00	0.0e+00	3.4e-08	Leachate-industrial-scrap
Na-22	3.2e-02	7.8e-03	2.0e-02	9.7e-02	1.2e-04	2.9e-05	7.5e-05	3.6e-04	Scrap yard
P-32	2.4e-05	4.2e-06	1.4e-05	7.4e-05	8.8e-08	1.5e-08	5.2e-08	2.7e-07	Scrap yard
S-35	9.2e-07	2.2e-07	5.8e-07	2.8e-06	3.4e-09	8.2e-10	2.1e-09	1.0e-08	Scrap yard
Cl-36	6.6e-05	0.0e+00	0.0e+00	2.6e-04	2.5e-07	0.0e+00	0.0e+00	9.8e-07	Leachate-industrial-scrap
K-40	2.5e-03	6.0e-04	1.6e-03	7.4e-03	9.1e-06	2.2e-06	5.7e-06	2.7e-05	Scrap yard
Ca-41	3.2e-05	0.0e+00	0.0e+00	1.4e-04	1.2e-07	0.0e+00	0.0e+00	5.1e-07	Leachate-industrial-scrap
Ca-45	4.3e-06	8.8e-07	2.7e-06	1.3e-05	1.6e-08	3.3e-09	9.9e-09	4.9e-08	Scrap yard
Sc-46	2.6e-02	6.3e-03	1.6e-02	7.8e-02	9.7e-05	2.3e-05	6.1e-05	2.9e-04	Scrap yard
Cr-51	2.7e-04	5.9e-05	1.7e-04	8.2e-04	9.9e-07	2.2e-07	6.1e-07	3.0e-06	Scrap yard
Mn-53	7.4e-07	4.7e-07	6.7e-07	1.4e-06	2.7e-09	1.7e-09	2.5e-09	5.1e-09	Aluminum cookware
Mn-54	6.3e-02	3.4e-02	5.7e-02	1.2e-01	2.3e-04	1.2e-04	2.1e-04	4.3e-04	Driver-engine block
Fe-55	3.5e-06	2.2e-06	3.2e-06	6.5e-06	1.3e-08	8.1e-09	1.2e-08	2.4e-08	Aluminum cookware
Fe-59	1.4e-02	3.2e-03	8.6e-03	4.2e-02	5.0e-05	1.2e-05	3.2e-05	1.5e-04	Scrap yard
Co-56	5.3e-02	1.8e-02	4.5e-02	1.2e-01	2.0e-04	6.7e-05	1.7e-04	4.3e-04	Driver-engine block
Co-57	8.0e-03	4.2e-03	7.2e-03	1.5e-02	3.0e-05	1.6e-05	2.7e-05	5.5e-05	Driver-engine block
Co-58	1.4e-02	4.3e-03	1.2e-02	3.1e-02	5.2e-05	1.6e-05	4.3e-05	1.2e-04	Driver-engine block
Co-60	2.9e-01	1.6e-01	2.6e-01	5.3e-01	1.1e-03	5.9e-04	9.6e-04	1.9e-03	Driver-engine block
Ni-59	2.5e-06	1.4e-06	2.2e-06	4.5e-06	9.1e-09	5.1e-09	8.2e-09	1.7e-08	Driver-engine block
Ni-63	3.9e-06	2.5e-06	3.6e-06	7.3e-06	1.5e-08	9.3e-09	1.3e-08	2.7e-08	Aluminum cookware
Zn-65	3.5e-02	1.8e-02	3.1e-02	6.4e-02	1.3e-04	6.7e-05	1.2e-04	2.4e-04	Driver-engine block
As-73	2.0e-05	6.6e-06	1.6e-05	4.2e-05	7.2e-08	2.4e-08	6.1e-08	1.6e-07	Driver-engine block
Se-75	1.1e-02	4.8e-03	9.9e-03	2.2e-02	4.2e-05	1.8e-05	3.7e-05	8.3e-05	Driver-engine block
Sr-85	5.7e-03	1.4e-03	3.6e-03	1.7e-02	2.1e-05	5.1e-06	1.3e-05	5.4e-05	Scrap yard
Sr-89	3.3e-05	8.3e-06	2.1e-05	9.8e-05	1.2e-07	3.1e-08	7.6e-08	3.6e-07	Scrap yard
Sr-90	2.9e-04	6.9e-05	1.8e-04	8.9e-04	1.1e-06	2.5e-07	6.7e-07	3.3e-06	Scrap yard
Y-91	8.8e-05	2.3e-05	5.6e-05	2.6e-04	3.3e-07	8.4e-08	2.1e-07	9.8e-07	Scrap yard
Zr-93	2.3e-05	5.7e-06	1.4e-05	7.0e-05	8.5e-08	2.1e-08	5.3e-08	2.6e-07	Scrap yard
Zr-95	1.2e-02	2.9e-03	7.5e-03	3.6e-02	4.4e-05	1.1e-05	2.8e-05	1.3e-04	Scrap yard
Nb-93m	8.1e-06	2.0e-06	5.1e-06	2.5e-05	3.0e-08	7.6e-09	1.9e-08	9.1e-08	Scrap yard
Nb-94	2.2e-01	1.2e-01	2.0e-01	4.0e-01	8.2e-04	4.6e-04	7.4e-04	1.5e-03	Driver-engine block
Nb-95	7.9e-03	1.8e-03	4.9e-03	2.4e-02	2.9e-05	6.7e-06	1.8e-05	8.9e-05	Scrap yard
Mo-93	1.0e-05	6.0e-06	9.1e-06	1.9e-05	3.7e-08	2.2e-08	3.4e-08	6.9e-08	Aluminum cookware
Tc-97	3.3e-05	0.0e+00	0.0e+00	1.4e-04	1.2e-07	0.0e+00	0.0e+00	5.1e-07	Leachate-industrial-scrap
Tc-97m	5.1e-06	1.4e-06	3.2e-06	1.5e-05	1.9e-08	5.0e-09	1.2e-08	5.6e-08	Scrap yard
Tc-99	2.8e-04	0.0e+00	0.0e+00	1.2e-03	1.1e-06	0.0e+00	0.0e+00	4.4e-06	Leachate-industrial-scrap
Ru-103	5.1e-03	1.2e-03	3.2e-03	1.5e-02	1.9e-05	4.4e-06	1.2e-05	5.7e-05	Scrap yard
Ru-106	2.2e-02	1.2e-02	2.0e-02	4.0e-02	8.0e-05	4.4e-05	7.2e-05	1.5e-04	Driver-engine block

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval



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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 5.10 Normalized surficial effective doses to critical groups for aluminum

Radionuclide	$\mu\text{Sv/y}$ per $\text{Bq}/\text{cm}^2$				mrem/y per $\text{pCi}/\text{cm}^2$				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
H-3	3.2e-06	0.0e+00	3.0e-09	1.2e-05	1.2e-08	0.0e+00	1.1e-11	4.4e-08	Leachate-industrial-scrap
C-14	5.1e-06	0.0e+00	0.0e+00	9.4e-06	1.9e-08	0.0e+00	0.0e+00	3.5e-08	Leachate-industrial-scrap
Na-22	3.2e-02	7.7e-03	2.0e-02	9.6e-02	1.2e-04	2.9e-05	7.5e-05	3.5e-04	Scrap yard
P-32	2.3e-05	4.1e-06	1.4e-05	7.3e-05	8.6e-08	1.5e-08	5.2e-08	2.7e-07	Scrap yard
S-35	1.5e-06	3.7e-07	9.3e-07	4.5e-06	5.5e-09	1.4e-09	3.4e-09	1.7e-08	Scrap yard
Cl-36	7.5e-05	0.0e+00	0.0e+00	3.0e-04	2.8e-07	0.0e+00	0.0e+00	1.1e-06	Leachate-industrial-scrap
K-40	2.5e-03	6.0e-04	1.6e-03	7.4e-03	8.1e-06	2.2e-06	5.7e-06	2.7e-05	Scrap yard
Ca-41	2.7e-05	0.0e+00	0.0e+00	1.2e-04	9.9e-08	0.0e+00	0.0e+00	4.3e-07	Leachate-industrial-scrap
Ca-45	4.8e-06	1.1e-06	3.0e-06	1.5e-05	1.8e-08	4.0e-09	1.1e-08	5.4e-08	Scrap yard
Sc-46	2.6e-02	6.3e-03	1.6e-02	7.8e-02	9.6e-05	2.3e-05	6.1e-05	2.9e-04	Scrap yard
Cr-51	2.7e-04	5.9e-05	1.7e-04	8.2e-04	9.9e-07	2.2e-07	6.1e-07	3.0e-06	Scrap yard
Mn-53	7.6e-07	4.8e-07	6.9e-07	1.4e-06	2.8e-09	1.8e-09	2.6e-09	5.2e-09	Aluminum cookware
Mn-54	6.1e-02	3.3e-02	5.5e-02	1.1e-01	2.3e-04	1.2e-04	2.0e-04	4.1e-04	Driver-engine block
Fe-55	7.0e-06	4.4e-06	6.4e-06	1.3e-05	2.6e-08	1.6e-08	2.3e-08	4.8e-08	Aluminum cookware
Fe-59	1.3e-02	3.2e-03	8.5e-03	4.2e-02	5.0e-05	1.2e-05	3.1e-05	1.5e-04	Scrap yard
Co-56	5.2e-02	1.8e-02	4.4e-02	1.1e-01	1.9e-04	6.5e-05	1.6e-04	4.2e-04	Driver-engine block
Co-57	7.8e-03	4.1e-03	7.0e-03	1.4e-02	2.9e-05	1.5e-05	2.6e-05	5.3e-05	Driver-engine block
Co-58	1.4e-02	4.2e-03	1.1e-02	3.0e-02	5.0e-05	1.5e-05	4.1e-05	1.1e-04	Driver-engine block
Co-60	2.8e-01	1.6e-01	2.5e-01	5.1e-01	1.0e-03	5.8e-04	9.4e-04	1.9e-03	Driver-engine block
Ni-59	2.4e-06	1.3e-06	2.1e-06	4.3e-06	8.8e-09	4.9e-09	7.9e-09	1.6e-08	Driver-engine block
Ni-63	3.8e-06	2.4e-06	3.4e-06	7.0e-06	1.4e-08	8.9e-09	1.3e-08	2.6e-08	Aluminum cookware
Zn-65	3.4e-02	1.8e-02	3.0e-02	6.2e-02	1.3e-04	6.5e-05	1.1e-04	2.3e-04	Driver-engine block
As-73	1.8e-05	6.2e-06	1.5e-05	4.0e-05	6.8e-08	2.3e-08	5.7e-08	1.5e-07	Driver-engine block
Se-75	1.1e-02	4.7e-03	9.7e-03	2.2e-02	4.1e-05	1.7e-05	3.6e-05	8.0e-05	Driver-engine block
Sr-85	5.7e-03	1.4e-03	3.6e-03	1.7e-02	2.1e-05	5.0e-06	1.3e-05	6.4e-05	Scrap yard
Sr-89	3.2e-05	8.2e-06	2.0e-05	9.7e-05	1.2e-07	3.0e-08	7.5e-08	3.6e-07	Scrap yard
Sr-90	2.1e-04	5.1e-05	1.3e-04	6.6e-04	7.9e-07	1.9e-07	5.0e-07	2.4e-06	Scrap yard
Y-91	8.4e-05	2.1e-05	5.3e-05	2.5e-04	3.1e-07	7.9e-08	2.0e-07	9.3e-07	Scrap yard
Zr-93	1.0e-05	2.5e-06	6.3e-06	3.1e-05	3.7e-08	9.3e-09	2.3e-08	1.1e-07	Scrap yard
Zr-95	1.2e-02	2.9e-03	7.5e-03	3.6e-02	4.4e-05	1.1e-05	2.8e-05	1.3e-04	Scrap yard
Nb-93m	3.1e-06	1.9e-06	2.8e-06	5.7e-06	1.1e-08	7.2e-09	1.0e-08	2.1e-08	Aluminum cookware
Nb-94	2.1e-01	1.2e-01	1.9e-01	3.9e-01	7.9e-04	4.4e-04	7.2e-04	1.5e-03	Driver-engine block
Nb-95	7.8e-03	1.8e-03	4.9e-03	2.4e-02	2.9e-05	6.7e-06	1.8e-05	8.8e-05	Scrap yard
Mo-93	5.8e-05	3.5e-05	5.3e-05	1.1e-04	2.1e-07	1.3e-07	2.0e-07	4.0e-07	Aluminum cookware
Tc-97	6.0e-05	0.0e+00	0.0e+00	2.5e-04	2.2e-07	0.0e+00	0.0e+00	9.2e-07	Leachate-industrial-scrap
Tc-97m	7.1e-06	1.9e-06	4.5e-06	2.1e-05	2.6e-08	7.0e-09	1.7e-08	7.8e-08	Scrap yard
Tc-99	5.6e-04	0.0e+00	0.0e+00	2.3e-03	2.1e-06	0.0e+00	0.0e+00	8.6e-06	Leachate-industrial-scrap
Ru-103	5.0e-03	1.2e-03	3.2e-03	1.5e-02	1.9e-05	4.3e-06	1.2e-05	5.7e-05	Scrap yard
Ru-106	2.1e-02	1.1e-02	1.9e-02	3.9e-02	7.8e-05	4.2e-05	7.0e-05	1.4e-04	Driver-engine block

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

**Table 5.10 Normalized surficial effective doses to critical groups for aluminum**

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 5.10 Normalized surficial effective doses to critical groups for aluminum

Radionuclide	$\mu\text{Sv/y}$ per $\text{Bq}/\text{cm}^2$				mrem/y per $\text{pCi}/\text{cm}^2$				Scenario
	Mean	Percentile <sup>a</sup>			Mean	Percentile <sup>a</sup>			
		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>		5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	
Ac-227	8.5e-02	2.2e-02	5.3e-02	2.6e-01	3.2e-04	8.0e-05	2.0e-04	9.6e-04	Scrap yard
Th-228	5.3e-02	1.5e-02	3.4e-02	1.6e-01	2.0e-04	5.4e-05	1.2e-04	5.8e-04	Scrap yard
Th-229	1.1e-01	2.8e-02	7.0e-02	3.5e-01	4.2e-04	1.0e-04	2.6e-04	1.3e-03	Scrap yard
Th-230	3.9e-02	9.5e-03	2.4e-02	1.2e-01	1.4e-04	3.5e-05	8.9e-05	4.4e-04	Scrap yard
Th-232	4.1e-02	1.0e-02	2.5e-02	1.2e-01	1.5e-04	3.7e-05	9.4e-05	4.6e-04	Scrap yard
Pa-231	1.3e-01	3.1e-02	7.9e-02	3.9e-01	4.7e-04	1.2e-04	2.9e-04	1.4e-03	Scrap yard
U-232	3.5e-02	8.8e-03	2.2e-02	1.1e-01	1.3e-04	3.3e-05	8.2e-05	4.0e-04	Scrap yard
U-233	8.4e-03	2.1e-03	5.3e-03	2.6e-02	3.1e-05	7.7e-06	1.9e-05	9.6e-05	Scrap yard
U-234	8.2e-03	2.0e-03	5.1e-03	2.5e-02	3.1e-05	7.5e-06	1.9e-05	9.3e-05	Scrap yard
U-235	9.3e-03	2.5e-03	5.9e-03	2.8e-02	3.5e-05	9.1e-06	2.2e-05	1.0e-04	Scrap yard
U-236	7.7e-03	1.9e-03	4.8e-03	2.3e-02	2.8e-05	7.0e-06	1.8e-05	8.7e-05	Scrap yard
U-238	7.5e-03	1.9e-03	4.7e-03	2.3e-02	2.8e-05	7.0e-06	1.7e-05	8.5e-05	Scrap yard
Np-237	2.3e-02	5.9e-03	1.4e-02	7.0e-02	8.5e-05	2.2e-05	5.4e-05	2.6e-04	Scrap yard
Pu-236	1.7e-02	4.2e-03	1.1e-02	5.3e-02	6.4e-05	1.6e-05	4.0e-05	1.9e-04	Scrap yard
Pu-238	4.2e-02	1.0e-02	2.6e-02	1.3e-01	1.5e-04	3.8e-05	9.6e-05	4.7e-04	Scrap yard
Pu-239	4.6e-02	1.1e-02	2.8e-02	1.4e-01	1.7e-04	4.1e-05	1.1e-04	5.2e-04	Scrap yard
Pu-240	4.6e-02	1.1e-02	2.8e-02	1.4e-01	1.7e-04	4.1e-05	1.1e-04	5.2e-04	Scrap yard
Pu-241	8.2e-04	2.0e-04	5.1e-04	2.5e-03	3.1e-06	7.5e-07	1.9e-06	9.3e-06	Scrap yard
Pu-242	4.3e-02	1.0e-02	2.7e-02	1.3e-01	1.6e-04	3.9e-05	9.8e-05	4.8e-04	Scrap yard
Pu-244	4.7e-02	1.2e-02	3.0e-02	1.5e-01	1.8e-04	4.5e-05	1.1e-04	5.4e-04	Scrap yard
Am-241	3.8e-02	9.3e-03	2.4e-02	1.2e-01	1.4e-04	3.4e-05	8.7e-05	4.3e-04	Scrap yard
Am-242m	3.8e-02	9.3e-03	2.4e-02	1.2e-01	1.4e-04	3.5e-05	8.7e-05	4.3e-04	Scrap yard
Am-243	4.0e-02	1.0e-02	2.5e-02	1.2e-01	1.5e-04	3.7e-05	9.2e-05	4.5e-04	Scrap yard
Cm-242	4.3e-03	1.0e-03	2.7e-03	1.3e-02	1.6e-05	3.8e-06	9.8e-06	4.8e-05	Scrap yard
Cm-243	2.9e-02	7.3e-03	1.8e-02	9.0e-02	1.1e-04	2.7e-05	6.8e-05	3.3e-04	Scrap yard
Cm-244	2.4e-02	5.9e-03	1.5e-02	7.4e-02	8.9e-05	2.2e-05	5.6e-05	2.7e-04	Scrap yard
Cm-245	4.0e-02	9.8e-03	2.5e-02	1.2e-01	1.5e-04	3.6e-05	9.1e-05	4.5e-04	Scrap yard
Cm-246	3.9e-02	9.5e-03	2.4e-02	1.2e-01	1.4e-04	3.5e-05	8.9e-05	4.4e-04	Scrap yard
Cm-247	3.9e-02	1.0e-02	2.5e-02	1.2e-01	1.5e-04	3.7e-05	9.1e-05	4.4e-04	Scrap yard
Cm-248	1.4e-01	3.3e-02	8.5e-02	4.2e-01	5.0e-04	1.2e-04	3.1e-04	1.5e-03	Scrap yard
Bk-249	1.5e-04	3.6e-05	9.2e-05	4.5e-04	5.4e-07	1.3e-07	3.4e-07	1.7e-06	Scrap yard
Cf-248	7.6e-03	1.9e-03	4.8e-03	2.3e-02	2.8e-05	6.9e-06	1.8e-05	8.6e-05	Scrap yard
Cf-249	6.8e-02	1.7e-02	4.3e-02	2.1e-01	2.5e-04	6.4e-05	1.6e-04	7.7e-04	Scrap yard
Cf-250	3.1e-02	7.6e-03	1.9e-02	9.5e-02	1.1e-04	2.8e-05	7.1e-05	3.5e-04	Scrap yard
Cf-251	6.6e-02	1.6e-02	4.1e-02	2.0e-01	2.4e-04	6.0e-05	1.5e-04	7.5e-04	Scrap yard
Cf-252	1.7e-02	4.2e-03	1.1e-02	5.3e-02	6.4e-05	1.6e-05	4.0e-05	1.9e-04	Scrap yard
Cf-254	2.4e-01	6.1e-02	1.5e-01	7.2e-01	8.9e-04	2.2e-04	5.6e-04	2.7e-03	Scrap yard
Es-254	2.0e-02	5.5e-03	1.3e-02	6.0e-02	7.5e-05	2.0e-05	4.8e-05	2.2e-04	Scrap yard

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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## 6 RECYCLING AND DISPOSAL OF CONCRETE RUBBLE

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

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

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

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

### 6.1 Introduction to Analysis

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

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

### 6.2 Flow of Concrete Rubble

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



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

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

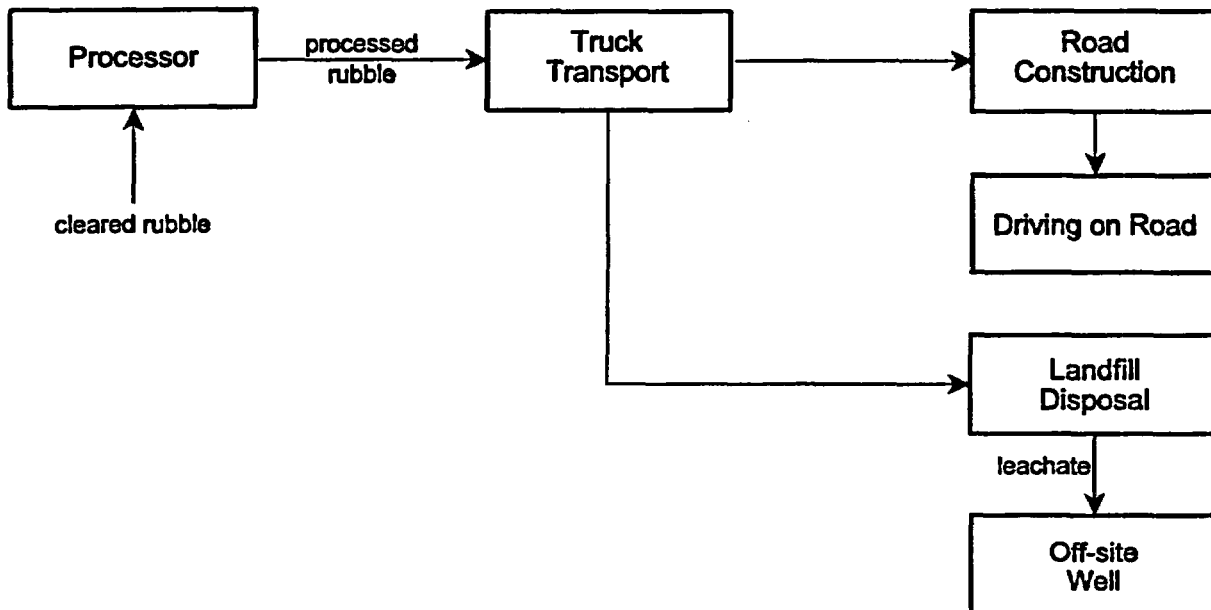


Figure 6.1 Flow of concrete rubble

### 6.2.1 Sources of Material

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

According to Table A.10, the reference 1,000 MWe PWR nuclear power plant contains approximately 180,000 t of concrete. About 36,900 t of concrete is associated with non-impacted areas of the plant. The remaining concrete is associated with the reactor building, reactor auxiliaries, fuel storage, turbine building, turbine plant equipment, and reactor plant

equipment. About 284 t of this material is likely to be surface-contaminated and would therefore be removed by scabbling; an indeterminate but small additional amount would be neutron-activated. The balance—about 143,000 t—would be subject to clearance.

### 6.2.1.1 Mass-to-Surface Ratio

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

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

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

<sup>a</sup> Assumes that only one side is contaminated

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

### 6.2.2 Transportation and Processing

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

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

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

RCM [reclaimed concrete material] is generated through the demolition of portland cement concrete elements of roads, runways, and structures during road reconstruction, utility excavations, or demolition operations.

In many metropolitan areas, the RCM source is from existing portland cement concrete curb, sidewalk and driveway sections that may or may not be lightly reinforced. The RCM is usually removed with a backhoe or payloader and is loaded into dump trucks for removal from the site. The RCM excavation may include 10 to 30 percent subbase soil material and asphalt pavement. Therefore, the RCM is not pure portland cement concrete, but a mixture of concrete, soil, and small quantities of bituminous concrete.

The excavated concrete that will be recycled is typically hauled to a central facility for stockpiling and processing or, in some cases (such as large reconstruction projects), processed on site using a mobile plant. At the central processing facility, crushing, screening, and ferrous metal recovery operations occur. Present crushing systems, with magnetic separators, are capable of removing reinforcing steel without much difficulty. Welded wire mesh reinforcement, however, may be difficult or impossible to remove effectively.

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

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

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<sup>1</sup> It is assumed that concrete rubble destined for landfill disposal would also be processed to remove the rebar.

### 6.2.3 Use of Recycled Concrete

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

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

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

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

TFHRC (1997) also reports that

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

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

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

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

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

#### 6.2.4 Disposal

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

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

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

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<sup>3</sup> Jim Miller, Sales & Estimating Dept., Southern Crushed Concrete Inc., private communication with William C. Thurber, SC&A, Inc., December, 2001.

<sup>4</sup> William Turley, Executive Director, Construction Materials Recycling Association, private communication with William C. Thurber, SC&A, Inc., January 7, 2002.

<sup>5</sup> In the present report, C&D landfills are subsumed under the more general category of industrial landfills.

### 6.3 Concrete Recycling and Disposal Scenarios

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

**Table 6.2 Scenario and exposure pathway matrix**

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

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

<sup>b</sup> Ext = external, Inh = inhalation, Ing = inadvertent ingestion; ingestion of drinking water

<sup>c</sup> External exposure dose factors:

50 Concrete pile

51 Concrete truck

F1 Soil contaminated to an infinite depth (Eckerman and Ryman 1993)

#### 6.3.1 Inhalation of Dust

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

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

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

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

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

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

$\chi_d$  = 8-h TWA level of respirable dust containing crystalline silica in the form of quartz  
 = 0.14 mg/m<sup>3</sup>

$\% \text{SiO}_2$  = percentage of crystalline SiO<sub>2</sub>  
 = 67.5% (see below)

In the present analysis, the fraction of SiO<sub>2</sub> in concrete is calculated from the elemental composition of concrete listed by the American Nuclear Society (1987),<sup>6</sup> assuming that all of the silicon is in the form of silica. In all scenarios which include the inhalation exposure pathway, it is assumed that dust suppression techniques (e.g., water sprays) will be employed in order that these TWA values are not exceeded.

The SiO<sub>2</sub> in concrete is primarily in the form of quartz. According to Prof. T. Taylor Eighmy:

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

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

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

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

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

### 6.3.2 Processing Concrete Rubble at Satellite Facility

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

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

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

### 6.3.3 Transport of Concrete Rubble

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

### 6.3.4 Landfill Disposal Workers

The inhalation exposures of landfill disposal workers are also subject to the OSHA limits on crystalline silica. However, since the workers handle materials other than the cleared concrete,



the percentage of crystalline  $\text{SiO}_2$  in Equation 6.1 is adjusted by multiplying the silica in concrete (67.5%) by the amount of cleared concrete (in a given realization) as a fraction of the total waste stream to a given landfill.<sup>8</sup> The distribution representing the 8-hour TWA dust concentration is adjusted in the same manner.

### 6.3.5 Concrete Road Scenarios

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

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

### 6.3.6 Scenario Timing

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

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

## 6.4 Dose Assessments of Recycling and Disposal of Concrete Rubble

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

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<sup>8</sup> The annual flow of waste to various landfills is discussed in Section D.2.1.1.

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

#### 6.4.1 Calculation of Effective Dose Equivalent (EDEs)

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

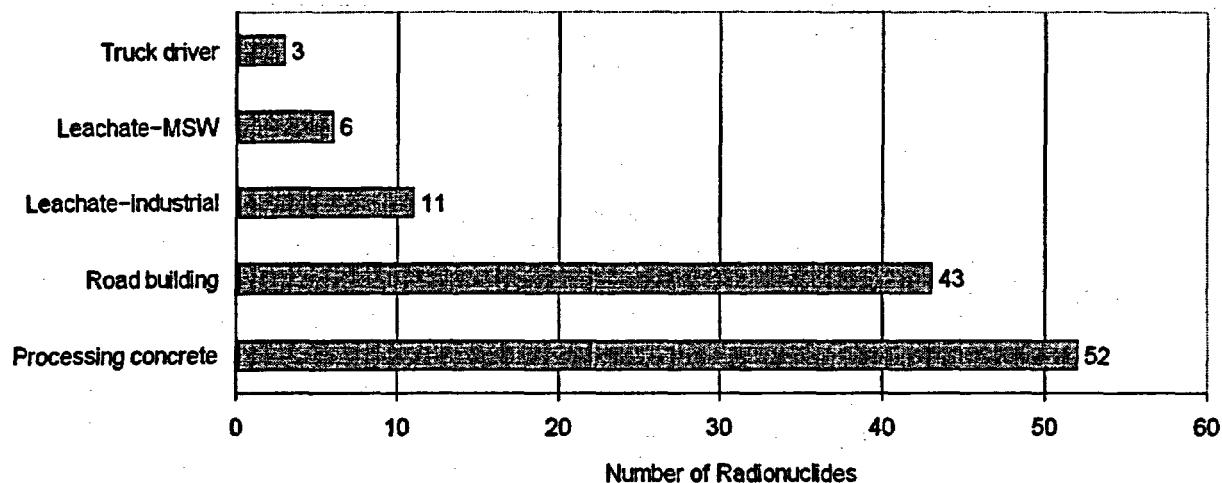


Figure 6.2 Scenarios giving rise to EDE-critical groups for concrete

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

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

**Table 6.3 Normalized mass-based EDE from selected nuclides ( $\mu\text{Sv/y}$  per Bq/g)**

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

<sup>a</sup> Nuclides from which mean normalized EDE exceeds 90th percentile EDE

<sup>b</sup> Group with maximum mean EDE which does not exceed 90th percentile EDE to *that* group

#### 6.4.2 Calculation of Effective Doses

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

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

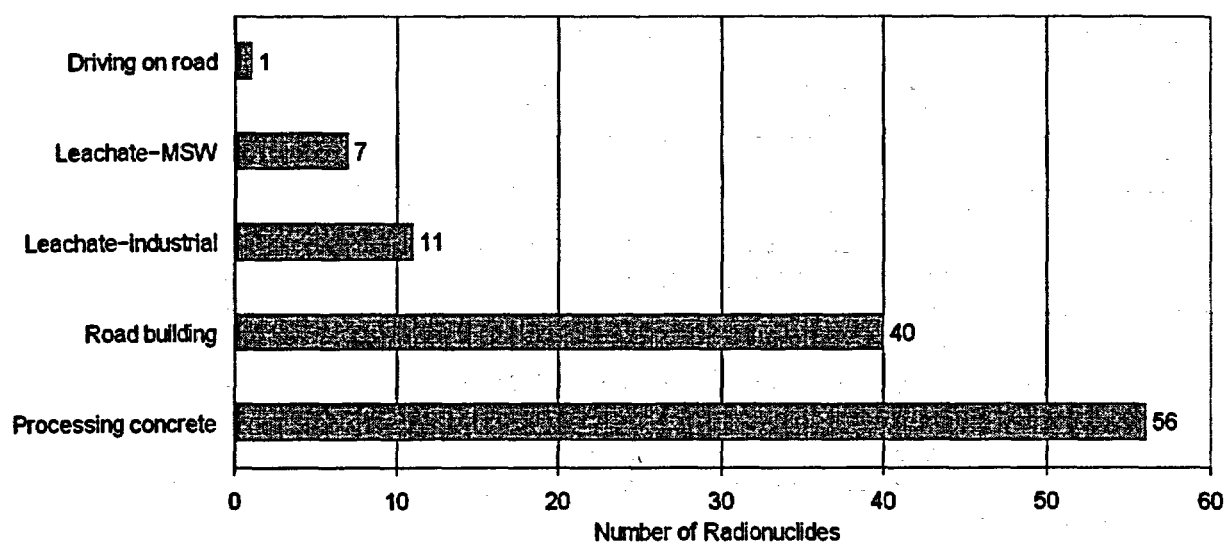


Figure 6.3 Scenarios giving rise to effective dose-critical groups for concrete

Table 6.4 Normalized mass-based effective doses from selected nuclides ( $\mu\text{Sv/y}$  per Bq/g)

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

<sup>a</sup> Nuclides from which mean normalized effective dose exceeds 90th percentile effective dose

<sup>b</sup> Group with maximum mean effective dose which does not exceed 90th percentile effective dose to *that* group

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval



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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

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

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 6.8 Normalized surficial effective doses to critical groups for concrete

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

**Table 6.8 Normalized surficial effective doses to critical groups for concrete**

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval

Table 6.8 Normalized surficial effective doses to critical groups for concrete

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

<sup>a</sup> 5th percentile to 95th percentile = 90% confidence interval



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## 7 QUALITY CONTROL PROGRAM

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

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

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

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

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

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

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

- **Traceability.** Citations of references are complete enough to enable independent retrieval or copies of cited material are included in the Engineering Design Files.
- **Accuracy.** Results of calculations are checked for accuracy and consistency with the design objectives.
- **Organization.** Records in the Engineering Design Files are logically organized and indexed to facilitate data retrieval.
- **Archives.** Sufficient backup of files and work in progress are maintained to guard against loss due to unexpected events, such as fire or theft.

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

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

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## 8 GLOSSARY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**dose coefficient (intake):** A set of coefficients that relate the intake of a unit *activity* of a given *radionuclide* in a given chemical form to the 50-year committed *effective dose*. In the present report, the terms “committed effective dose” and *effective dose* are synonymous. The dose

coefficients in the present analysis are based on the values tabulated in "ICRP Publication 68" (ICRP 1994). Separate dose coefficients are tabulated for the inhalation and ingestion pathways. In addition, there are separate coefficients for the inhalation of 1  $\mu\text{m}$  and 5  $\mu\text{m}$  particles.

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

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

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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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11. ABSTRACT (200 words or less)

This report provides a complete description of calculations and their results estimating potential annual doses, normalized to a unit concentration, to an individual following the clearance of specific materials. These materials are scrap iron and steel, copper, aluminum, and concrete rubble from licensed nuclear facilities. Clearance means the removal of radiological controls by the licensing authority. The estimated potential doses are calculated probabilistically to account for a large number of possible variations in each of the 86 scenarios. These scenarios encompass the full range of realistic situations likely to yield the greatest normalized doses. Each scenario was analyzed with the 115 radionuclides considered most likely to be associated with materials from licensed nuclear facilities. The design basis of the analyses is to realistically model current processes, to identify critical groups on a nuclide-by-nuclide basis, and to enable the conversion of a dose criterion to a concentration.

Material for recycle or disposal was evaluated using material flow models and dose assessment models. Both models are based on probabilistic methods. This resulted in distributions of nuclide-by-nuclide normalized doses from one year of exposure per mass- or surface-based concentrations. The means and the 5th, 50th, 90th, and 95th percentiles are reported. These percentiles can be used to generically evaluate the likelihood that the derived mean concentration would correspond to a particular dose criterion. Additionally, they can be used to quantify the confidence that a safety goal is not exceeded.

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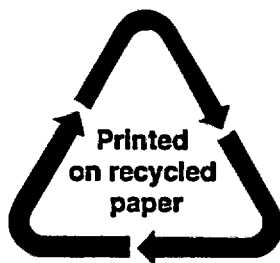
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