

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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Appendices

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- 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

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.

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.

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
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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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ABBREVIATIONS

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

Abbreviations

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

1 INTRODUCTION

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.

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).¹ 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 (: Sv per Bq/g) and surficial normalized doses (: Sv per Bq/cm²). 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 : Sv/y.²

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.

¹ 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.

² 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.

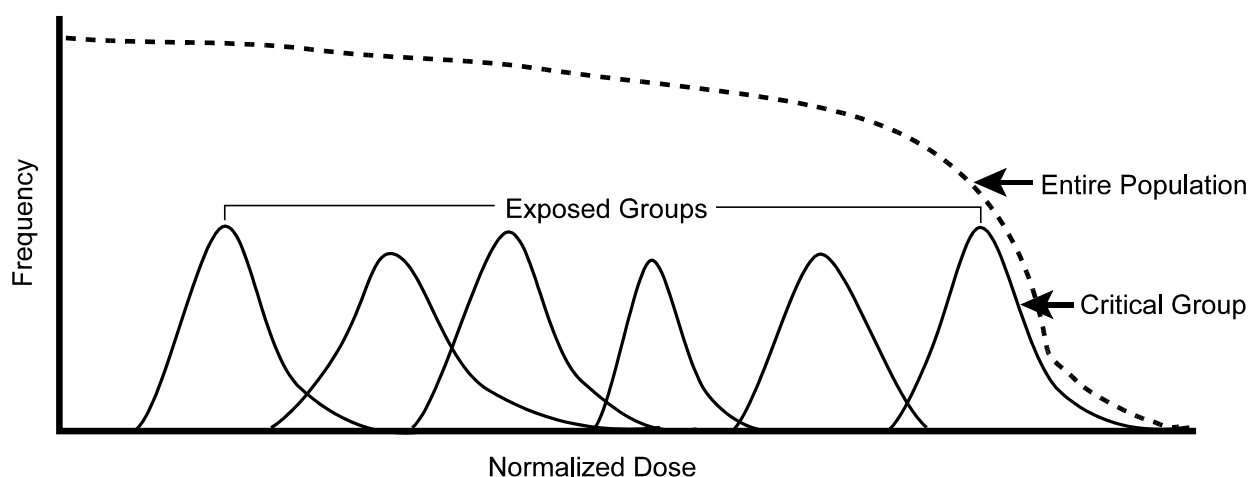


Figure 1.1 Frequency distributions of normalized doses from a hypothetical source

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.³ 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.

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

^a NRC correspondence with IAEA^b Fuchs and McDonald (1993)^c Dyer (1995)^d activation product^e radioactive progeny^f 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 1.41×10^{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 fl- or x-rays emitted during the radioactive decay of the atomic nucleus, or bremsstrahlung x-rays generated following β^- -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 (: Sv/h)

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

F_{ix} = dose coefficient for external exposure to nuclide i (: 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 β^- -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, $U_x / 1$. 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 (DCF) 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.

References

Code of Federal Regulations, *Title 10, Energy*, Part 20, “Standards for Protection Against Radiation,” Subpart A—“General Provisions,” 20.1003 “Definitions.”

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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., : Sv/y per Bq/g or : Sv/y per Bq/cm²).

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 : 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 : Sv/y per Bq/cm² from Th-229. The critical group comprises workers processing copper slag. The highest mean surficial normalized effective dose is 64 : Sv/y per Bq/cm² 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 kt¹ 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/cm², while the corresponding value for concrete is 280 g/cm². 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.

¹ 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 (: Sv/y per Bq/g)				Surficial (: Sv/y per Bq/cm ²)			
	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 (: Sv/y per Bq/g)				Surficial (: Sv/y per Bq/cm ²)			
	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	3.6e-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 (: Sv/y per Bq/g)				Surficial (: Sv/y per Bq/cm ²)			
	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	8.7e+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/cm²), multiply by 0.0037

Table 2.2 Normalized effective doses to critical groups for all materials

Radionuclide	Mass-based (: Sv/y per Bq/g)				Surficial (: Sv/y per Bq/cm ²)			
	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 (: Sv/y per Bq/g)				Surficial (: Sv/y per Bq/cm ²)			
	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 (: Sv/y per Bq/g)				Surficial (: Sv/y per Bq/cm ²)			
	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	3.6e+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/cm²), 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 : Sv/y per Bq/g (1.2 mrem/y per pCi/g) from Cf-254 to a low of $3.7\text{e-}4$: 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 $7.4\text{e-}5$: Sv/y per Bq/cm², 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 : Sv/y per Bq/g (1.2 mrem/y per pCi/g) from I-129 to a low of $3.7\text{e-}4$: 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 $7.3\text{e-}5$: Sv/y per Bq/cm², 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.¹ 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 scrap² 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

¹ 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.

² 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/cm²).

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
7 Decontamination and dismantling of concrete and steel structures and handling scrap generated during the process	7 Use of end products (i.e. frying pan, steel furniture, automobile, steel reinforcement in houses, large and small objects)
7 Transport of scrap to recycling or disposal facility	7 Melting and refining process (airborne effluents)
7 Exposure to scrap piles	7 Slag in roadbeds, foundations of houses, use of contaminated slag in concrete
7 Repair of contaminated machinery	7 Landfill and sanitary disposal of waste products or contaminated scrap (leachate, inadvertent intrusion)
7 Operation of melter and subsequent processing	7 Incineration of contaminated scrap
7 Building renovation or demolition	7 Building occupancy by members of the public
7 Landfill disposal (operation of facility or waste fires)	7 Drinking water that contains radionuclides leached from surface soils
7 Reuse of large concrete masses (building renovation)	7 Residential (contaminated soil)
7 Reuse of contaminated slag in concrete manufacture, production/manufacture of end products	7 Shallow land disposal
	7 Reuse of large concrete masses (building occupancy)

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 truck³ 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.⁴ The scrap dealer then ships the

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

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

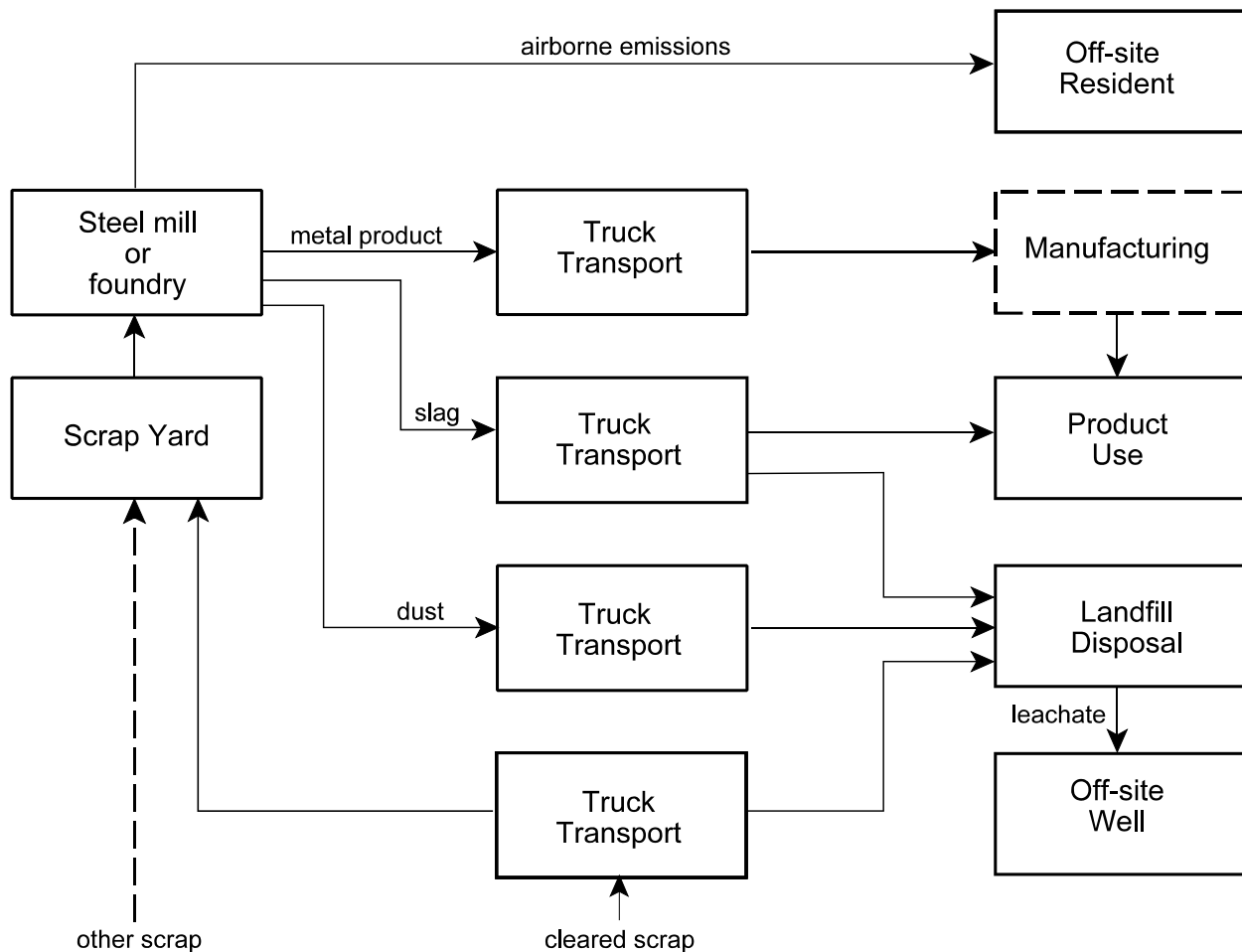


Figure 3.1 Flow of steel scrap

processed scrap to a melt shop,⁵ 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.⁶

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

⁵ 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.

⁶ 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.⁷ 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-listed⁸ 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.⁹ 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

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

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

⁹ 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 truck¹⁰ 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 t¹¹
- 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

¹⁰ See Footnote 3 on page 3-4.

¹¹ 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., γ -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.¹²
- 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 fraction¹³ 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),¹⁴ is produced each year. Eventually, through recycling, a similar

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

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

¹⁴ 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% ($0.1 \div 6 = 0.016$) 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 (8.2×10^7 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,¹⁵ 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.

¹⁵ The scrap consumed was comprised of 45 Mt of purchased scrap and 14 Mt of home scrap.

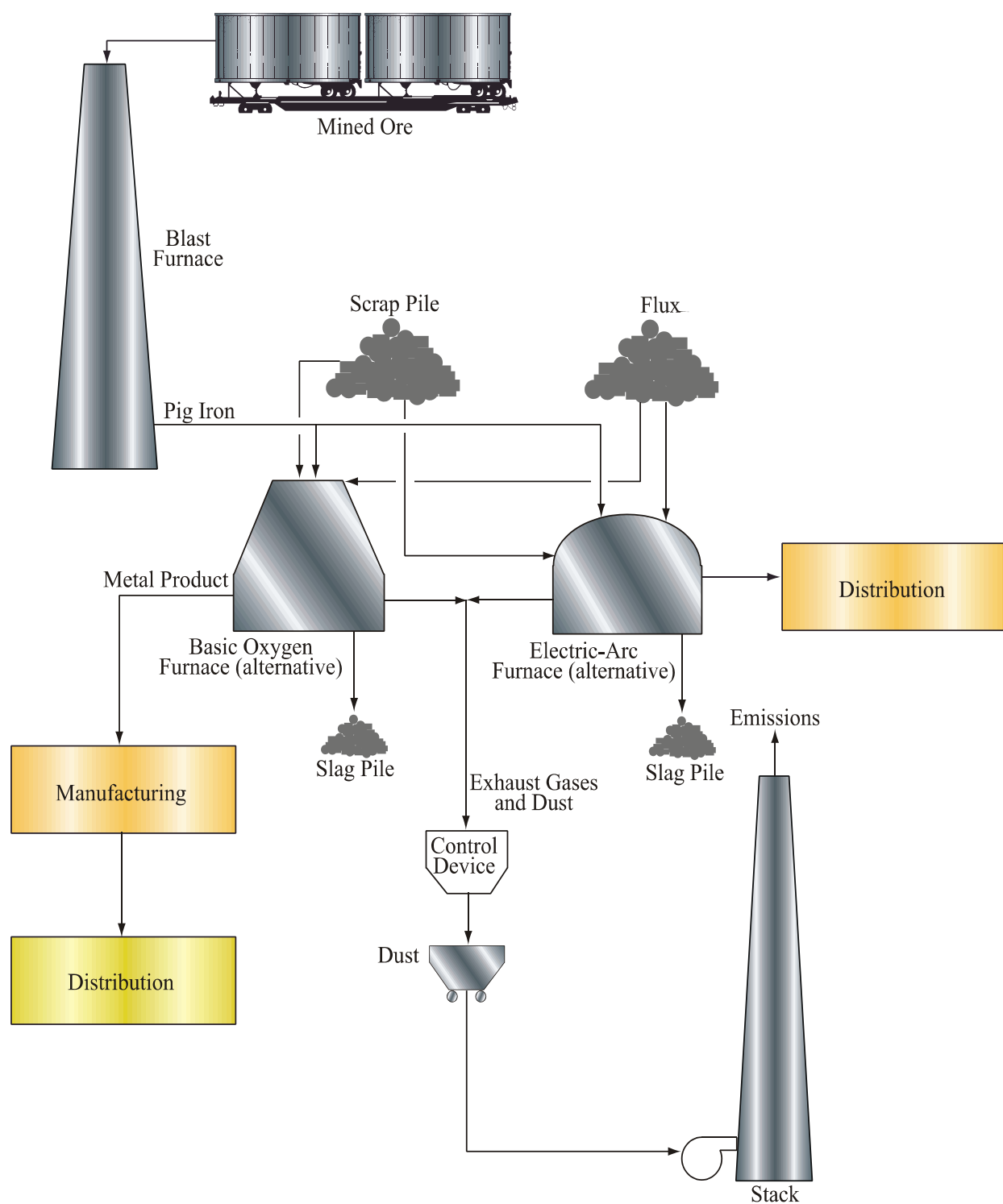
**Figure 3.2 Examples of steelmaking processes**

Table 3.2 Integrated iron and steel mills

Company	Location	BOF Shops		Blast Furnaces	Sinter Plants	Capacity ^a	
		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
Wheeling-Pittsburgh Steel	Mingo Junction, OH	2	1	2		2,600,000	2,359
	Follansbee, WV				1	—	—
Total		50	23	39	9	68,448,000	62,096

Source: EPA 2001a

^a 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).¹⁶ 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).

¹⁶ 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.¹⁷

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 ₂	12.0
MgO	6.30
FeO	26.4
MnO	5.00
P ₂ O ₅	1.10
Al ₂ O ₃	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.¹⁷ At some shops, 100% of the slag is landfilled.

¹⁷ 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.¹⁷ 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 ($54 \text{ Mt steel} \times 0.12 = 6.5 \text{ Mt}$).

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).¹⁸ 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.

¹⁸ 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 ³ at STP)	
	BOF (top-blown)	Q-BOP
Aluminum	MC ^a	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

^a 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.¹⁹ 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).

¹⁹ 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,²⁰ 178 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.

²⁰ 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).²¹ 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,²² 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)²³ 2 kt
- Total²⁴ 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).

²¹ 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).

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

²³ Excludes data withheld to avoid disclosing company proprietary data.

²⁴ 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)²⁵ and an average melt rate of 27 tons per hour (24 t/h).²⁶ 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.²⁶ 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).

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

²⁶ 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.²⁶ 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 ^a	kg/t
Uncontrolled	13.9	7.0
Scrubber ^b	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

^a lb of pollutant/ton of gray iron produced

^b 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.²⁷ 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

²⁷ 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 ^a	55	424	384	351	290	310	330
HTMR-ZN ^b	17	50	82	82	110	125	135
HTMR-Misc. ^c	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.

^a HTMR (High Temperature Metals Recovery) - HRDC (Horsehead Resource Development Co.)

^b HTMR - ZN (Zinc Nacional)

^c 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".^{28, 29} 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.³⁰ (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

²⁸ 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.

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

³⁰ 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/cm³ (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).³¹ 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

³¹ 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 ^a	91%	90%	90 – 98%	98 – 99%
Scrap in feed ^a	24%	95.5%	91.5%	91.5%
Home scrap ^b	24%	25%	38%	38%
Dust/sludge generation	0.4 – 3.1% ^c	0.1 – 0.2% ^d	0.33 – 1.0% ^c	0.41 – 0.5% ^c
Efficiency of APCD	99.4 – 99.9%	99.88 – 99.91%	95% max.	78% max.
Slag generation	5.0 – 22.0% ^c	12 – 14% ^c	6.5 – 8.6% ^d	1.57% ^c
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

^a With respect to total metal in furnace charge

^b With respect to total scrap in furnace charge

^c With respect to metal produced

^d 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.³² 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.³³

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 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,

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

³³ 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.

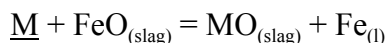
The main components of a typical melt shop that play significant roles in the analysis are the primary melting chamber (the furnace) and the APCD. As stated previously, the latter system typically consists of a fabric baghouse filter, a scrubber, or an electrostatic precipitator. Other components of 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 $\text{Fe}_{(\text{l})}$ 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,³⁴ 168 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.³⁵

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.³⁶ 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

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

³⁵ 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.

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

from 5 to 20 sources.³⁷ 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

³⁷ 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 (8.39×10^{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
 $= 0.75^{38}$

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:

³⁸ 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")

$= g_{hk} f_{sk}$

g_{hk} = fraction of scrap in furnace type k derived from home scrap (see Table B.3)

f_{sk} = 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)

= annual production capacity of particular furnace or melt shop

\check{z}_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:

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

- D_{ix} = dose from external exposure to nuclide i during assessment period (: Sv)
 C_{ij} = average activity concentration of nuclide i in medium j (from Equation 3.2) (Bq/g)
 F_{ix} = dose coefficient for external exposure to nuclide i (: Sv/h per Bq/g)
 t_{xy} = exposure duration during assessment period (h)
 U_x = uncertainty factor
 λ_i = radioactive decay rate of nuclide i (d^{-1})
 t_s = 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:

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

D_{ix} = dose from external exposure during assessment period (: 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:

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

D_{ih} = dose from inhalation of radionuclide i during assessment period (: Sv)

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

R_h = inhalation rate (m^3/h)

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

D_d = airborne concentration of dust (mass loading) (g/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 m³/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 m³/h for sedentary activities, 1.2 m³/h for light activities, and 1.8 m³/h for moderate activities. Based on these data, this parameter was assigned a triangular distribution, with a mode of 1.2 m³/h and a range of 0.6 – 1.8 m³/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:

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

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

F_{ig} = dose conversion factor for ingestion of radionuclide i (: 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.³⁹ 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.

³⁹ 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 ^a	Pathways ^b		
			Ext ^c	Inh	Ing
Handling and Processing					
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	●	●
Atmospheric Release					
Airborne emissions	Emission of airborne effluents from furnace	AA	F2	●	●
Transportation					
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		
Product Use					
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		
Landfill Disposal					
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		
Groundwater Infiltrated by Leachate from Landfills or Storage Piles					
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

^a 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

^b Ext = external, Inh = inhalation, Ing = ingestion

^c 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/m³, 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 Fe₂O₃, 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:

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

C_{ig} = average activity concentration of nuclide i in slag (Bq/g)

F_{ix} = dose coefficient for external exposure to nuclide i (: 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/m³ 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/m³ and a mean of 2.5 mg/m³.

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.⁴⁰ 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)

⁴⁰ 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 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 hours⁴¹ 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

⁴¹ 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.

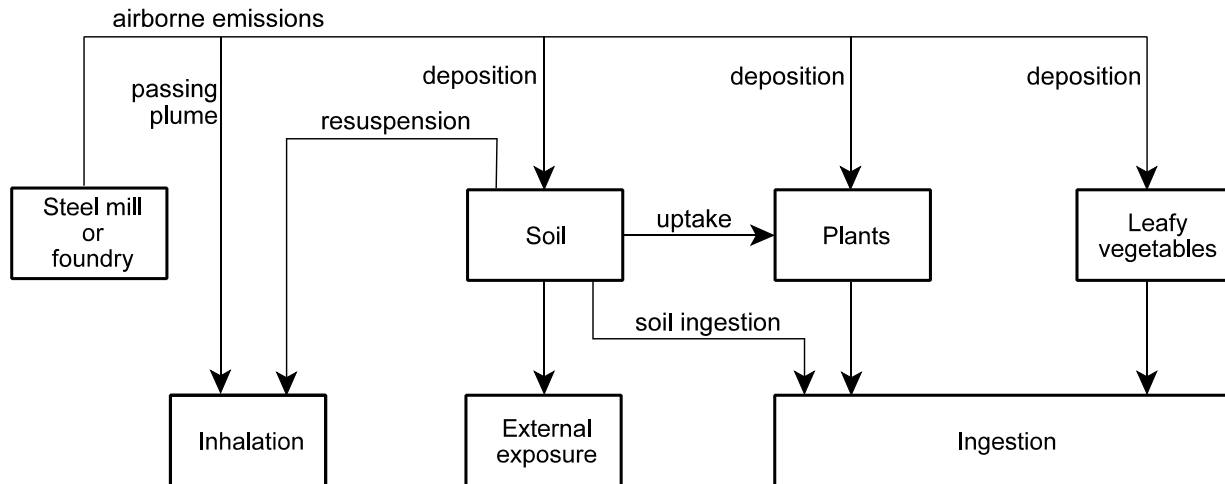


Figure 3.3 Schematic diagram of airborne emissions scenario

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/m³)

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, D/Q.

An examination of the available STAR (STability ARray) data obtained from the Department of Energy⁴² 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 (D/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 D/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 D/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:

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

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

$$\Sigma_{zj}(x) = \left(\sigma_{zj}^2(x) + \frac{D_z^2}{2} \right)^{1/2} \leq \sqrt{3} \sigma_{zj}(x) \quad 3.13$$

$\sigma_{zj}(x)$ = 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 D/Q calculation described above.

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

$D(x)$ = deposition rate of radionuclide at distance x (Bq/(s m²))

$f_p(x)$ = relative deposition rate at distance x (m⁻¹)

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/m²)

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

λ = radioactive decay constant (d⁻¹)

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)

ρ_s = average density of soil in surface layer (g/m³)

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.

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

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

- λ_e = effective weathering and decay constant at harvest (d^{-1})
 $\lambda_e = \lambda_j + \lambda_w$
 λ_j = radioactive decay constant of nuclide j (d^{-1})
 λ_w = weathering constant (d^{-1})
 t_{gv} = 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 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
 $= 0.11$
 D_{C-14} = concentration of C-14 (as $^{14}CO_2$) in air at receptor location (Bq/ m^3)
 D_C = concentration of stable carbon (as 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:

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

- $C_{v,H-3}$ = 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
 $= 0.75$
 r_{H-3} = ratio of tritium concentration in plant water to tritium concentration in atmospheric water
 $= 0.5$
 D_{H-3} = concentration of H-3 (as THO) in air at receptor location (Bq/ m^3)

H = absolute humidity of the atmosphere at receptor (g/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 (g/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 (Bq/g wet-weight plant)

λ = radioactive decay constant (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/m²)

F_{ix} = dose coefficient for external exposure to nuclide i on contaminated ground surface (: Sv/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 Streng (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 (m³/h)

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

R_{hod} = breathing rate for normal activities outdoors (m³/h)

D_i = average concentration of radionuclide i in ambient air from passing plume, from Equation 3.12 (Bq/m³)

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)

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

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

D_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)

ρ_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:

- 7 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.
- 7 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.
- 7 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.⁴³ 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)

⁴³ 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 yd³ (7.6 m³) 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 : m and < 5 : m.⁴⁴ In the present analysis, the concentrations of particles with AMAD < 10 : m were calculated by first subtracting the upwind (background) concentrations from the downwind measurements and then performing a log-log interpolation between the 30 : m and 5 : m 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:

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

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)

⁴⁴ 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 ^a	55	38	70
Driving ^a	49	30	65
In driver's seat ^b	51	32.7	66.7
Hauling one-way load ^c	26.5	17.7	34.2

^a American Trucking Association 2000

^b Estimated—see text

^c 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.⁴⁵ 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)

⁴⁵ 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.⁴⁶ 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.⁴⁷ 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 ^a	58	47	76
Driving ^a	52	38	67
In driver's seat ^b	54	41	70
Hauling one-way load ^c	28	22	36.5

^a American Trucking Association 2000

^b Estimated—see text

^c 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).⁴⁸

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:

⁴⁶ 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.”

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

⁴⁸ See Footnote 40 on page 3-46.

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

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

tB_{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).⁴⁹

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.⁵⁰

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 tons⁵¹ (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

⁴⁹ See Footnote 47 on page 3-62.

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

⁵¹ “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 fl-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 code⁵² 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

⁵² 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 (" 30-cm) pavement base of 1½-inch diameter (" 4-cm) crushed stone has a production rate of 3,800 yd² (3,177 m²) per day. A crew laying down 4-inch-thick (" 10-cm) asphaltic concrete has a rate of 4,140 yd² (3,462 m²) 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 (m²/d)

R_b = Production rate of road base
= 3,177 m²/d

r_b = fraction of day spent laying down road base

R_c = Production rate of concrete pavement
= 3,462 m²/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:

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

$$\begin{aligned} \dot{m}_g &= \text{rate of slag utilization} \\ &= 1,279 \text{ t/d} \end{aligned}$$

$$\begin{aligned} d_c &= \text{thickness of concrete} \\ &= 0.102 \text{ m} \end{aligned}$$

$$\begin{aligned} f_c &= \text{fraction of slag in asphaltic concrete} \\ &= 0.8 \end{aligned}$$

$$\begin{aligned} d_b &= \text{thickness of road base} \\ &= 0.305 \text{ m} \end{aligned}$$

$$\begin{aligned} \rho_g &= \text{bulk density of slag} \\ &= 2 \text{ g/cm}^3 \end{aligned}$$

The exposure duration is calculated as follows:

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

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

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

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.⁵³ 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.

⁵³ 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^2)

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

w = width of typical U.S. highway
 = 2 lane \times 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,

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

t_{xs} = exposure duration (h/d)

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

t_c = 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:

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

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 (: Sv/h per Bq/g)

t_{ys} = 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.⁵⁴ 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.⁵⁵ 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

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

⁵⁵ 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.⁵⁶ 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.⁵⁷ The exposure duration is assigned a uniform distribution spanning this range of hours per year.

⁵⁶ 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.

⁵⁷ 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 truck⁵⁸ 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.

⁵⁸ 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,⁵⁹ 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.⁶⁰

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

⁶⁰ 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:

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

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

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

- Δt_{v_i} = travel time of i -th element through the vadose zone (y)
 Δz = 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)
 ρ_v = bulk soil density of vadose zone (g/cm³)
 $K_{d_{i,v}}$ = soil-water distribution coefficient for i -th element in vadose zone (cm³/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.

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

μ = fractional leach rate (y⁻¹)

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/cm³)

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

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

$t_a(x)$ = 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:

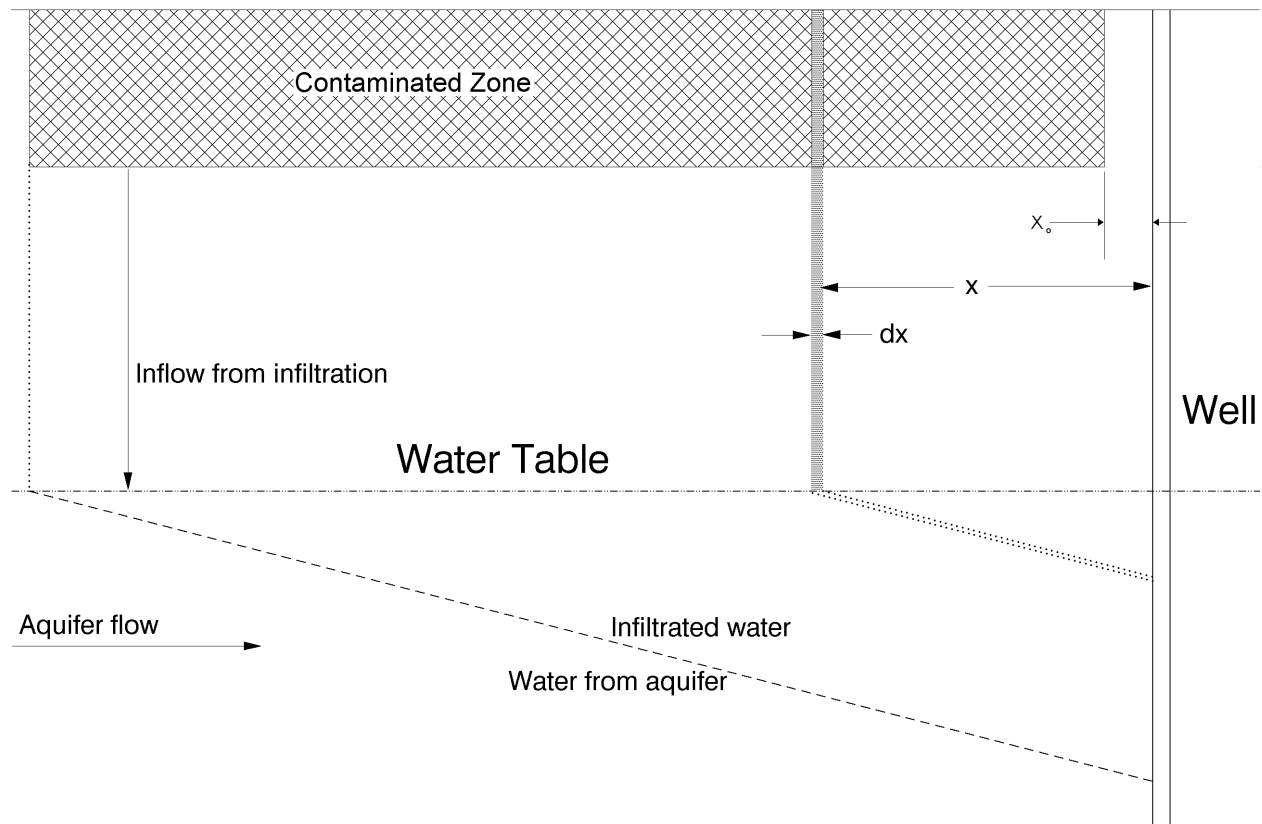


Figure 3.4 Transport of Leachate from Landfill to Well

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

df = incremental dilution factor (concentration in pore water \div concentration in well) of element dx

t_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:

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

$dC_w(>) =$ increment of concentration of nuclide in well at time $>$ (Bq/cm³)

$$\begin{aligned}
 > &= t - t_0 - t_a(2) \quad (y) \\
 &0 \\
 t_0 &= t_a(x_0) + t_v + t_s \quad (y) \\
 x_0 &= \text{distance from landfill boundary to well (m)} \\
 t_a(2) &= \text{travel time in aquifer of nuclide through length } 2(y) \\
 2 &= x - x_0 \quad (m)
 \end{aligned}$$

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 ,

$$dx = \frac{J K_{sa}}{p_{ea} R_{da}} dt_a$$

At a fixed time t , $A > - dt_a$. Substituting these expressions in Equation 3.25, we obtain

$$\partial C_w(\tau) = - \frac{C_o d_L \mu \rho_c e^{-\mu \tau}}{\delta_w p_{ea} R_{da}} \partial \tau$$

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:

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

At later times,

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

$$\begin{aligned}
 A &= \text{active area of landfill (m}^2\text{)} \\
 &= \frac{M_w T_w}{d_L \rho_w} \\
 M_w &= \text{annual mass flow of waste (t/y)} \\
 T_w &= \text{time period for emplacement of wastes} \\
 &= 1.7 \text{ y} \\
 U_w &= \text{pumping rate of well (m}^3\text{/y)} \\
 t_a(l) &= \text{travel time in aquifer of nuclide through length } l \text{ (y)} \\
 l &= l_o(m) \\
 &\quad + \frac{\delta_w J K_{sa}}{I} - x_o \\
 l_o &= \text{length of landfill parallel to aquifer flow (m)}
 \end{aligned}$$

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.

$$\begin{aligned}
 0 &= \frac{d}{dt} \left[\left(1 - e^{-\mu(t-t_o)} \right) e^{-\lambda t} \right] \\
 &= \left[\lambda \left(1 - e^{-\mu(t-t_o)} \right) - \mu \left(e^{-\mu(t-t_o)} \right) \right] e^{-\lambda t}
 \end{aligned} \tag{3.28}$$

Solving Equation 3.28,

$$\begin{aligned}
 t_m &= t_o + \frac{\ln \left(\frac{\lambda + \mu}{\lambda} \right)}{\mu} \\
 &\leq t_a(l) + t_o
 \end{aligned}$$

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

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:

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

D_{iw} = Dose from drinking water from well during year of peak dose (: Sv/y)

$\overline{C_{wi}}$ = average concentration of radionuclide i in well during peak year (Bq/cm³)

I_w = annual consumption of water (cm³/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 cm³/d, while the lower bound is 196 cm³/d. The latter value was calculated by assuming that the logarithms would be symmetrically distributed about the mean of 963 cm³/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
Contaminated zone			
Infiltration Rate (single liner)	I	m/y	EPA 2001c
Depth	d_L	m	EPA 2001c
Waste density	δ_w	g/cm ³	EPA 2001c
Density of zone	δ_c	g/cm ³	$f_w \delta_w + (1 - f_w) \delta_v$ ^a
Fraction of waste in landfill volume	f_w	—	Dehmel et al. 1994
Total porosity	p_{tc}	— = p_{tv}	
Hydraulic conductivity	K_{sc}	m/y = $5 K_{sv}$ ^b	
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 ³ /g	= $0.2 K_{dv}$ ^c
Length parallel to aquifer flow	l_o	m	= $2 \sqrt{\frac{A}{\pi}}$
Area	A	m ²	calculated
Vadose zone			
Saturated hydraulic conductivity	K_{sv}	m/y	EPA 2001c
Total porosity	p_{tv}	—	EPA 2001c
Thickness	l_{zv}	m	EPA 2001c
Bulk density	δ_v	g/cm ³	EPA 2001c
Soil-water distribution coefficient	K_{dv}	cm ³ /g	Yu et al. (2000, Attachment C, pp. 3-30/31) ^d
Soil-specific exponential parameter	b_v	— = b_c	
Effective porosity	p_{ev}	—	generic soil type (Yu et al. 2000, Attachment C, p. 3-9)
Aquifer			
Effective porosity	p_{ea}	—	EPA 2001c
Bulk density	δ_a	g/cm ³	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 ³ /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 ³ /a	Maximum (rounded) from Yu et al. (2000, Attachment C, p. 3-39)
Distance to well	x_o	m	EPA 2001c

^a Assumes uniform mixing of waste with daily soil cover

^b $\frac{1}{K_{sc}} = \frac{f_w}{K_{sw}} + \frac{(1 - f_w)}{K_{sv}}$, assume $K_{sw} \gg K_{sv}$

^c $K_{dc} = f_w K_{dw} + (1 - f_w) K_{dv}$, assume $K_{dw} \ll K_{dv}$

^d 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 (cm²/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 (cm³)

A_{io} = initial activity of nuclide i in sample (Bq)

t_{nt} = duration of n -th leaching interval (d)
 $= t_n - t_{n-1}$

S = surface area of sample (cm²)

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

$$\begin{aligned} f_i &= \left[\frac{2S}{V} \sqrt{\frac{D_i}{\pi}} \right] t^{1/2} \\ &= m_i t^{1/2} \end{aligned} \quad 3.31$$

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 (~ 7 d for Sr-90 and ~ 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 1.2×10^{-7} to 1.7×10^{-7} cm²/day for both deionized water and synthetic sea water at 25°C. Using average values of L_{Sr} for samples cured for seven days prior to testing in deionized water, and assuming a right circular cylinder, $h = 2r$, $V = 70$ cm³, we have derived values for m_{Sr} and α_{Sr} 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 $m_{Cs} = 10 m_{Sr}$ and $\alpha_{Cs} = 10 \alpha_{Sr}$. 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	$m \text{ (d}^{-1/2}\text{)}$		“	
	$r = 2.233 \text{ cm}^a$	$r = 0.5 \text{ cm}$	$r = 2.233 \text{ cm}$	$r = 0.5 \text{ cm}$
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 ^b	c	6.9e-06	0	0

^a Corresponds to 70 cm³ right circular cylinder ($h = 2r$)

^b Cr is used as a surrogate for Nb, Np, Pa and U—see discussion below.

^c 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:

$$m_i = \frac{2S}{V} \sqrt{\frac{D_i}{\pi}} = \frac{12}{r} \sqrt{\frac{D_i}{\pi}}$$

$$\begin{aligned} S &= 2\pi(r^2 + hr) = 6\pi r^2 \\ V &= \pi r^3 \end{aligned} \quad (h = 2r)$$

$$m_{Sr} = 1.54 \times 10^{-2} \text{ d}^{-1/2}$$

$$\begin{aligned} D_{Sr} &= 1.51 \times 10^{-11} \text{ cm}^2/\text{s} \text{ (mean of values in Table 3.18)} \\ &= 1.30 \times 10^{-6} \text{ cm}^2/\text{d} \end{aligned}$$

$$r = 0.5 \text{ cm}$$

Table 3.18 Diffusion coefficients for EAF slag monolithic samples

Slag Sample	Diffusion Coefficient (cm ² /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, λ_{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 $6.9 \times 10^{-6} \text{ d}^{-1/2}$, 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.⁶¹ 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

$$dn = \lambda_r N dt$$

λ_r = removal rate constant

⁶¹ Rick West, Sales Manager for International Mill Services, private communication with William C. Thurber, SC&A, Inc., August 22, 1996.

Assume that O_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

$$v(t) = v_0 e^{-\lambda_r t}$$

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:

$$dv = \lambda_r v_0 e^{-\lambda_r t} dt$$

Since this expression is independent of the initial time, it can be generalized to all the particles in the pile:

$$\frac{dn}{N} = \lambda_r e^{-\lambda_r t} dt \quad 3.35$$

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

$$f'_i(t) = \frac{m_i \lambda_r}{2} \int_0^t \tau^{-1/2} e^{-\lambda_r \tau} d\tau \quad (0 < t \leq T) \quad 3.36$$

$f'_i(t)$ = leach rate of nuclide i in slag pile at time t

t = time since the first residually radioactive slag was placed in pile

τ = 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 $t - T$.

$$f'_i(t) = \frac{m_i \lambda_r}{2} \int_{t-T}^t \tau^{-1/2} e^{-\lambda_r \tau} d\tau \quad (t > T) \quad 3.37$$

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/cm³)

C_{ig} = initial specific activity of nuclide i in slag (Bq/g)

d_g = thickness of slag layer (m)

ρ_g = density of slag (g/cm³)

The contribution of element dx to the concentration of radionuclide i in the well is given by the following expression:

$$\begin{aligned} dC_{wi}(\tau) &= C_{ip}(\tau) df \\ &= \frac{C_{ig} d_g f'_i(\tau) \rho_g}{\delta_w J K_a} dx \\ &= \frac{C_{ig} d_g f'_i(\tau) \rho_g}{\delta_w p'_e R'_{d_i}} d\tau \end{aligned} \quad 3.39$$

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 $>$ 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:

$$C_{wi}(t) = \frac{C_{ig} d_g f_U \rho_g e^{-\lambda_i t}}{\delta_w p_{ea} R_{dia}} \int_{t_1}^{t-t_0} f'_i(\tau) d\tau \quad 3.40$$

$$t_1 = 0 \quad (t_0 \leq t \leq t_0 + t_{ai}(l))$$

$$t_1 = t - t_0 - t_{ai}(l) \quad (t > t_0 + t_{ai}(l))$$

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.⁶² 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.⁶³ 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

⁶² Michael A. Mattia, Director, Risk Management, Institute for Scrap Recycling Industries, private communication with Kathleen Behling, SC&A, Inc., October 19, 2001.

⁶³ 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.⁶⁴

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.

⁶⁴ 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/cm²)

$$\begin{aligned} \rho_j &= \text{mass-to-surface ratio of component } j \text{ (g/cm}^2\text{)} \\ &= \frac{m_j}{a_j} \\ m_j &= \text{mass of component } j \text{ (g)} \\ a_j &= \text{exposed surface area of component } j \text{ (cm}^2\text{)} \end{aligned}$$

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.⁶⁵ 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

⁶⁵ 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 fission-emitting nuclides, as well as to the inhalation and secondary ingestion of the metallic oxide dust generated during the cutting and sizing operations.

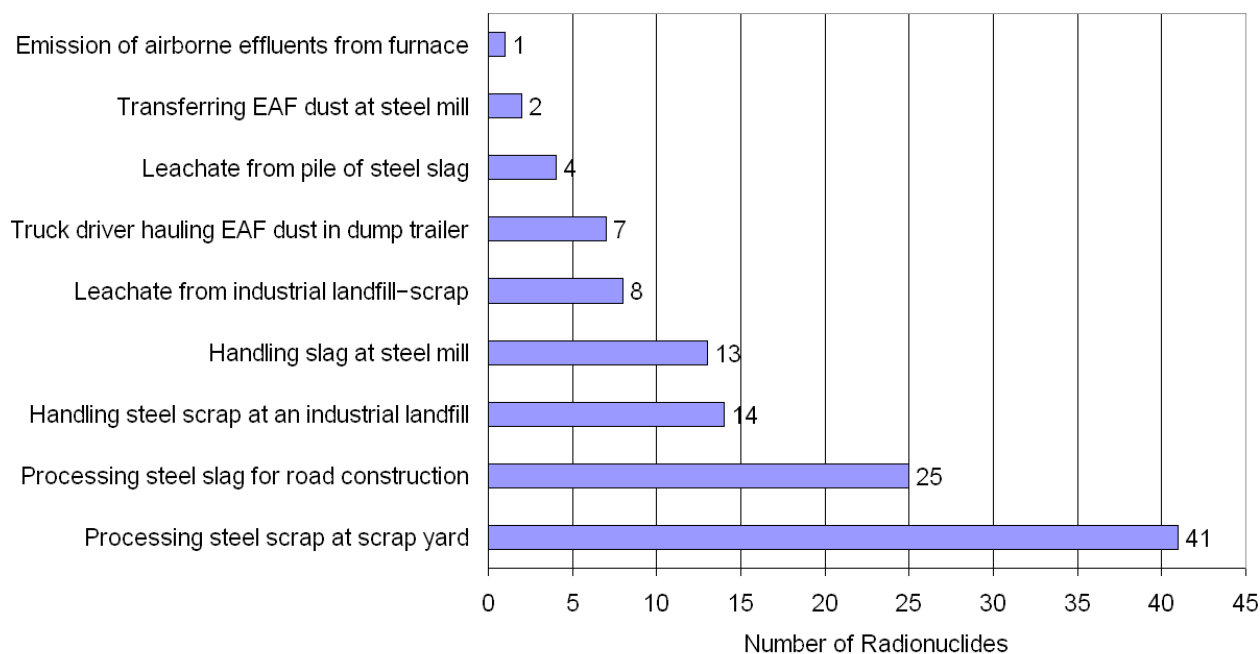


Figure 3.5 Scenarios giving rise to EDE-critical groups for steel

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 (: Sv/y per Bq/g)

Nuclide ^a	Critical group			Potential alternate critical group ^b		
	Mean	90 th %-ile	Scenario	Mean	90 th %-ile	Scenario
C-14	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

^a Nuclides from which mean normalized EDE exceeds 90th percentile EDE

^b Group with maximum mean EDE which does not exceed 90th percentile EDE to *that* group

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 (: Sv/y per Bq/g)

Nuclide ^a	Critical group			Potential alternate critical group ^b		
	Mean	90 th %-ile	Scenario	Mean	90 th %-ile	Scenario
C-14	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

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

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

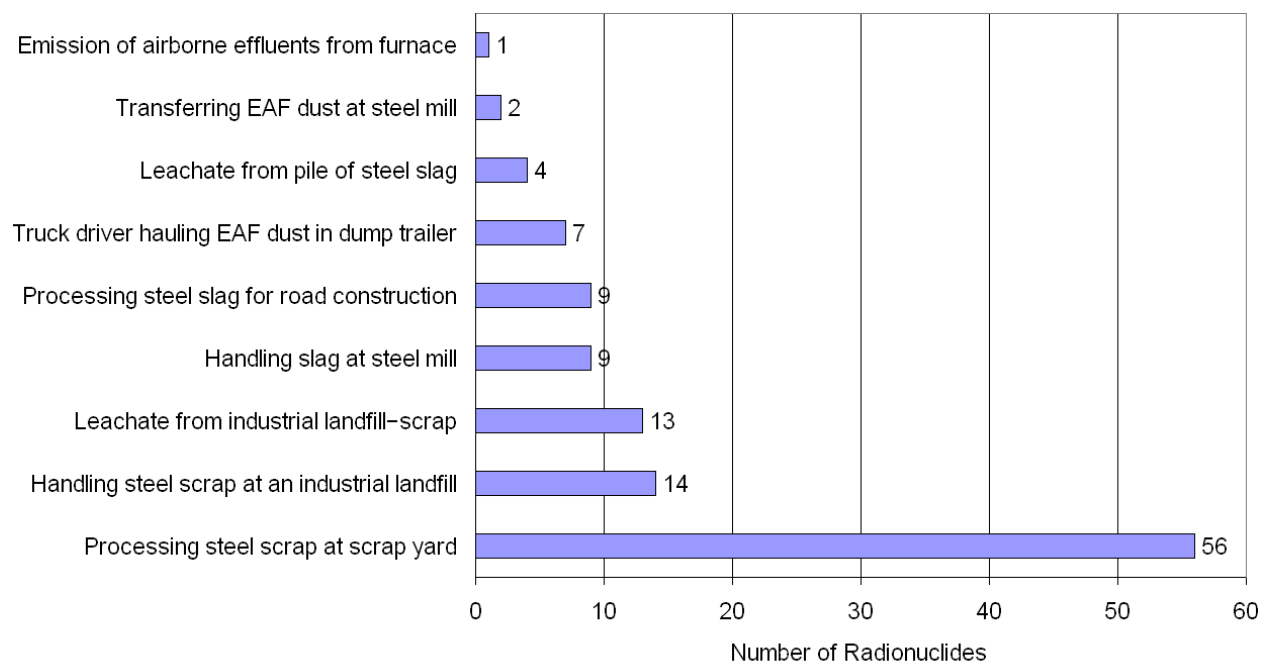


Figure 3.6 Scenarios giving rise to effective dose-critical groups for steel

Table 3.21 Normalized mass-based effective dose equivalents to critical groups for steel

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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	3.0e-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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.21 Normalized mass-based effective dose equivalents to critical groups for steel

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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
Tl-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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.21 Normalized mass-based effective dose equivalents to critical groups for steel

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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	6.1e+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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.22 Normalized surficial effective dose equivalents to critical groups for steel

Radionuclide	: Sv/y per Bq/cm ²				mrem/y per pCi/cm ²				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
H-3	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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.22 Normalized surficial effective dose equivalents to critical groups for steel

Radionuclide	: Sv/y per Bq/cm ²				mrem/y per pCi/cm ²				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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	1.6e-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	9.5e-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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.22 Normalized surficial effective dose equivalents to critical groups for steel

Radionuclide	: Sv/y per Bq/cm ²				mrem/y per pCi/cm ²				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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	5.6e+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-236	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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.23 Normalized mass-based effective doses to critical groups for steel

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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	9.0e-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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.23 Normalized mass-based effective doses to critical groups for steel

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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
Tl-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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.23 Normalized mass-based effective doses to critical groups for steel

Radionuclide	: Sv/y per Bq/g				mrem/y per pCi/g				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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	3.8e+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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.24 Normalized surficial effective doses to critical groups for steel

Radionuclide	: Sv/y per Bq/cm ²				mrem/y per pCi/cm ²				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
H-3	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-56	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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.24 Normalized surficial effective doses to critical groups for steel

Radionuclide	: Sv/y per Bq/cm ²				mrem/y per pCi/cm ²				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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	4.6e-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

^a 5th percentile to 95th percentile = 90% confidence interval

Table 3.24 Normalized surficial effective doses to critical groups for steel

Radionuclide	: Sv/y per Bq/cm ²				mrem/y per pCi/cm ²				Scenario
	Mean	Percentile ^a			Mean	Percentile ^a			
		5 th	50 th	95 th		5 th	50 th	95 th	
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	3.6e-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

^a 5th percentile to 95th percentile = 90% confidence interval

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