ANL/EAD-3

RESRAD-RECYCLE: A COMPUTER MODEL FOR ANALYZING THE RADIOLOGICAL DOSES AND RISKS RESULTING FROM THE RECYCLING OF RADIOACTIVE SCRAP METAL AND THE REUSE OF SURFACE-CONTAMINATED MATERIAL AND EQUIPMENT

Environmental Assessment Division

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The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in this document. Acronyms used only in tables or equations are defined in the respective tables or equations.

ABBREVIATIONS

CEC	Commission of the European Communities
DCF	dose-equivalent conversion factor
DOE	U.S. Department of Energy
EAF	electric arc furnace
EPA	U.S. Environmental Protection Agency
FGR	Federal Guidance Report
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ISCORS	Interagency Steering Committee on Radiation Standards
MEI	maximally exposed individual
NORM	naturally occurring radioactive material
NRC	U.S. Nuclear Regulatory Commission
OECD	Organization for Economic Cooperation and Development
SAIC	Science Applications International Corporation

UNITS OF MEASURE

Bq	becquerel(s)
cm	centimeter(s)
cm^2	square centimeter(s)
g	gram(s)
g/cm^3	gram(s) per cubic centimeter
g/m^3	gram(s) per cubic meter
h	hour(s)
in.	inch(es)
K	degree(s) Kelvin
kg	kilogram(s)
km	kilometer(s)
km^2	square kilometer(s)
km/h	kilometer(s) per hour
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
MB	megabyte(s)
mm	millimeter(s)
pCi	picocurie(s)
Sv	sievert(s)
t	metric ton(s)
yr	year(s)

ACKNOWLEDGMENTS

Since 1992, the RESRAD-RECYCLE code has undergone beta testing. During that time, approximately 10 training workshops were conducted on the methodology and use of the code. Many workshop participants and RESRAD-RECYCLE users have provided useful comments and thoughtful suggestions that have led to the release of an improved version of the code — RESRAD-RECYLE Version 3.0. The code is currently being applied in an international validation project that uses real measurement data.

We are grateful to William Murphie of the U.S. Department of Energy for his support of the international validation project. We also express our appreciation to Patricia Hollopeter and Margaret Clemmons of Argonne National Laboratory for their editorial assistance in preparing this document for publication.

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ABSTRACT

The RESRAD-RECYCLE computer code is a pathway analysis tool designed to calculate potential radiation doses and risks resulting from the recycling of radioactive scrap metal and the reuse of surface-contaminated material and equipment. RESRAD-RECYCLE is a member of the RESRAD family of codes developed by Argonne National Laboratory to assess dose and risk from decontamination, decommissioning, and remediation activities. RESRAD-RECYCLE applies the latest methodology and modeling parameters to provide a comprehensive risk analysis of the entire material recycling process. For modeling purposes, this process is divided into six steps: scrap delivery, scrap smelting, ingot delivery, product fabrication, product distribution, and use of the finished products. In addition, RESRAD-RECYCLE also considers reuse of the contaminated material in its original form. RESRAD-RECYCLE addresses short-term and lifetime risks for both workers and users of finished products and incorporates representative steps and scenarios that are significant in the recycling process. The code assesses individual and collective population risks for workers and the public and facilitates the derivation of release limits and standards. RESRAD-RECYCLE is a user-friendly, menu-driven, interactive code that can be run on an IBM-compatible personal computer under a Windows™ environment. The code accounts for decay and ingrowth of radionuclides, dilution of scrap metal, radionuclide and mass partitioning factors during the smelting operations, and the distribution of metal mass in the various consumer products, as well as the varying densities and geometries of the radiation sources. The structure of the code allows a complete material flow balance in terms of mass and radioactivity

during the recycling process. Individual, collective, and cumulative committed effective dose equivalents and risks are tabulated on the basis of the scenario, pathway, and radionuclide. The code uses the most up-to-date data and information from recent studies of metal recycling. The code also can perform probabilistic analysis for estimating the statistical distribution of radiation doses and risks that result from uncertainties of the parameters applied in the calculations.

1 INTRODUCTION

1.1 RESRAD-RECYCLE AND THE RESRAD FAMILY OF CODES

RESRAD-RECYCLE is a member of the RESRAD family of computer codes developed to assess doses and risks from decontamination, decommissioning, and remediation activities involving radioactive and other hazardous materials. The RESRAD family consists of the RESRAD code (Yu et al. 1993a) and the six subcodes shown in Figure 1.1. The RESRAD code was designed to estimate potential radiation exposures from a radioactively contaminated site and to derive soil cleanup criteria, whereas the RESRAD subcodes were developed to address other specific contamination issues. For example, RESRAD-CHEM addresses chemically contaminated sites and the corresponding chemical risks. These subcodes are currently in various stages of development and are available for use in risk assessments or for testing and evaluation.

RESRAD-RECYCLE addresses the recycling and reuse of radioactively contaminated materials, such as scrap metals and equipment. While this subcode focuses on the recycling process and its associated radiation exposures, other members of the RESRAD family of codes can be used for conducting a risk analysis of related issues. For example, the RESRAD code can be used for evaluating the risks associated with the disposal of recycled materials, and RESRAD-BUILD can be used for performing a detailed analysis of potential risks resulting from the use of buildings constructed with recycled materials. Although RESRAD-RECYCLE implements specific methodologies for the recycling process, the database of dose-equivalent conversion factors (DCFs) and the mathematical models for external exposure are consistent with those used by the other codes within the RESRAD family.

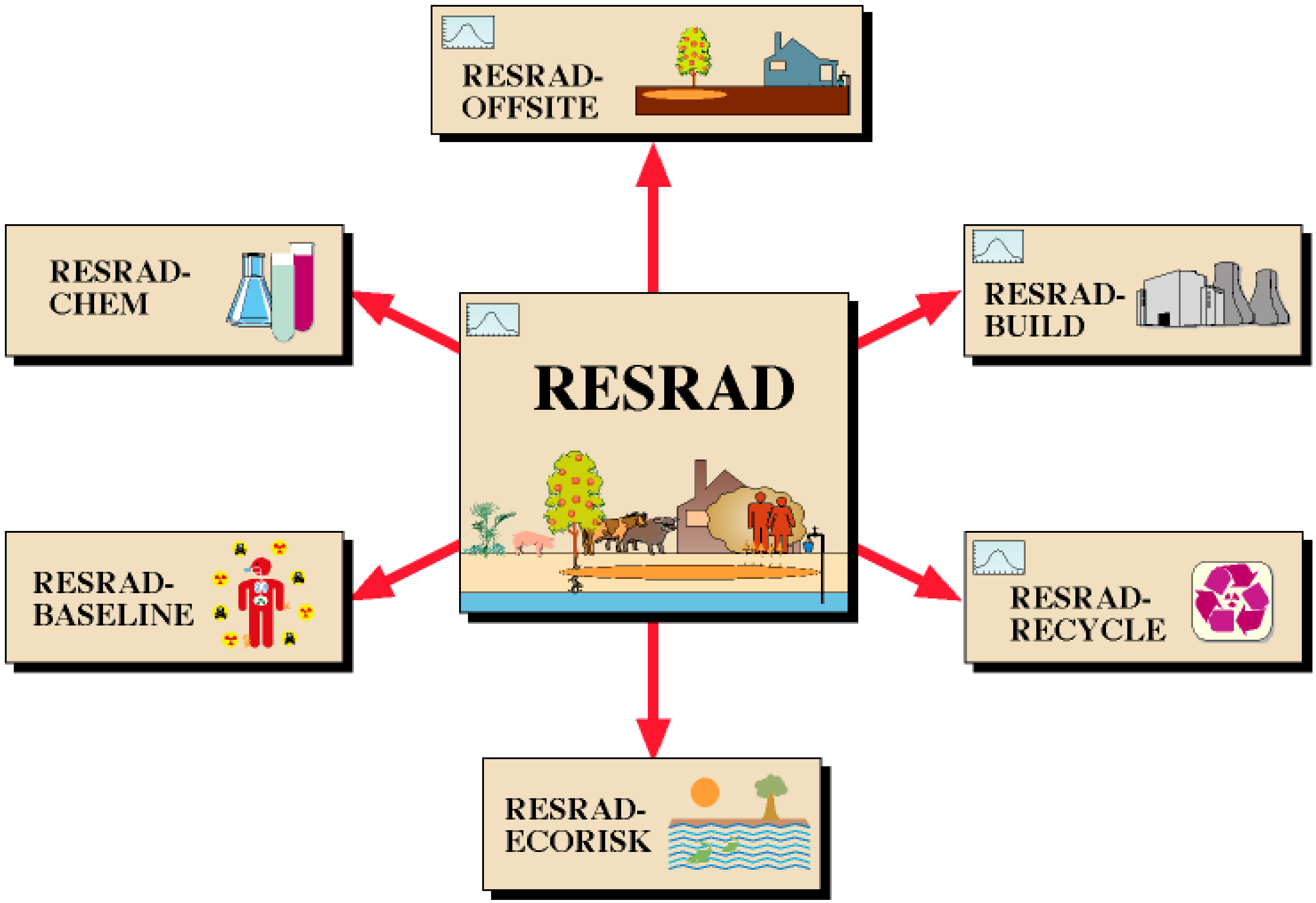

FIGURE 1.1 The RESRAD Family of Codes

1.2 THE RECYCLING ISSUE

The issue of assessing the risks associated with the recycling of radioactively contaminated materials is complicated by the need to consider the many steps in the recycling process that can lead to radiation exposure of various receptors. This document is not intended to provide an in-depth discussion of the complex steps involved in the recycling process; rather, it is intended to describe a computational tool that can be used for evaluating the potential risks resulting from the recycling process. Detailed discussions of the steps involved in the recycling process are provided in several studies, including those by Science Applications International Corporation (SAIC 1994, 1998), S. Cohen and Associates (1995), Nieves et al. (1995), the Organization for Economic Cooperation and Development (OECD 1994), the International Atomic Energy Agency (IAEA 1992), Kennedy and Strenge (1992), the Commission of the European Communities (CEC 1988), and O'Donnell et al. (1978).

Various degrees of restriction could be involved in the reuse of radioactively contaminated materials. Such restrictions could determine the types of final products of these contaminated materials and the potential receptors of radiation exposures. Figure 1.2 is a simplified overview of the conceptual recycling process with different release restrictions. In general, the reuse of radioactively contaminated materials can be classified into four categories:

- *Direct reuse* involves the reuse of contaminated materials and equipment in their original forms. Therefore, the contaminated materials are not smelted. Materials and equipment that can be reused directly typically include machinery and measurement tools, office furniture, and decommissioned buildings.

- *Unrestricted reuse* involves the recycling of contaminated materials and their release to commercial smelters for production of such consumer products as automobiles, frying pans, and beverage cans.

- *Restricted reuse* involves the release of contaminated materials to a radiologically licensed smelter for manufacturing of specific products that would minimize public exposure (e.g., manufacturing slag for use in road pavement or steel for use in bridge construction). This category usually

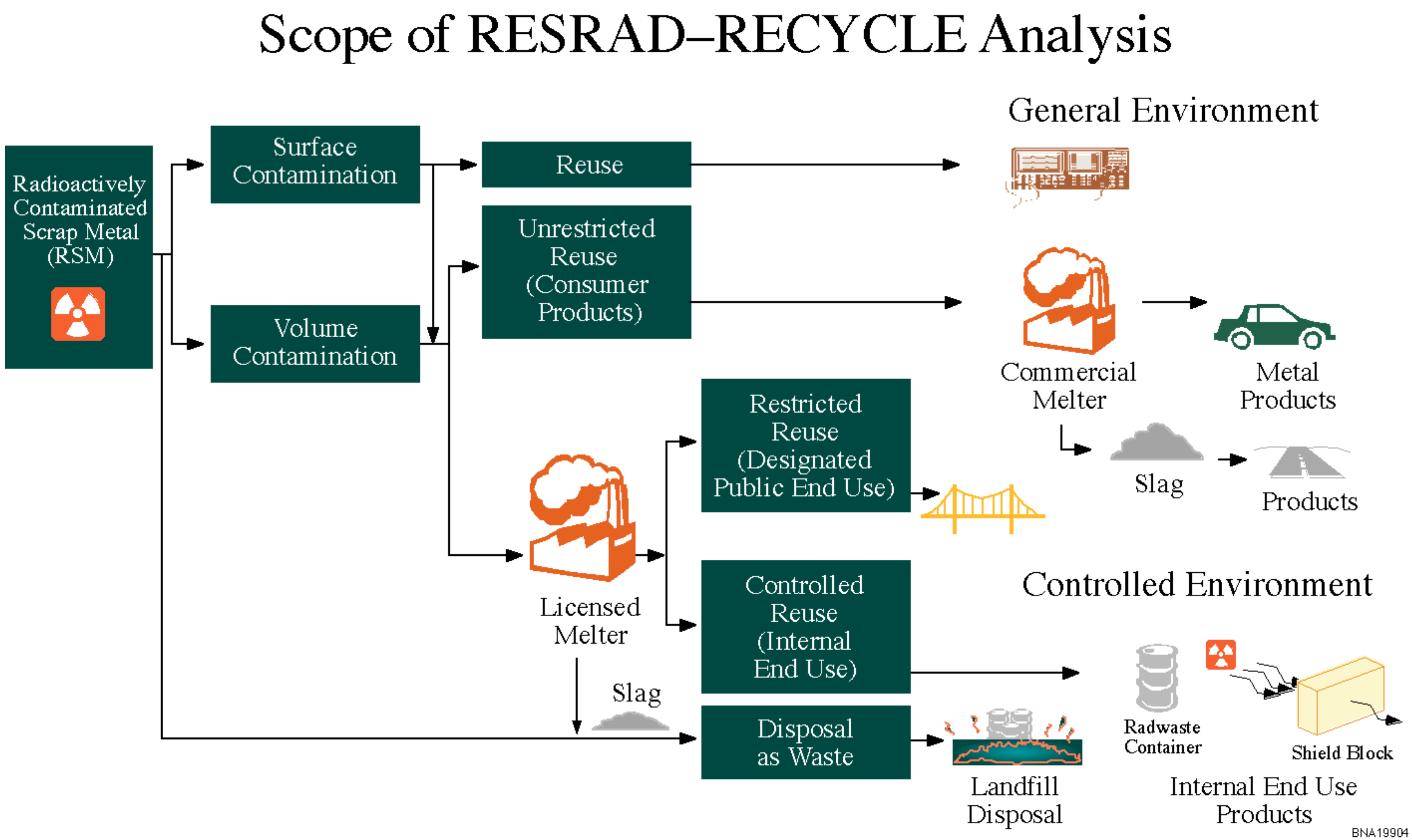

FIGURE 1.2 A Conceptual Diagram of the Recycling Process

involves large quantities of materials contaminated with relatively short-lived radionuclides that are reused as public products when the radioactivity in them has decayed significantly. The public products manufactured with contaminated materials of this category would not be released to the commercial market until the end of the radionuclide lifetimes.

- *Controlled reuse* usually involves contaminated materials from the nuclear industry and other regulated facilities. Materials from these facilities could be contaminated with long-lived radionuclides that have the potential for emitting high levels of radiation and causing a greater health concern; therefore, reuse of these materials is restricted to avoid public access and exposures. The recycling of these materials and other related issues have been the focus of the U.S. Department of Energy (DOE) Recycle 2000 initiative (Warren 1995).

1.3 EVALUATION OF EXISTING COMPUTER CODES

Several computer codes have been designed for assessing potential radiation doses that result from the reuse of radioactively contaminated scrap metals; however, these codes do not provide a comprehensive analysis of the recycling process. For example, CONDOS is limited to uranium- and thorium-contaminated materials (O'Donnell et al. 1975); CONDOS-II is an updated and expanded version of CONDOS and considers 46 radionuclides (O'Donnell et al. 1981). IMPACT-BRC is based on CONDOS and includes a disposal scenario (Oztunali and Roles 1984). These codes can evaluate only one exposure scenario at a time. Moreover, they use outdated DCFs and do not calculate health risks or analyze uncertainties.

The U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (NRC) have recently developed spreadsheets and computer codes for evaluating the recycling of contaminated materials (SAIC 1998; S. Cohen and Associates 1997). These spreadsheets and computer codes are not designed for general public use and consequently lack flexibility and a user-friendly interface.

1.4 OBJECTIVES AND GENERAL FEATURES OF RESRAD-RECYCLE

RESRAD-RECYCLE is a computer tool designed to provide a comprehensive assessment of radiation doses and risks associated with the recycling and reuse of radioactively contaminated materials. It considers the significant and representative steps involved in the recycling and manufacturing process and incorporates representative exposure scenarios for each step. Both short-term (one year) and long-term (the lifetime of a specific product) risks to recycling workers and users of the end products are calculated. The risks for individuals are calculated, as well as those for collective populations. A ranking routine has been incorporated to sort the exposure scenarios according to the magnitude of individual and collective exposures, respectively. The results of RESRAD-RECYCLE can be compared with target radiation protection limits, thereby facilitating the derivation of regulatory standards and limits for the release and reuse of radioactively contaminated materials. The code is based on the latest methodologies and incorporates parameters from current studies and publications.

RESRAD-RECYCLE is sufficiently flexible to allow modification of exposure parameters for developing user-specified scenarios. It is also capable of performing probabilistic analysis for investigating the statistical distributions of potential doses and risks. Its user-friendly interface facilitates data entry, code execution, and results viewing. A comprehensive on-line help capability is available to guide users through the code.

1.5 SCOPE OF RESRAD-RECYCLE

RESRAD-RECYCLE assesses potential radiation exposures from the entire recycling process on the basis of the various reuse restrictions discussed in Section 1.2. Figure 1.3 shows the main screen of the code, which consists of the major components of the code. For modeling purposes, the recycling process is divided into six representative steps: (1) scrap delivery, (2) scrap smelting, (3) ingot delivery, (4) product fabrication, (5) product distribution, and (6) use of the finished products. For each of the first five steps, scenarios were developed to consider potential exposures for the workers involved, such as material loaders, drivers, processors, and casters. Exposure scenarios for use of the finished products include use of a parking lot, rooms and offices, household appliances, automobiles, ships and boats, frying pans, beverage cans, office furniture, home furniture, road pavement, public buildings, and a bridge. In addition to scenarios considering exposures from the recycling process and use of the finished

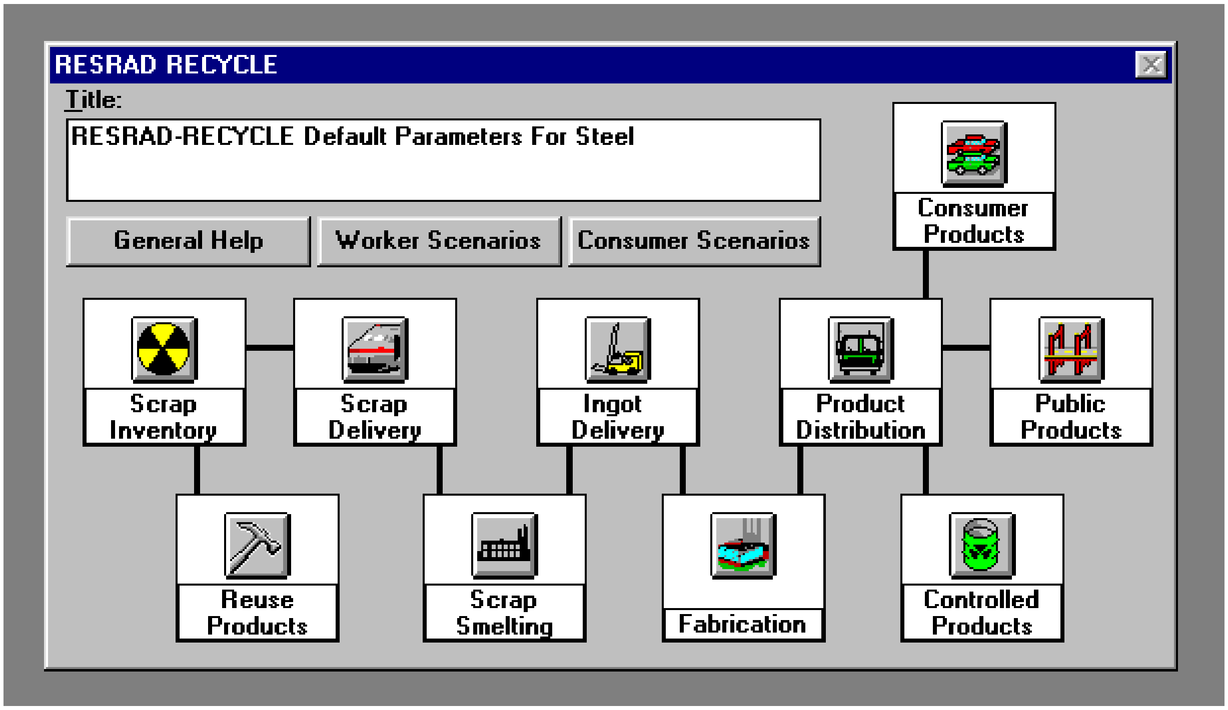

FIGURE 1.3 Scope of RESRAD-RECYCLE

products, scenarios considering exposures from direct reuse of such surface-contaminated materials as machinery tools and decommissioned buildings are included. In addition to these default scenarios, other scenarios can be created by selecting a default scenario and then modifying the exposure parameters to reflect the exposure conditions of the specific scenario.

The RESRAD-RECYCLE code considers 54 radionuclides pertinent to the recycling process for dose and risk assessment. Several exposure pathways — external radiation, inhalation, and incidental ingestion — are considered.

RESRAD-RECYCLE accounts for decay and ingrowth of radionuclides, dilution of scrap metal, partitioning of radionuclides during the melting process, and mass distribution of metal in the various consumer products. Text reports tabulate individual, collective, and cumulative effective dose equivalents and risks by scenario, pathway, and radionuclide. Graphic output shows the calculation results in bar charts and pie charts, which facilitate visual comparisons of doses and risks from different pathways and radionuclides.

1.6 ORGANIZATION OF THIS DOCUMENT

Features of the RESRAD-RECYCLE code and its use are described in detail in this document. Exposure scenarios included in the code for workers and users of finished products are described in Section 2. Section 3 describes the methodology used in the code. A user's guide for installing and applying the various features of the code is provided in Section 4. Section 5 discusses benchmarking and validation of the RESRAD-RECYCLE code with other recent studies. Section 6 lists the references cited in the report.

1.7 TECHNICAL SUPPORT

For technical support and assistance with regard to questions not addressed in this document, contact:

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2 DESCRIPTION OF SCENARIOS

For dose assessment purposes, representative exposure scenarios were developed for each of the six recycling process steps: (1) scrap delivery, (2) scrap smelting, (3) ingot delivery, (4) product fabrication, (5) product distribution, and (6) use of the finished products. In general, the scenarios are based on information from recent publications, including SAIC (1994, 1998), Nieves et al. (1995), S. Cohen and Associates (1995), OECD (1994), IAEA (1992), Kennedy and Strenge (1992), CEC (1988), and O'Donnell et al. (1978). Two general types of exposure scenarios have been incorporated into RESRAD-RECYCLE: (1) worker scenarios for evaluating the dose and risk to workers who process recycled materials and (2) end-use product scenarios for evaluating the dose and risk to persons using or otherwise being exposed to products made from recycled radioactive materials. The worker scenarios model potential exposures associated with (1) the transport of radioactive scrap metal from the place of origin to the smelter (step 1, scrap delivery), (2) the smelting process and manufacture of metal ingots for industrial products (step 2, scrap smelting), (3) transport of metal ingots to product fabrication plants (step 3, ingot delivery), (4) product fabrication (step 4, initial and final fabrications) and (5) product distribution (step 5, product distribution). End-use product scenarios model the use of finished products or facilities, including (1) consumer products, (2) public products (pavement, bridges, and buildings), (3) controlled products (shielding blocks and radioactive waste containers), and (4) surface-contaminated reuse products (tools and decontaminated buildings). In addition to the worker and end-use product scenarios, potential radiation exposures of the public from the transport of radioactive scrap metals are also considered and discussed in the transportation scenario. A total of 41 scenarios are included in RESRAD-RECYCLE. Of these, 35 apply to both steel and aluminum; 3 apply only to steel, and 3 apply only to aluminum. Table 2.1 summarizes the scenarios included in the code.

Exposure scenarios that can be modeled by RESRAD-RECYCLE are not restricted to the representative default scenarios included in the code. New scenarios can be created by selecting a default scenario, modifying the exposure parameters, and constructing a geometry for the radiation sources that reflects the appropriate exposure conditions.

TABLE 2.1 RESRAD-RECYCLE Scenarios Applicable to Steel and Aluminum

	Applicability to Metal	
Scenario Description	Steel	Aluminum
Worker scenarios		
Scrap delivery: scrap cutter	Yes	Yes
Scrap delivery: scrap loader	Yes	Yes
Scrap delivery: scrap truck driver	Yes	Yes
Scrap smelting: scrap processor	Yes	Yes
Scrap smelting: smelter yard worker	Yes	Yes
Scrap smelting: smelter loader	Yes	Yes
Scrap smelting: furnace operator	Yes	Yes
Scrap smelting: baghouse processor	Yes	Yes
Scrap smelting: refinery worker	Yes	Yes
Scrap smelting: ingot caster	Yes	Yes
Scrap smelting: small object caster	Yes	Yes
Scrap smelting: slag worker	Yes	Yes
Ingot delivery: ingot loader	Yes	Yes
Ingot delivery: ingot truck driver	Yes	Yes
Initial fabrication: storage yard worker	Yes	Yes
Initial fabrication: sheet maker	Yes	Yes
Initial fabrication: coil maker	Yes	Yes
Final fabrication: sheet handler	Yes	Yes
Final fabrication: coil handler	Yes	Yes
Product distribution: product loader	Yes	Yes
Product distribution: product truck driver	Yes	Yes
Product distribution: sheet assembler	Yes	Yes
Product distribution: warehouse worker	Yes	Yes
End-use product scenarios		
Consumer product: parking lot	Yes	Yes
Consumer product: room/office and house siding	Yes	Yes
Consumer product: appliance	Yes	Yes
Consumer product: automobile	Yes	Yes
Consumer product: ship/boat	No	Yes
Consumer product: office furniture	Yes	Yes
Consumer product: home furniture	Yes	Yes
Consumer product: frying pan	Yes	Yes
Consumer product: beverage can	No	Yes
Public product: pavement	Yes	Yes
Public product: building with rebars	Yes	No
Public product: building with geodesic dome	No	Yes
Public product: bridge	Yes	Yes
Controlled product: shielding block	Yes	No
Controlled product: radwaste container	Yes	No
Reuse product scenarios		
Reuse product: tool reuse	Yes	Yes
Reuse product: building reuse	Yes	Yes
Transportation scenario		
Scrap transportation: public exposure	Yes	Yes

2.1 WORKER SCENARIOS

The worker scenarios considered under each recycling step are described in the following sections. Default values for the exposure duration and the number of individuals involved in every step are provided. These values are based on processing 100 metric tons (t) of scrap metal per year. Tables 2.2 and 2.3 summarize the modeling parameters of all worker scenarios for steel and aluminum scrap, respectively.

2.1.1 Scrap Delivery Step

Scenarios for three different workers are included under the scrap delivery step: a scrap cutter, a scrap loader, and a scrap truck driver. The default values for each scenario are specified on the basis of processing 100 t of scrap metal. Because these operations occur before the metal is melted, mass and radionuclide partitioning factors (see Section 3) are not applied in the scrap delivery step. The radionuclide concentration of the scrap metal is used directly in the dose calculation.

For steel scrap, an average density of 3.93 g/cm^3 is assumed. For aluminum scrap, an average density of 1.4 g/cm^3 is assumed. A smaller density than that of a solid metal is used to account for air voids and the bulky nature of the scrap. The individual scenarios included in this step are discussed below. (Public exposure from the transport of scrap metal is discussed in Section 2.6.)

2.1.1.1 Scrap Cutter Scenario

The scrap cutter scenario models a worker who prepares the scrap for delivery to the smelter. This worker’s activities include shredding, cutting, smashing, chopping, bailing, and banding the scrap metal.

It is estimated that 3 individuals would each have to work 12 hours to process 100 t of steel scrap. The exposure pathways assumed for this scenario include external exposure, ingestion and inhalation of airborne particulates from the cutting process, and incidental ingestion of particulates that attach to the hands during the cutting process. The default for the

TABLE 2.2 Default Parameters Used to Model Worker Scenarios in RESRAD-RECYCLE for Steel

Recycle Step	Scenario	Source Geometry	Mass (t)	Density (g/cm^3)	Thickness (cm)	Radius (cm)	Distance (cm)	Time (h)	Medium Concentration Used for the External Pathway[a]	Medium Concentration Used for the Internal Pathway[b]	Default Internal Pathway[c]	Dust Loading (g/m^3)	Number of Workers
Scrap delivery	Scrap cutter	1 half cylinder	0.50	3.93	90	30	200	12	Scrap	Scrap	inh, ing	5×10^{-4}	3
	Scrap loader	1 half cylinder	25	3.93	253	127	400	4	Scrap	Scrap	inh, ing	5×10^{-4}	2
	Scrap truck driver	1 half cylinder	20	3.93	900	60	200	4	Scrap	Scrap	None	0	5
Scrap smelting	Scrap processor	1 half cylinder	0.50	5.90	60	30	200	12	Scrap	Scrap	inh, ing	1×10^{-4}	3
	Smelter yard worker	1 half cylinder	100	5.90	351	175	1,000	80	Scrap	Scrap	inh, ing	1×10^{-4}	10
	Smelter loader	1 half cylinder	50	5.90	279	139	400	4	Scrap	Baghouse	inh, ing	1×10^{-3}	5
	Furnace operator	1 full cylinder	100	7.86	253	127	300	5	Scrap	Baghouse	inh, ing	1×10^{-3}	3
	Baghouse processor	1 full cylinder	1.0	2.00	100	40	200	1	Baghouse	Baghouse	inh, ing	1×10^{-3}	1
	Refinery worker	1 full cylinder	90	7.86	228	127	300	5	Ingot	Baghouse	inh, ing	1×10^{-3}	3
	Ingot caster	1 full cylinder	10	7.86	100	64	150	2.5	Ingot	Ingot	inh, ing	1×10^{-3}	2
	Small object caster	1 full cylinder	1.0	7.86	1	201	100	50	Ingot	Ingot	inh, ing	1×10^{-3}	2
	Slag worker	1 half cylinder	10	2.70	45.5	228	150	25	Slag	Slag	inh, ing	1×10^{-3}	1
Ingot delivery	Ingot loader	1 half cylinder	50	7.86	100	201	400	2	Ingot	Ingot	None	0	2
	Ingot truck driver	1 full cylinder	20	7.86	200	64	200	5	Ingot	Ingot	None	0	5
Initial fabrication	Storage yard worker	1 half cylinder	50	7.86	100	201	1,000	40	Ingot	Ingot	None	0	10
	Sheet maker	1 half cylinder	0.047	7.86	0.2	138	100	1	Ingot	Ingot	inh, ing	1×10^{-4}	15
	Coil maker	1 full cylinder	10	7.86	122	58	150	1	Ingot	Ingot	inh, ing	1×10^{-4}	1
Final fabrication	Sheet handler	1 half cylinder	0.047	7.86	0.2	138	100	1	Ingot	Ingot	None	0	20
	Coil handler	1 full cylinder	10	7.86	122	58	150	80	Ingot	Ingot	None	0	5
Product distribution	Product loader	1 half cylinder	50	7.86	100	201	400	20	Ingot	Ingot	None	0	2
	Product truck driver	1 full cylinder	20	7.86	200	64	200	8	Ingot	Ingot	None	0	5
	Sheet assembler	1 half cylinder	0.047	7.86	0.2	138	100	20	Ingot	Ingot	None	0	20
	Warehouse worker	1 half cylinder	0.28	7.86	1.2	138	600	2,000	Ingot	Ingot	None	0	5

[a] Radionuclide concentrations in ingot, slag, or baghouse are calculated by using the corresponding mass and radionuclide partitioning factors.

[b] The medium is either the material handled by a worker or the material from which airborne dust particles originate. Concentrations in the medium are calculated by using the corresponding mass and radionuclide partitioning factors. The medium concentration, multiplied by the dust loading factor, gives the concentration of radionuclides in air.

[c] If by default no internal pathway is considered, "none" is listed. However, the user can elect to consider the internal pathways. In that case, radionuclide concentrations in the air are calculated by using the medium concentrations listed in the column immediately to the left. Here, "inh" denotes inhalation and "ing" denotes ingestion.

TABLE 2.3 Default Parameters Used to Model Worker Scenarios in RESRAD-RECYCLE for Aluminum

Recycle Step	Scenario	Source Geometry	Mass (t)	Density (g/cm³)	Thickness (cm)	Radius (cm)	Distance (cm)	Time (h)	Medium Concentration for the External Pathway[a]	Medium Concentration for the Internal Pathway[b]	Default Internal Pathway[c]	Dust Loading (g/m³)	Number of Workers
Scrap delivery	Scrap cutter	1 half cylinder	0.50	1.4	90	50	200	12	Scrap	Scrap	inh, ing	5×10^{-4}	3
	Scrap loader	1 half cylinder	25	1.4	253	213	400	4	Scrap	Scrap	inh, ing	5×10^{-4}	2
	Scrap truck driver	1 half cylinder	20	1.4	900	101	200	4	Scrap	Scrap	None	0	5
Scrap smelting	Scrap processor	1 half cylinder	0.50	2.03	60	51	200	12	Scrap	Scrap	inh, ing	1×10^{-4}	3
	Smelter yard worker	1 half cylinder	100	2.03	351	298	1,000	80	Scrap	Scrap	inh, ing	1×10^{-4}	10
	Smelter loader	1 half cylinder	5	2.03	200	88	400	20	Scrap	Baghouse	inh, ing	1×10^{-3}	5
	Furnace operator	1 full cylinder	10	2.7	170	83	300	50	Scrap	Baghouse	inh, ing	1×10^{-3}	3
	Baghouse processor	1 full cylinder	0.5	1.4	100	34	200	3	Baghouse	Baghouse	inh, ing	1×10^{-3}	1
	Refinery worker	1 full cylinder	10	2.7	150	89	300	14	Ingot	Baghouse	inh, ing	$1 \text{ x } 10^{-4}$	3
	Ingot caster	1 full cylinder	2	2.7	100	48	150	17.5	Ingot	Ingot	inh, ing	1×10^{-3}	2
	Small object caster	1 full cylinder	0.3	2.7	1	188	100	50	Ingot	Ingot	inh, ing	1×10^{-3}	2
	Slag worker	1 half cylinder	6.4	2.0	45	213	150	50	Slag	Slag	inh, ing	1×10^{-3}	1
Ingot delivery	Ingot loader	1 half cylinder	50	2.7	200	242	400	2	Ingot	Ingot	None	0	2
	Ingot truck driver	1 full cylinder	20	2.7	230	100	200	5	Ingot	Ingot	None	0	5
Initial fabrication	Storage yard worker	1 half cylinder	50	2.7	100	343	1,000	40	Ingot	Ingot	None	0	10
	Sheet maker	1 half cylinder	0.016	2.7	0.2	138	100	2	Ingot	Ingot	inh, ing	1×10^{-4}	15
	Coil maker	1 full cylinder	5	2.7	122	70	150	2	Ingot	Ingot	inh, ing	1×10^{-4}	1
Final fabrication	Sheet handler	1 half cylinder	0.016	2.7	0.2	138	100	2	Ingot	Ingot	None	0	20
	Coil handler	1 full cylinder	5	2.7	122	70	150	80	Ingot	Ingot	None	0	5
Product distribution	Product loader	1 half cylinder	50	2.7	200	242	400	20	Ingot	Ingot	None	0	2
	Product truck driver	1 full cylinder	20	2.7	230	100	200	8	Ingot	Ingot	None	0	5
	Sheet assembler	1 half cylinder	0.016	2.7	0.2	138	100	20	Ingot	Ingot	None	0	20
	Warehouse worker	1 half cylinder	0.1	2.7	1.2	138	600	2000	Ingot	Ingot	None	0	5

[a] Radionuclide concentrations in ingot, slag, or baghouse are calculated by using the corresponding mass and radionuclide partitioning factors.

[b] The medium is either the material handled by a worker or the material from which airborne dust particles originate. Concentrations in the medium are calculated by using the corresponding mass and radionuclide partitioning factors. The medium concentration multiplied by the dust loading factor, gives the concentration of radionuclides in air.

[c] If by default no internal pathway is considered, "none" is listed. However, the user can elect to consider the internal pathways. In that case, radionuclide concentrations in the air are calculated by using the medium concentrations listed in the column immediately to the left. Here, "inh" denotes inhalation and "ing" denotes ingestion.

source for the external exposure pathway is modeled as a 0.5-t half cylinder with a thickness of 90 cm, a radius of 30 cm, and a density of 3.93 g/cm^3. The average distance from the source is assumed to be 200 cm.

Aluminum scrap is not as dense (assumed to be 1.4 g/cm^3) as steel scrap. Therefore, the volume of aluminum scrap to be processed would be greater than that of steel scrap. It is estimated that 3 workers would each have to work 12 hours to process 100 t of aluminum scrap. In the default case, the scrap handled is modeled as a half cylinder with a thickness of 90 cm and a radius of 50 cm. The exposure pathways and exposure distance considered are the same as those for steel scrap.

2.1.1.2 Scrap Loader Scenario

The scrap loader scenario models the potential doses to a worker who loads the radioactively contaminated scrap metal onto trucks for transport to the smelter. Standard mechanical loading equipment would be used for this operation.

It is estimated that 2 individuals would each have to work 4 hours to load 100 t of scrap steel. The exposure pathways evaluated for this scenario include external exposure, ingestion and inhalation of airborne particulates, and ingestion of particulates attached to the hands. For the external exposure pathway, the steel source is modeled as a 25-t half cylinder with a thickness of 253 cm, a radius of 127 cm, and a density of 3.93 g/cm^3. The average distance from the source is assumed to be 400 cm.

For aluminum scrap, the number of workers, exposure duration, exposure distance, and exposure pathways considered in the default case are the same as those for steel scrap. The radiation source is modeled as a half cylinder with a thickness of 253 cm, a radius of 213 cm, and a density of 1.4 g/cm^3.

2.1.1.3 Scrap Truck Driver Scenario

The scrap truck driver scenario models the potential doses to a worker who transports contaminated scrap metal from the place of origin to the processing facility. It is estimated that 5 drivers would each incur an exposure duration of 4 hours to transport 100 t of steel scrap.

Because a driver would not be directly in contact with the radioactive scrap metal, the ingestion pathway is not included in this scenario. The inhalation pathway is not expected to be significant because the driver would be inside the truck cab and presumably would not be exposed to dust from the scrap metal. Thus, the only pathway considered in this scenario is external exposure.

For the external dose calculation, the source for steel is modeled as a 20-t half cylinder with a thickness of 900 cm, a radius of 60 cm, and a density of 3.93 g/cm^3. For aluminum scrap, the radiation source is modeled as a 20-t half cylinder with a thickness of 900 cm, a radius of 101 cm, and a density of 1.4 g/cm^3. The driver is assumed to be 200 cm from the source. For conservative purposes, the shielding from the truck cab is not taken into account.

2.1.2 Scrap Smelting Step

Scenarios for nine different workers are included under the scrap smelting step: a scrap processor, a smelter yard worker, a smelter loader, a furnace operator, a baghouse processor, a refinery worker, an ingot caster, a small object caster, and a slag worker. The default values for each scenario are specified on the basis of processing 100 t of scrap metal. Because these operations occur inside the smelting facility, mass and radionuclide partitioning factors (see Sections 3.4 and 3.5 for detailed discussions) are applied in the calculation of the external, inhalation, and ingestion doses. The individual scenarios included in this step are discussed below.

2.1.2.1 Scrap Processor Scenario

The scrap processor scenario models a worker who prepares the scrap for processing at the smelter. This individual's activities include shredding, cutting, smashing, chopping, bailing, and banding the scrap metal. It is estimated that 3 individuals would each have to work 12 hours to process 100 t of scrap metal. The exposure pathways considered for this scenario include external exposure, ingestion, and inhalation of airborne particulates.

For steel scrap, the radiation source is modeled as a 0.5-t half cylinder with a thickness of 60 cm, a radius of 30 cm, and a density of 5.9 g/cm^3. For aluminum scrap, the thickness of the half cylinder is 60 cm, the radius is 51 cm, and the density is 2.03 g/cm^3. The average distance of the processor from the source is assumed to be 200 cm.

2.1.2.2 Smelter Yard Worker Scenario

The smelter yard worker scenario models potential doses to an individual who works at the storage yard at the smelting facility. It is estimated that 10 workers would each have to work a total of 80 hours to process 100 t of scrap metal. The pathways evaluated for this scenario include external exposure, inhalation, and ingestion. The inhalation and ingestion pathways are considered because the worker would be in the vicinity of the smelting facility where radioactive air particulates could be present.

For steel scrap, the radiation source is modeled as a 100-t half cylinder with a thickness of 351 cm, a radius of 175 cm, and a density of 5.9 g/cm^3. For aluminum scrap, the source is a 100-t half cylinder with a thickness of 351 cm, a radius of 298 cm, and a density of 2.03 g/cm^3. The yard worker is assumed to be 1,000 cm from the radiation source.

2.1.2.3 Smelter Loader Scenario

The smelter loader scenario models the potential doses to a crane operator who loads scrap metal into the furnace. The pathways evaluated for this scenario include external exposure, inhalation, and ingestion. For steel scrap, the furnace is assumed to have a capacity of 100 t; for aluminum scrap, the capacity of the furnace is assumed to be 10 t. It is estimated that 5 workers would each have to work a total of 4 hours to process 100 t of steel scrap. It is estimated that 5 workers would each have to work a total of 20 hours to process 100 t of aluminum scrap.

For steel scrap, the radiation source is modeled as a 50-t half cylinder with a thickness of 279 cm, a radius of 139 cm, and a density of 5.9 g/cm^3. For aluminum scrap, the radiation source is a 5-t half cylinder with a thickness of 200 cm, a radius of 88 cm, and a density of 2.03 g/cm^3. The loader is assumed to work at a distance of 400 cm from the radiation source.

2.1.2.4 Furnace Operator Scenario

The furnace operator scenario models the potential doses to an individual who operates the furnace. The capacity of the furnace is assumed to be 100 t for steel and 10 t for aluminum. It is estimated that 3 operators would each have to work a total of 5 hours to melt 100 t of steel scrap. To process the same amount of aluminum scrap, it is estimated that 3 operators would each have to work 50 hours. The pathways evaluated for this scenario include external exposure, inhalation, and ingestion.

For steel scrap, the furnace is modeled as a 100-t full cylinder with a thickness of 253 cm, a radius of 127 cm, and a density of 7.86 g/cm^3. For aluminum scrap, the furnace is modeled as a 10-t full cylinder with a thickness of 170 cm, a radius of 83 cm, and a density of 2.7 g/cm^3. The operator is assumed to work 300 cm from the source.

2.1.2.5 Baghouse Processor Scenario

The baghouse processor scenario models the potential doses to an individual who handles the baghouse contents. The processor loads the baghouse contents into special dust bags. It is assumed that the contents of the baghouse have been sprayed with water to reduce dust inhalation before loading. The loaded dust bags are transported to a storage or processing area. The number of dust bags to be processed is a function of furnace throughput and the mass partitioning factor of the baghouse. The amount of dust collected in the baghouse can range from 0.2 to 2% of the throughput mass. Because of this mass partitioning during smelting, the radionuclide concentration in the baghouse dust could be higher than that in the radioactive scrap metal. The external exposure, inhalation, and ingestion pathways are included in the dose assessment for this scenario.

The radiation source for steel is modeled as a 1-t full cylinder with a thickness of 100 cm, a radius of 40 cm, and a density of 2.0 g/cm^3. It is estimated that one processor would have to spend a total of 1 hour processing dust bags generated by the smelting of 100 t of steel scrap. The radiation source for aluminum is modeled as a 0.5-t full cylinder with a thickness of 100 cm, a radius of 34 cm, and a density of 1.4 g/cm^3. The baghouse processor is assumed to spend 3 hours processing the contaminated dust bags. The exposure distance is assumed to be 200 cm.

2.1.2.6 Refinery Worker Scenario

Depending on quality requirements for the final products, the metal melt from the smelting process could need further refinement. It is assumed that the refinement would not result in substantial loss of the metal; therefore, additional mass and radionuclide partitioning factors are not applied.

It is estimated that 3 workers would each have to work 5 hours to process 90 t of steel (a mass partitioning factor of 90% to melt). The radiation source is modeled as a 90-t cylinder, with a thickness of 228 cm, a radius of 127 cm, and a density of 7.86 g/cm^3. The radiation source for aluminum is modeled as a 10-t full cylinder with a thickness of 150 cm, a radius of 89 cm, and a density of 2.7 g/cm^3. It is estimated that 3 workers would each have to work 14 hours to process a total of 70 t of aluminum (a mass partitioning factor of 70% to melt). The refinery worker is assumed to work at a distance of 300 cm from the source.

2.1.2.7 Ingot Caster Scenario

The ingot caster scenario models potential doses to a worker casting metal ingots. The external exposure, inhalation, and ingestion pathways are included in the dose assessment for this scenario. For the external exposure calculation, the steel ingot is modeled as a 10-t full cylinder with a thickness of 100 cm, a radius of 64 cm, and a density of 7.86 g/cm^3. It is estimated that two casters would spend 2.5 hours each casting steel ingots at a distance of 150 cm. Aluminum ingot is modeled as a 2-t full cylinder with a thickness of 100 cm, a radius of 48 cm, and a density of 2.7 g/cm^3. Two workers would have to work a total of 17.5 hours each casting aluminum ingots at a distance of 150 cm.

2.1.2.8 Small Object Caster Scenario

The small object caster scenario models the potential doses to a worker casting small objects at the smelting facility for use in industrial and consumer products. The external exposure, inhalation, and ingestion pathways are included in the dose assessment for this scenario. The radiation source for steel is modeled as a 1-t full cylinder with a thickness of 1 cm, a radius of 201 cm, and a density of 7.86 g/cm^3. It is estimated that 2 casters would each have to spend about 50 hours to process 90 t of steel. The radiation source for aluminum is modeled as a 0.3-t full cylinder with a thickness of 1 cm, a radius of 188 cm, and a density of 2.7 g/cm^3. It is estimated that 2 casters would each have to work 50 hours to cast 70 t of aluminum into small objects. The caster is assumed to work at a distance of 100 cm from the source.

2.1.2.9 Slag Worker Scenario

The slag worker scenario models the potential doses to a worker who uses standard loading and unloading equipment to handle the slag product at the smelting facility. After it cools, the slag is typically a glassy solid material. The amount of slag generated would depend on the smelting process and the use of slag forming agents. The mass partitioning factor to slag for steel is assumed to be 10% of the smelting throughput and 30% of the throughput for aluminum because aluminum oxidizes much more easily than steel. Because of this mass partitioning during smelting, the radionuclide concentration in the slag may be higher than that in the scrap metal. The pathways evaluated for the slag worker include external exposure, inhalation, and ingestion.

For steel, the slag handled is modeled as a 10-t half cylinder with a thickness of 45.5 cm, a radius of 228 cm, and a density of 2.7 g/cm^3. It is estimated that 1 worker would have to work a total of 25 hours to process 10 t of slag from the smelting of 100 t of scrap steel. For aluminum, the slag handled is modeled as a 6.4-t half cylinder with a thickness of 45 cm, a radius of 213 cm, and a density of 2.0 g/cm^3. It is estimated that 1 worker would have to work 50 hours to process 30 t of slag from the smelting of 100 t of scrap aluminum. The slag worker is assumed to work at a distance of 150 cm from the source.

2.1.3 Ingot Delivery Step

Scenarios for two different workers are included under the ingot delivery step: a loader and a truck driver for the delivery of cast ingots to a fabrication plant. The default values for each scenario are specified on the basis of processing 100 t of scrap metal. Because these operations occur outside the smelting facility after the smelting process, mass and radionuclide partitioning factors (see Section 3) are applied in the dose calculation. The inhalation and ingestion pathways are not considered in this step because an ingot is a solid, and radionuclide releases to the air are not possible under normal delivery conditions. The only potential pathway considered in this step is external exposure. The individual scenarios included in this step are discussed below.

2.1.3.1 Ingot Loader Scenario

The ingot loader scenario models the potential doses to a worker who loads the cast ingots produced at the smelter for transport to a fabrication plant. It is estimated that 2 loaders would each have to work 2 hours to handle the metal ingots produced from 100 t of radioactive scrap metal.

For steel ingots, the external source is modeled as a 50-t half cylinder with a thickness of 100 cm, a radius of 201 cm, and a density of 7.86 g/cm^3. For aluminum ingots, the external source is modeled as a 50-t half cylinder with a thickness of 200 cm, a radius of 242 cm, and a density of 2.7 g/cm^3. The ingot loader is assumed to work at a distance of 400 cm from the source.

2.1.3.2 Ingot Truck Driver Scenario

The truck driver scenario models the potential doses to a worker who drives a truck that transports the cast ingots to a fabrication facility. It is estimated that 5 drivers would each have to work an average of 5 hours to transport the metal ingots generated from 100 t of scrap metal.

For steel ingots, the radiation source is modeled as a 20-t cylinder with a thickness of 200 cm, a radius of 64 cm, and a density of 7.86 g/cm^3. For aluminum ingots, the radiation source is modeled as a 20-t full cylinder with a thickness of 230 cm, a radius of 100 cm, and a density of 2.7 g/cm^3. The driver is assumed to be located 200 cm from the source; shielding from the truck cab is not considered in the dose calculations.

2.1.4 Initial Fabrication Step

Scenarios for three different workers are included under the initial fabrication step: a storage yard worker, a sheet maker, and a coil maker. The default values for each scenario are specified on the basis of processing 100 t of scrap metal. Because these operations occur in a separate facility from the smelter and after the smelting process, mass and radionuclide partitioning factors into ingot are applied in the dose calculation. The individual scenarios included in this step are discussed below.

2.1.4.1 Storage Yard Worker Scenario

The storage yard worker scenario models the potential exposures to a worker who processes the cast ingots at the storage yard of the fabrication plant. The only pathway evaluated in this scenario is external exposure. It is estimated that 10 workers would each work a total of 40 hours to process the cast ingots from 100 t of scrap metal.

The external radiation source for steel is modeled as a 50-t half cylinder ingot with a thickness of 100 cm, a radius of 201 cm, and a density of 7.86 g/cm^3. The external radiation source for aluminum is modeled as a 50-t half cylinder with a thickness of 100 cm, a radius of 343 cm, and a density of 2.7 g/cm^3. The distance between the worker and the source is assumed to be 1,000 cm.

2.1.4.2 Sheet Maker Scenario

The sheet maker scenario models the potential doses to an individual who fabricates metal sheets from the recycled scrap metal. The pathways included in the dose assessment for this scenario are external exposure, inhalation, and ingestion. The external radiation source for steel is modeled as a 0.047-t half cylinder with a thickness of 0.2 cm, a radius of 138 cm, and a density of 7.86 g/cm^3. It is estimated that 15 sheet makers would each have to work 1 hour to process the steel generated from 100 t of scrap metal. The external radiation source for aluminum is modeled with the same geometry as for steel, but with a density of 2.7 g/cm^3. It is estimated that 15 sheet makers would each have to work 2 hours to process the aluminum generated from 100 t of scrap metal. The exposure distance from the sheet makers to the radiation source is assumed to be 100 cm.

2.1.4.3 Coil Maker Scenario

The coil maker scenario models the potential doses to a worker who makes coils from the metal sheets produced in the previous step. The external exposure, inhalation, and ingestion pathways are included in the dose assessment for this scenario. The radiation source for steel is modeled as a 10-t full cylinder with a thickness of 122 cm, a radius of 58 cm, and a density of 7.86 g/cm^3. It is estimated that 1 coil maker would have to work 1 hour to process 100 t of scrap metal. The radiation source for aluminum is modeled as a 5-t full cylinder with a thickness of

122 cm, a radius of 70 cm, and a density of 2.7 g/cm^3. It is estimated that 1 coil maker would have to work 2 hours to process all the aluminum. The average distance between the coil maker and the radiation source is assumed to be 150 cm.

2.1.5 Final Fabrication Step

Evaluation of the final fabrication step takes into account workers involved in manufacturing end-use products from the metal sheets and coils made from the radioactive scrap metal. Scenarios for two different workers are included under the final fabrication step: a sheet handler and a coil handler. The default values for each scenario are specified on the basis of processing 100 t of scrap. Because these operations occur in a facility that is separate from the smelter and occur after the smelting process has been completed, mass and radionuclide partitioning factors into ingot are applied in the dose calculations. The inhalation and ingestion pathways are not a consideration, as the metal sheets and coils are solids. It is not possible under normal operational conditions for radionuclides to be released into the air. However, if it is decided to include the inhalation and ingestion pathways in the analysis, the ingot partitioning factors would be applied to estimate the radionuclide concentrations in the ingested or inhaled particles. The individual scenarios included in this step are discussed below.

2.1.5.1 Sheet Handler Scenario

The sheet handler scenario models the potential doses to an individual who handles metal sheets made from radioactive scrap metal. For steel sheets, the external radiation source is modeled as a 0.047-t half cylinder with a thickness of 0.2 cm, a radius of 138 cm, and a density of 7.86 g/cm^3. It is estimated that 20 sheet handlers would each have to work 1 hour to process the steel sheets generated from 100 t of scrap metal. For aluminum sheets, the external radiation source is modeled with the same geometry as for the steel sheets, but with a density of 2.7 g/cm^3. It is estimated that a total of 20 workers would each have to work 2 hours to process all of the aluminum generated from 100 t of scrap metal. The distance between the sheet handler and the radiation source is estimated to be 100 cm.

2.1.5.2 Coil Handler Scenario

The coil handler scenario evaluates the potential doses to a worker who handles coils of metal sheets in the fabrication step. For steel coils, the radiation source is modeled as a 10-t full cylinder with a thickness of 122 cm, a radius of 58 cm, and a density of 7.86 g/cm^3. For aluminum coils, the radiation source is modeled as a 5-t full cylinder with a thickness of 122 cm, a radius of 70 cm, and a density of 2.7 g/cm^3. The distance between the worker and the radiation source is assumed to be 150 cm. It is estimated that 5 coil handlers would each have to work 80 hours to handle the coils from metal sheets processed from 100 t of scrap metal.

2.1.6 Product Distribution Step

The product distribution step considers the transport and distribution of final products, such as metal sheets, made from the recycled metal at the fabrication facility. Scenarios for four different workers are included under the product distribution step: a product loader, a product truck driver, a sheet assembler, and a warehouse worker. The default values for each scenario are specified on the basis of processing 100 t of scrap metal. Because these operations involve the finished product, only the external exposure pathway is considered in the dose assessment. If it is decided to include the inhalation and ingestion pathways, ingot mass and radionuclide partitioning factors would be applied to estimate the radionuclide concentrations in the inhaled or ingested particles. The individual scenarios included in this step are discussed below.

2.1.6.1 Product Loader Scenario

The product loader scenario models the potential doses to an individual who loads and unloads trucks used for the distribution of final products. For steel products, the external radiation source is modeled as a 50-t half cylinder with a thickness of 100 cm, a radius of 201 cm, and a density of 7.86 g/cm^3. For aluminum products, the external radiation source is modeled as a 50-t half cylinder with a thickness of 200 cm, a radius of 242 cm, and a density of 2.7 g/cm^3. The distance between the product loader and the radiation source is assumed to be 400 cm from the source. It is estimated that for a throughput of 100 t of scrap metal, 2 loaders would each have to work 20 hours.

2.1.6.2 Product Truck Driver Scenario

The product truck driver scenario models the potential doses to a worker who transports finished products for distribution. For steel products, the external radiation source is modeled as a 20-t full cylinder with a thickness of 200 cm, a radius of 64 cm, and a density of 7.86 g/cm^3. For aluminum products, the radiation source is modeled as a 20-t full cylinder with a thickness of 230 cm, a radius of 100 cm, and a density of 2.7 g/cm^3. The driver is assumed to be located 200 cm from the radiation source. It is estimated that for a 100-t throughput of scrap metal, 5 drivers would each have to work 8 hours.

2.1.6.3 Sheet Assembler Scenario

The sheet assembler scenario models the potential doses to an individual assembling metal sheets into end-use products. For external dose calculations, the radiation source is modeled as a 0.047-t half cylinder with a thickness of 0.2 cm, a radius of 138 cm, and a density of 7.86 g/cm^3 and 2.7 g/cm^3 for steel and aluminum products, respectively. The worker is assumed to be 100 cm from the radiation source. It is estimated that for a 100-t throughput of scrap metal, 20 sheet assemblers would each have to work 20 hours.

2.1.6.4 Warehouse Worker Scenario

The warehouse worker scenario models the potential doses to a worker involved in managing the warehouse inventory of consumer products made from recycled radioactive metal. For steel, the external source is modeled as a 0.28-t half cylinder with a length of 1.2 cm, a radius of 138 cm, and a density of 7.86 g/cm^3. For aluminum, the external radiation source is modeled with the same geometry as that of steel, but with a density of 2.7 g/cm^3. It is estimated that 5 workers would each have to work 2,000 hours in the warehouse. The warehouse worker is assumed to be 600 cm from the radiation source.

2.2 END-USE PRODUCT SCENARIOS

This section describes the consumer end-use product scenarios considered in RESRAD-RECYCLE. Default values for the number of people considered in the collective dose calculations are based on recycling 100 t of scrap metal. Tables 2.4 and 2.5 summarize the default modeling parameters for all the end-use product scenarios for steel and aluminum, respectively.

The amount of steel available for manufacturing consumer products from the recycling of 100 t of radioactive scrap metal is assumed to be 90 t (i.e., the ingot mass partitioning factor is 90%), and the amount of slag produced from the smelting operation is assumed to be 10 t (i.e., the slag mass partitioning factor is 10%). The amount of aluminum available for manufacturing consumer products from 100 t of scrap metal is assumed to be 70 t (i.e., the ingot mass partitioning factor is 70%), and the amount of slag is assumed to be 30 t. The mass partitioning factors are input variables in RESRAD-RECYCLE and are discussed in detail in Section 3.5.

The finished metal produced from the recycling process would be distributed among and used by various industries. Statistical data showing the distribution of steel and aluminum among different industries are listed in Tables 2.6 and 2.7, respectively. However, to estimate the maximum radiation doses from the use of end products in the default cases, 100% of the finished metal is assumed to be used to manufacture one of the end products. The distribution of finished metal is an input variable for each product scenario and, therefore, can be changed by the user to conserve mass balance among the various products.

2.2.1 Parking Lot Scenario

This scenario models the use of slag produced from the smelting process in an asphalt parking lot. The slag is assumed to be diluted with concrete by a factor of 100 (1:100 ratio). The mixture of slag and concrete is assumed to have a density of 2.7 g/cm^3.

If the slag mass partitioning factor is assumed to be 10%, as is the case for steel, and all of the slag is used for constructing a parking lot, the total mass of the slag-concrete mixture would be 1,000 t. On the basis of this assumption, when the scrap metal is steel, the parking lot is modeled as a homogenous full cylinder with a radius of 3,400 cm and a thickness of 10 cm. The average individual is assumed to spend 10 minutes a day in the parking lot, which yields an annual exposure time of 62 hours. For the collective dose calculation, the number of exposed

TABLE 2.4 Default Parameters Used to Model End-Use Product Scenarios in RESRAD-RECYCLE for Steel

Recycle Step	Scenario	Source Geometry	Density (g/cm^3)	Thickness (cm)	Radius (cm)	Distance from Source (cm)	Time (h)	Radiation Source for the External Pathway[a]	Radiation Source for the Internal Pathway[b]	Default Internal Pathway[c]	Number of Individuals[d]
Consumer products	Parking lot	1 full cylinder	2.70	10	3,400	100	62	Slag	None	None	1,000
	Room/office	4 half cylinders	7.86	0.2	300	100, 250, 250, 400	2,000	Ingot	None	None	380
	Appliance	1 half cylinder	7.86	0.1	92	100	730	Ingot	None	None	4,300
	Automobile	4 full cylinders	7.86	0.1	150	50	730	Ingot	None	None	800
	Office furniture	1 half cylinder	7.86	0.1	103	15	2,000	Ingot	None	None	7,000
	Home furniture	1 half cylinder	7.86	0.1	110	15	3,650	Ingot	None	None	6,000
	Frying pan	1 full cylinder	7.86	0.4	15	30	180	Ingot	None	ing	41,000
Public products	Pavement	1 full cylinder	2.70	10	3,400	100	0.0074[f]	Slag	None	None	8,200,000
	Public building[e] (with rebars)	4 half cylinders	7.86	0.5	300	100, 250, 250, 400	2,000	Ingot	None	None	164
	Bridge	2 half cylinders	7.86	1.2	1,800	100, 400	0.002[f]	Ingot	None	None	8,200,000
Controlled products	Shielding block	1 half cylinder	7.86	132	105	100	1	Ingot	None	None	–[g]
	Radwaste container	1 half cylinder	7.86	0.27	100	100	1	Ingot	None	None	–
Reuse products	Tool reuse	1 full disk	–	–	56	60	2,000	Reuse product	Reuse product	inh, ing	1
	Building reuse	4 half disks	–	–	300	100, 250, 250, 400	2,000	Reuse product	Reuse product	inh, ing	4

[a] Radionuclide concentrations in slag or ingot are calculated by using the corresponding mass and radionuclide partitioning factors. For the reuse product scenarios, concentrations in the products are used directly in dose calculations.

[b] The source material is the material from which the product is made. It is assumed to be the source from which the airborne dust particles originate. When no internal pathway is considered, "none" is listed. For the reuse product scenarios, concentrations in the products are used directly in dose calculations.

[c] If by default no internal pathway is considered, "none" is listed. However, the user can elect to consider the internal pathways. In that case, radionuclide concentrations are calculated by using the source material listed in the column immediately to the left. Here, "inh" denotes inhalation and "ing" denotes ingestion.

[d] Based on the assumption that 100% of the ingot or slag from recycling 100 t of scrap metal would be used.

[e] Shielded by 15 cm of concrete.

[f] For MEI dose calculations, exposure durations of 6 and 1 hour(s) are applied for the pavement and bridge scenarios, respectively.

[g] A hyphen indicates not applicable or various.

TABLE 2.5 Default Parameters Used to Model End-Use Product Scenarios in RESRAD-RECYCLE for Aluminum

Recycle Step	Scenario	Source Geometry	Density (g/cm^3)	Thickness (cm)	Radius (cm)	Distance from Source (cm)	Time (h)	Radiation Source for the External Pathway[a]	Radiation Source for the Internal Pathway[b]	Default Internal Pathway[c]	Number of Individuals[d]
Consumer products	Parking lot	1 full cylinder	2.7	10	5,900	100	62	Slag	None	None	3,000
	House siding	4 half cylinders	2.7	0.2	600	600, 1100, 600, 100	5,600[e]	Ingot	None	None	180
	Appliance	1 half cylinder	2.7	0.1	100	100	730	Ingot	None	None	16,510
	Automobile	4 full cylinders	2.7	0.1	190	50	730	Ingot	None	None	1,120
	Ship/boat	4 half cylinders	2.7	0.2	384	100, 280, 280, 100	16[e]	Ingot	None	None	2,800
	Office furniture	1 half cylinder	2.7	0.1	103	15	2,000	Ingot	None	None	15,560
	Home furniture	1 half cylinder	2.7	0.1	110	15	3,650	Ingot	None	None	13,640
	Frying pan	1 full cylinder	2.7	0.4	15	30	180	Ingot	None	ing	91,700
	Beverage can	1 full cylinder	2.7	0.03	8	15	0.5[e]	Ingot	None	None	4,300,000
Public products	Pavement	1 full cylinder	2.7	10	5,900	100	0.0074[e]	Slag	None	None	8,200,000
	Public building[f]	1 full cylinder	2.7	0.2	5,000	500	4[e]	Ingot	None	None	375,000
	Bridge	2 half cylinders	2.7	1.2	1,800	100, 400	0.002[e]	Ingot	None	None	16,400,000
Reuse products	Tool reuse	1 full disk	–[g]	–	56	60	2,000	Reuse product	Reuse product	inh, ing	1
	Building reuse	4 half disks	–	–	300	100, 250, 250, 400	2,000	Reuse product	Reuse product	inh, ing	4

[a] Radionuclide concentrations in slag or ingot are calculated by using the corresponding mass and radionuclide partitioning factors. For the reuse product scenarios, concentrations in the products are used directly in dose calculations.

[b] The source material is the material from which the product is made. It is assumed to be the source from which the airborne dust particles originate. When no internal pathway is considered, "none" is listed. For the reuse product scenarios, concentrations in the products are used directly in dose calculations.

[c] If by default no internal pathway is considered, "none" is listed. However, the user can elect to consider the internal pathways. In that case, radionuclide concentrations are calculated by using the source material listed in the column immediately to the left. Here, "inh" denotes inhalation and "ing" denotes ingestion.

[d] Based on the assumption that 100% of the ingot or slag from recycling 100 t of scrap metal would be used.

[e] For MEI dose calculations, exposure durations are 7,300 hours for the house siding scenario, 160 hours for the ship/boat scenario, 30 hours for the beverage can scenario, 6 hours for the pavement scenario, 1 hour for the bridge scenario, and 500 hours for the public building scenario.

[f] Shielded by 15 cm of concrete.

[g] A hyphen indicates not applicable or various.

TABLE 2.6 End-Use Distribution of Recycled Steel in the United States

Representative End-Use Product	Mass Distribution (% of total)
Room/office	38
Appliance	8
Automobile	30
Office furniture	8
Home furniture	8
Frying pan	8

Source: U.S. Bureau of Mines (1985), after normalization.

TABLE 2.7 End-Use Distribution of Recycled Aluminum in the United States

End-Use Product	Mass Distribution (% of total)
Containers and packaging	25
Building and construction	15
Transportation	34
Electric	8
Consumer durables	8
Machinery and equipment	7
Others	3

Source: The Aluminum Association, Inc. (1998), after excluding export distribution and normalization.

individuals is estimated to be 1,000. This estimate is based on the surface area of the parking lot, the surface area of an average automobile, and an average occupancy of two individuals per automobile. The external exposure is calculated by assuming a distance of 100 cm between the radiation source and the receptors.

If the mass partitioning factor of slag is assumed to be 30%, as is the case for aluminum, and all of the slag is used for constructing a parking lot, the total mass of the slag-concrete mixture would be 3,000 t. On the basis of this assumption, when the scrap metal is aluminum, the parking lot is modeled as a full cylinder with a thickness of 10 cm and a radius of 5,900 cm. The exposure duration for the receptors would be the same as in the case for steel scrap; however, because of the larger size of the parking lot, the number of individuals exposed to radiation is estimated to be 3,000.

2.2.2 Room/Office and House Siding Scenario

The room/office and house siding scenario models the use of recycled steel sheets to construct the four walls of an office or room and the use of recycled aluminum sheets for the exterior siding of a house.

For steel, the size of the room is assumed to be 5 m × 5 m × 3 m. In the dose calculations, each wall is modeled as a half cylinder with a thickness of 0.2 cm, a radius of 300 cm, and a density of 7.86 g/cm^3. The average individual is assumed to be located 100 cm from one wall, 400 cm from the opposite wall, and 250 cm from the two adjacent walls. The individual is assumed to spend 8 hours per day in the room for a total of 2,000 hours (50 work weeks) per year.

If 940 kg of steel is needed to construct one room, about 96 rooms could be built from recycling 100 t of radioactive scrap metal, assuming that 100% of the finished steel is used in the construction of the walls. Thus, for an average occupancy of four persons per room, the number of exposed individuals for collective dose assessment is estimated to be 380.

For aluminum, the size of the house is assumed to be 12 m × 12 m × 6 m. Each side of the house is modeled as a half cylinder with a thickness of 0.2 cm, a radius of 600 cm, and a density of 2.7 g/cm^3. The exposed individual is assumed to be located at the center line of the nearest wall, with a distance of 100 cm from the wall. For the maximally exposed individual (MEI), an exposure time of 7,300 hours per year (20 hours per day, 365 days per year) is assumed. For the collective dose calculation, an average exposure time of 5,600 hours is assumed. An estimated 1.5 t of aluminum would be required for siding a single house; therefore, approximately 45 houses could be sided with the finished aluminum produced from recycling 100 t of scrap metal, assuming that all the finished aluminum is used for siding. On the basis of the above assumption and the assumption that an average household has 4 members, a total of 180 persons could be exposed to radiation under this scenario.

2.2.3 Appliance Scenario

The appliance scenario models the use of recycled steel in manufacturing home appliances. Three types of appliances were modeled: refrigerators, stoves, and dishwashers. Because of its large size, the refrigerator represents the most conservative case (i.e., yields the highest dose). The refrigerator is modeled as a half cylinder with a thickness of 0.1 cm, a radius of 92 cm, and a density of 7.86 g/cm^3. The external exposure is calculated at a distance of 100 cm from the source. The exposed individual is assumed to spend 2 hours per day near the refrigerator for a total exposure time of 730 hours per year. For the collective dose calculation, it is assumed that one person is exposed per appliance. The average mass of steel used in a refrigerator is estimated to be 21 kg. If 100% of available recycled steel is used in manufacturing refrigerators, approximately 4,300 refrigerators could be manufactured from the recycling of 100 t of radioactive scrap metal. Therefore, the number of exposed individuals used in calculating the collective dose is 4,300.

The home appliance modeled for aluminum is a heating radiator, which is represented by a half cylinder with a thickness of 0.1 cm, a radius of 100 cm, and a density of 2.7 g/cm^3. It is assumed that an individual would spend 2 hours per day, 365 days per year, at a distance of 100 cm from the radiator. If 100% of the finished aluminum is used in manufacturing radiators, a total of 16,510 radiators could be produced, resulting in 16,510 persons being exposed to radiation.

2.2.4 Automobile Scenario

The automobile scenario models the use of recycled steel in the manufacturing of automobile bodies. The automobile is modeled as 4 full cylinders with a 0.1-cm thickness, a 150-cm radius, and a density of 7.86 g/cm^3. The exposed individual is assumed to be located 50 cm from the source. The exposure time for an average individual is assumed to be 2 hours per day, thus yielding a total exposure time of 730 hours per year. If 100% of the available recycled steel is used in manufacturing automobiles and if an average of 222 kg of steel is used for each one, it is estimated that 400 automobiles could be manufactured from recycling 100 t of radioactive scrap metal. Thus, on the basis of an average occupancy of 2 persons per automobile, the number of exposed individuals used for the collective dose assessment is 800.

The amount of aluminum used in each automobile is less than that for steel, although it has been increasing over the years. An average of 125 kg of aluminum per automobile is assumed in the dose calculation. The radiation source is modeled as 4 half cylinders each with a thickness of 0.1 cm, a radius of 190 cm, and a density of 2.7 g/cm^3. The exposed individual is assumed to sit inside the automobile at a distance of 50 cm from the sources. A total exposure time of 730 hours is assumed. According to the estimation, the finished aluminum from recycling 100 t of scrap metal could be distributed into 560 automobiles. On the basis of the assumption that an average occupancy per automobile is 2 persons, the number of exposed individuals would be 1,120.

2.2.5 Ship/Boat Scenario

The ship/boat scenario was developed specifically to model aluminum. The amount of aluminum used to manufacture the body of a ship/boat is assumed to be 500 kg. The ship/boat body is represented by 4 half cylinders each with a thickness of 0.2 cm, a radius of 380 cm, and a density of 2.7 g/cm^3. The exposed individual is assumed to be 100 cm above the bottom of the ship/boat, and 100 cm from the closest wall of the ship/boat. The MEI is assumed to spend 160 hours per year sailing the ship/boat, while the average exposed individual is assumed to spend 16 hours per year riding the ship/boat. If it is assumed that the capacity of the ship/boat is 20 persons, a total of 2,800 persons could possibly be exposed to radiation.

2.2.6 Office Furniture Scenario

This scenario models the use of recycled metal in the manufacturing of office furniture. Three types of office furniture were considered for modeling this scenario: desks, bookcases, and file cabinets. Calculations indicated that the desk would be the most conservative case (i.e., yield the greatest dose) because of the close distance and long period of time that an average individual could be exposed. The desk is modeled as a half cylinder with a 0.1-cm thickness, a 103-cm radius, and a density of 7.86 g/cm^3 (for steel) or 2.7 g/cm^3 (for aluminum). The external exposure is assumed to be 15 cm from the source. The average individual is assumed to spend 8 hours per day at the desk, which yields a total exposure time of 2,000 hours per year. The amount of steel used in making a desk is estimated to be approximately 13 kg; for aluminum, it is estimated to be approximately 4.5 kg. If 100% of available recycled metal is used to manufacture office furniture, it is estimated that 7,000 steel or 15,560 aluminum desks could be produced from recycling 100 t of radioactive scrap metal. The number of individuals used for calculating of the collective dose is 7,000 and 15,560 for steel and aluminum, respectively, assuming that 1 person is exposed per desk.

2.2.7 Home Furniture Scenario

This scenario models the use of recycled metal in the manufacturing of home furniture such as wire bedsprings. The home furniture is modeled as a half cylinder with a 0.1-cm thickness, a 110-cm radius, and a density of 7.86 g/cm^3 (for steel) or 2.7 g/cm^3 (for aluminum). The external exposure is calculated at 15 cm above the source. The average individual is estimated to be exposed for 10 hours per day, which yields a total exposure time of 3,650 hours per year. About 15 kg of steel or 5.15 kg of aluminum is estimated to be used in each piece of home furniture. About 6,000 pieces of furniture made with steel or 13,640 pieces of furniture made with aluminum could be produced from recycling 100 t of radioactive scrap metal. Assuming 1 person is exposed per piece of furniture, the total number of exposed individuals used to calculate the collective dose is 6,000 for steel and 13,640 for aluminum.

2.2.8 Frying Pan Scenario

This scenario models the use of recycled metal in the manufacturing of frying pans for household use. The pan is modeled as a full cylinder with a 0.4-cm thickness, a 15-cm radius, and a density of 7.86 g/cm^3 for a steel pan and 2.7 g/cm^3 for an aluminum pan. The external exposure is assumed to be 30 cm above the source. The average individual is assumed to be exposed for 0.5 hour per day, which yields a total exposure time of 180 hours per year. The amount of metal used in a pan is 2.2 kg for steel and 0.76 kg for aluminum. Assuming that 100% of finished metal is used to make frying pans, it is estimated that approximately 41,000 steel and 91,700 aluminum pans could be produced. For collective dose calculations, the number of exposed individuals is 41,000 for steel pans and 91,700 for aluminum pans, on the basis of the assumption that 1 person is exposed per pan. The internal dose is included in this scenario by considering the ingestion of corroded metal from the pan. The ingestion exposure is calculated by using the estimated corrosion mass of frying pans. The default corrosion rate of frying pans is assumed to be 0.13 mm/yr.

2.2.9 Beverage Can Scenario

The beverage can scenario was developed specifically for aluminum because aluminum cans account for more than 90% of the beverage can industry. Although it is unlikely that the recycled radioactive metal would be used for manufacturing beverage cans, this scenario is included in the RESRAD-RECYCLE code so that the potential radiation exposure can be compared with that from other scenarios. Aluminum is a lightweight metal, and if all the finished aluminum were used to produce beverage cans, approximately 4,300,000 cans could be produced from recycling 100 t of scrap metal. For dose calculations, the beverage can is modeled as a full cylinder with a thickness of 0.03 cm, a radius of 8 cm, and a density of 2.7 g/cm^3. It is assumed that an individual would take 0.5 hour to consume one can of beverage and that the MEI would consume 60 cans of beverage in a year, which would yield a total exposure time of 30 hours. The exposure distance assumed in the dose calculation is 15 cm.

2.3 PUBLIC PRODUCT SCENARIOS

Public product scenarios model the use of major products by the general public. These products would require the use of a large amount of metal in one area for a long period of time. Such usage might be an attractive approach for recycling materials contaminated with relatively short-lived radionuclides such as cobalt-60. Four representative public products are modeled in the code: pavement made from slag generated during smelting of radioactive scrap metal, a building constructed with reinforcing bars made from recycled steel, a building constructed with a geodesic dome made from recycled aluminum, and a bridge constructed of recycled metal. Tables 2.4 and 2.5 give the modeling parameters for steel and aluminum, respectively, for the public product scenarios.

2.3.1 Pavement Scenario

The pavement scenario models the use of slag from the smelting of radioactive scrap metal in the construction of pavement. The slag is assumed to be diluted with concrete by a factor of 100. The mixture of slag and concrete is assumed to have a density of 2.7 g/cm^3.

If the slag mass partitioning factor is assumed to be 10% of the total scrap, as in the case for steel, the estimated total mass of the slag-concrete mixture would be 1,000 t. Then, assuming all of the slag is used to construct the pavement, it would cover an area 370 m long and 10 m wide. For dose calculations, the pavement constructed with steel slag is modeled as a homogenous full cylinder with a radius of 3,400 cm and a thickness of 10 cm. The external exposure is calculated at 100 cm above the pavement. For collective dose calculations, it is assumed that 470 cars per hour pass over the pavement, a frequency that is typical for rural areas (Neuhauser and Kanipe 1993). Each car is assumed to have 2 passengers and to be traveling at 50 km/h for a total exposure duration of 0.0074 hour per year. The number of exposed individuals is approximately 8,200,000 per year. For calculation of the dose to the MEI, an exposure duration of 6 hours per year from driving on the pavement twice a day at a speed of 50 km/h is used.

If the slag mass partitioning factor is assumed to be 30% of the total scrap, as is in the case for aluminum, then the estimated slag-concrete mixture would be 3,000 t. On the basis of the same assumption for steel, the pavement is modeled as a full cylinder with a radius of 5,900 cm and a thickness of 10 cm. The exposure duration and number of exposed individuals are assumed to be the same as those used for steel.

2.3.2 Building with Rebars Scenario

This scenario was developed specifically for steel and considers the use of reinforcement bars (rebars) manufactured from recycled steel in the construction of public buildings. Four walls of a 500 cm × 500 cm × 300 cm room are assumed to be constructed with rebars placed 15 cm deep inside concrete. Each wall is modeled as a half cylinder with a 30-cm radius, a 0.5-cm thickness, and a steel density of 7.86 g/cm^3. The average individual is assumed to be located 100 cm from one wall, 400 cm from the opposite wall, and 250 cm from the two adjacent walls. The individual is assumed to spend 8 hours per day in the room for a total of 2,000 hours per year (50 work weeks per year). If 2.2 t of steel is needed to construct 1 room, about 41 rooms could be built from recycling 100 t of radioactive scrap metal. Thus, for an average occupancy of four persons per room, the number of exposed individuals used for the collective dose assessment would be 164 (4 × 41).

2.3.3 Building with Geodesic Dome Scenario

This scenario was developed specifically for aluminum and considers the construction of a geodesic dome with recycled aluminum on the top of a public building (museum, exhibition hall, etc.). The dome is modeled as a full cylinder with a radius of 5,000-cm radius, a 0.2-cm thickness, and a density of 2.7 g/cm^3. A 15-cm thick concrete shielding is assumed for the dose calculation. Assuming that the building is open to the public 250 days a year, and an average of 1,500 people visit daily, a total of 375,000 people would visit the building annually. For the collective dose calculation, each visit is assumed to last for 4 hours. For individual dose calculations, the MEI is assumed to spend a total of 500 hours per year inside the public building. It is assumed that the receptor is 500 cm from the radiation source.

2.3.4 Bridge Scenario

This scenario models the use of recycled metal for the construction of support beams for a bridge. The bridge is assumed to be 500 cm wide and 10,000 cm long, with a beam height of 500 cm. Each side of the bridge is modeled as a half cylinder with a 1.2-cm thickness, a 1,800-cm radius, and a density of 7.86 g/cm^3 for steel or 2.7 g/cm^3 for aluminum. The external exposure is calculated at 100 cm from one side and 400 cm from the other side of the bridge. For the collective dose calculation, it is assumed that 470 cars cross the bridge each hour, a typical rural traffic frequency (Neuhauser and Kanipe 1993). Each car is assumed to have 2 passengers and to be traveling at 50 km/h, for a total exposure duration of 0.002 hour per year. The number of exposed individuals is approximately 8,200,000 per year for steel, because one bridge could be built from recycling 100 t of radioactive scrap metal. For aluminum, the number of exposed individuals is approximately 16,400,000 per year, because two bridges could be built from recycling 100 t of scrap materials. For MEI dose calculations, the individual is assumed to be exposed for 1 hour per year driving across the bridge twice a day at a speed of 50 km/h.

2.4 CONTROLLED PRODUCT SCENARIOS

Controlled products are items manufactured for use by the nuclear industry and, therefore, are not released for use by the general public. Two representative scenarios are considered: construction of a shielding block and a radioactive waste container made from recycled metal. Because of its low density, aluminum is usually not used for radiation shielding. Therefore, the controlled product scenarios are considered specifically for steel. Modeling parameters for the controlled product scenarios for steel is shown in Table 2.4.

2.4.1 Shielding Block Scenario

This scenario models the use of recycled steel for producing shielding blocks for use in the nuclear industry and at DOE facilities. A typical steel block in use at high-energy accelerators has a mass of approximately 20 t and dimensions of 132 cm × 132 cm × 132 cm (Scientific Ecology Group 1993). The shielding block is modeled as a half cylinder with a thickness of 132 cm, a radius of 105 cm, and a steel density of 7.86 g/cm^3. The external dose is calculated at a distance of 100 cm from the radiation source for a duration of 1 hour per year.

2.4.2 Radioactive Waste Container Scenario

This scenario models the use of recycled steel in the manufacture of radioactive waste containers. A typical low-level radioactive waste container has dimensions of 214 cm × 100 cm × 114 cm (Moghissi et al. 1986). The container is modeled in this scenario as a half cylinder with a thickness of 0.27 cm, a radius of 100 cm, and a steel density of 7.86 g/cm^3. The external exposure is calculated for a distance of 100 cm from the radiation source for a duration of 1 hour per year.

2.5 REUSE PRODUCT SCENARIOS

Reuse product scenarios model the direct reuse of surface-contaminated material and equipment. These items are used in their original forms; they do not undergo the smelting process as scrap metal. Two representative scenarios are included in the code: tool reuse and building reuse. Modeling parameters of the reuse product scenarios are shown in Tables 2.4 and 2.5 for steel and aluminum, respectively.

2.5.1 Tool Reuse Scenario

This scenario models the use of a small surface-contaminated tool. The tool is assumed to have a total surface area of 1 m^2. For the external dose calculation, the tool is modeled as a full disk, with a 56-cm radius. The exposed individual is assumed to be located 60 cm from the tool inside a 500 cm × 500 cm × 300 cm room and is assumed to spend 8 hours per day in that room, for a total of 2,000 hours per year (50 work weeks per year). One person is assumed to be in the room for the collective dose calculation. Inhalation and ingestion doses are included in the assessment. A building ventilation rate of one room volume per hour is applied as a default.

2.5.2 Building Reuse Scenario

This scenario models the use of a surface-contaminated room. The room is assumed to be 500 cm × 500 cm × 300 cm. Each wall is modeled as a half disk with a 300-cm radius. The exposed individual is assumed to be located 100 cm from one wall, 400 cm from the opposite wall, and 250 cm from each of the two adjacent walls. The individual is assumed to spend

8 hours per day in the room for a total of 2,000 hours per year (50 work weeks per year). For the collective dose calculation, four people are assumed to be exposed in the room. Inhalation and ingestion doses are included in the assessment. A building ventilation rate of one room volume per hour is applied as a default.

2.6 TRANSPORTATION SCENARIO

This scenario models the potential radiation exposure of a member of the public that resides along the routes traveled by a truck that transports radioactive scrap metal from the place of origin to a smelter. The scenario is included under the scrap delivery step (Section 2.1.1). The truck is assumed to be loaded with 20 t of scrap metal with a density of 3.93 g/cm^3 for steel and 1.4 g/cm^3 for aluminum. Shielding provided by the truck body is considered to be 0.2 cm thick. The population dose is evaluated as a function of truck velocity, distance traveled, population density, and number of shipments needed. The truck velocity, distance traveled, and the number of shipments needed are used to calculate the exposure time. The population density along the route is used to estimate the number of people exposed. The user can modify these variables as needed. Five shipments would be required to deliver 100 t of radioactive scrap metal. The default values used in the code are 3,861 people/km^2 for population density (Neuhauser and Kanipe 1993), 80 km/h for truck velocity, and 100 km for distance traveled.

The capacity of a truck is generally limited by the weight of the loaded materials. Because the densities of ingots and finished metal products are greater than that of scrap metal, it is expected that radiation exposure to the public under the transportation scenarios for ingots and finished products would be less than that for scrap metal, given the same transportation route, population density, and transport velocity. Estimates of the radiation doses that result from the transport of ingot and finished products can be performed by modifying the variables in the scrap transport scenario.

2.7 OTHER SCENARIOS

In addition to the calculation of radiation doses and risks for workers and end-use product scenarios, the RESRAD-RECYCLE code also generates data that can be used by other computer codes to address specific issues not evaluated in the code, such as stack emissions from the smelter, land disposal of slag and baghouse contents, and occupancy of a multicompartment building constructed of recycled metal. These issues and related dose assessments are described below.

2.7.1 Stack Emissions from a Smelter

RESRAD-RECYCLE provides information on the atmospheric release of radionuclides during smelting operations. This information is provided in a table included in the summary report, which is generated after the dose calculations are completed. The release amount accounts for mass and radionuclide partitioning during the smelting process and the efficiency of the filters installed in the smelting facility. The atmospheric release amount can be used by an air dispersion model such as CAP88PC (Parks 1997), RESRAD-OFFSITE, or GENII (Napier et al. 1988) to evaluate the potential radiation exposure of individuals working or living at a downwind location from the release point.

2.7.2 Land Disposal of Slag and Baghouse Content

RESRAD-RECYCLE does not evaluate radiation exposure for land disposal scenarios. However, the summary report generated by the code provides information such as the total mass and radionuclide activities in the slag and baghouse. The RESRAD code can use this information to estimate the potential radiation doses resulting from disposal of baghouse contents and slag. Detailed information about the RESRAD code can be found in Yu et al. (1993a).

2.7.3 Occupancy of a Multicompartment Building

The RESRAD-RECYCLE code includes scenarios that model the reuse of decontaminated buildings or the use of buildings constructed with finished products from radioactive scrap metal. It implements a one-compartment model to estimate potential radiation exposures. A sophisticated multicompartment model for use with various types of radiation sources (point, line, area, and volume) and air exchange between compartments (and between compartments and the outdoor environment) is implemented in the RESRAD-BUILD computer code, a subcode of RESRAD. Detailed information about RESRAD-BUILD can be found in Yu et al. (1994).

3 METHODOLOGY

This section describes the methodology used in the RESRAD-RECYCLE code for calculating potential doses and risks from the recycling of radioactive scrap metal and the use of end-products. In general, the exposure scenarios developed, the pathways considered, and the exposure parameters used are based on information from recent publications [O'Donnell et al. (1978), CEC (1988), IAEA (1992), Kennedy and Strenge (1992), OECD (1994), S. Cohen and Associates (1995, 1997), SAIC (1994, 1998), and Nieves et al. (1995)]. The external exposure model implemented in the RESRAD-RECYCLE code is consistent with the one implemented in the RESRAD code (Kamboj et al. 1998). The internal DCFs used in the internal dose calculations are those in EPA Federal Guidance Report (FGR) No. 11 (Eckerman et al. 1988).

For assessment purposes, the recycling process is divided into six steps (scrap delivery, scrap smelting, ingot delivery, product fabrication, product distribution, and use of the finished products), as discussed in Section 2, and representative exposure scenarios are considered under each step. Figure 3.1, a flowchart of the RESRAD-RECYCLE code, outlines the calculation procedure.

3.1 SELECTION OF RADIONUCLIDES

The following selection criteria for radionuclides were established to identify (from a comprehensive list of more than 200 radionuclides) the radionuclides pertinent to the recycling process analysis:

- Radionuclides analyzed in previous recycling studies were retained.

- Radionuclides with half-lives of less than one year were excluded, except for those expected to be prevalent in radioactive scrap metal, such as zinc-65 and manganese-54.

- Naturally occurring radioactive materials (NORM), such as radium-226 and radium-228, were included.

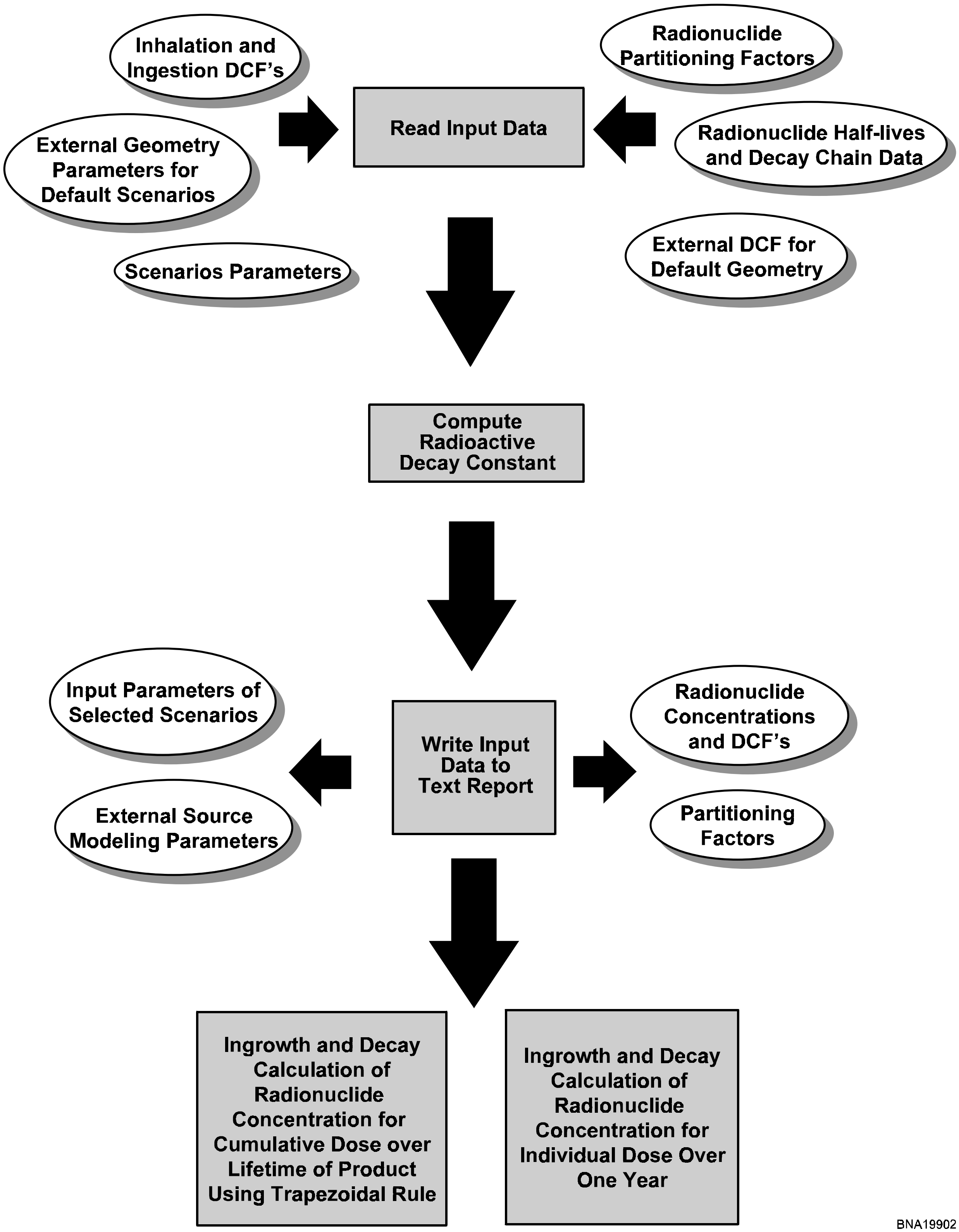

FIGURE 3.1 Flowchart of the RESRAD-RECYCLE Computer Code (PCFLOW-L)

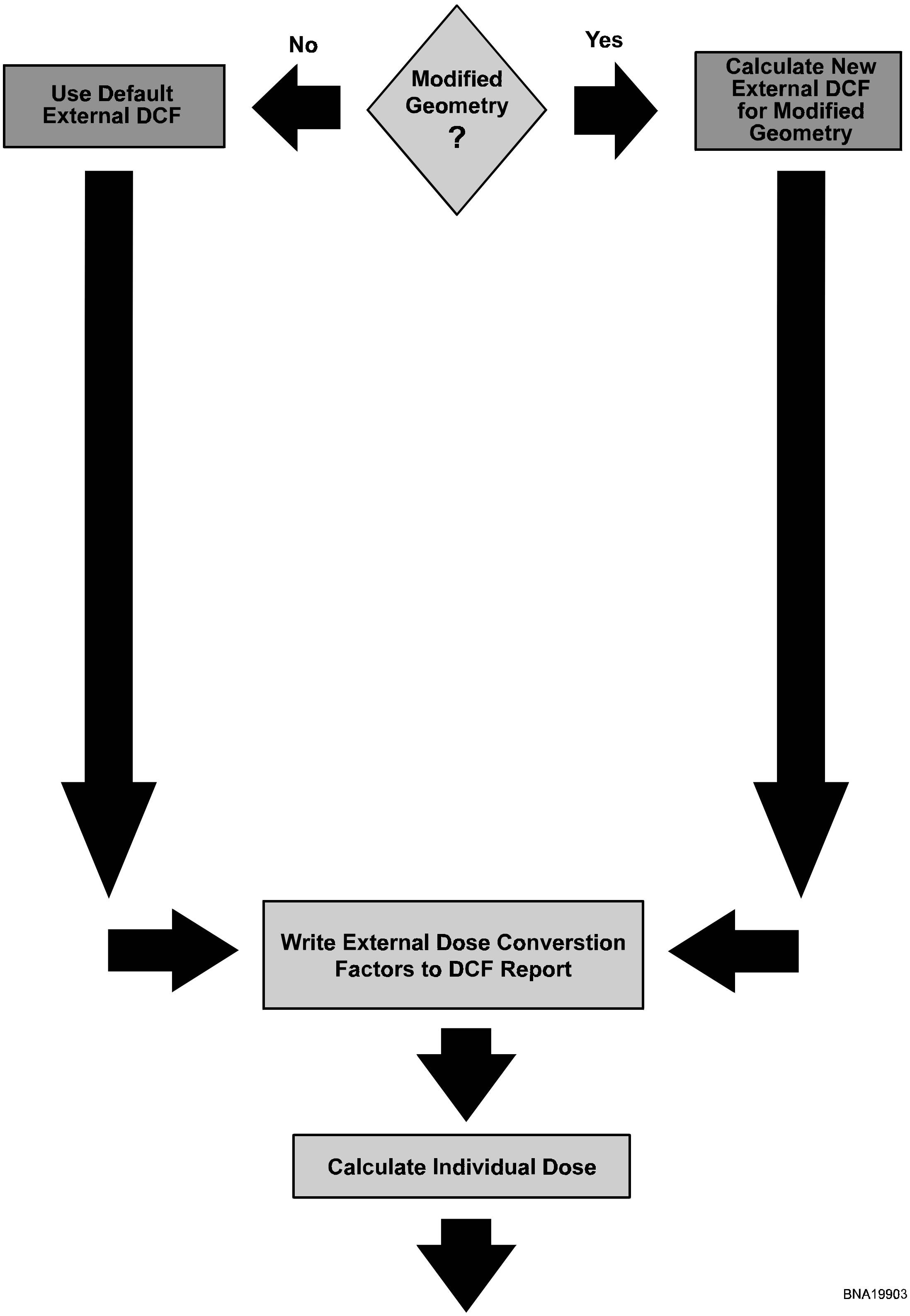

FIGURE 3.1 (Cont.) (PCFLOW1-L)

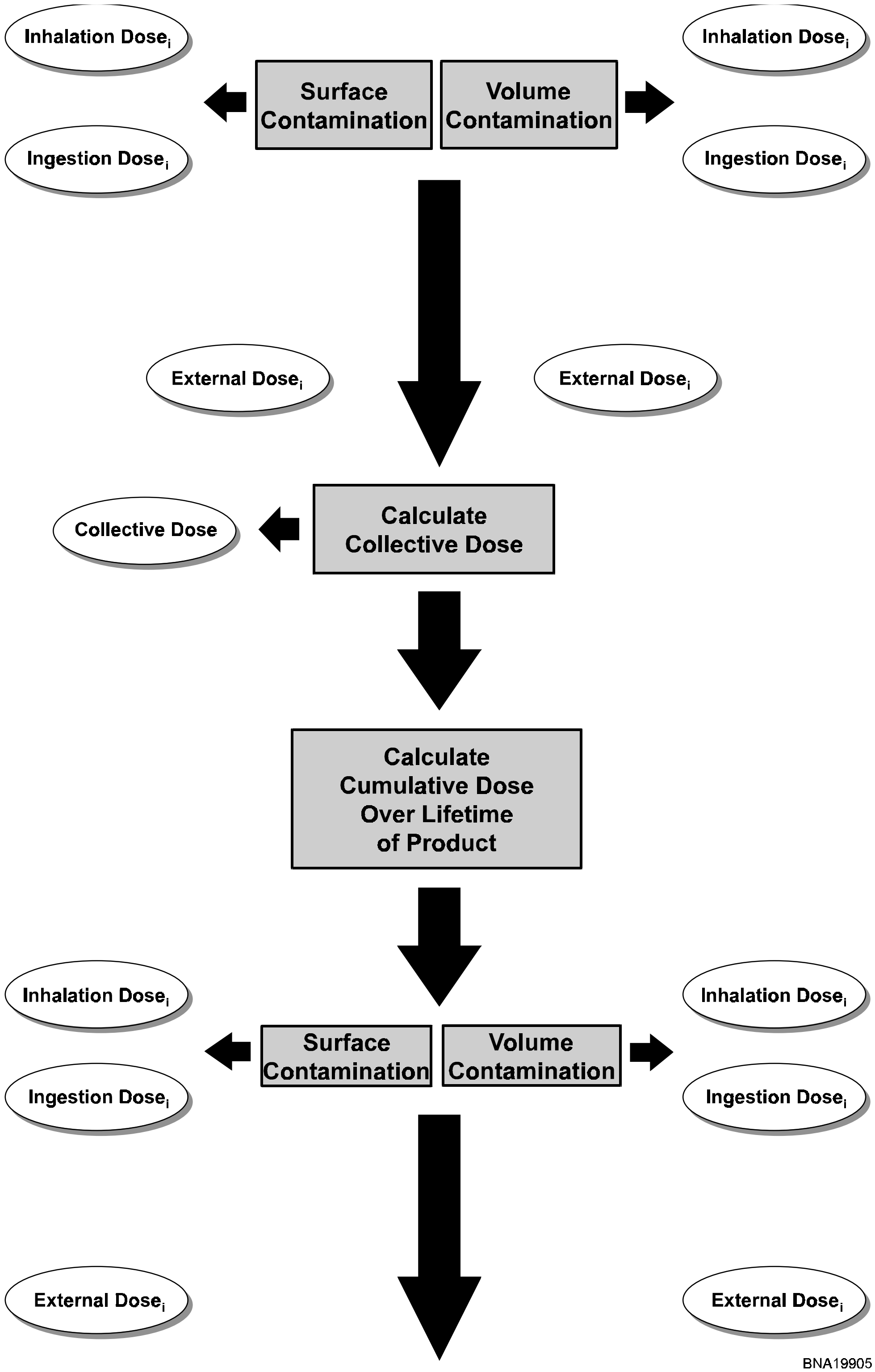

FIGURE 3.1 (Cont.) (PCFLOW2-L)

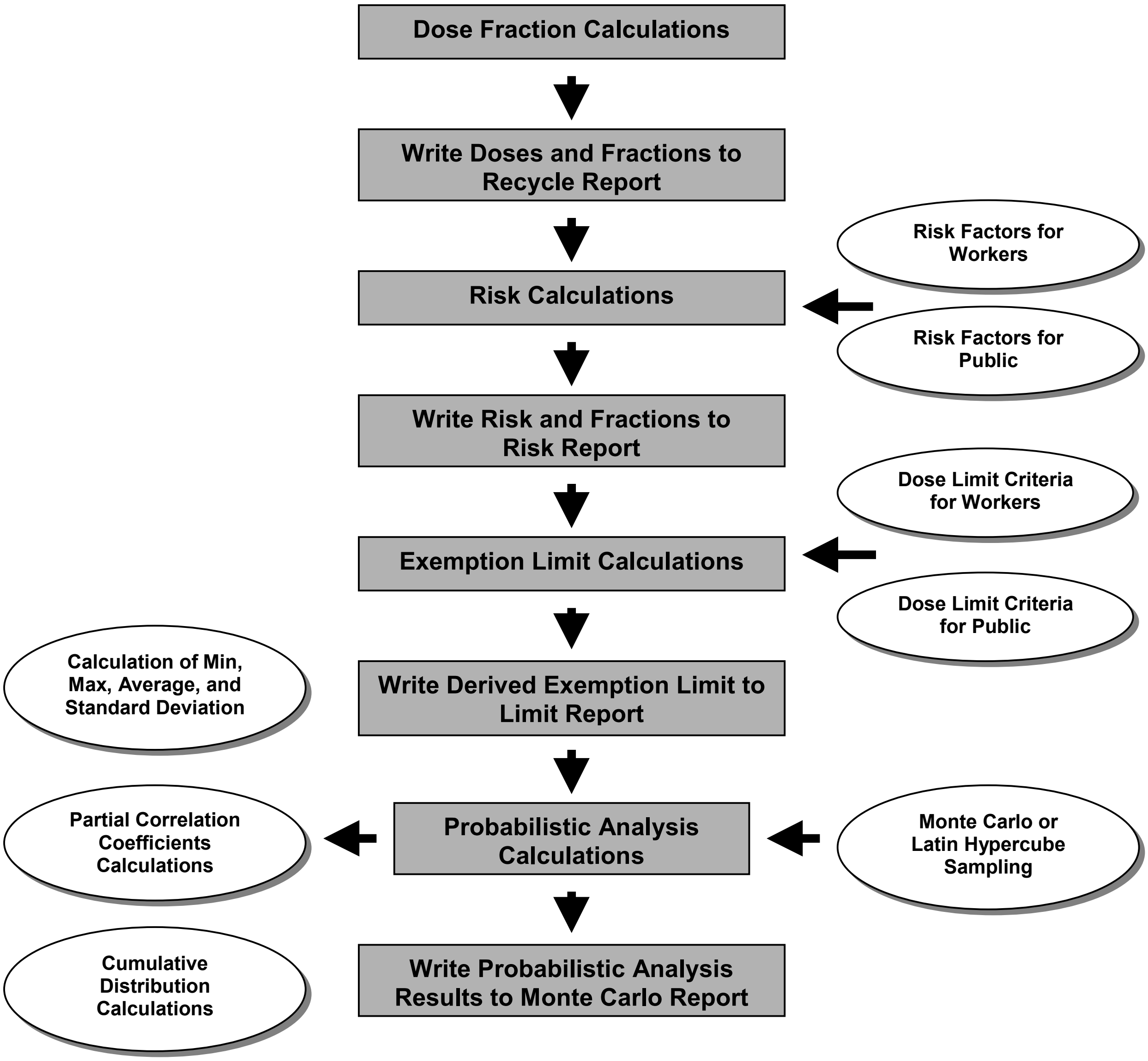

FIGURE 3.1 (Cont.) (PCFLOW3-L)

- Progeny radionuclides were included so that complete decay chains could be analyzed in dose calculations.

- Radionuclides found in smelted metal that originated from decontamination and decommissioning of nuclear facilities were included (Johnson 1993).

Table 3.1 lists the radionuclides included in the RESRAD-RECYCLE code and their related properties.

3.2 INTERNAL DOSE CONVERSION FACTORS

The RESRAD-RECYCLE code calculates inhalation and ingestion doses with the latest committed effective DCFs obtained from EPA FGR No. 11 (Eckerman et al. 1988). These DCFs were developed on the basis of recommendations in International Commission on Radiological Protection (ICRP) Publications 30 (1979–1988) and 48 (1986) for plutonium and related elements. The internal DCFs used in the code are listed in Table 3.1.

3.3 DECAY AND INGROWTH OF RADIONUCLIDES

Radioactive decay and ingrowth of progeny radionuclides are accounted for in the RESRAD-RECYCLE code. Initial decay of radioactivity before the start of the recycling process or use of a product is calculated with the following equation:

$$C_i = C_{i,0}\, e^{-\lambda\, t_{initial}} \quad , \qquad (3.1)$$

where

C_i = concentration of radionuclide i in the source at the time of recycling or use (Bq/g or pCi/g for volume contamination, $C_{i,v}$, and Bq/cm^2 or pCi/cm^2 for surface contamination, $C_{i,s}$);

TABLE 3.1 Half-Lives, Average Decay Factors over One Year, and Ingestion and Inhalation Dose Conversion Factors for Radionuclides Included in RESRAD-RECYCLE

Radionuclide[a]	Half-Life (yr)	Decay Factor over 1 Year	Dose Conversion Factor[b] (Sv/Bq)	
			Ingestion	Inhalation
Ac-227+D	2.18E+01	9.84E-01	4.00E-06	1.82E-03
Ag-110m+D	6.84E-01	6.29E-01	2.92E-09	2.17E-08
Am-241	4.32E+02	9.99E-01	9.84E-07	1.20E-04
Am-243+D	7.38E+03	1.00E+00	9.81E-07	1.19E-04
Ca-41	1.40E+05	1.00E+00	3.44E-10	3.64E-10
Ce-144+D	7.78E-01	6.62E-01	5.70E-09	1.01E-07
Cl-36	3.01E+05	1.00E+00	8.18E-10	5.93E-09
Cm-243	2.85E+01	9.88E-01	6.79E-07	8.30E-05
Cm-244	1.81E+01	9.81E-01	5.45E-07	6.70E-05
Cm-245	8.50E+03	1.00E+00	1.01E-06	1.23E-04
Cm-246	4.73E+03	1.00E+00	1.00E-06	1.22E-04
Cm-247	1.56E+07	1.00E+00	9.24E-07	1.12E-04
Co-57	7.42E-01	6.50E-01	3.20E-10	2.45E-09
Co-60	5.27E+00	9.37E-01	7.28E-09	5.91E-08
Cs-134	2.06E+00	8.49E-01	1.98E-08	1.25E-08
Cs-135	2.30E+06	1.00E+00	1.91E-09	1.23E-09
Cs-137+D	3.00E+01	9.89E-01	1.35E-08	8.63E-09
Eu-152	1.33E+01	9.74E-01	1.75E-09	5.97E-08
Eu-154	8.80E+00	9.62E-01	2.58E-09	7.73E-08
Fe-55	2.70E+00	8.82E-01	1.64E-10	7.26E-10
Mn-54	8.56E-01	6.85E-01	7.48E-10	1.81E-09
Na-22	2.60E+00	8.78E-01	3.10E-09	2.07E-09
Nb-94	2.03E+04	1.00E+00	1.93E-09	1.12E-07
Ni-59	7.50E+04	1.00E+00	5.67E-11	7.31E-10
Ni-63	9.60E+01	9.96E-01	1.56E-10	1.70E-09
Np-237+D	2.14E+06	1.00E+00	1.20E-06	1.46E-04
Pa-231	3.28E+04	1.00E+00	2.86E-06	3.47E-04
Pb-210+D	2.23E+01	9.85E-01	1.96E-06	6.26E-06
Pm-147	2.62E+00	8.79E-01	2.83E-10	1.06E-08
Pu-238	8.77E+01	9.96E-01	8.65E-07	1.06E-04
Pu-239	2.41E+04	1.00E+00	9.56E-07	1.16E-04
Pu-240	6.54E+03	1.00E+00	9.56E-07	1.16E-04
Pu-241+D	1.44E+01	9.76E-01	1.85E-08	2.23E-06
Pu-242	3.76E+05	1.00E+00	9.08E-07	1.11E-04
Ra-226+D	1.60E+03	1.00E+00	3.59E-07	2.32E-06
Ra-228+D	5.75E+00	9.42E-01	3.88E-07	1.37E-06
Ru-106+D	1.01E+00	7.24E-01	7.40E-09	1.29E-07
Sb-125+D	2.77E+00	8.85E-01	7.59E-10	3.30E-09
Se-79	6.50E+04	1.00E+00	2.35E-09	2.66E-09
Sm-151	9.00E+01	9.96E-01	1.05E-10	8.10E-09

TABLE 3.1 (Cont.)

Radionuclide[a]	Half-Life (yr)	Decay Factor over 1 Year	Dose Conversion Factor[b] (Sv/Bq) Ingestion	Inhalation
Sr-90+D	2.91E+01	9.88E-01	4.13E-08	3.54E-07
Tc-99	2.13E+05	1.00E+00	3.95E-10	2.25E-09
Th-229+D	7.34E+03	1.00E+00	1.09E-06	5.84E-04
Th-230	7.70E+04	1.00E+00	1.48E-07	8.80E-05
Th-232	1.41E+10	1.00E+00	7.38E-07	4.43E-04
U-232	7.20E+01	9.95E-01	3.54E-07	1.78E-04
U-233	1.59E+05	1.00E+00	7.81E-08	3.66E-05
U-234	2.45E+05	1.00E+00	7.66E-08	3.58E-05
U-235+D	7.04E+08	1.00E+00	7.21E-08	3.32E-05
U-236	2.34E+07	1.00E+00	7.26E-08	3.39E-05
U-238+D	4.47E+09	1.00E+00	7.27E-08	3.20E-05
Zn-65	6.68E-01	6.22E-01	3.90E-09	5.51E-09
Zr-93	1.53E+06	1.00E+00	4.48E-10	8.67E-08

[a] +D denotes that the contributions of decay radionuclides with half-lives of six months or less are included in the DCFs.

[b] Source: Eckerman et al. (1988).

$C_{i,0}$ = concentration of radionuclide i in the scrap metal at the time of measurement, i.e., the input concentration (Bq/g or pCi/g for volume contamination and Bq/cm^2 or pCi/cm^2 for surface contamination);

λ = radionuclide decay constant (yr^{-1}); and

$t_{initial}$ = initial time for decay before recycling or use (yr).

A weighting factor (average decay factor) is used in the code to account for radioactive decay over a one-year period and is also used to adjust the radionuclide concentrations at the beginning of recycle or usage. This factor represents the average fraction of activity present over one year and is calculated as follows:

$$F_{decay} = \left(1 - e^{-\lambda}\right) / \lambda \ , \tag{3.2}$$

where F_{decay} is the radionuclide average decay factor over one year (unitless) and λ is defined previously.

The average decay factors over one year for all radionuclides included in the code are shown in Table 3.1.

Ingrowth of progeny concentrations is calculated by using the Bateman equation; their dose contributions are included in the individual, collective, and cumulative doses for the parent radionuclide.

The collective dose is defined in the RESRAD-RECYCLE code as the sum of doses received by all exposed individuals over a one-year period.

The cumulative dose is defined as the collective dose received over the exposure duration. For worker scenarios, the cumulative dose is the same as the collective dose because the exposure duration is assumed to last for one year. For end-use product scenarios, the cumulative dose is the collective dose received over the lifetime of the products. In the cumulative dose calculation, the average concentration over the lifetime of the product is derived by using the following equation:

$$C_{i,lifetime} = C_{i,0} \int_{t_{initial}}^{t_{initial}+t_{product}} e^{-\lambda t}\, dt \Big/ t_{product} \ , \qquad (3.3)$$

where

$C_{i,\,lifetime}$ = average concentration of radionuclide i in the product over the lifetime of the product (Bq/g or pCi/g for volume contamination and Bq/cm^2 or pCi/cm^2 for surface contamination) and

$t_{product}$ = lifetime of the product (yr).

This average concentration over the product lifetime is evaluated in RESRAD-RECYCLE by using the trapezoidal rule of integration with 1,000 intervals.

3.4 RADIONUCLIDE PARTITIONING FACTORS

The smelting process generally results in three types of by-products: (1) ingot, (2) slag, and (3) dust. During melting operations, the radionuclides present in scrap metal distribute among these three by-products. Radionuclides with low boiling points, such as cesium, typically concentrate in the dust; those that oxidize easily tend to concentrate in slag. The distribution of radionuclides among the three by-products has not been extensively studied, and so far, almost all of the studies focus on steel. Data available in the literature also vary significantly. The distribution generally depends on the chemical properties of the radionuclides, the metallurgical composition of the scrap metal, the slag-forming substances added to the melt, the melting temperature, and the melting method.

Because of the considerable uncertainty in the radionuclide distribution, conservative values have been estimated; in many cases, the sum exceeds 100%. Tables 3.2 and 3.3 give the default radionuclide partitioning factors used in RESRAD-RECYCLE for steel and aluminum, respectively. The partitioning factors for steel are based on a review of recent available data and literature [Chapuis et al. (1987), Elert and Wiborgh (1992), IAEA (1992), Hertzler et al. (1993), Johnson (1993), OECD (1994), S. Cohen and Associates (1995), Nieves et al. (1995), Otis (1995)] and the authors' best engineering judgment. The partitioning factors for aluminum are based on thermodynamic considerations in the formation of metal oxides, the furnace operating temperature of 1,000 K, the boiling points of metals and metal oxides, and the authors' best engineering judgment. RESRAD-RECYCLE users are encouraged to use available data pertinent to the specific melting process under consideration.

3.5 MASS PARTITIONING FACTORS

The term *mass partitioning factor* refers to the fraction of throughput mass of the smelting process that gets into the smelting by-product. Ingot is the main by-product of the smelting process; depending on the source of the scrap, its mass can range from 40 to more than 90% of the throughput. The mass partitioning to the slag is affected by the mass partitioning to the ingot and can account for more than 10% of the throughput. Dust and off-gas generated by the furnace are collected in the baghouse. Some of the baghouse contents may be released to the atmosphere through a stack. The amount of radionuclides released from the stack depends on the efficiency of the filters at the facility and the volatility of the radionuclides. In general, gaseous

TABLE 3.2 Radionuclide Partitioning Factors Used in RESRAD-RECYCLE for Steel

	Partitioning Factor (%)		
Radionuclide	Ingot	Baghouse Contents	Slag
Ac-227	1	2	97
Ag-110m	0	100	0
Am-241	1	2	97
Am-243	1	2	97
Ca-41	0	10	90
Ce-144	1	1	98
Cl-36[a]	0	10	0
Cm-243	1	2	97
Cm-244	1	2	97
Cm-245	1	2	97
Cm-246	1	2	97
Cm-247	1	2	97
Co-57	100	1	1
Co-60	100	1	1
Cs-134	1	97	2
Cs-135	1	97	2
Cs-137	1	97	2
Eu-152	20	0.5	80
Eu-154	20	0.5	80
Fe-55	100	1	1
Mn-54	100	1	1
Na-22	0	80	20
Nb-94	2	1	98
Ni-59	100	1	1
Ni-63	100	1	1
Np-237	1	2	97
Pa-231	1	2	97
Pb-210[b]	0.6	0	0
Pm-147	2	0	98
Pu-238	1	2	97
Pu-239	1	2	97
Pu-240	1	2	97
Pu-241	1	2	97
Pu-242	1	2	97
Ra-226	1	2	97
Ru-106	0	0	100
Sb-125	5	0	95
Se-79	0	80	20
Sm-151	2	0	98
Sr-90	20	10	80
Tc-99	10	100	10
Th-228	0	0	100
Th-229	0	0	100
Th-230	0	0	100
Th-232	0	0	100

TABLE 3.2 (Cont.)

Radionuclide	Partitioning Factor (%) Ingot	Baghouse Contents	Slag
U-232	1	2	97
U-233	1	2	97
U-234	1	2	97
U-235	1	2	97
U-236	1	2	97
U-238	1	2	97
Zn-65	1	100	1
Zr-93	2	0	98

[a] 90% of Cl-36 is assumed to be released through a stack.

[b] 99.4% of Pb-210 is assumed to partition to the refractory (Johnson 1993).

Sources: Chapuis et al. (1987); Elert and Wiborgh (1992); IAEA (1992); Hertzler et al. (1993); Johnson (1993); OECD (1994); S. Cohen and Associates (1995); Nieves et al. (1995); Otis (1995).

radionuclides can be released through the stack completely. Off-gas and dust generated during the smelting operation can contaminate the entire smelting facility. Table 3.4 gives the default mass partitioning factors used in RESRAD-RECYCLE. Mass partitioning of the throughput varies from furnace to furnace; thus, users of the RESRAD-RECYCLE code are encouraged to use specific data pertaining to the furnace under consideration.

Because of partitioning of radionuclides and distribution of mass in the by-products, the concentrations of some radionuclides can be much higher in one of the by-products than the original concentrations in the scrap metal. The radionuclide concentrations in the various smelting by-products are derived as follows:

$$C_{i,by\text{-}product} = C_{i,scrap} \times RPF_i \times W_{scrap} \; / \; MPF_{by\text{-}product} \quad , \tag{3.4}$$

TABLE 3.3 Radionuclide Partitioning Factors Used in RESRAD-RECYCLE for Aluminum[a]

	Partitioning Factor (%)		
Radionuclide	Ingot	Baghouse Contents	Slag
Ac-227	100	1	10
Ag-110m	100	1	1
Am-241	5	1	100
Am-243	5	1	100
Ca-41	100	1	10
Ce-144	5	1	100
Cl-36[b]	0	10	0
Cm-243	5	2	100
Cm-244	5	1	100
Cm-245	5	1	100
Cm-246	5	1	100
Cm-247	5	1	100
Co-57	100	1	10
Co-60	100	1	10
Cs-134	5	100	1
Cs-135	5	100	1
Cs-137	5	100	1
Eu-152	5	1	100
Eu-154	5	1	100
Fe-55	100	1	10
Mn-54	100	1	10
Na-22	100	5	10
Nb-94	100	1	10
Ni-59	100	1	10
Ni-63	100	1	10
Np-237	100	1	10
Pa-231	100	1	10
Pb-210	100	1	10
Pm-147	5	1	10
Pu-238	10	1	100
Pu-239	10	1	100
Pu-240	10	1	100
Pu-241	10	1	100
Pu-242	10	1	100
Ra-226	10	1	100
Ra-228	10	1	100
Ru-106	100	1	10
Sb-125	100	1	10
Se-79	5	100	1
Sm-151	5	1	100
Sr-90	100	1	10
Tc-99	100	1	10
Th-228	5	1	100
Th-229	5	1	100
Th-230	5	1	100
Th-232	5	1	100

TABLE 3.3 (Cont.)

	Partitioning Factor (%)		
Radionuclide	Ingot	Baghouse Contents	Slag
U-232	10	1	100
U-233	10	1	100
U-234	10	1	100
U-235	10	1	100
U-236	10	1	100
U-238	10	1	100
Zn-65	100	5	10
Zr-93	5	1	100

[a] The partitioning factors were developed by comparing the oxidization potential of the elements with that of aluminum, and the boiling temperature of the element and its oxides with the assumed furnace operation temperature of 1,000 K. For conservative purposes, a sum of greater than 100% was used.

[b] 90% of Cl-36 is assumed to be released through a stack.

TABLE 3.4 Default Mass Partitioning Factors in RESRAD-RECYCLE

By-Product	Range	Default
Percentage for Steel		
Ingot	90–99	90
Slag	1–10	10
Baghouse[a]	0.2–2	1
Percentage for Aluminum		
Ingot	–	70
Slag	–	30
Baghouse	–	1

[a] 0.003 to 0.06% released to the atmosphere through a stack.

Sources: CEC (1988); Sappok (1989); Elert and Wiborgh (1992); IAEA (1992); SAIC (1994); S. Cohen and Associates (1995).

where

$C_{i,by\text{-}product}$ = concentration of radionuclide *i* in the by-product (ingot, slag, or baghouse) (Bq/g or pCi/g);

$C_{i,scrap}$ = concentration of radionuclide *i* in scrap (Bq/g or pCi/g);

RPF_i = radionuclide *i* partitioning factor (unitless);

W_{scrap} = dilution factor of scrap metal to account for fraction of contaminated scrap metal to the total amount of scrap metal fed to the smelter (unitless); and

$MPF_{by\text{-}product}$ = mass partitioning factor of the by-product (unitless).

3.6 THROUGHPUT CONSIDERATIONS

The amount of radioactive scrap metal that is recycled (throughput) affects the exposure duration for workers and the number of workers involved in each step of the recycling process. Moreover, the number of exposed individuals in the end-use product scenarios is also affected. RESRAD-RECYCLE takes into account the influence of throughput on radiation exposure for the various worker and end-use product scenarios.

For worker scenarios, the collective exposure duration is assumed to vary linearly with the amount of throughput; by default, the number of workers is fixed and the exposure duration of each worker is adjusted linearly. The limit on the exposure duration for the individual worker is assumed to be 2,000 hours per year. If the exposure duration is greater than 2,000 hours per year, a value of 2,000 hours per year is used, and the code increases the required number of workers accordingly.

For the transportation scenarios considered in the scrap delivery and product delivery steps, the number of trucks, or the number of drivers, is assumed to be fixed. The code then linearly adjusts the exposure duration to reflect the change in the throughput mass.

For end-use product scenarios, the adjustment to reflect changes in the throughput mass is limited to the number of exposed individuals. The exposure duration in these scenarios is related to the use of the products and, therefore, is not adjusted. RESRAD-RECYCLE assumes that the result of recycling of more scrap is the generation of more products. Therefore, it adjusts the number of exposed individuals linearly with the throughput mass. Scenarios pertinent to the reuse of surface-contaminated material and equipment are not affected by the throughput of scrap metal, because the material and equipment are reused directly and do not involve the smelting of scrap metal.

3.7 VOLUME CONTAMINATION METHODOLOGY

Radiation doses assessed for scenarios that model volume contamination of scrap metal include contributions from the inhalation, ingestion, and external exposure pathways. Calculations for these pathways are described below.

3.7.1 Inhalation Pathway

The radiation dose from the inhalation of airborne radioactive particulates generated from volume-contaminated metal is calculated as follows:

$$CEDE_{inh,i} = C_{i,v} \times IR \times AD \times ED \times DCF_{inh,i} \times F_{decay,i} \times W_v \times RPF_i \times PF \times RF / MPF \ , \qquad (3.5)$$

where

$CEDE_{inh,i}$ = committed effective dose equivalent from inhalation of radionuclide i (Sv or rem);

$C_{i,v}$ = concentration of radionuclide i in the volume source (Bq/g or pCi/g);

IR = inhalation rate (m^3/h);

AD = airborne-dust-loading factor (g/m^3);

ED = exposure duration (h);

$DCF_{inh,i}$ = inhalation DCF for radionuclide i (Sv/Bq or rem/pCi);

$F_{decay,i}$ = radionuclide i average decay factor over one year (unitless);

W_v = dilution factor to account for dilution of contaminated metal with clean material in the source (unitless);

PF = respiratory protection factor (unitless); and

RF = respirable fraction (unitless).

The concentration of radionuclide i in the volume source, $C_{i,v}$, can be that in the scrap metal, $C_{i,scrap}$, or that in one of the smelting by-products (ingot, baghouse, or slag), $C_{i,by\text{-}product}$, depending on the material that the worker handles or the user uses, or the material from which dust particles are assumed to originate. Source materials considered in the dose calculations are listed in Tables 2.2–2.5.

A critical parameter in determining the radiation exposure from inhalation is the concentration of respirable dust in the air. This parameter depends on many factors, including ventilation rate, activities that create dust suspension, size distribution of dust particles, and the amount of material being handled during the activities. Because little information is available about the amount of respirable dust in air, this parameter is estimated by using an airborne-dust-loading factor and a respirable-fraction factor. The airborne-dust-loading factor, that is, airborne particulate concentration, generally ranges from 5.0×10^{-5} g/m^3 for a residential scenario (Kennedy and Strenge 1992) to 1.8×10^{-3} g/m^3 for a coal mining scenario (Oztunali et al. 1981). A value of 1.0×10^{-3} g/m^3 is used in RESRAD-RECYCLE as an upper-bound value for some of the worker scenarios. For scenarios that have less potential for creating dust suspension, a fraction of the upper-bound value is used as a default. This default value is consistent with those used by the IAEA (1992). The default value used for the respirable fraction is 0.1, whereas that for the inhalation rate is 1.2 m^3/h (ICRP 1975). For workers, a respiratory protection factor is used to account for the efficiency of the respiratory mask. For conservation, the default respiratory protection factor is 1.0 (i.e., no respirator is assumed). Discussion of the inhalation rate and dust loading factor can be found in the data collection handbook for the RESRAD code (Yu et al. 1993b).

3.7.2 Ingestion Pathway

The ingestion dose can be acquired by two exposure routes: (1) through inhalation of airborne particulates larger than the respirable size and (2) through incidental ingestion of dust particles deposited on the hands. The first route accounts for the dust particles being inhaled through the nostrils and gaining access to the gastrointestinal tract. The incidental ingestion dose from volume contamination is based on a mass ingestion rate. The ingestion dose is evaluated as follows:

$$\begin{aligned} CEDE_{ing,i} = {} & C_{i,v} \times IR \times AD \times ED \times DCF_{ing,i} \times F_{decay,i} \\ & \times W_v \times RPF_i \times PF \times (1 - RF) / MPF + C_{i,v} \times IG_v \times ED \\ & \times DCF_{ing,i} \times F_{decay,i} \times W_v \times RPF_i / MPF \quad , \end{aligned} \tag{3.6}$$

where

$DCF_{ing,i}$ = ingestion DCF for radionuclide i (Sv/Bq or rem/pCi) and

IG_v = incidental ingestion rate for volume contamination (g/h).

The concentration of radionuclide i in the volume source, $C_{i,v}$, is the same as that used for the inhalation pathway. It varies among different scenarios and can be either $C_{i,scrap}$ or $C_{i,by\text{-}product}$. The source materials considered in the dose calculations are listed in Tables 2.2–2.5 for different scenarios and metals.

An incidental ingestion rate of 0.00625 g/h is used as a default value for the worker scenarios for which incidental ingestion is considered.. This ingestion rate is recommended by the EPA for adults in an occupational setting (EPA 1991). For the frying-pan scenario, the ingestion rate is derived from the size of the frying pan and the input corrosion rate of the metal. RESRAD-RECYCLE uses a default value of 0.013 cm/yr for the corrosion rate (IAEA 1992). It is assumed that 50% of the corroded material would be ingested by the user of the frying pan. The ingestion rate for the frying-pan scenario is calculated as follows:

$$IG_{pan} = A_{pan} \times CR \times \rho \times 0.5 \;/\; 8{,}760 \quad , \tag{3.7}$$

where

IG_{pan} = ingestion rate for the frying-pan scenario (g/h);

A_{pan} = surface area of the frying pan (cm^2);

CR = corrosion rate of metal (cm/yr);

ρ = density of frying-pan material (g/cm^3);

8,760 = conversion factor (h/yr); and

0.5 = 50% of the corroded material is ingested.

3.7.3 External Pathway

Each contaminated volume contributes to the external exposure. In RESRAD-RECYCLE, multiple contaminated volumes are considered for the various sides of a contamination source. For example, in the automobile scenario for public products, a radiation source with four contaminated sides is considered in the default case. Each contaminated side can be modeled as either a full or a half cylinder. Like radiation doses calculated for the inhalation and ingestion pathways, the radiation dose calculated for the external pathway is obtained by using external DCFs, which are calculated for each contaminated volume. The DCFs depend on the material in the radiation source, size of the radiation source (i.e., radius and thickness), and distance (i.e., parallel and perpendicular) between the receptor and the contaminated volume being considered. Figure 3.2 shows the relative position between the

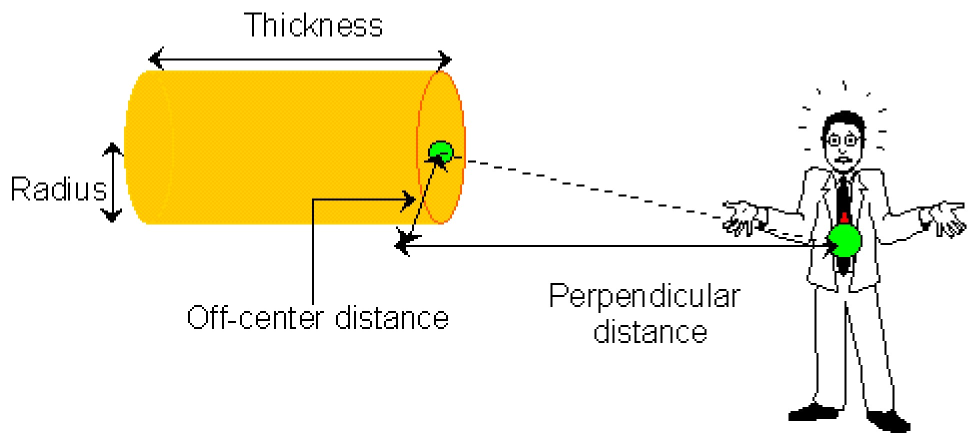

FIGURE 3.2 Illustration of the Relative Position between the Volume Source and the Receptor

contaminated volume and the receptor considered in the RESRAD-RECYCLE code. In addition to source geometry, material characteristics, and exposure distance, RESRAD-RECYCLE also takes into account the potential attenuation of the radiation dose caused by shielding materials. The user can specify the type of shielding material and its density and thickness for consideration when the external dose is calculated.

The methodology used in RESRAD-RECYCLE for calculating external DCFs is the same as that used in RESRAD; its development is based on the latest EPA external DCFs (Eckerman and Ryman 1993). A detailed discussion of the methodology for calculating external DCFs is provided in Kamboj et al. (1998).

The external dose incurred by the receptor is calculated with the following equation:

$$EDE_{ext,i} = C_{i,v} \times ED \times \left(\sum_{nside} DCF_{ext,i,nside} \right) \times F_{decay,i} \times W_v \times RPF_i \,/\, MPF \,, \tag{3.8}$$

where

$EDE_{ext,i}$ = effective dose equivalent from external exposure to radionuclide i (Sv or rem);

$DCF_{ext,i,nside}$ = external DCF for radionuclide *i* from the *n*th side of the source ([Sv/h]/[Bq/g] or [rem/h]/[pCi/g]); and

$nside$ = *n*'th side of the source (unitless).

The source concentration, $C_{i,v}$, varies among different scenarios. It can be either $C_{i,scrap}$ or $C_{i,by\text{-}product}$. Tables 2.2–2.5 list the radiation sources considered for the external pathway in different scenarios.

3.8 SURFACE CONTAMINATION METHODOLOGY

Radiation exposure from surface-contaminated materials is assessed for the reuse scenarios. The inhalation, ingestion, and external exposure pathways are considered. The radiation source is assumed to be inside a room; consequently, the air concentrations of radionuclides are affected by the room ventilation system.

3.8.1 Inhalation Pathway

The inhalation dose from surface contamination, which is calculated by using an emission rate (h^{-1}) (Healy 1971), accounts for dilution of the air concentration by the ventilation system. The effective dose equivalent is calculated as follows:

$$CEDE_{inh,i} = C_{i,s} \times A_s \times ER \times IR \times PF \times RF \times ED \times DCF_{ing,i}$$
$$\times F_{decay,i} \times W_s \;/ (V \times k) \ , \qquad (3.9)$$

where

$C_{i,s}$ = concentration of radionuclide *i* on the surface (Bq/cm^2 or pCi/cm^2);

A_s = surface area of the source (cm^2);

ER = emission rate (h^{-1});

W_s = surface transfer fraction, i.e., fraction of contaminants available for emission (unitless);

V = volume of the room (m^3); and

k = ventilation rate (h^{-1}).

The default value for the inhalation rate used in the code is 1.2 m^3/h (ICRP 1975), and that for the emission rate is 1×10^{-6}/h (Healy 1971).

3.8.2 Ingestion Pathway

Ingestion of radionuclides that are the result of surface contamination is possible through two exposure routes: (1) inhalation of air particulates larger than the respirable size and (2) incidental ingestion of dust deposited on the hands. The incidental ingestion dose from surface contamination is based on a surface ingestion rate. The ingestion dose is calculated as follows:

$$CEDE_{ing,i} = C_{i,s} \times A_s \times ER \times IR \times PF \times (1 - RF) \times ED \times DCF_{ing,i} \times F_{decay,i} \times W_s \,/\, (V \times k) + C_{i,s} \times IG_s \times ED \times DCF_{i,ing} \times F_{decay,i} \times W_s \quad , \tag{3.10}$$

where

$CEDE_{ing,i}$ = committed effective dose equivalent from ingestion of radionuclide i (Sv or rem);

$DCF_{ing,i}$ = ingestion DCF for radionuclide i (Sv/Bq or rem/pCi); and

IG_s = ingestion rate of removable surface contamination (cm^2/h).

RESRAD-RECYCLE uses a default value of 1 cm^2/h for the ingestion rate for surface contamination scenarios.

3.8.3 External Pathway

Each contaminated surface contributes to the external exposure. In RESRAD-RECYCLE, multiple contaminated surfaces are modeled for the various sides of a contamination source. Each contaminated side can be modeled as either a full or half disk. Like the radiation doses calculated for the inhalation and ingestion pathways, the radiation dose calculated for the external pathway is obtained by using external DCFs. An external DCF is calculated for each contaminated surface and depends on the size of the radiation source and distance (i.e., parallel and perpendicular) between the receptor and the contaminated surface being considered. In addition to source geometry and exposure distance, RESRAD-RECYLE also takes into account the potential attenuation of the radiation dose caused by shielding materials. The user can specify the type of shielding material and its density and thickness for consideration when the external dose is calculated.

The DCF for a contaminated surface is calculated by using the same methodology for a contaminated volume and assuming a very small thickness (0.01 cm). The external exposure is calculated with the following equation:

$$EDE_{ext,i} = C_{i,s} \times ED \times DCF_{ext,i} \times F_{decay,i} \quad , \tag{3.11}$$

where

$EDE_{ext,i}$ = effective dose equivalent from external exposure to radionuclide i (Sv or rem) and

$DCF_{ext,i}$ = external DCF for radionuclide i ([Sv/h]/[Bq/cm^2] or [rem/h]/[pCi/cm^2]).

3.9 COLLECTIVE-DOSE CALCULATION

The collective dose for both worker and end-use-product scenarios is calculated by multiplying the individual dose that is representative of the population by the size of the population, that is, by the number of exposed individuals. Two exposure times are used in RESRAD-RECYCLE to estimate individual dose; one for the maximally exposed individual

(MEI), to obtain the upper bound of the individual dose; and one for the representative individual in the population, to obtain the collective dose. Depending on the scenario under consideration, these two exposure times may differ.

For the consumer product scenarios, the number of exposed individuals is pertinent to the assumption that 100% of the slag or ingot from the smelter is used to produce the specific product modeled in the scenario. Therefore, when the slag or ingot distribution to the specific product is less than 100%, the collective dose is further multiplied by the distribution percentage.

3.10 CUMULATIVE-DOSE CALCULATION

For end-use-product scenarios, the cumulative dose is the integrated population dose delivered over the lifetime of the end-use products. The average activity concentration over the lifetime of the product (see Section 3.3 for the average concentration calculation) is obtained, and then it is multiplied by the lifetime of the product to get the integrated activity concentration for use in the dose calculation. As for the collective-dose calculation, the distribution of the smelting product (ingot or slag) in the various consumer products is taken into account when the cumulative dose is calculated. For worker scenarios, the cumulative dose is equivalent to the collective dose because the exposure duration is one year.

3.11 TRANSPORTATION METHODOLOGY

The transportation scenario addresses the external dose to members of the public that reside along routes traveled by trucks loaded with radioactive scrap metal. For a truck loaded with 20 t of scrap metal, external DCFs were derived in terms of dose per unit concentration per unit population density per unit velocity per unit time traveled. The derivations of the DCFs were based on the methodologies of RISKIND (Yuan et al. 1993) and RADTRAN (Neuhauser and Kanipe 1993), computer codes designed specifically to estimate radiation doses that result from the transport of radioactive materials. Because the transport of scrap metal would occur before the smelting operations, concentrations of radionuclides in scrap metal are used directly without adjustment by the partitioning factors. The collective dose is calculated as follows:

$$CEDE_{ext,i} = C_{i,s} \times DCF_{ext,i} \times F_{decay,i} \times \rho_{pop} \times (D/Vel) \times (throughput/20) \ , \qquad (3.12)$$

where

$CEDE_{ext,i}$ = collective effective dose equivalent from external exposure to radionuclide *i* (person-Sv or person-rem);

$DCF_{ext,i}$ = external DCF for radionuclide *i* (Sv/h per Bq/g per person/m^2 or rem/h per pCi/g per person/m^2);

ρ_{pop} = population density (person/m^2);

D = distance traveled by truck (km);

Vel = truck velocity (km/h); and

throughput = throughput or amount of metal recycled (t).

3.12 CANCER RISK CALCULATION

Potential cancer risks from radiation exposure are calculated in the RESRAD-RECYCLE code by multiplying the radiation doses by latent cancer incidence risk factors. The default values for the risk factors (0.0567/Sv for workers and 0.076/Sv for the public) correspond with EPA recommendations (EPA 1991); however, the user has the option of entering other risk factors for the risk calculation. These risk factors are accessible by selecting “risk parameters” under the “file” menu item.

3.13 TOTAL IMPACT FROM RECYCLING

The total impact on workers from processing radioactive scrap metal is calculated by summing the cumulative (collective) doses for all the selected worker scenarios. Similarly, the total impact on end-product users is calculated by summing the collective and cumulative doses, respectively, for all the selected product scenarios. Users are advised to select scenarios that are applicable to the recycling process being considered. The estimated total impact on the end-product users, however, is meaningful only when the sum of the distribution percentages (for both ingot and slag, respectively) for all the considered products is 100%.

3.14 SCENARIO RANKINGS

After the calculations have been completed, the scenarios are ranked in descending order according to individual, collective, or cumulative dose. A scenario in which an individual dose ranks as 1, therefore, could potentially result in the highest MEI dose. These scenario rankings are listed in the summary report generated by RESRAD-RECYCLE.

3.15 RELEASE-CRITERIA DERIVATION

The release criteria for scrap metal calculated by RESRAD-RECYCLE satisfy the given dose limits set for individual and population exposures. In other words, scrap metal with contamination levels less than the release criteria would not lead to individual and population exposures greater than the set dose limits, once the scrap metal has been released for reuse or recycle. The code allows the user to enter distinct dose limits for four groups of receptors: the individual worker, the worker population, the individual member of the public, and the general public. These dose limits can be accessed by selecting “risk parameters” under the “file” menu item. The release criteria are calculated for each radionuclide and each scenario as follows:

$$L_{i,k} = H_k \, C_i \, / \, Dose_{i,k} \quad , \tag{3.13}$$

where

$L_{i,k}$ = derived release criteria for radionuclide i and receptor k (Bq/g or Bq/cm^2 or pCi/g or pCi/cm^2);

$Dose_{i,k}$ = estimated radiation dose for radionuclide i and receptor k (Sv or rem for individual receptors and person-Sv or person-rem for collective receptors); and

H_k = radiation dose limit for receptor k (Sv or rem for individual receptors and person-Sv or person-rem for collective receptors.)

The release criterion estimated for each end-product scenario is meaningful only when the distribution percentage (slag or ingot) to that product is 100%.

3.16 PROBABILISTIC ANALYSIS

For a mathematical model, probabilistic analysis is the computation of statistical variance in the output results that is induced by the variance in the input parameters. It is imortant to quantify variance in the output results when performing an analysis in which parameters with potentially differing values must be used and combined. In a probabilistic analysis, information about distribution of the input parameters must be provided before distribution of the output results can be calculated. In addition to analyzing the distribution of output results, this type of analysis also determines the contributions to the variance in the output results by the variance in the individual input parameters. Therefore, the probabilistic analysis can be used to help decide whether resources should be expended to obtain additional information or data to reduce variance in the input parameters.

The RESRAD-RECYCLE code is designed to perform probabilistic analysis to examine the effects of input parameter variance on the potential radiation doses of various receptors. A standard Monte Carlo method or modified Monte Carlo method, that is, Latin hypercube sampling (LHS) (Iman and Shortencarier 1984), can be applied to generate differing sets of input data. Each set of input data is used to generate one set of output data. The output data sets are then analyzed and presented in a statistical format in terms of cumulative distribution of radiation dose, average radiation dose, standard deviation of the radiation dose, minimum radiation dose, and maximum radiation dose.

3.16.1 Distribution of Input Parameters

A set of input parameters can be selected for analysis through the code's interface. Each selected parameter must be assigned a probability distribution function and can be correlated with other input parameters included in the analysis. Table 3.5 lists the distribution functions and the pertinent parameters that characterize the distributions considered by the RESRAD-RECYCLE code. Figure 3.3 shows graphs of various distribution functions.

TABLE 3.5 Distribution Functions Considered by RESRAD-RECYCLE

Distribution Functions	Parameter Distribution	Parameter Description
Normal	Mean (μ) and standard deviation (σ)	Cutoffs of the normal distribution are taken to be ±3.09 σ from the mean.
Lognormal	Minimum and maximum values	The specified minimum and maximum values are the logarithms of the cutoffs of the input parameter. Normal distribution of the input parameter is observed within the range of the cutoffs.
Uniform	Minimum and maximum values	Equal probability within the specified range on linear scale.
Loguniform	Minimum and maximum values	Equal probability within the specified range on a logarithmic scale. The specified values must be > 0.
Triangular	Minimum value (a), peak value (b), and maximum value (c)	Three cases are possible: $a < b < c$, $a \leq b < c$, or $a < b \leq c$.

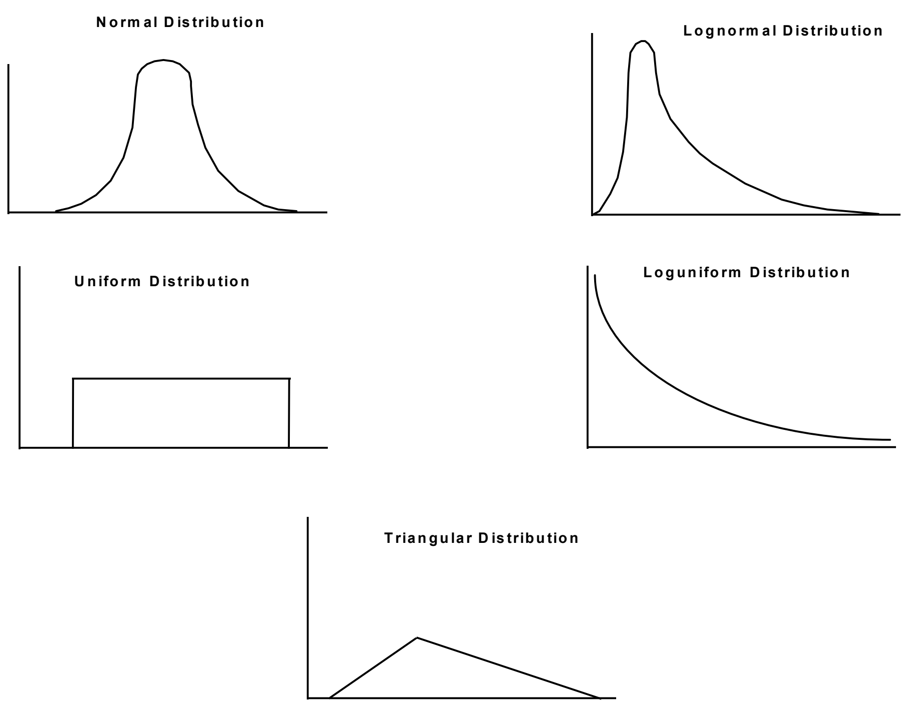

FIGURE 3.3 Plots of Distribution Functions Available in RESRAD-RECYCLE (PCDIST-L)

One input parameter can be correlated with another input parameter by specifying a correlation factor. The larger the absolute value of the correlation factor, the stronger the correlation between the input parameters. A negative correlation indicates that while the value of one parameter increases, the value of the other parameter decreases. Positive correlation indicates the opposite trend. Correlation between the selected input parameters is handled in RESRAD-RECYCLE with the rank correlation method, which is discussed in the following section.

3.16.2 Sampling Method

Values for the input parameters are generated by the preprocessor of the RESRAD-RECYCLE code, which is adapted from a computer code developed by Iman and Shortencarier (1984). The interface screens of RESRAD-RECYCLE collect all of the information necessary for generating various sets of input data, such as initial seed value for the random number generator, number of observations, number of sampling repetitions, type of distribution, characteristic parameters of the distribution, and correlation factors between input parameters. The number of samples generated is the product of the number of observations, N_{obs}, and the number of repetitions, N_{rep}.

The LHS method, a constrained sampling method developed by McKay et al. (1979), divides the distribution range of each input parameter into N_{obs} nonoverlapping regions on the basis of equal probability according to the distribution characteristics. One value in each region is randomly selected with respect to the probability density over that region. After N_{obs} samples of the input parameter have been selected, the process is repeated first for the second parameter and then for the remainder of the selected parameters. The samples of the first parameter are randomly grouped (equally likely combinations) with the samples of the second parameter. If no correlation is observed, these N_{obs} pairs of data are combined with the samples from the next parameter in a random manner. This technique of randomly grouping samples is repeated to include all input parameters considered in the analysis. The result is N_{obs} sets of input data. The sampling and grouping procedures are repeated N_{rep} times. Therefore, a total of $N_{rep} \times N_{obs}$ sets of data are available for calculating dose.

LHS is a constrained sampling method because one distinct value is selected from each region of equal probability. However, if the number of observations is set to one, the entire distribution range is not partitioned; therefore, a standard Monte Carlo sampling method is performed.

The random grouping among parameters is not applied if the user chooses to correlate the parameters. Because data correlation is difficult and complicated to implement, correlation is based on the ranks of the data. The generated data of each parameter are ranked by their values. The parameter with the smallest value is assigned a rank of 1; the one with the largest value is assigned a rank of N_{obs}. Grouping of data among input parameters is implemented according to some specific orders, which then would lead to a rank correlation factor close to the specified value.

The rank correlation method is easy to implement and especially useful for mathematical models in which the relationships between input parameters and output results are nonlinear. Further information on the rank correlation method and its implementation in the RESRAD-RECYCLE code can be found in Davenport and Iman (1982).

The random grouping of input parameters can lead to undesired correlations. Such correlations can be reduced by implementing the restricted-pairing technique among the sampling data, as discussed in the rank correlation method, or by increasing the number of observations for data sampling. To use the restricted sampling technique, N_{obs} must be greater than the number of selected parameters (*K*). According to Iman and Helton (1985), good results can be obtained with $N_{obs} \geq (4/3)\ K$; however, this is not an absolute rule. If the model is inexpensive to run, N_{obs} could be larger, e.g., between 2 and 5 *K*.

3.16.3 Cumulative Probability of Potential Doses

The RESRAD-RECYCLE code calculates the cumulative probabilities of the individual, collective, and cumulative doses for all radionuclides. The cumulative probability at a certain dose value is a measure of the likelihood of which dose value would not be exceeded. Calculation results, presented in tabular form, list radiation doses that correspond to specified cumulative probabilities. The increment of the specified cumulative probabilities is 0.025, or 2.5%. Thus, 40 (100/2.5) dose values are presented regardless of the sampling size. In addition to the tabular form, graphical presentation is provided.

3.16.4 Correlation between Radiation Doses and Input Parameters

The linear regression method is used to evaluate the correlation between the resultant doses and the input parameters selected for probabilistic analysis. A linear relationship is assumed between the resultant dose and the input parameters. The standardized regression coefficient is calculated with the standardized values (i.e., [actual value-mean]/[standard deviation]) of the input parameters and the total dose (Iman et al. 1985). These coefficients provide a direct measure of the importance of each input parameter to the total dose, regardless of the units being used for the input parameters.

The regression coefficients of the input parameters are ranked to determine the relative influence of the input parameters on the results. The correlation ranking of the input parameters is based on the absolute value of the standardized regression coefficients; a rank of 1 is assigned to the variable with the highest value. Thus, a parameter with a correlation rank of 1 has the strongest influence on the total dose. The correlation rank is set to 0 if the regression coefficient is 0 or if the resultant correlation matrix is singular.

The RESRAD-RECYCLE code also calculates the coefficient of determination of the regression analysis. The coefficient of determination is defined as the ratio between the variation in the resultant dose caused by regression in the input parameters and the total variation in the resultant doses. Therefore, it provides a measure of the percentage of variation in the dose explained by regression of the input parameters and varies between 0 and 1. The coefficient of determination provides a convenient way to measure the adequacy of the regression model.

4 USER'S GUIDE

4.1 INSTALLING RESRAD-RECYCLE

RESRAD-RECYCLE, available on two 1.44-megabyte (MB), 3.5-in. diskettes, is a self-installing program in the Windows environment and requires a minimum of a Microsoft Windows 3.1 operating system, an 80386 processor-based computer with a math coprocessor, and 3 MB of hard disk space. The code can be installed by inserting the diskette into the appropriate floppy disk drive (a: or b:). For the Windows 3.1 operating system, the *File* menu must be chosen and the *Run* option selected from the Program Manager or File Manager. For the Windows 95 or later operating system, *Start* must be selected, then the *Run* option chosen; or, the *My Computer* icon must be selected, then the appropriate floppy disk drive chosen. The SETUP.EXE program can be run from the drive that contains the RESRAD-RECYCLE diskette (e.g., a:SETUP). The SETUP program displays a screen that shows the status of the installation.

When the installation is complete in the Windows 3.1 operating system, a new RESRAD-RECYCLE icon is placed in the RESRAD Group, which is created if not present, under the Program Manager. For the Windows 95 or later operating system, when the installation is complete, a new RESRAD-RECYCLE option is placed in the RESRAD program group under the programs list; the RESRAD program group is created if not present.

The code is fully Windows compatible and allows data entry and scenario selection, text and graphical results display, and file opening and saving in a user-friendly environment.

4.2 RUNNING RESRAD-RECYCLE

Double-clicking the RESRAD-RECYCLE icon (option) starts the program. The first screen provides simple information about the code. The next screen is the code's main graphical screen.

The main graphical screen (Figure 4.1) displays a modular diagram of the various steps that are modeled in the recycling of radioactive scrap metal. The input box in the upper left corner contains the case title. Clicking any module icon in the graphical main screen opens

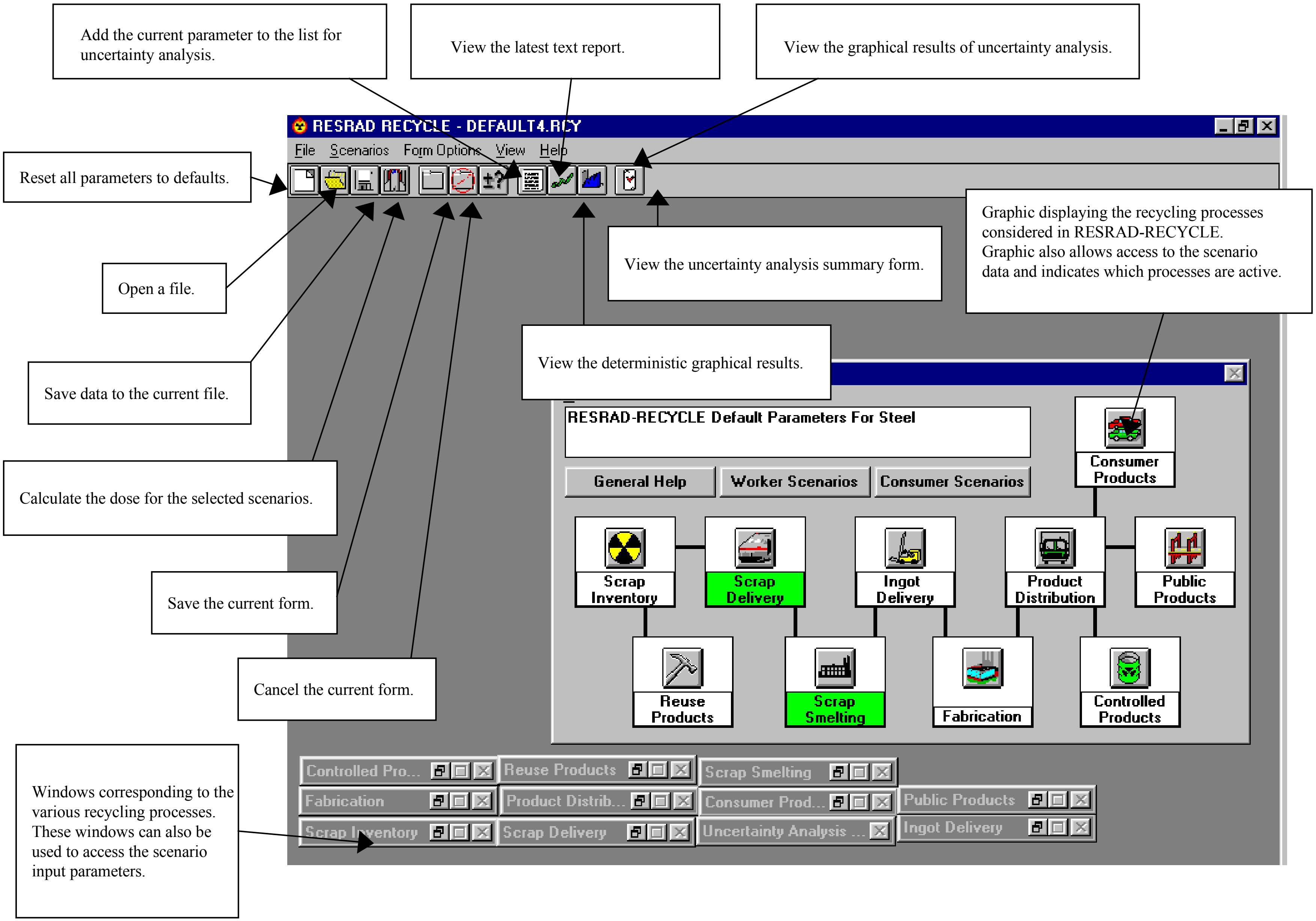

FIGURE 4.1 RESRAD-RECYCLE Main Graphical Screen

another screen for entering data, selecting a scenario, or opening associated input. The scrap inventory module allows the user to select radionuclides and to specify activity concentrations and throughput for scrap metal. The other modules, which correspond to the various recycling steps, from initial transport of scrap metal to the use of end products, permit the user to select various scenarios for dose analysis and to modify the input parameters used in the analysis. The scrap smelting module also allows the user to specify mass and radionuclide partitioning factors for the smelting process.

The menu bar at the top of the main screen contains five options: *File* for managing files, *Scenarios* for selecting recycling steps for consideration, *Form Options* for handling data input forms, *View* for viewing calculation results, and *Help* for accessing on-line help. These items and the associated options can be activated by clicking the left mouse button when the option is highlighted, or by pressing both the *Alt* key and the underlined letter on the keyboard. Table 4.1 provides a complete list of the RESRAD-RECYCLE menu options.

4.2.1 Using the Button Bar

RESRAD-RECYCLE includes a button bar, located below the menu bar at the top of the screen, that contains several buttons for the most frequently used menu options. Clicking the button has the same effect as choosing the corresponding option from the menu bar. Choosing *Button Prompts* from the View menu option displays prompts that briefly explain the function of each button as the mouse pointer moves over the button. The function of each button is explained in Figure 4.1.

4.2.2 Entering the Radionuclide Inventory

The first module of the RESRAD-RECYCLE main graphical screen is “Scrap Inventory.” Clicking this module opens the inventory input window (Figure 4.2). This window can also be accessed by double-clicking the *Scrap Inventory* button bar at the bottom of the main screen.

The Scrap Inventory Input window contains data concerning parameters that apply to the overall scrap inventory, such as scrap metal type, throughput of scrap metal to be recycled, and

TABLE 4.1 RESRAD-RECYCLE Main Menu Options[a]

Item	Option	Access Key	Function
File	New		Resets all input parameters to the default value.
	Open	Ctrl-O	Opens a new data file.
	Save	Ctrl-S	Saves the current data to the current data file.
	Save As	Ctrl-A	Allows the current data to be saved to a new data file.
	Calculate Dose	Ctrl-R	Calculates doses and risks for the current case.
	Risk Parameters		Allows dose limit and risk parameters to be modified.
	Exit		Exits the RESRAD-RECYCLE program.
Scenarios	Edit		Brings up the scenario input window for editing.
	On/Off		Toggles on or off the recycling step.
	Select All Scenarios		Selects all exposure scenarios for analysis.
	Deselect All Scenarios		Deselects all exposure scenarios included in the current case.
Form Options	Save Current Form	Ctrl-K (F10)	Accepts the values of and closes the current input form.
	Cancel Current Form	Ctrl-U (Esc)	Cancels changes made and closes the current input form.
	Uncertainty Analysis	F8	Adds the current parameters to the list for uncertainty analysis.
View	Text Output		Allows text reports to be viewed.
	Graphical Output		Allows graphical output to be viewed.
	Message Log	Ctrl-E	Displays the latest diagnostic information from the calculations.
	Uncertainty Summary	Ctrl-F8	Toggles the visibility of the uncertainty analysis summary form.
	Button Prompts		Toggles the mouse cursor button prompts.
Help	General Help	F1	Provides overall help for navigating through the code.
	Context Sensitive Help	F2	Provides help for the current parameter or scenario.
	Help for the Current Form		Provides help for the current process module form.
	Worker Scenarios		Provides overall help for all worker scenarios.
	Consumer Scenarios		Provides overall help for all end-product scenarios.
	About RESRAD-RECYCLE	F3	Shows the “about” form for RESRAD-RECYCLE.

[a] The options listed under each menu item can be selected by pressing the mouse button while the option is highlighted or by entering the access key listed in this table.

the radionuclides present in the scrap metal. The scrap metal type can be selected by clicking the dropdown box and selecting the appropriate material type. When the material type is changed, the default parameter values are loaded for that material type. In addition, the user can click the *Adjust Population for Throughput* button. This option allows the code to change the default exposure duration (for worker scenarios) and the number of people exposed (end-product scenarios) to reflect the input throughput value (see the discussion on Throughput Considerations in Section 3.6). The user can also apply an initial decay time and a dilution fraction for all selected scenarios by entering the desired values and clicking the corresponding *Reset* buttons.

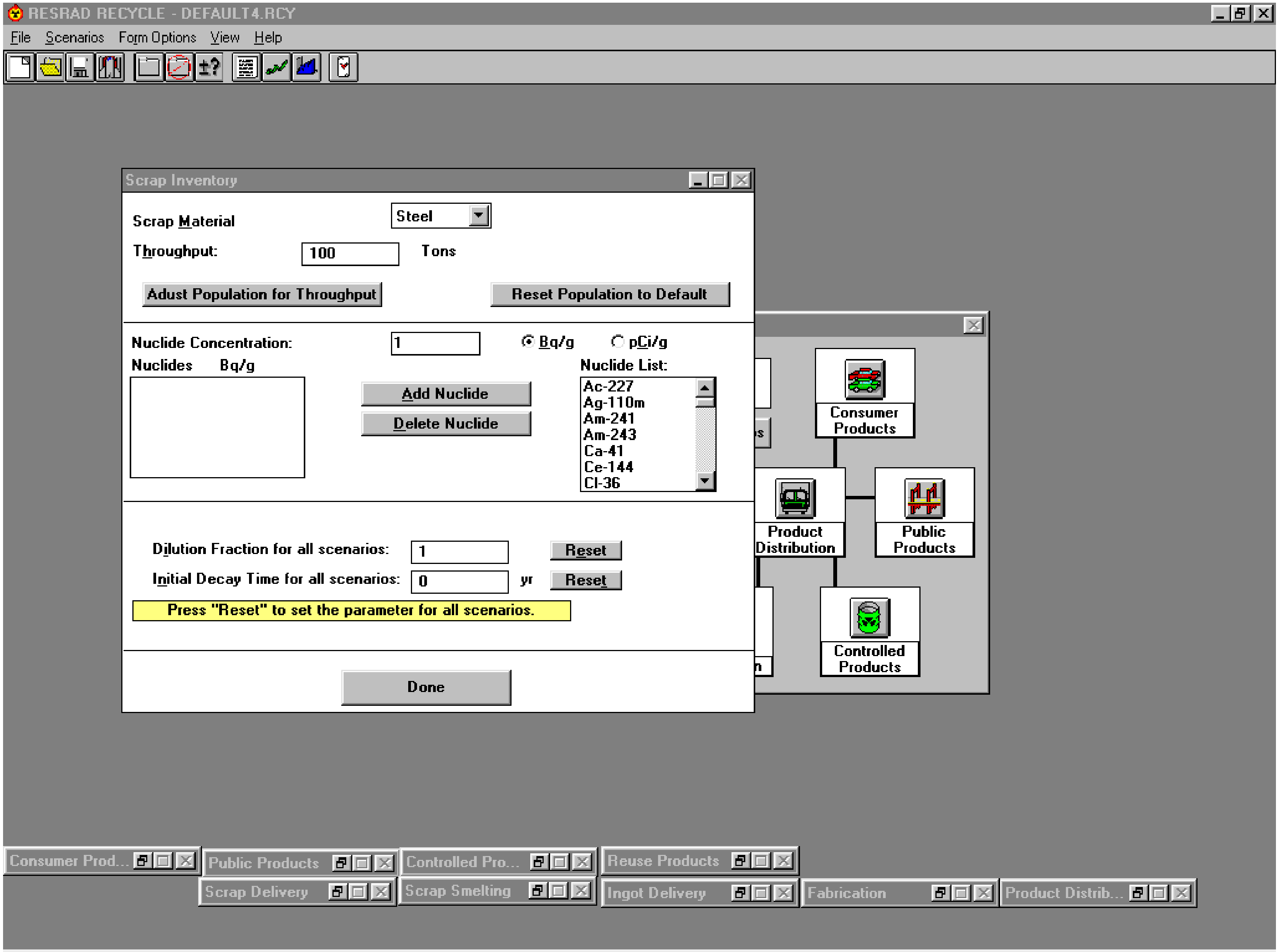

FIGURE 4.2 RESRAD-RECYCLE Inventory Input Window

To add a radionuclide in the Scrap Inventory window, the user can select the desired radionuclide from the Nuclide List and press the *Add Nuclide* button. The cursor control keys can be used to scroll down or up the list. Pressing a letter moves the cursor to that portion of the alphabetized Nuclide List. Pressing the *Enter* key adds the highlighted radionuclide to the scrap inventory list. Double-clicking a radionuclide with the mouse also adds the radionuclide to the scrap inventory list. Clicking the *Delete Nuclide* button on the Inventory window removes the highlighted radionuclide from the inventory list. When a radionuclide is selected, an asterisk appears by its symbol in the Nuclide List.

The cursor control arrow keys and the *Enter* key can be used to move through the Nuclide List included in the selected inventory. The nuclide concentration can be specified by typing in the concentration for the highlighted radionuclide in the field provided. Clicking a selected radionuclide highlights that radionuclide. The user has the option of specifying either the volume concentration (in pCi/g or Bq/g) or the surface concentration (in pCi/cm^2 or Bq/cm^2) by clicking the corresponding unit option buttons, located to the right of the Nuclide Concentration value (see Figure 4.2). In the reuse scenarios, surface contamination is assumed. Clicking the *Delete Nuclide* button removes the currently highlighted radionuclide from the inventory. The Scrap Inventory screen can be closed by clicking the *Save* button on the button bar, pressing the *F10* key, or by clicking the *Done* button on the scrap inventory screen. **Changes made to the scrap inventory window cannot be canceled**. In addition, a case calculation cannot be performed unless at least one radionuclide is selected.

4.2.3 Selecting Scenarios

Clicking a recycling step module in the main screen displays a list of representative scenarios for that particular step, as shown in Figure 4.3 for the scrap smelting step. The scenario screen can also be accessed by double-clicking on the main screen or by double-clicking the appropriate button for the module, which is also located at the bottom of the main screen. Scenarios are selected by checking the box next to the scenario name. A box can be “checked” by using the mouse, the *Enter* key, or the space bar. The cursor can be moved among the scenarios with the *Tab* key or the cursor movement (arrow) keys.

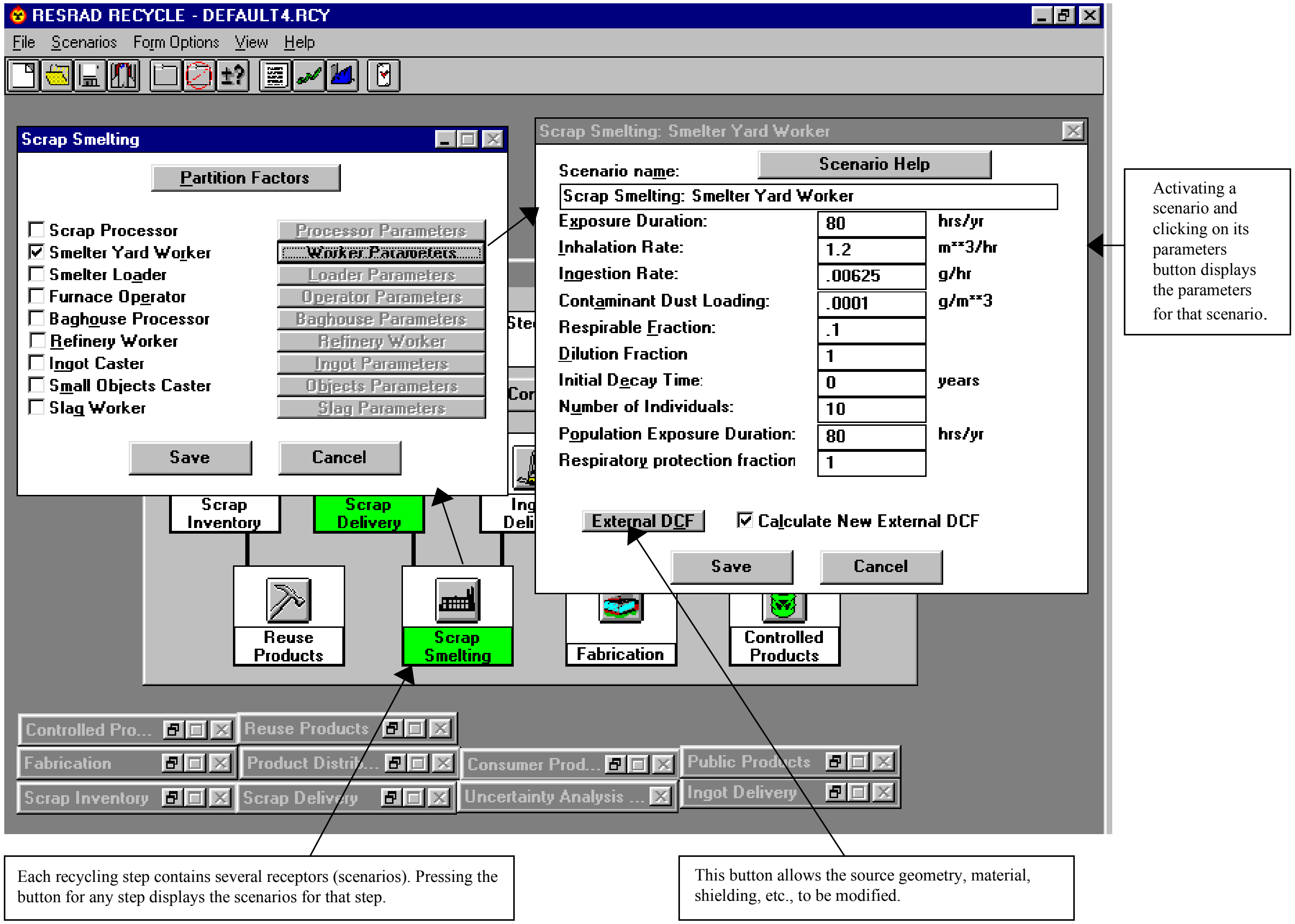

FIGURE 4.3 RESRAD-RECYCLE Module for the Scrap Smelting Step

4.2.4 Editing Partitioning Factors

The mass and radionuclide partitioning factors input window (see Figure 4.4) is displayed by clicking the *Partition Factors* command button in the Scrap Smelting panel. The access key for this button is "*P*." The default values are displayed for the mass and radionuclide partitioning factors, and the user can enter various values. Clicking the *Normalize* button under the radionuclide partitioning factors causes the partitioning factors to be normalized when the total, which appears at the bottom, is not exactly 100%. The partitioning factors input window can be closed by pressing *Ok*.

4.2.5 Editing Scenarios

Clicking the parameter button next to a scenario opens the input form, which lists the modeling parameters for that scenario (see Figure 4.3; the panel is labeled "Scrap Smelting: Smelter Yard Worker"). The parameter button can be clicked by pressing the left mouse button or by pressing the *Alt* key and the underlined letter (access key) in the scenario name simultaneously. The input form displays the default values for all parameters, which can be modified by the user. Moving about the input fields in the input form can be accomplished by using the mouse, the *Tab* key, the *Enter* key, or the underlined access keys. The cursor control keys move the cursor within an input field, but not between input fields.

Parameter values for a given scenario can be saved by pressing the *F10* key, which also closes the displayed input form. The *Save Current Form* option under the *Form Option* menu on the menu bar also can be used to save any changes and close the input form. The corresponding button on the button bar also provides the same function. The *ESC* key can be used to close a window and discard any changes that have been made. The *Cancel Current Form* option under the *Form Options* menu on the menu bar, as well as the corresponding button on the button bar, also closes a form without saving any changes.

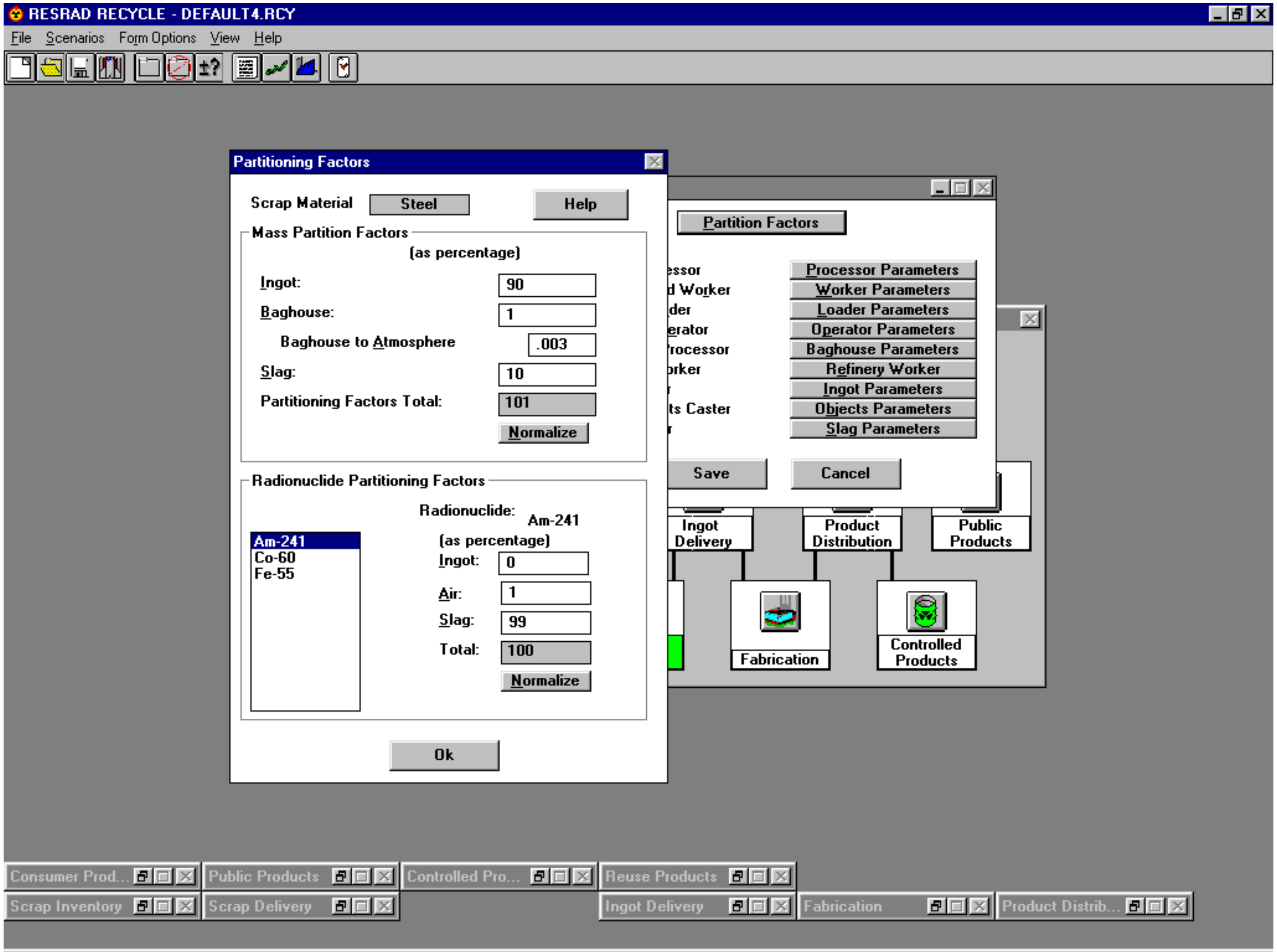

FIGURE 4.4 Input Window for Partitioning Factors in RESRAD-RECYCLE

4.2.6 Getting Help

RESRAD-RECYCLE provides on-line help, which is accessed through the *Help* menu on the main window. The following options are available:

- *General Help* provides overall help for navigating the code.

- *Context Sensitive Help* provides help for the current parameter or scenario.

- *Help for the Current Form* provides help for the current input window.

- *Worker Scenarios* provides an overall description of the worker scenarios.

- *Consumer Scenarios* provides an overall description of the end-product scenarios.

4.3 ENTERING UNCERTAINTY ANALYSIS PARAMETERS

Uncertainty analysis can be performed by examining the distribution of any scenario input parameter. An input parameter can be selected for examination by pressing the *F8* key, by selecting the *Uncertainty Analysis* option under the *Form Options* menu on the menu bar, or by selecting the corresponding button on the button bar while the parameter is highlighted. After a parameter is selected, the *Uncertainty Analysis Summary* window is displayed on the screen or can be selected for review by clicking the corresponding window icon at the bottom of the main screen.

The *Uncertainty Analysis Summary* window, shown in Figure 4.5, allows the user to specify the distribution format as well as the characterization parameters for each selected parameter. The correlation between any two selected parameters can also be specified. In addition, the *Random Seed* Value, the *Number of Observations*, and the *Number of Repetitions* for data sampling can also be specified.

4.3.1 Setting Distributions for Parameters

Once a parameter is selected for uncertainty analysis, it is included in the *Uncertainty Analysis Summary* window (Figure 4.5). The lower half of this window provides descriptions of the selected variables, names of the variables used in the RESRAD-RECYCLE code, and their distribution characteristics. The distribution format of a variable, or parameter, can be changed by highlighting the corresponding cell under the *Distribution* column and selecting the distribution format (normal, lognormal, uniform, loguniform, or triangular) by scrolling down the input field or by checking the representative distribution graphics, then pressing *Enter*. The input field and the distribution graphics are displayed in the middle of the window directly above the distribution description. After the distribution format has been specified, the user can enter the corresponding characteristic parameters, such as the maximum and minimum, by highlighting the corresponding cell and entering the appropriate value in the input field.

RESRAD-RECYCLE supports five distribution formats — normal, lognormal, uniform, loguniform, and triangular. For all except the normal distribution format, the characterizing parameters are the minimum and maximum values. Normal distribution is characterized by the mean and standard deviation. In addition to being characterized by the minimum and maximum values, the triangular distribution is also characterized by the peak value of the distribution.

4.3.2 Setting Correlation between Parameters

Two parameters can be correlated by selecting the first parameter from the lower portion of the summary window, clicking the *Correlate* button (or using the access key *Alt-E*), selecting the second parameter (also from the lower portion of the summary window), and clicking the *Correlate* button. The two parameters appear in the *Correlation* panel — a summary table — at the upper right of the screen. Moving the cursor to the *Factor* column of the correlation summary table allows the user to enter the correlation factor from the input field.

4.3.3 Removing Parameters from Uncertainty Analysis

The *Delete* button in the *Uncertainty Analysis Summary* window (Figure 4.5) can be used to remove information entered for uncertainty analysis. When the cursor is placed in the

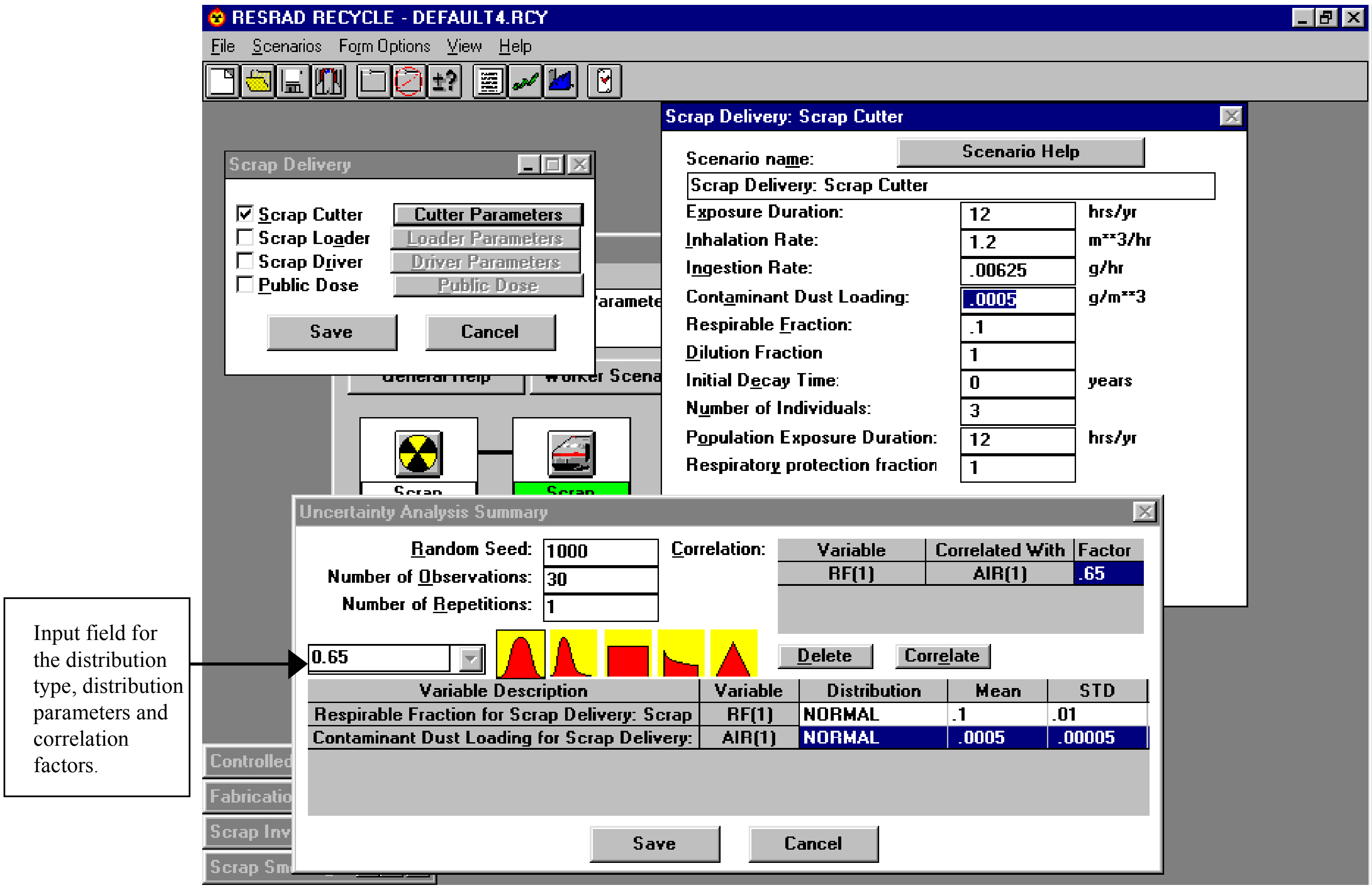

FIGURE 4.5 RESRAD-RECYCLE Uncertainty Analysis Summary Window

Correlation panel, the *Delete* button removes the correlation that the cursor points to. If the input cursor is in the lower portion of the window, where the parameter distribution information is summarized, the *Delete* button removes the corresponding parameter from the uncertainty analysis, including any correlation that involves that parameter. Removing all listed parameters suppresses the uncertainty analysis. Setting the number of samples (i.e., the product of the number of observations and the number of repetitions) to 0 also suppresses the uncertainty analysis.

4.3.4 Saving and Retrieving Uncertainty Analysis Information

Pressing the *Save* or *Cancel* button closes the *Uncertainty Analysis Summary* window, and normal RESRAD-RECYCLE input data editing can be resumed. The *Uncertainty Analysis Summary* window must be closed before normal editing can be continued. The window can be displayed again by selecting another parameter for uncertainty analysis or by double-clicking the *Uncertainty Analysis Summary* window icon at the bottom of the main screen.

The visibility of the icon of the *Uncertainty Analysis Summary* window can be toggled on/off by checking the *Uncertainty Summary* option under the *View* menu on the menu bar. The corresponding button on the button bar and the access key *Ctrl-F8* also perform the same function.

4.4 SAVING INPUT DATA FILES

Data can be saved on a disk file by using the *Save* or *Save As* option under the *File* menu. The *Save* option saves the data in the current data file, whereas *Save As* allows the data to be saved in a new file. A file can be retrieved from the disk by using the *Open* option under the File menu. The *New* option under the *File* menu resets all parameters to the default values.

4.5 PERFORMING CALCULATIONS

The current data can be used to perform dose and risk calculations by choosing the *Calculate Dose* option under the *File* menu. If the current data have not been saved, the user is prompted to save them in a disk file before the calculation. Dose and risk calculations can also be performed by clicking the corresponding button on the button bar. A message window appears on the screen to indicate the progress of the calculations.

4.6 VIEWING RESULTS

Once the calculations have been completed, the report viewer displays the text of the RECYCLE.REP file. The report viewer contains its own menu bar and menu options that control the viewing activities. The function of the main menu (for the main screen) can be resumed by clicking any window other than the report viewer, or by closing the report viewer. The report viewer can be closed by selecting the *Exit Viewer* option from the *File* menu of the report viewer or by pressing the *Close* button, which is at the far right top of the viewer window.

The report viewer can be opened at any time by selecting the desired report from the *Text Output* option from the *View* menu of the main screen. In addition to the RECYCLE.REP report, which provides calculated doses for each selected scenario, four other reports are also generated in each calculation: (1) DCF_EXT.REP, which provides calculated external radiation dose conversion factors; (2) LIMIT.REP, which provides derived radionuclide concentration levels for scrap metal that will meet a given dose limit; (3) RISK.REP, which provides calculated excess cancer risks for each selected scenario; and (4) MRECYLE.REP, which provides the results of the uncertainty analysis.

To view a specific page of a report, the user can type in a page number in the *Page* input field or scroll through the page list to select the specific page. Another way to view a specific page is to tab the cursor into the text of the report and use the cursor control keys to move to the desired page. The cursor control keys include the *Next Page* and *Previous Page* buttons on the viewer and the *Page Up* and *Page Down* keys on the keyboard.

The report viewer can also be used to view any ASCII (American Standard Code for Information Interchange) file. In the main screen, this can be executed by selecting the *Any File* suboption from the *Text Output* option of the *View* menu on the menu bar. While in the report viewer, this can be executed by selecting the *Another File* option from the *View* menu.

4.6.1 Saving and Printing a Report

The *File* menu of the report viewer provides options for selecting and setting up a printer, printing the report, and saving the report in a file. Selecting the *Print* option will open a dialog window in which a page range can be entered for printing. The selected pages are sent to the Windows printer. The default printer and page setup can be changed by choosing the *Printer Setup* option. Clicking the *Print* button on the button bar of the report viewer also prints the report. Clicking this button prints the entire report, unless a page range had been entered the last time the *Print* option was selected from the *File* menu; in the latter case, the pages are printed within the previously defined range.

The *Font* option on the report viewer allows the report to be displayed and printed in any font installed on the system. The default font is the MS Line Draw font, if installed. The *Size* option is used to specify the size of the font used for displaying and printing the report. The paper layout shown next to the *Size* option indicates the current orientation of the paper, either portrait or landscape; the number next to this paper layout image indicates the printing width, in inches, of the current report page if the current font and the current font size are used.

The *Save* option on the *File* menu saves the entire report in a text file. Selecting this option will open a file selection window that allows the disk drive, directory, and file name of the new file to be specified.

4.6.2 Copying Reports to Other Windows Applications

The *Copy* option of the *Edit* menu in the report viewer allows the user to copy highlighted text onto the Windows clipboard for pasting into other Windows applications. Text can be selected by the standard Windows methods: by using the mouse to drag across the text with the left mouse button pressed, or by using the cursor control keys across the text while pressing *Shift*. In addition, the *Select All* option on the *Edit* menu can be used to select the entire text of the current page. The *Copy* button on the report viewer button bar also allows copying of the selected text onto the Windows clipboard.

4.6.3 Viewing Graphics

The RESRAD-RECYCLE code can plot the estimated radiation doses and dose fractions attributed to various pathways, radionuclides, and scenarios. The graphics interface form, shown in Figure 4.6 is designed to facilitate specifications for graphics display. The graphic interface can be activated by selecting the *Graphic Output* option from the *View* menu on the main screen, then selecting the appropriate calculation results (deterministic or uncertainty) for display. The boxes at the lower left of the interface window can be used to check the category (pathway, radionuclide, or scenario) to be used in comparing the doses or fraction of doses. The other input fields are used to select the component from each of the other categories to which the doses contribute. For example, if the user has indicated that radiation doses should be compared by pathways, a specific radionuclide and scenario must be selected so that the radiation doses from that radionuclide and scenario can be compared by pathways.

The RESRAD-RECYCLE graphics program draws either bar or pie charts. Clicking the *Dose* button indicates that bar charts should be provided, whereas the *Fraction* button produces pie charts. For bar charts, one or two of the check boxes at the lower left corner of the interface can be selected; for pie charts, only one check box can be selected.

Clicking the *Graph* button on the interface form opens a new window that displays graphic results based on the current selections. The number of new windows that can be opened at a time is only limited by the system's resources. The two buttons on the new window are used to print the graphics and to close the new window.

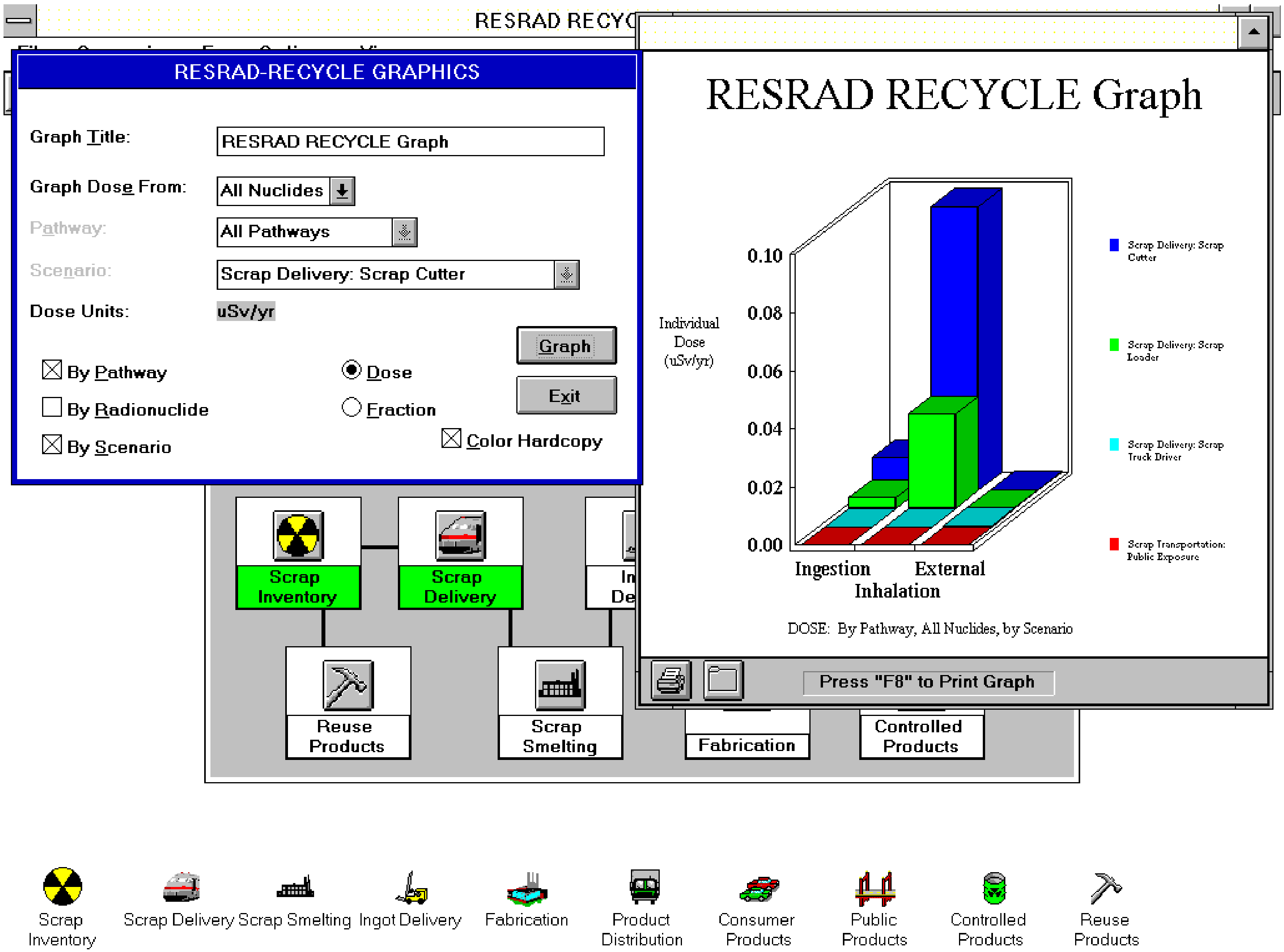

FIGURE 4.6 RESRAD-RECYCLE Graphics Interface Form

5 BENCHMARKING AND VALIDATION

Data from a study prepared by S. Cohen and Associates (1995) for the EPA were compared with the results from RESRAD-RECYCLE Version 2.2 for two scenarios: baghouse processor and slag worker. All input parameters and geometries used in the EPA study were applied in RESRAD-RECYCLE. Table 5.1 lists the assumptions used in the EPA scenarios. Fifteen radionuclides were included in the comparison. The concentration of each radionuclide was set to 1 pCi/g. Table 5.2 gives the EPA radionuclide partitioning factors that were used in these benchmark calculations in place of the default values of RESRAD-RECYCLE.

A comparison of the results indicated good agreement between the RESRAD-RECYCLE and EPA values (S. Cohen and Associates 1995). The RESRAD-RECYCLE code did not require any modification because all of the parameters used in the dose evaluations are input variables, and any desired values can be used. The EPA model, however, used differing exposure durations for the ingestion dose and for the inhalation and external doses in the baghouse scenario. It was unclear why the EPA used two exposure durations in its model. RESRAD-RECYCLE uses a single exposure duration for all pathways; therefore, two runs, with differing exposure durations, were needed to duplicate the EPA baghouse scenario.

Tables 5.3 and 5.4 give the benchmark results for the baghouse processor and slag worker scenarios, respectively. Results for the relatively short-lived radionuclides, including cobalt-60, cesium-134, manganese-54, and ruthenium-106, in the baghouse processor scenario showed higher deviations than for the other radionuclides. These results occurred because RESRAD-RECYCLE applies a decay factor to account for activity decay over a period of one year (see Table 3.1). Removing this factor led to better agreement with EPA values. For example, ruthenium-106 has an average decay factor of 0.724 (from Table 3.1). Dividing the total RESRAD-RECYCLE dose of 2.2×10^{-3} mrem/yr by this factor yields a value of 3.0×10^{-3} mrem/yr, which is essentially equal to the EPA value shown in Table 5.3. In addition to the decay factors, the minor discrepancies between the RESRAD-RECYCLE results and the EPA values occurred because different external radiation methodologies were used.

In general, the results are in good agreement. The deviation between the two models is within 30%, which can be attributed to the application of the average decay factor in RESRAD-RECYCLE and the different external exposure model applied in the code. The EPA study applies predetermined external DCFs derived with the Microshield computer code.

TABLE 5.1 Assumptions for the Baghouse Processor and Slag Worker Scenario Benchmarking Comparisons[a]

Parameter	Baghouse Processor	Slag Worker
Inhalation rate (m^3/h)	0.91	0.91
Ingestion rate (g/h)	0.06	0.06
Dilution fraction	1	1
Respirable fraction	1	1
Dust loading (g/m^3)	0.05	0.005
Respiratory protection factor	0.125	1
Exposure duration (h)	49 (1,750 for ingestion dose)	1,750
Slag mass partitioning (%)	NA[b]	5.5%
Baghouse mass partitioning (%)	1	NA
Source radius (cm)	200	185
Source thickness (cm)	61	153
Source density (g/cm^3)	0.00137	1.7
Receptor distance (cm)	10	150
Source shape	Two full cylinders	One half cylinder
Source material	Water	Aluminum

[a] The external geometry in the EPA study was modeled as two rectangles for the baghouse scenario and as half sphere for the slag worker. Because RESRAD-RECYCLE uses cylindrical geometry, the external source is modified for use in the code, thus keeping the volume constant.

[b] NA = not applicable.

TABLE 5.2 Benchmark Radionuclide Partitioning Factors

	Partitioning Factor (%)		
Radionuclide	Ingot	Baghouse	Slag
Am-241	1	1	100
Co-60	100	1	1
Cs-134	1	100	25
Cs-137	1	100	25
Mn-54	1	1	100
Ni-63	100	1	1
Pu-239	1	1	100
Pu-241	1	1	100
Ra-226	1	1	100
Ra-228	1	1	100
Ru-106	100	1	1
Sr-90	1	1	100
Tc-99	1	1	100
U-235	1	1	100
U-238	1	1	100

Source: S. Cohen and Associates (1995).

TABLE 5.3 Benchmark Results for the Baghouse Processor Scenario

	Doses (mrem/yr)					
	RESRAD-RECYCLE					
Radionuclide	Ingestion[a]	Inhalation	External	Total	EPA Total[b]	Ratio RESRAD/EPA
Am-241	3.8E-01	1.2E-01	1.5E-05	5.1E-01	5.1E-01	1.0
Co-60	2.7E-03	5.7E-05	7.9E-04	3.5E-03	3.8E-03	0.9
Cs-134	6.5E-01	1.1E-03	4.6E-02	7.0E-01	8.3E-01	0.8
Cs-137	5.2E-01	8.8E-04	2.0E-02	5.4E-01	5.5E-01	1.0
Mn-54	2.0E-04	1.3E-06	2.0E-04	4.0E-04	6.2E-04	0.6
Ni-63	6.0E-05	1.8E-06	0.0E+00	6.2E-05	6.2E-05	1.0
Pu-239	3.7E-01	1.2E-01	1.4E-06	4.9E-01	4.9E-01	1.0
Pu-241	7.0E-03	2.2E-03	1.9E-09	9.2E-03	9.5E-03	1.0
Ra-226	1.4E-01	2.4E-03	5.9E-04	1.4E-01	1.4E-01	1.0
Ra-228	1.4E-01	1.3E-03	3.1E-04	1.4E-01	1.5E-01	1.0
Ru-106	2.1E-03	9.6E-05	5.4E-05	2.2E-03	3.1E-03	0.7
Sr-90	1.6E-02	3.6E-04	1.2E-05	1.6E-02	1.7E-02	1.0
Tc-99	1.5E-04	2.3E-06	7.7E-08	1.6E-04	1.6E-04	1.0
U-235	2.8E-02	3.4E-02	5.6E-05	6.2E-02	6.2E-02	1.0
U-238	2.8E-02	3.3E-02	1.1E-05	6.1E-02	6.1E-02	1.0
Total	2.3E+00	3.2E-01	6.8E-02	2.7E+00	2.8E+00	0.9

[a] The ingestion dose is calculated with an exposure duration of 1,750 h/yr; the other pathways are calculated with an exposure duration of 49 h/yr.

[b] Source: S. Cohen and Associates (1995).

TABLE 5.4 Benchmark Results for the Slag Worker Scenario

	Dose (mrem/yr)					
	RESRAD-RECYCLE					
Radionuclide	Ingestion[a]	Inhalation	External	Total	EPA Total[b]	Ratio RESRAD/EPA
Am-241	7.0E+00	6.4E+01	2.5E-02	7.1E+01	7.1E+01	1.0
Co-60	4.8E-04	3.0E-04	1.0E-01	1.0E-01	7.9E-02	1.3
Cs-134	3.0E-02	1.4E-03	1.4E+00	1.4E+00	1.2E+00	1.2
Cs-137	2.4E-02	1.1E-03	5.7E-01	5.9E-01	4.7E-01	1.3
Mn-54	3.6E-03	6.6E-04	2.4E+00	2.4E+00	2.5E+00	0.9
Ni-63	1.1E-05	9.1E-06	0.0E+00	2.0E-05	2.0E-05	1.0
Pu-239	6.8E+00	6.2E+01	2.0E-04	6.9E+01	6.9E+01	1.0
Pu-241	1.3E-01	1.2E+00	1.2E-05	1.3E+00	1.3E+00	1.0
Ra-226	2.5E+00	1.2E+00	7.5E+00	1.1E+01	9.0E+00	1.3
Ra-228	2.6E+00	6.9E-01	3.8E+00	7.1E+00	6.9E+00	1.0
Ru-106	3.8E-04	5.0E-04	6.3E-03	7.2E-03	7.3E-03	1.0
Sr-90	2.9E-01	1.9E-01	1.6E-02	4.9E-01	4.8E-01	1.0
Tc-99	2.8E-03	1.2E-03	2.3E-04	4.2E-03	4.0E-03	1.1
U-235	5.1E-01	1.8E+01	5.0E-01	1.9E+01	1.9E+01	1.0
U-238	5.1E-01	1.7E+01	8.9E-02	1.8E+01	1.8E+01	1.0
Total	2.0E+01	1.6E+02	1.6E+01	2.0E+02	2.0E+02	1.0

[a] The ingestion dose is calculated with an exposure duration of 1,750 h/yr; the other pathways are calculated with an exposure duration of 49 h/yr.

[b] Source: S. Cohen and Associates (1995).

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