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RISKIND — A Computer Program for Calculating Radiological Consequences and Health Risks from Transportation of Spent Nuclear Fuel

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AVAILABILITY OF COMPUTER SOFTWARE

Electronic copies of the software described in this publication will be distributed with appropriate restrictions by:

Energy Science and Technology Software Center
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NOTATION

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

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

ANL	Argonne National Laboratory
BEIR	Committee on the Biological Effects of Ionizing Radiation
BWR	boiling-water reactor
CFR	Code of Federal Regulations
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
FGR	Federal Guidance Report
GI	gastrointestinal
ICRP	International Commission on Radiological Protection
LET	linear energy transfer
LLI	lower large intestine
LLNL	Lawrence Livermore National Laboratory
LWR	light-water reactor
NEPA	National Environmental Policy Act
NRC	U.S. Nuclear Regulatory Commission
OCRWM	Office of Civilian Radioactive Waste Management
ORNL	Oak Ridge National Laboratory
PAG	protective action guideline
PWR	pressurized-water reactor
QA	quality assurance
SNF	spent nuclear fuel
UNSCEAR	United Nation's Scientific Committee on the Effects of Ionizing Radiation

UNITS OF MEASURE

Bq	becquerel(s)	cm	centimeter(s)
cal	calorie(s)	cm^2	square centimeter(s)
Ci	curie(s)	d	day(s)
µCi	microcurie(s)	ft	foot (feet)

°F	degree(s) Fahrenheit
g	gram(s)
gal	gallon(s)
Gy	gray(s)
h	hour(s)
in.	inch(es)
kg	kilogram(s)
K	degree(s) Kelvin, kilobyte(s)
km	kilometer(s)
km^2	square kilometer(s)
L	liter(s)
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
m^4	meters(s) to the fourth
mm	millimeter(s)
MB	megabyte(s)
min	minute(s)
mph	mile(s) per hour
mrem	millirem(s)
MTIHM	metric ton(s) of initial heavy metal
MTU	metric ton(s) of uranium
MWd	megawatt-day(s)
rad	radiation absorbed dose(s)
rem	roentgen-equivalent man
s	second(s)
s^2	second(s) squared
s^3	second(s) to the third
Sv	sievert(s)
yr	year(s)

RISKIND — A COMPUTER PROGRAM FOR CALCULATING RADIOLOGICAL CONSEQUENCES AND HEALTH RISKS FROM TRANSPORTATION OF SPENT NUCLEAR FUEL

by

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ABSTRACT

This report presents the technical details of RISKIND, a computer code designed to estimate potential radiological consequences and health risks to individuals and the collective population from exposures associated with the transportation of spent nuclear fuel. RISKIND is a user-friendly, interactive program that can be run on an IBM or equivalent personal computer under the Windows™ environment. Several models are included in RISKIND that have been tailored to calculate the exposure to individuals under various incident-free and accident conditions. The incident-free models assess exposures from both gamma and neutron radiation and can account for different cask designs. The accident models include accidental release, atmospheric transport, and the environmental pathways of radionuclides from spent fuels; these models also assess health risks to individuals and the collective population. The models are supported by databases that are specific to spent nuclear fuels and include a radionuclide inventory and dose conversion factors. In addition, the flexibility of the models allows them to be used for assessing any accidental release involving radioactive materials. The RISKIND code allows for user-specified accident scenarios as well as receptor locations under various exposure conditions, thereby facilitating the estimation of radiological consequences and health risks for individuals. Median (50% probability) and typical worst-case (less than 5% probability of being exceeded) doses and health consequences from potential accidental releases can be calculated by constructing a cumulative dose/probability distribution curve for a complete matrix of site joint-wind-frequency data. These consequence results, together with the estimated probability of the entire spectrum of potential accidents, form a comprehensive, probabilistic risk assessment of a spent nuclear fuel transportation accident.

1 INTRODUCTION

The RISKIND computer program was developed by Argonne National Laboratory under the support of the U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM). The program was developed for analyzing the potential radiological health consequences to individuals or specific population subgroups exposed to radiation associated with the transportation of spent nuclear fuel (SNF). RISKIND is designed to address the local, scenario-specific (i.e., "what if") concerns frequently encountered in environmental assessment activities (including public scoping processes) performed under the National Environmental Policy Act (NEPA) of 1969 or other environmental regulatory requirements.

1.1 BACKGROUND

Currently, RISKIND is used in conjunction with the latest version of RADTRAN, RADTRAN 4 (Neuhauser and Kanipe 1992), for performing comprehensive transportation risk assessments (DOE 1995; Chen et al. 1995). RADTRAN was originally developed pursuant to the U.S. Nuclear Regulatory Commission (NRC) report *Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes* (NRC 1977b), which was issued to demonstrate compliance with NEPA.

The NRC report is primarily concerned with estimating the collective population risk from the transportation of radioactive materials under incident-free or accident conditions. Traditionally, such an analysis has been supplemented by other models so that consequences to individuals or population subgroups could be estimated. These latter analyses are documented in DOE environmental assessment reports (DOE 1986a,b,c,d, 1990, 1992b). However, different models were used in these reports, which has resulted in inconsistent approaches.

RISKIND was initially developed in 1993 (Version 0, Yuan et al. 1993), in light of public comments and the need for a more complete and consistent methodology for addressing radiological consequence issues. Since that time, RISKIND has undergone a number of substantial improvements and enhancements resulting from user feedback, new methodologies for some models, revised databases, and a peer review process. This latest version, Version 1, represents the updated program since its original release.

1.2 SCOPE

The major objective of RISKIND is to provide data for addressing public concern regarding the transport of SNF along a specific route. The data consist of calculations of incident-free and accident impacts for a particular radioactive material shipment at specific

locations along a truck or rail transport route. Public comments on transportation risk analyses for individuals may include the following scenarios:

- An individual stuck in traffic next to a radioactive materials shipment;
- An individual working near heavily traveled transport routes;
- An individual living near heavily traveled transport routes, such as shipment origin or destination site entrances;
- An individual near rail grade-crossings where accident rates are higher;
- Individuals in an area near a postulated SNF transportation accident location;
- An individual eating locally grown food following a SNF transportation accident; and
- An individual drinking water that has been contaminated by an accidental release near a drinking water supply.

The radiological consequences and health risks from these "what if" situations are of great interest and concern to the public. These concerns can only be addressed on the basis of a methodology that analyzes the potential health risk of a specific situation. Substantial databases and technologies relevant to the transportation of SNF and other radioactive materials have been made available through the efforts of various research organizations. These databases and technologies were used to develop RISKIND in accordance with the needs of the local community.

The RISKIND code was implemented on the basis of five objectives:

1. Calculation of site- and route-specific radiological consequences and health risks to exposed individuals and the collective local population;
2. Modeling of the different exposure pathways for specific exposure scenarios;
3. Estimation of the amount of radioactive material released under potential accident scenarios;
4. Estimation of cask accident responses specific to the transportation of SNF; and

5. Enhancement of risk communication, that is, to help the user better understand and appreciate the complexities of the problems to be analyzed and the relevant input parameters, as well as the resulting consequences.

To accomplish the first objective, RISKIND is designed to calculate radiological impacts at specific receptor locations for a variety of exposure scenarios. Comprehensive mathematical models capable of handling site-specific information at the time of exposure are used; such information includes specific receptor locations, exposure conditions (including individual air and food intake rates), and meteorological conditions. The model used to assess the potential acute health effects from short-term exposures is based on the model developed by Harvard University and the NRC (1985) and the revised model of Abrahamson et al. (1989, 1991). The dose-to-health-risk conversion factors for estimating latent health effects are taken from Publication 60 of the International Commission on Radiological Protection (ICRP 1991).

RISKIND meets the second objective by considering all environmental pathways, including short-term exposure from the initial passing radioactive cloud, accidental exposure from loss of the cask shield, and long-term exposure from ground deposition and ingestion from the food chain pathways. Pathway analysis can be tailored to model impacts in a wide range of locations, from large metropolitan areas to rural agricultural areas.

To meet the third objective, a radionuclide source inventory was compiled from the database developed by Oak Ridge National Laboratory (ORNL) in which the data are specific to the type of spent fuel (pressurized-water reactor [PWR] or boiling-water reactor [BWR]), cooling times, and burnup rates (DOE 1987b, 1992a). User-supplied inventories are also permitted for different spent fuel types and other radioactive materials.

To meet the fourth objective, the cask accident responses and the radionuclide release fractions modeled by Lawrence Livermore National Laboratory (LLNL) in its report for the NRC were incorporated into RISKIND as default values. This LLNL/NRC report is commonly referred to as the "NRC modal study" (LLNL 1987). Other cask responses and release fractions supplied by the user may be used as input in place of the default values.

To meet the fifth objective, RISKIND was equipped with an easy to use Windows™ interface and a scenario-oriented program input structure with on-line help capabilities. The input is flexible enough to allow the user to model most plausible situations. Input parameters are grouped according to function, and the parameter definitions are available via on-line help. The on-line help also contains diagrams depicting scenarios with the relevant input parameters highlighted to aid the user in understanding how the input relates to the problem. Graphical output displays help convey the consequences in a more meaningful context.

1.3 OVERVIEW

The RISKIND code was developed on the basis of the considerations discussed above. The primary function of this code is the estimation of radiological risk to individuals and to local population subgroups under various site-specific environmental settings. The radiological risks analyzed by RISKIND include incident-free transportation as well as accident conditions. The code is designed to be responsive to scenarios associated with truck or rail transport of SNF. Therefore, the coding approach in RISKIND emphasizes the scenario descriptions, environmental settings, receptor locations, and potential health effects. The code also incorporates the latest available methodologies and databases to facilitate the analysis of radiological risks. Figure 1.1 is a flow diagram of RISKIND showing the calculation of radiological risk to an individual from the transportation of SNF or other radioactive materials.

1.3.1 Incident-Free Transportation

Exposure from incident-free (i.e., routine) transportation results solely from the external doses received by individuals from the neutron and gamma radiation emitted from the SNF cask or other radioactive material shipping package. Incident-free exposure includes those occurrences when the transport vehicle is in transit (i.e., moving) or at a stop. The receptors for the in-transit exposure may include the residents living adjacent to a highway or railway and the passengers sharing the traffic route with the transport vehicle; exposed individuals at a stop may include the vehicle inspector, a gas station attendant, a nearby person in a traffic jam, and so forth.

The model used by RISKIND for predicting external exposure is based on dose rates (Chen and Yuan 1988) derived specifically for a spent fuel cask and takes into account the ground/air scattering of the emitted gamma or neutron radiation. The model also contains provisions for adjusting the dose rate for changes in cask sizes (i.e., outer radius and length) and provides a realistic, although still somewhat conservative, estimate of the external doses to a receptor.

1.3.2 Accident Conditions

Potential exposure to individuals under accident conditions can occur through many environmental pathways if an accident leads to the environmental release of the radioactive contents of the cask. In RISKIND, the estimated exposure and the resulting health effects are presented individually and for each potential pathway.

Various scenarios in RISKIND have been characterized according to an array of SNF cask responses as described in the NRC's modal study (LLNL 1987). In that study, all accidents are represented by discrete response regions (severity categories). These response regions range

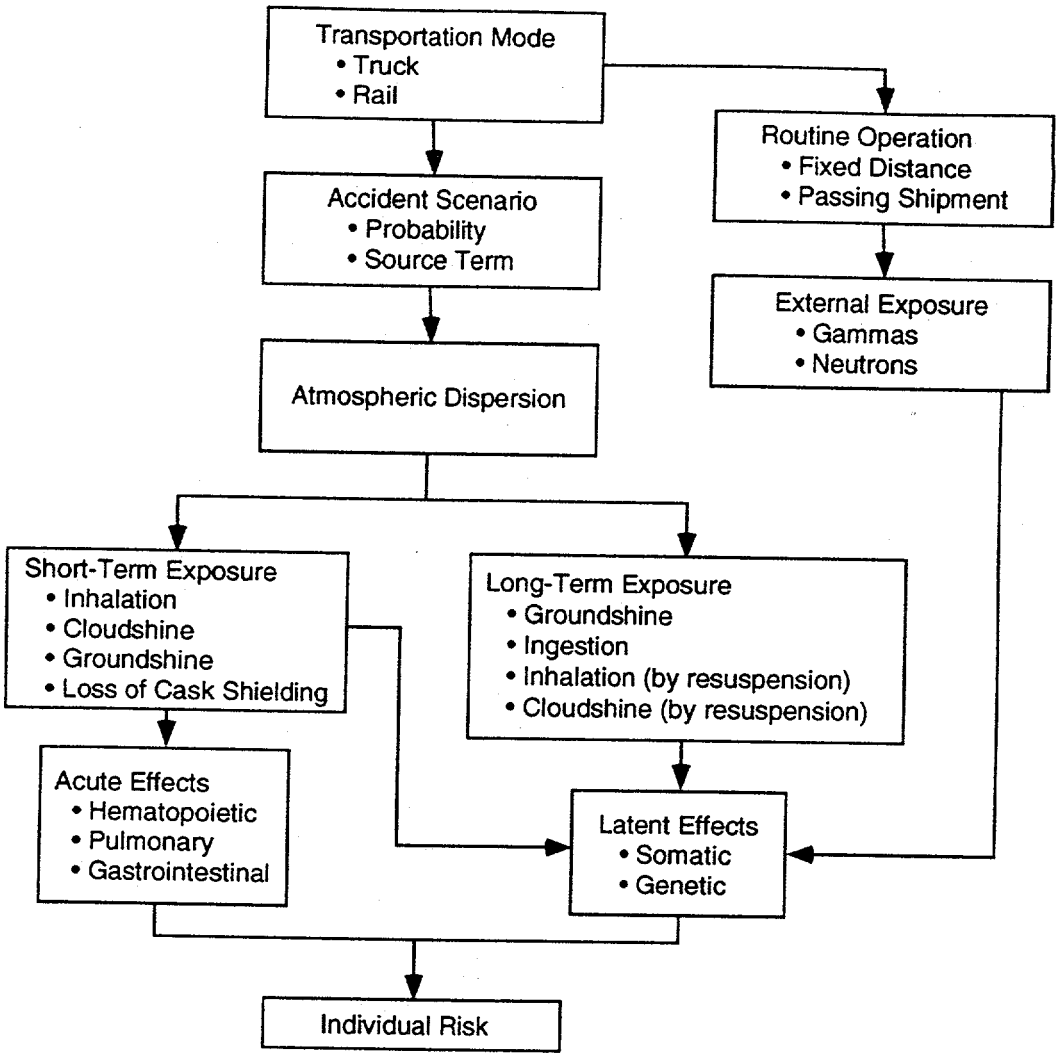

FIGURE 1.1 Flow Diagram for Calculating the Radiological Risk to an Individual from Transportation of Spent Nuclear Fuel

from likely events (with minor consequences) to highly unlikely events (with severe consequences). Twenty response regions are characterized according to two major accident parameters: impact force and thermal force (i.e., heat from a fire). Thus, accident conditions would be affected by vehicle speed, object hardness, impact angle and orientation, and fire duration and location. In the NRC modal study, the bounding case release fractions have also been estimated for each response region. All credible accident scenarios are thus fully represented by the 20 response regions.

To support the consistency of release estimates, the SNF radionuclide source inventory was derived from the database developed by ORNL (DOE 1987b, 1992a). In addition, potential release from crud (i.e., a mixture of reactor coolant corrosion products) spalling off (breaking

loose from) the fuel rods is also incorporated. The estimate of crud release is based on a study by Sandia National Laboratories (Sandoval et al. 1991).

The atmospheric transport module in RISKIND includes models that simulate dispersion phenomena following a short release. RISKIND's transport model estimates levels of air and ground contamination on the basis of specific meteorological conditions, geometry, and elevation of the release. Plume rise from the thermal buoyancy of a release involving fire and dispersion effects near the release are also considered. The uncertainty of the effect of weather conditions on the calculated doses can be considered by constructing a cumulative probability distribution of dose values with wind-rose data for a given site. This probabilistic dose distribution is then used to determine the "median" (50% weather probability) and reasonable "maximum" (95% weather probability) dose values at a given receptor.

The pathway model includes exposure pathways from direct external radiation from the cask (due to loss of shielding), external exposure from the radioactive cloud and ground contamination, and internal exposure from inhalation of radionuclides in the air and potential ingestion of contaminated foods and water.

Health effects to individuals are estimated in terms of potential acute or latent fatalities, latent nonfatal cancer incidence, and latent adverse genetic effects from short-term exposure during initial plume passage and long-term exposure originating from deposited radioactive material. Acute fatalities are estimated using the latest NRC health effects model (NRC 1985; Abrahamson et al. 1989, 1991). The latent health effects are estimated using dose-to-health-risk conversion factors suggested in ICRP Publication 60 (ICRP 1991).

The consequence model of RISKIND includes provisions for incorporating the consequence reduction benefits of indoor shielding, evacuation, interdiction of contaminated foods, and other protective actions such as cleanup of contamination to comply with U.S. Environmental Protection Agency (EPA) protective action guide (PAG) levels (EPA 1991). Consequences can be presented either deterministically (i.e., with fixed accident parameters and weather conditions) or probabilistically (analyzed over the spectrum of accident response regions and weather conditions).

1.4 REVISIONS TO RISKIND

RISKIND, Version 1, incorporates a number of changes to the original code (Yuan et al. 1993) that increase the user-friendliness and flexibility of the program. Some of the major changes are listed in the following subsections.

1.4.1 New User Interface

The user interface has been totally revamped. The original DOS menu system has been replaced by the now familiar look and feel of a Windows™ application. Even users unfamiliar with the Windows™ operating system will quickly become accustomed to the intuitive interface. The main input window provides for selection of the major input options and a quick visual summary of the case under analysis. All input parameters are grouped logically according to function and are only one or two windows away from the main input window. The use of a mouse is preferred for navigating the input windows and displaying results; however, input from the keyboard for navigation is also supported. Another benefit of the Windows™ interface is its support of graphics. The original graphical display of results for certain health risks has been enhanced and upgraded. The user is able to gain a better understanding of the results through studying the data in a clearer pictorial format.

1.4.2 Model Input Parameters

To enhance the flexibility of the program, the remaining model input parameters for dose calculations that were previously unmodifiable by the user have been made user accessible. The interface can now accept user-supplied receptor shielding values and dose rate curves for incident-free calculations, and, for accident calculations, user-supplied shipment inventories, release characteristics, the remaining ingestion pathway input parameters, and receptor shielding values.

Receptor shielding values for incident-free and accident calculations had been user selectable from a predefined list, but custom values could not be input. This restriction has been revoked, and users may now input their own shielding values for a custom analysis if the data are available.

Previously, the user was confined to the use of the default gamma and neutron dose rate curves for estimating external exposures from stopped or passing shipments. These dose rate curves are based on representative radiation spectra from commercial spent fuel. To accommodate fuel-specific dose rate curves, RISKIND, Version 1, is equipped to accept user input values for the dose rate curve coefficients. This new feature allows the user to input external dose rate information that can be derived from realistic data such as actual measurements. In addition, this capability provides the means for adjusting dose rates for nonstandard SNF or other radioactive materials.

Radionuclide shipment inventories input by the user are now supported by RISKIND, Version 1. This new feature offers additional capabilities to accommodate fuel types that are outside the spectrum represented by BWR or PWR fuels; thus, the user is able to input a set of specific radionuclides and their respective amounts for nonstandard spent fuel. Furthermore,

inventories input by the user offer the flexibility of conducting analyses for shipments of radioactive materials other than SNF.

Shipping cask release characteristics (response region conditional probabilities and radionuclide release and dispersion fractions) can now be input by the user with RISKIND, Version 1. The user is able to use the latest available data and can evaluate results using different cask or shipping container designs. This new feature also permits user input of accident classification schemes other than those used in the modal study (LLNL 1987), such as that employed in NUREG 0170 (NRC 1977b).

1.4.3 Enhanced Capabilities

Potential accident consequences are highly dependent on weather conditions for the dispersion of released radioactivity. RISKIND is now capable of reading joint frequency data in Stability Array (STAR) format. Data in this standard format are widely available, and this new capability frees the user from having to convert data to the format used in RISKIND. The data from the STAR file are averaged over all directions for a complete health risk analysis, or, in keeping with the site-specific capabilities of RISKIND, the weather data for a particular direction may be selected for conducting a direction-specific risk analysis.

Deposition of radionuclides from the passing radioactive cloud after a potential radionuclide release caused by a possible accident would result in cloud depletion and ground contamination. The rate at which this deposition occurs is accounted for in the health risk calculations with the use of the radionuclide deposition velocity. A single deposition velocity had been used for all radionuclides with the exception of inert gases, which are assumed not to deposit. However, a radionuclide such as iodine deposits much more quickly than many other radionuclides. RISKIND, Version 1, assigns independent, user-accessible, deposition velocities to each of the five radionuclide types recognized by the program for individual receptor calculations. In addition, each radionuclide may be independently assigned to a particular radionuclide type. This flexibility permits the analyst to account for speciation of a particular radionuclide under the given circumstances, if the relevant data are available.

The health effects models have been revised. A new method for estimating acute dose rates and doses has been implemented, and updated latent health dose-to-health-risk conversion factors are used. Latent nonfatal cancer incidence has also been added to the effects estimated.

1.4.4 Databases Revised and Updated

The original SNF radionuclide database (Notz et al. 1987) has been updated in RISKIND, Version 1, with information from DOE (1992a). These updated data have been qualified by an OCRWM-sponsored peer review as meeting the requirements of the OCRWM

Quality Assurance Program. More information on the radionuclide database can be found in Appendix A.

The dose conversion factor (DCF) file database has been revised and now reflects the values from EPA Federal Guidance Reports (FGR) 11 and 12 (Eckerman et al. 1988; Eckerman and Ryman 1993). Dose conversion factors for internal exposure from inhalation and ingestion are taken from FGR 11, and factors for external exposure are taken from FGR 12. The DCF data are now maintained in an ASCII text file that also contains the data format for those who wish to substitute custom values for exposure calculations. This accessibility allows for the analysis of sensitive populations, such as children or the elderly, if the appropriate DCFs are available.

1.4.5 Output Revised

The output file has been reformatted for a clearer presentation of results. In addition, a complete input echo of all RISKIND input parameters to the output file has been added in Version 1. The presence of the input echo adds a new level of quality assurance and provides a permanent record of the input data used to calculate the accompanying results.

Isopleth contours for ground-level air concentrations and ground contamination are determined for estimating the risks to a population subgroup from a potential accidental release of radioactivity. RISKIND, Version 1, reports the number of persons per isopleth and their associated risks separately on an isopleth-by-isopleth basis, as well as collectively. This breakdown of the results enables the user to better understand where the highest areas of risk are located in the affected area.

The calculations in RISKIND are now based on input parameters using the SI system of units. However, the doses estimated for receptors are presented in conventional units of rem rather than sieverts (1 Sv = 100 rem), since the rem is the more commonly reported unit.

1.4.6 On-Line Help Added

On-line help with explanatory diagrams and definitions of all input parameters has been added to aid the user in program input. Scenario diagrams are available under the Help menu to aid the user in visualizing the situation to be modeled and to inform the user of the pertinent input parameters. Other diagrams are available that depict various input parameters to help the user understand their meanings. Pressing the F1 function key while a certain input parameter is selected will bring up the Help support with a description of the parameter. Help on individual input parameters may be accessed from the main menu bar as well.

1.5 REPORT ORGANIZATION

The information presented in this report is organized as follows:

- Incident-free transport models used in RISKIND — Section 2;
- Accident impact models used in RISKIND — Section 3;
- Health effects models used in RISKIND, including descriptions of the acute effects and latent health effects models — Section 4;
- Radionuclide inventory database specific to SNFs — Appendix A;
- Model for estimating the external dose rates for varying dimensions (radius and length) of the SNF cask — Appendix B;
- Method for screening the radionuclides that are significant for radiological risk analysis — Appendix C;
- Method for estimating the spallation of crud material during accidents — Appendix D
- Method for estimating the cask response from user-supplied accident scenarios — Appendix E;
- Program structure and data transfer used in RISKIND — Appendix F;
- Input required to execute RISKIND —Appendix G;
- Sample problems — Appendix H; and
- Quality assurance — Appendix I.

2 RADIOLOGICAL DOSE ASSESSMENT FOR INCIDENT-FREE TRANSPORT

During incident-free transportation, individuals are exposed to the direct external radiation emitted from the shipping package, such as a spent fuel cask. The radiation may consist of gamma rays and neutrons.

2.1 EXTERNAL DOSE MODEL

The external dose model in RISKIND is based on dose rates (Chen and Yuan 1988) that have been calculated separately for gamma and neutron radiation for a specific spent fuel cask configuration (Figure 2.1). These dose rates represent the values at the midplane perpendicular to the cask axis and account for both air and ground scattering from the cask in a horizontal position. Doses derived from this approach can be adjusted to accommodate different cask dimensions, according to the method described in Appendix B. The total external radiation dose rate at a given location with respect to the cask can be derived from the following equation:

$$\dot{D}(r) = \dot{D}_g(r) + \dot{D}_n(r) \ , \tag{2.1}$$

where

$\dot{D}(r)$ = total dose rate (rem/h) at a distance r meters from the cask surface;

$\dot{D}_i(r)$ = dose rate (rem/h) from gamma ($i = g$) or neutron ($i = n$) radiation at a distance r meters from the cask surface; and

r = distance in meters from the cask surface: $r = r_0 + r_1$, where r_0 is the distance from the outer lateral surface of the vehicle; and r_1 is the distance between the cask surface and the outer lateral surface of the vehicle.

The default dose rates (rem/h) for gamma and neutron radiation were derived from a representative spent fuel cask (DOE 1987a) used in assessing radiation exposures from the transportation of spent fuel (Chen and Yuan 1988). Other scenario-specific dose rates can be calculated with existing codes such as MCNP (the Monte Carlo N-Particle Transport Code System) (Los Alamos National Laboratory [LANL] 1994) and SCALE 3 (ORNL 1986) for gamma or neutron radiation and Microshield (Negin and Worku 1992) for gamma radiation. The calculated dose rates can be expressed by the following empirical formula for input to RISKIND:

$$\begin{aligned} \log [\dot{D}_i(\mathrm{r})] = {} & A_{0_i} + A_{1i} \log r + A_{2i} (\log r)^2 + A_{3i} (\log r)^3 + A_{4i} (\log r)^4 \\ & + A_{5i} (\log r)^5 + A_{6i} (\log r)^6 + A_{7i} (\log r)^7 . \end{aligned} \tag{2.2}$$

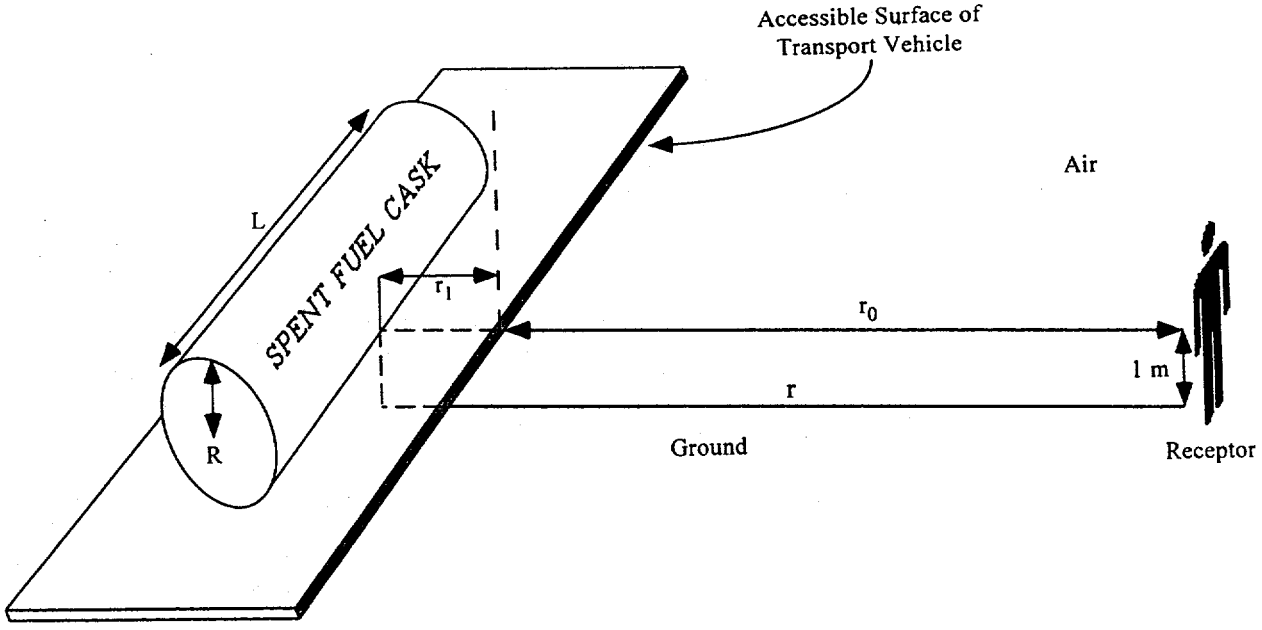

FIGURE 2.1 Configuration of Spent Fuel Cask Relative to the Receptor and Scattering Media (air and ground)

The coefficients A_{0i} to A_{7i} ($i = g$ for gamma, n for neutron [ACOEFU(8,i)]) are fitted coefficients in the applicable range of 1 to 1,000 m. These coefficients were obtained from statistical dose rates calculated by using the Monte Carlo method, with an assumed air/ground environmental setting. A simple $1/r^2$ relationship is assumed to extrapolate the dose rates for distances exceeding 1,000 m. These coefficients are normalized so that the dose rate is set at the regulatory limit[1] of 0.01 rem/h (10 mrem/h) at 2 m from the side of the transport vehicle or from the cask edge ($r_1 = 0$ m in Figure 2.1). The normalized coefficients are listed in Table 2.1.

The coefficients are adjusted accordingly, when other dose rates are specified. At 1 m ($r = 1$), Equation 2.2 reduces to

$$\log [\dot{D}_i(1)] = A_{0_i} \ . \tag{2.3}$$

The coefficient A_{0i} is actually the logarithm of the dose rate due to gamma (i = g) or neutron (i = n) radiation, which, in RISKIND, is derived from the total dose rate and the fraction due to gamma radiation:

$$\begin{aligned} A_{0_g} &= \log [f_g \dot{D}(1)] \ , \ \text{(gamma)} \\ A_{0_n} &= \log [(1 - f_g) \dot{D}(1)] \ , \ \text{(neutron)} \end{aligned} \tag{2.4}$$

[1] The 10 mrem/h limit at 2 m is based on specifications of the *Code of Federal Regulations* (CFR), Title 10, Part 71 (NRC 1994), and Title 49, Part 173 (U.S. Department of Transportation [DOT] 1994).

TABLE 2.1 Coefficients of the Fitted Equations for Neutron and Gamma Dose Rates from a Spent Fuel Cask, with Groundscattering

Coefficients	Gamma (i = g)	Neutron (i = n)
A_{0_i}	1.32271	1.29038
A_{1_i}	-0.863263	-0.97916
A_{2_i}	-0.78497	0.855591
A_{3_i}	0.361914	-3.77234
A_{4_i}	-0.22023	4.27579
A_{5_i}	0.094219	-2.36094
A_{6_i}	-0.015457	0.650231
A_{7_i}	-0.000746	-0.072219

Note: The dose rate is normalized to 10 mrem/h at 2 m from the cask surface.

Source: Chen and Yuan (1988). Extrapolation beyond 1,000 m is assumed to follow the $1/r^2$ relationship.

where

$\dot{D}(1)$ = total dose rate (mrem/h) at 1 m from the cask surface [TIDX]; and

f_g = fraction of total dose rate due to gamma radiation [FRAD(1)]); the remaining fraction is attributed to neutron radiation; $\dot{D}_g(1) = f_g\ \dot{D}(1)$ and $\dot{D}_n(1) = (1 - f_g)\ \dot{D}(1)$.

2.2 EXPOSURE AT FIXED DISTANCES

For transportation vehicles at stops (Figure 2.2), radiation exposure concerns are usually limited to persons located at fixed distances from the cask. Such individuals would include truck drivers, train crews, inspectors, escorts, service attendants, and members of the public who are exposed at shipment stops or in traffic jams.

The radiation dose to an individual receptor exposed at a fixed distance can be calculated by

$$D(r) = [\dot{D}_g(r) + \dot{D}_n(r)]\, SF(j)\, T(j) \ , \qquad (2.5)$$

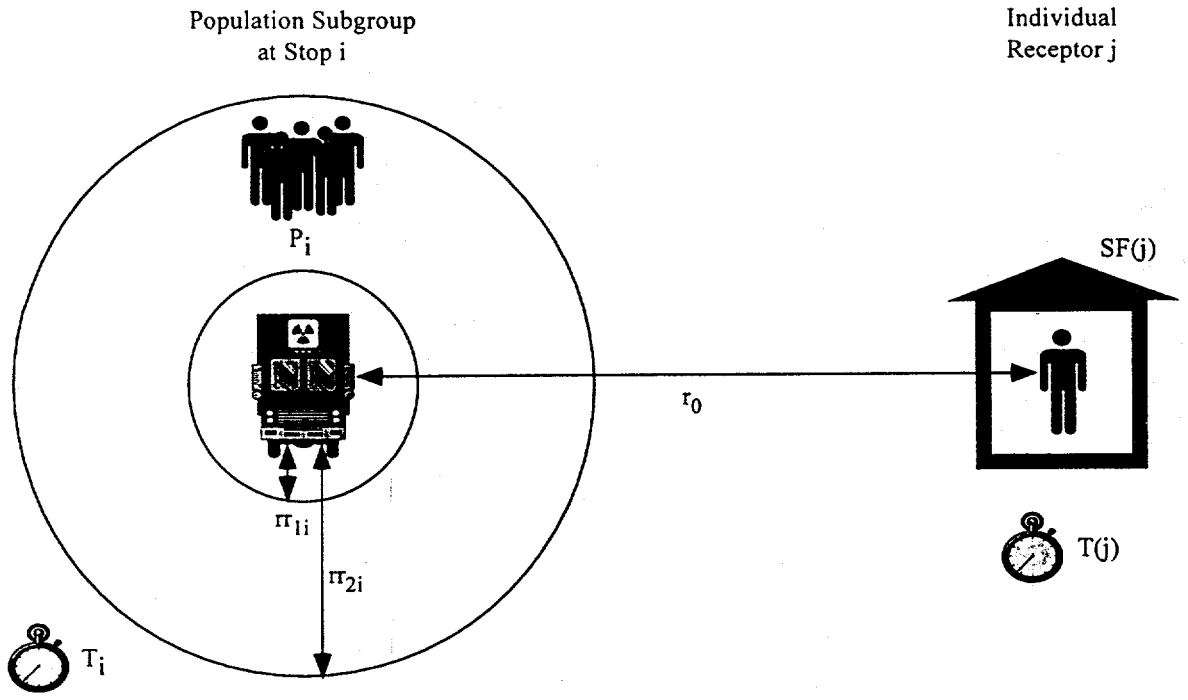

FIGURE 2.2 Schematic Diagram of External Exposures to Various Receptors from a Stationary Spent Fuel Shipment (Equation 2.5 for individuals, Equation 2.6 for a population subgroup).

where

$D(r)$ = individual dose to receptor j at distance r (rem);

r = distance in meters from the cask surface to receptor j: $r = r_0 + r_1$, where r_0 [DISTSTOP(j)] is the distance from the outer lateral surface of the vehicle to the receptor; and r_1 [TIOFF] is the distance between the cask surface and the outer lateral surface of the vehicle;

$SF(j)$ = shielding factor for receptor j for incident-free transportation: 0 = full shielding, 1 = no shielding (unitless) [set to the value in Table 3.5 as determined by ISHLT(j) (shelter type), which uses groundshine shielding factors]; and

$T(j)$ = time duration of exposure (h) for receptor j [TSTP(j)].

For exposure to a population subgroup, such as members of the public at shipment stops, the population density is assumed to be uniform within two concentric circles (representing minimum and maximum distances) around the cask. The dose received is

$$D_{psi} = 2\,[P_i / (r_{2i}^2 - r_{1i}^2)]\, N_i\, T_i \int_{r_{1i}}^{r_{2i}} \dot{D}(r)\, r\, dr \ , \qquad (2.6)$$

where

D_{psi} = dose to population subgroup at stop i (person-rem);

N_i = number of times at stop i [NSTP(i)];

P_i = number of persons at stop i [PSTP(i)];

r_{1i} = minimum distance in meters from the cask surface at stop i: $r_{1i} = rr_{1i} + r_1$, where rr_{1i} [DSTP(1,i)] is the distance from the outer lateral surface of the vehicle; and r_1 [TIOFF] is the distance between the cask surface and the outer lateral surface of the vehicle (m);

r_{2i} = maximum distance in meters from the cask surface at stop i: $r_{2i} = rr_{2i} + r_1$, where rr_{2i} [DSTP(2,i)] is the distance from the outer lateral surface of the vehicle; and r_1 [TIOFF] is the distance between the cask surface and the outer lateral surface of the vehicle (m); and

T_i = duration of exposure at stop i (h) [HSTP(i)].

2.3 EXPOSURE FROM A PASSING SHIPMENT

An off-link individual (e.g., roadside resident) will experience a changing exposure field that is dictated by the constantly changing distance between a passing shipment vehicle and the individual, as shown in Figure 2.3. The total dose, $D(x)$, received by an individual at the nearest distance x from the passing shipment is calculated by the integration of the dose rate, $\dot{D}(r)$, over the total exposure period:

$$D(x) = 2\,SF(j) \int_{t=0}^{\infty} \dot{D}(r)\,dt \ . \tag{2.7}$$

From the relationship $y = vt$ (speed × traveling time), Equation 2.7 becomes

$$D(x) = K_0\,SF(j)\,\frac{2}{v} \int_{0}^{\infty} \dot{D}(r)\,dy \ , \tag{2.8}$$

where

$D(x)$ = total dose to receptor j at distance x (rem);

x = nearest distance (m) of receptor j to passing shipment [DISTPASS(j)];

r = distance to cask surface (m) given by

$$r = [(x + r_1)^2 + y^2]^{1/2}; \tag{2.9}$$

r_1 = distance between the cask surface and the outer lateral surface of the vehicle (m) [TIOFF];

v = vehicle speed (km/h) [SPEED];

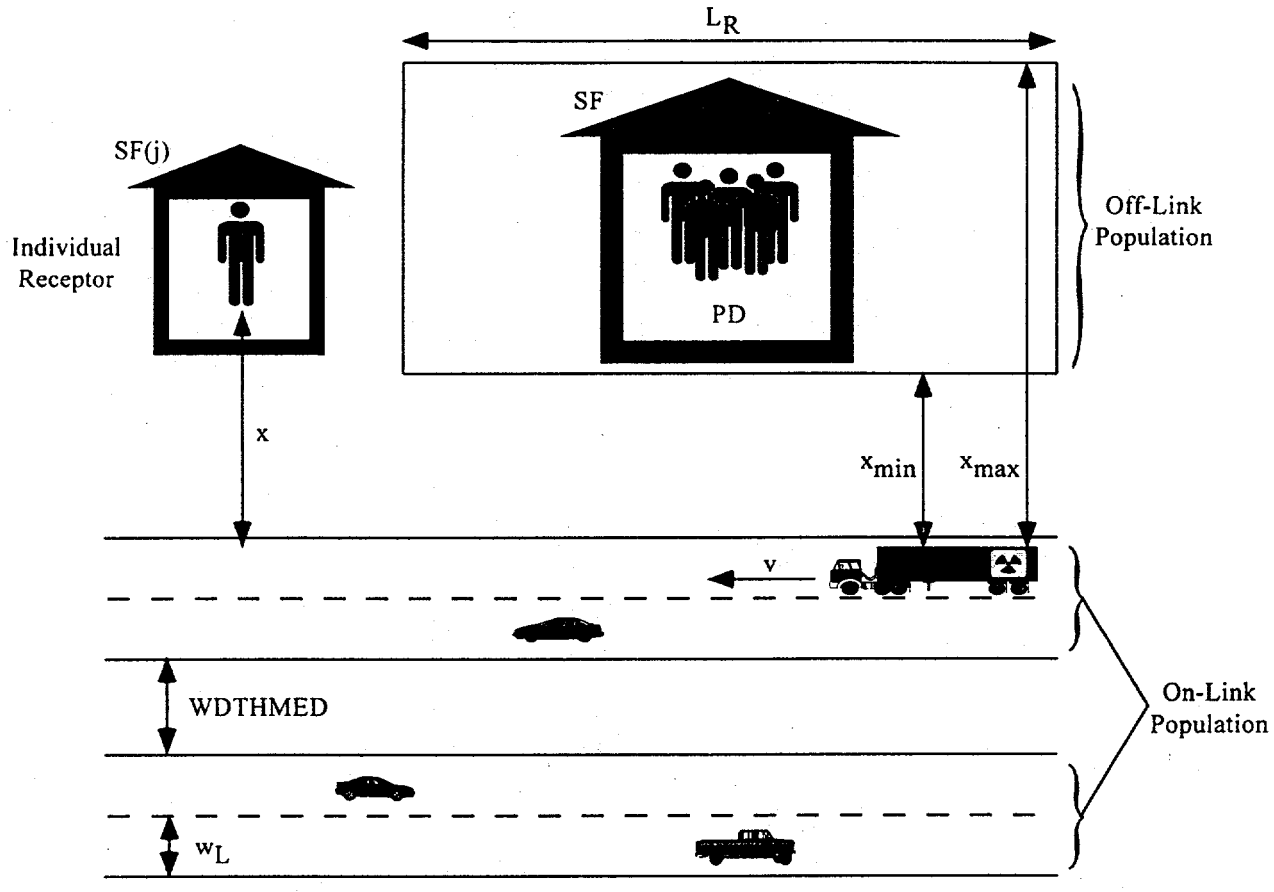

FIGURE 2.3 Schematic Diagram of External Exposures to Various Receptors from a Moving Spent Fuel Shipment (Equation 2.12 for individuals, Equations 2.14 and 2.16 for population groups)

K_0 = unit conversion constant (10^{-3} km/m); and

dy = $v\,dt$, the distance traveled in time dt (m).

Equation 2.8 can be rewritten (NRC 1977b) by substituting for y, according to Equation 2.9:

$$D(x) = K_0 \frac{2}{v} I(x) \ , \tag{2.10}$$

where

$$I(x) = \int_x^\infty \dot{D}(r) \frac{r}{\sqrt{r^2 - x^2}}\, dr \ . \tag{2.11}$$

Two different population groups are exposed during transit of a shipment, those off-link (e.g., roadside residents) and on-link (i.e., drivers and passengers). Figure 2.3 depicts the two groups and the relevant parameters for dose estimation. The off-link population dose from a passing shipment is an extension of Equation 2.10 to cover an area with a uniform population

density from the minimum distance of the group (x_{min}) to the route, to a maximum distance from the route (x_{max}) for a distance L_R:

$$D_{off} = [(SF\,F_{in} + (1-F_{in})]\,PD\,L_R\,K_0\,\frac{2}{v}\int_{x_{min}}^{x_{max}} I(x)\,dx\ , \qquad (2.12)$$

where

D_{off} = dose (person-rem) to off-link population in a given area from a passing shipment;

F_{in} = fraction of people indoors while shipment passes by the area [RFIE];

PD = population density for the area (persons/km^2) [POPD];

L_R = length of the route along the area (km) [SHIPDIST];

x_{min} = nearest distance of area to shipment route (km) [XPZ(1)];

x_{max} = farthest distance of area to shipment route (km) [XPZ(2)]; and

SF = shielding factor: 0 = full shielding, 1 = no shielding:

$$SF = \sum_{i=1\ \text{to}\ 5} Fr_i\,SF_i\ ; \qquad (2.13)$$

Fr_i = fraction of indoor population located in a given shelter type i [WSHLT(i)]: frame house (i = 1), office building (i = 2), brick house (i = 3), automobile (i = 4), or other (i = 5, user-defined); and

SF_i = shielding factor for each shelter type i, values from (NRC 1975), user-defined type variable is SHLDVAL.

The dose is computed for three groups in on-link dose estimation. The estimated dose for those persons traveling in the same direction as the shipment is calculated for two groups — those traveling in adjacent lanes to the shipment and those in the same lane (in front and behind) as the shipment. The third group consists of those traveling in the opposing direction of the shipment.

For those persons traveling in the same direction and in the same lane as the shipment, the dose is estimated by

$$D_{on} = PD_{on}\,L\,K_0\left(\frac{2}{v}\right)w_L\int_{d_0}^{\infty}\dot{D}\,(r)\,dr\ , \qquad (2.14)$$

where

D_{on} = dose (person-rem) to persons sharing the route (on-link population);

PD_{on} = on-link population density for the route (persons/km^2) given by

$$PD_{on} = \frac{P_{veh}\, TD\, K_0}{v\, w_L}; \tag{2.15}$$

P_{veh} = number of persons per vehicle [PPVH];

TD = traffic density for one lane (vehicles/h) [TRAF_DEN];

L = length of travel assumed to be 1 km;

w_L = lane width (m) [RDWTH];

d_0 = 2 m; and

$\dot{D}(r)$ = total dose rate (rem/h) at a distance r meters from the cask surface, estimated according to Equation 2.1.

For truck transport, the dose to an exposed population in lanes adjacent to the shipment traveling in the same direction and to those traveling in the opposite direction is calculated in a manner similar to the off-link population. The truck shipment is assumed to travel in the rightmost traffic lane. An average population density over the road width is assumed, and the dose is estimated by integration over the appropriate portion of the roadway:

$$D_{on} = PD_{on}\, L\, K_0\, \frac{2}{v} \int_{x_1}^{x_2} I(x)\, dx\ , \tag{2.16}$$

where

D_{on} = dose to on-link population in adjacent lanes or opposing traffic (person-rem);

x_1 = nearest distance to traffic of interest (m), assumed to be 1 m for adjacent lanes or, for opposing traffic, the distance across the adjacent lanes and any median separating traffic traveling in opposite directions [1 + (NUMLANES − 1) × RDWTH + WDTHMED]; and

x_2 = farthest distance to traffic of interest (m): for adjacent traffic, x_1 + (NUMLANES − 1) × RDWTH; for opposing traffic, x_1 + NUMLANES × RDWTH.

For rail transport, the on-link dose estimate is for opposing traffic on neighboring tracks.

3 RADIOLOGICAL HAZARD FROM ACCIDENTS

Accidents associated with the transport of SNF are very rare. The probability has been estimated (Saricks and Kvitek 1994) to be on the order of one incident per ten million miles of truck or rail shipment in the United States. In addition, SNF is shipped in NRC-certified, or equivalent, casks that meet the extremely stringent safety standards of 10 CFR 71 (NRC 1994). Thus, even in the event of an accident, the robustness of such casks would adequately protect the health and safety of the public. However, as in the case of other existing regulations, cask certification procedures are designed to provide protection against "design-basis" accidents, the majority of all potential accidents. No radioactive contents, or an insignificant amount, would be released as the result of a design-basis accident. This section addresses the hypothetical, including the exceedingly rare "beyond-design-basis," accidents that could potentially release SNF radioactive contents to the atmosphere, thereby threatening public health and safety.

The fuel assemblies used in commercial power reactors contain solid ceramic uranium oxide (UO_2) fuel pellets. During reactor operation, the fission of uranium fuel creates a number of radioactive products. Physically, most of the radioactive material remains in solid form within the pellets, although the pellets may exhibit some degree of fracturing. A small fraction of the fission products, however, is in gaseous or volatile form. The radiological hazards that could conceivably be created by this material can occur through two distinct mechanisms: (1) a release of material from a damaged cask, or (2) an increase in the external radiation level emanating from material within a damaged cask. Material releases can occur in gaseous, volatile, or solid form. Significant hazards to humans can result from inhalation of the released material, ingestion of contaminated food, and exposure to external radiation from a passing cloud of the material or from the material deposited on the ground. Increased radiation levels from material still within the cask could occur as the result of voids in the cask shielding, which can result from mechanical forces or temperatures high enough to cause shield materials to melt. The following sections describe the methods used to assess these potential radiological hazards. Section 3.1 describes the cask accident response release model, Section 3.2 the accident release model, Section 3.3 the dose calculation model for individuals, and Section 3.4 the dose model for the collective local population. Further discussions on the models and the relevant input parameters can be found in Appendix G.

3.1 ACCIDENT RESPONSE MODEL

The response of SNF casks under a range of highway and railway accident conditions has been investigated by LLNL for the NRC. The results of this study are provided in detail in the NRC modal study (LLNL 1987). In the NRC modal study, all potential damage to a shipping cask during an accident is categorized according to two principal variables: the cask structural and thermal responses induced by cask impact and fire, respectively. Twenty cask response

regions (or categories) based on varying levels of cask strain and temperature are categorized to represent the entire spectrum of transportation accidents. The regions range from those with high probability and low impacts to those with low probability and higher impacts. Figure 3.1 shows the cask response regions and the conditional probabilities of occurrence for combined mechanical and thermal loads [FSEV(i) for each response region *i*] should an accident occur.

The most important accident conditions used to define the mechanical loads imposed on a cask during an accident are those associated with various physical impacts. Because of the large weight, hardness, and rigidity of spent fuel casks, loads caused by crushing, projectiles, or other mechanisms have been demonstrated to be far less damaging than loads caused by impacts with hard, massive objects. As in any impact involving a motor vehicle or train, the damage sustained would depend on vehicle speed, angle of impact, hardness of the object struck, and orientation of the vehicle and object at the time of impact.

The temperature of an accident-generated fire is the most important consideration in assessing potential cask functional degradation. The cumulative heat affecting a cask depends not only on the temperature and duration of the fire but also on the extent to which the cask is exposed. Data on fire temperatures and durations are not readily available in accident records; however, conservative estimates of fire temperatures and durations can be calculated on the basis of pertinent information about the accident, such as the maximum fuel volume carried by a typical truck and the nature of the product being shipped. Another accident condition required to describe cask response is the location of a cask relative to the fire during an accident. Appendix E presents the method used in RISKIND for estimating the cask response from user-supplied accident scenarios.

3.2 ACCIDENT RELEASE MODEL

According to the NRC modal study (LLNL 1987), three mechanisms are necessary for establishing a release path from the spent fuel to the environment: (1) diffusion from cracked fuel pellets, (2) a leak from a breach of the fuel rod cladding, and (3) a leak through deteriorated cask seals. Before radioactive material is released into the cask cavity, the cladding must be breached during an accident as a result of high impact or high temperature. The percentage of fuel rods that may be breached under various impact and fire conditions in a transportation accident is estimated in the NRC modal study. After a fuel rod is breached, radioactive gases, volatiles, and solids can potentially escape into the cask cavity. Only rod burst and oxidation were considered significant release mechanisms in the NRC modal study. It was conservatively assumed that all the released materials in the cask cavity would be released to the environment if a leak path developed in the containment (LLNL 1987). A leak path is assumed to occur for any transportation accident resulting in a maximum strain in the inner containment shell greater than 0.2%, or in a lead midlayer thickness temperature exceeding 500°F.

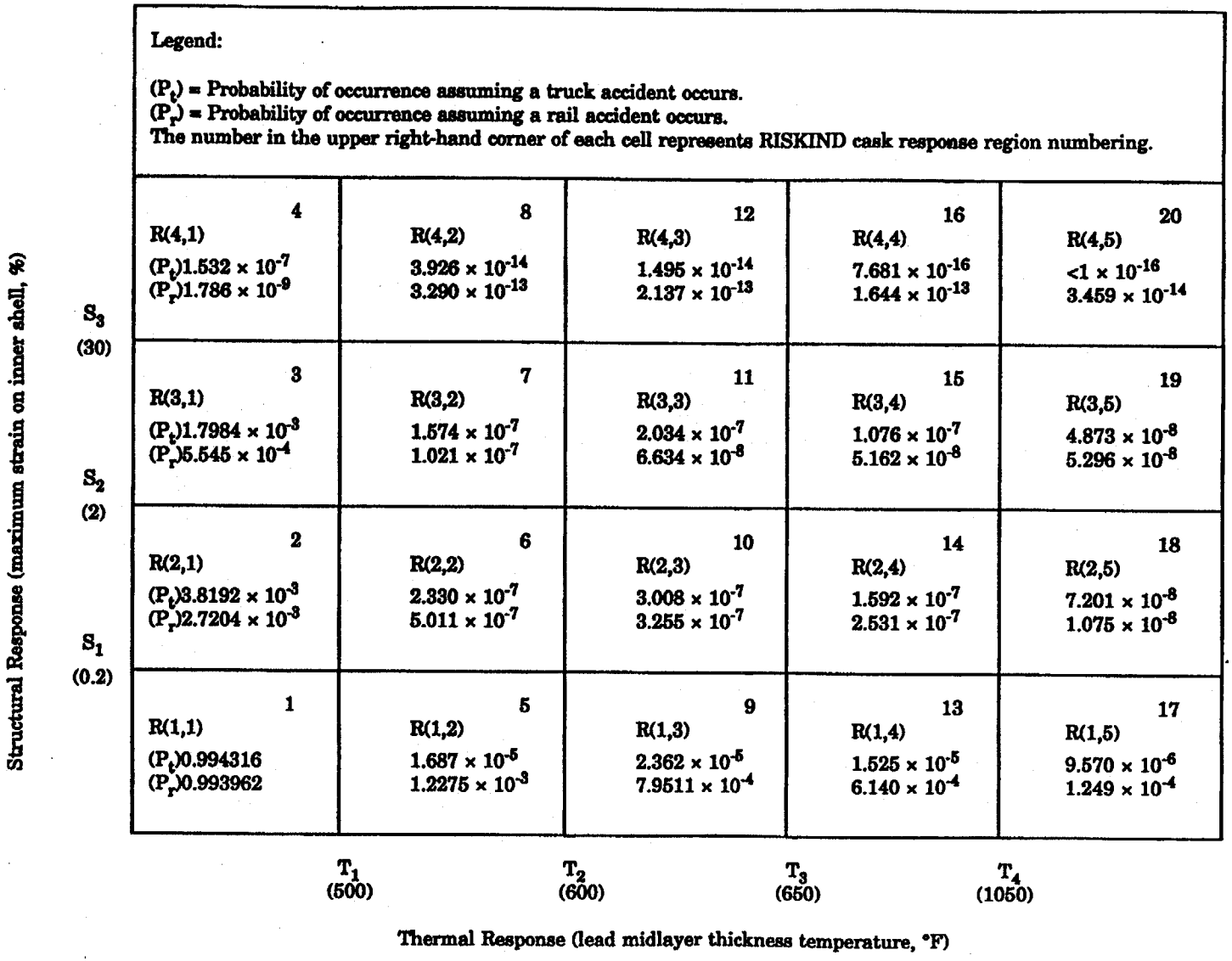

FIGURE 3.1 Matrix of Cask Response Regions and Probabilities of Occurrence for Combined Mechanical and Thermal Loads (Source: LLNL 1987)

On the basis of the above assumptions, the radionuclide fractions released and dispersed to the atmosphere are presented in Table 3.1 for five types of radionuclides [NUTYPE(5)] and the 20 modal study cask response regions. Radionuclides are grouped by physical and chemical behavior: particulates; ruthenium, cesium, and iodine isotopes (considered to be in the form of vapors); and noble or inert gases. The total release to the environment for a radionuclide in a dispersed, respirable form is given by

$$Q_{0_i} = Q_i \, F_{FAIL_j} \, F_{REL_{jk}} \, F_{DISP_{jk}}, \tag{3.1}$$

where

Q_{0_i} = initial amount of radionuclide i released (Ci);

Q_i = radionuclide i inventory amount in the spent fuel cask, which can also be used for total shipment inventory of a multiple package shipment (Ci);

F_{FAIL_j} = fraction of failed rods in the spent fuel cask that can also be used for fraction of failed packages in a multiple package shipment for other radioactive materials (unitless) [FAILS(j) for accident response region j];

$F_{REL_{jk}}$ = fraction of inventory released from failed rods to the cask cavity, which can also be used for the fraction released from the shipping package (unitless) [FRELS(j,k) for accident response region j for radionuclide type k]; and

$F_{DISP_{jk}}$ = fraction of released inventory dispersed to the atmosphere as a respirable aerosol for accident response region j for radionuclide type k (unitless) [FDISP(j,k)].

Appendix A describes the SNF radionuclide inventory derived for use in RISKIND. The program can perform an assessment with up to 100 radionuclides. A screening method is available, as described in Appendix C, to limit the analysis to the most radiologically significant radionuclides.

The release of radioactivity in the crud is treated separately in RISKIND because crud is a mixture of reactor coolant corrosion products that have deposited on the surfaces of fuel rods and can be released during a transportation accident without severe damage to the fuel rods or cladding. The approach used in RISKIND to estimate the crud spalled (broken off) from the fuel rods during an accident is based on the method of Sandoval et al. (1991) and is described in Appendix D. All of the spalled crud material is conservatively assumed to be released to the environment for all accident response regions except R(1,1), for which no release is assumed because there is no leak path to the environment.

TABLE 3.1 Radioactive Material Release Fractions from Accidents Occurring under Various Cask Response Regions

Cask Response Region		Release Fraction[c]				
			Vapors			
Modal Study[a]	RISKIND[b]	Inert Gas	Iodine	Cesium	Ruthenium	Particulates
R(1,1)	(1)	0.0	0.0	0.0	0.0	0.0
R(1,2), R(1,3)	(5,9)	9.9×10^{-3}	7.5×10^{-5}	6.0×10^{-6}	8.1×10^{-7}	6.0×10^{-8}
R(2,1), R(2,2), R(2,3)	(2,6,10)	3.3×10^{-2}	2.5×10^{-4}	2.0×10^{-5}	2.7×10^{-6}	2.0×10^{-7}
R(1,4), R(2,4), R(3,4)	(13,14,15)	3.9×10^{-1}	4.3×10^{-3}	2.0×10^{-4}	4.8×10^{-5}	2.0×10^{-6}
R(3,1), R(3,2), R(3,3)	(3,7,11)	3.3×10^{-1}	2.5×10^{-3}	2.0×10^{-4}	2.7×10^{-5}	2.0×10^{-6}
R(1,5), R(2,5), R(3,5), R(4,5), R(4,1), R(4,2), R(4,3), R(4,4)	(17, 18, 19, 20,4, 8, 12, 16)	6.3×10^{-1}	4.3×10^{-2}	2.0×10^{-3}	4.8×10^{-4}	2.0×10^{-5}

[a] R(N1,N2) represents the NRC modal study designation of discrete severity (cask response) regions, with N1 representing the impact strain and N2 representing the temperature caused by fire (see Figure 3.1).

[b] The NRC modal study severity regions are represented in RISKIND by 20 discrete numbers (see Figure 3.1).

[c] The release fraction represents the fraction of the total fuel inventory in the cask that would be released into the atmosphere.

Source: LLNL (1987).

3.3 INDIVIDUAL DOSE MODEL

RISKIND incorporates a standard Gaussian plume atmospheric dispersion model that also considers the effective emission height of a release (plume rise); corrects the wind speed according to height with a power law adjustment; and accounts for terrain height, the initial dispersion geometry of the waste package, and buoyancy-induced dispersion. Doses are calculated for individual exposure to external radiation from the shipping cask, the passing radioactive cloud following the accident, resuspended contamination, and radionuclides deposited on the ground; exposure from inhalation during the radioactive cloud passage following the accident; and exposure from ingestion of contaminated foodstuffs and water.

3.3.1 Atmospheric Transport Model

The atmospheric transport model used in RISKIND is a Gaussian puff dispersion model. Radionuclides released from a shipping cask are transported by the wind and are diffused as a result of atmospheric turbulence. The source must be described in terms of location and other physical parameters, type of radionuclide, and the amount released to the atmosphere. For individual receptors, the atmospheric transport model in RISKIND calculates concentrations in air at the specified downwind location for the five types of radionuclides identified in the NRC modal study: (1) particulate radionuclides; (2) ruthenium, (3) cesium, and (4) iodine vapors; and (5) inert gaseous radionuclides. RISKIND uses a plume-rise model developed by Briggs (1969) to estimate buoyancy-induced rise of the release, if applicable. An initial source dispersion parameter is used to model the source geometry of the release. Depending on circumstances, either the standard Pasquill-Gifford dispersion coefficients (Slade 1968; Eimutis and Konicek 1972) or the Briggs (1974) dispersion coefficients can be used. The former are suitable for ground-level releases; the latter are better for elevated releases. For vapor or particulate radionuclides, deposition of the plume content from the puff by dry and wet deposition is also considered for any user-specified receptor location. Both air and ground concentrations of radionuclides are calculated for the estimation of exposure via various pathways.

3.3.1.1 Effective Release Height

Material discharged to the atmosphere as a result of a transportation accident may rise above the release point as a result of thermal buoyancy. The thermal buoyancy is fire related in most accident cases. An effective release height H is used in the atmospheric dispersion equations to account for the additional height of the release. The effective release height is the sum of the actual physical release height, h, and the thermally-induced plume rise, Δh, with an adjustment for terrain height:

$$H = h + \Delta h - (1 - P_c)\,[\min(h + \Delta h, E_r - E_p)]\ , \qquad (3.2)$$

where

H = effective release height (m);

h = physical release height (m) [HS];

Δh = plume rise (m) [Equation 3.3, 3.4, 3.5, 3.6, or 3.7];

P_c = plume-path coefficient (unitless) (Section 3.3.1.1.2);

E_r = receptor elevation (m) [XRECEP(3,i) for individual i, 0 for population]; and

E_p = release elevation, the reference point for the release height (m) [0].

3.3.1.1.1 Plume Rise. Plume rise is estimated in RISKIND with the formulas derived by Briggs (1969) for buoyant plumes. The rise from thermal buoyancy is seen to be dependent on stability class, wind speed, and receptor distance. For stability classes A, B, C, and D, the plume rise is given by

$$\Delta h = \frac{1.6\, F^{1/3}\, x^{2/3}}{u_H} \quad , \text{for } x \leq 10\, h \ ; \tag{3.3}$$

$$\Delta h = \frac{1.6\, F^{1/3}\, (10\, h)^{2/3}}{u_H} \quad , \text{for } x > 10\, h \ ; \tag{3.4}$$

where

F = $3.7 \times 10^{-5}\, Q_h$ (m^4/s^3),

Q_h = heat flux from radionuclide release area (cal/s) [HEATF(i) for accident response region i],

x = downwind receptor distance from release point (m) [XRECEP(1,i) for individual receptor i, XPZ(1) to XPZ(2) for population], and

u_H = wind speed at effective release height (m/s) [Equation 3.10].

For stability classes E and F, the plume rise is calculated according to

$$\Delta h = \frac{1.6\, F^{1/3}\, x^{2/3}}{u_H} \quad , \text{for } x \leq 2.4\, \frac{u_H}{\sqrt{s}} \tag{3.5}$$

or

$$\Delta h = 2.9 \left(\frac{F}{u_H\, s} \right)^{1/3} \quad , \text{for } x > 2.4\, \frac{u_H}{\sqrt{s}} \ , \tag{3.6}$$

except when the wind is so light that the plume rises vertically. Under such conditions, the final plume rise is given by Briggs as

$$\Delta h = \frac{5.0\, F^{1/4}}{s^{3/8}} \text{ , when } u_H \leq u_{test} \text{ ,} \tag{3.7}$$

where

$$s = \frac{g}{T_a}\left(\frac{\partial T_a}{\partial z} + \ell\right), \tag{3.8}$$

$$u_{test} = 0.195\, F^{1/4}\, s^{1/8} \text{ ,} \tag{3.9}$$

s = stability parameter [Equation 3.8],

g = gravitational acceleration (9.80665 m/s^2),

T_a = ambient air temperature (K) [TABK],

ℓ = normal adiabatic lapse rate of the atmosphere (0.0098 K/m),

$\frac{\partial T_a}{\partial z} + \ell$ = potential temperature lapse rate [0.002 and 0.035 for stability classes E and F respectively], and

z = vertical distance above the release point (m).

As recommended by Briggs, Equations 3.3 to 3.6 contain wind speed in the denominator, which would produce unrealistically high values for very low wind speeds. Because the Briggs equations are applicable only to windy conditions, a minimum wind speed of 0.1 m/s is imposed in the above plume-rise calculations.

3.3.1.1.2 Terrain Height Adjustment. Rising terrain downwind from a transportation accident requires that the release height derived for flat terrain be adjusted accordingly. Stability-dependent plume-path coefficients are used in RISKIND to estimate the effects of terrain elevation on the height of the plume centerline. The correction to the release height for downwind elevations is the third term in Equation 3.2, as given in Ross et al. (1985).

An increase in receptor elevation downwind effectively reduces the release height if the release height is greater than zero. This condition is embodied in the min($h + \Delta h$, $E_r - E_p$) portion of Equation 3.2. On the other hand, the radioactive puff will not travel straight into a hillside but will follow air currents part way up the hill on its approach. The portion of Equation 3.2 with the plume-path coefficient, $(1 - P_c)$, partially defines the amount of the effective reduction in release height and assures that the terrain height adjustment is not too extreme. For neutral and unstable conditions (stability classes A, B, C, and D), P_c is set to 0.5 so

that the puff height remains at least one-half the distance above ground as it would be if no adjustment were made. Similarly for stable conditions (stability classes E and F), P_c is set to 0.3 so that the puff height remains at least one-third the height above ground as it would be if no adjustment were made. A plume path coefficient of 1 represents a nonterrain-lifted plume.

3.3.1.2 Wind Power-Law Adjustment

For atmospheric dispersion calculations, the measured average wind speed at the effective release height, u_H, is not always available. RISKIND uses a power-law function with the following form to estimate the wind speed at the desired height:

$$\frac{u_H}{u_a} = \left(\frac{H}{z_a}\right)^p , \tag{3.10}$$

where

u_a = wind speed at measurement height (m/s) [WSM],

z_a = height of anemometer for wind speed measurement (m) [ANH], and

p = power for height ratio (unitless) [Table 3.2].

The wind speed of u_a from the measurement height z_a is adjusted to the effective release height H of the plume for the dispersion calculations. Values for the exponent p were taken from Irwin (1979), as modified by Hanna et al. (1982), for the different population zones and stability classes.

3.3.1.3 Atmospheric Dispersion

For a puff generated from a point source with an effective release height H above ground level, the Gaussian time-dependent dispersion equation is (Pasquill 1974)

$$C_a(i,x,y,z,t) = \frac{Q_{x_i}}{(2\pi)^{3/2}\,\sigma_y^2\,\sigma_z}\exp\left(\frac{-r^2}{2\sigma_y^2}\right)\left[\exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right)+\exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right] \tag{3.11}$$

where

$C_a(i,x,y,z,t)$ = air concentration of radionuclide i at x, y, z from a release at 0, 0, H at time t after release (Ci/m^3);

Q_{x_i} = depleted source strength of nuclide i at distance x [Equation 3.27];

σ_y = horizontal dispersion coefficient [Equation 3.46];

σ_z = vertical dispersion coefficient [Equation 3.44];

r^2 = $(x - u_H t)^2 + y^2$, assumes Gaussian symmetry, that is, $\sigma_x = \sigma_y$ (m^2);

x = downwind receptor distance from the release point (m) [XRECEP(1,i) for individual receptor i];

y = crosswind receptor distance from the plume centerline (m) [XRECEP(2,i) for receptor i];

u_H = average wind speed at the effective release height (m/s) [Equation. 3.10];

t = time following accidental release(s); and

H = effective release height (m) [Equation 3.2].

The ground-level air concentration (Ci/m^3) for a discrete puff is obtained by setting $z = 0$ in Equation 3.11.

$$C_a\,(i, x, y, 0, t) = \frac{2\,Q_{x_i}}{(2\pi)^{3/2}\,\sigma_y^2\,\sigma_z}\left\{\exp -\left(\frac{r^2}{2\,\sigma_y^2} + \frac{H^2}{2\,\sigma_z^2}\right)\right\} . \qquad (3.12)$$

As a conservative measure, the receptor is assumed to be located downwind of the plume throughout the entire course of plume passage; radionuclide decay is ignored during this time period. Thus, the time-integrated ground-level air concentration ($Ci\text{-}s/m^3$) from the time of release to infinity at the receptor location is used for the dose estimation and is calculated as

$$\overline{C}_a\,(i, x, y) = \int_0^\infty C_a\,(i, x, y, 0, t)\,dt \ , \qquad (3.13)$$

TABLE 3.2 Estimates of the Power (p) in Equation 3.10 for Population Zones as a Function of Stability Class

Population Zone	Stability Class					
	A	B	C	D	E	F
Rural	0.07	0.07	0.10	0.15	0.35	0.55
Suburban/urban	0.15	0.15	0.20	0.25	0.40	0.60

which can be shown to be (Slade 1968)

$$\overline{C}_a\,(i, x, y) = \frac{Q_{x_i}}{\pi\,\sigma_y\,\sigma_z\,u_H}\left[\exp -\left(\frac{y^2}{2\,\sigma_y^2} + \frac{H^2}{2\,\sigma_z^2}\right)\right], \tag{3.14}$$

where Q_{x_i} is the initial source term for radionuclide i, corrected for wet and dry deposition from the puff (Equation 3.27).

3.3.1.4 Plume Reflection

The existence of a stable air layer at higher altitudes under unstable and neutral atmospheric conditions affects the atmospheric dispersion at great distances from the release point. The upward dispersion of the plume is eventually restricted when the plume encounters an elevated stable layer (or lid) or a mixing height at some height L. In RISKIND, the plume is assumed to be reflected by this stable layer at these distances. With vertical distribution limited by reflections, Equation 3.14 becomes

$$\overline{C}_a\,(i, x, y) = \frac{Q_{xi}}{\sqrt{2\pi}\,\sigma_y\,u_H\,L}\exp -\left(\frac{y^2}{2\,\sigma_y^2}\right), \tag{3.15}$$

where

L = mixing layer height sometimes referred to as lid height (m) [DMIX].

The following conditions (Powell et al. 1979) are used to determine which of these two equations, Equation 3.14 or 3.15, is used for the dispersion calculation.

Equation 3.14 is used for distances where σ_z is small compared to L, when

$$\frac{\sigma_z}{L} \le \frac{\sqrt{1 - \frac{H}{L}}}{1.2}. \tag{3.16}$$

Equation 3.15 is used when σ_z is of the same order as L and a uniform distribution can be assumed, when

(1) $0 \le H/L < 0.5$, and

$$\frac{\sigma_z}{L} \ge -2.37\left(\frac{H}{L}\right)^2 + 0.489\left(\frac{H}{L}\right) + 0.756 \tag{3.17}$$

or

$$(2)\ 0.5 \leq H/L < 1.0, \text{ and}$$

$$\frac{\sigma_z}{L} \geq -2.37\left(\frac{H}{L}\right)^2 + 4.25\left(\frac{H}{L}\right) - 1.13 \ . \tag{3.18}$$

At downwind distances between the no-mixing (Equation 3.16) and the total-mixing (Equations 3.17 and 3.18) conditions, the concentration is determined by a linear interpolation between Equations 3.14 and 3.15.

3.3.1.5 Depletion Correction and Ground Contamination

As a radioactive plume travels downwind, its radionuclide content decreases as the result of ground deposition. Two deposition mechanisms, dry and wet, account for this radionuclide depletion from the plume. This section describes the methods used in RISKIND for calculating plume depletion and ground contamination from radionuclide deposition.

3.3.1.5.1 Dry Deposition. With the exception of inert gases, all fission products released from a shipping cask will primarily be in particulate form. Unless the shipping casks are severely damaged, these particulates are generally released in small sizes (i.e., less than a few microns). The vertical movement of these small particles is largely dependent on the vertical turbulence and mean motion of the air; settling of the particles by gravity is minimal. Deposition of such small particles on the ground surface is the result of turbulent diffusion and Brownian motion. Chemical absorption, impaction, and other physical and chemical processes cause the material to be retained at the surface. Such a deposition mechanism depletes the amount of radioactivity in the plume, causing ground contamination, and thus affects the potential radiological hazards as the plume travels farther downwind. Radiological hazards to individuals occur by way of either direct exposure from the ground or indirect exposure via the ingestion of contaminated foodstuff.

Calculation of the dry deposition rate involves the concept of deposition velocity, that is, the ratio of the deposition rate to the air concentration expressed in units of velocity. The time-integrated ground surface concentration is given by

$$C_g\ (i, x, y) = \overline{C}_a\ (i, x, y)\, V_{d_j} \ , \tag{3.19}$$

where

$C_g(i,x,y)$ = initial ground concentration of radionuclide i at receptor location x, y after plume passage (Ci/m^2),

$\overline{C}_a(i,x,y)$ = time-integrated ground-level air concentration (Ci-s/m^3) [Equation 3.14 or 3.15], and

V_{d_j} = deposition velocity (m/s) [VDEPNUC(j) for nuclide class *j*].

The deposition velocity is determined from either field or laboratory measurements of air and ground concentrations.

When plume depletion by dry deposition is considered, the initial source term, Q_{0_i} at the release point can be replaced by a depleted source term Q_{x_i} along the downwind sector. In this approach, known as the source depletion model, it is assumed that the depletion reduces only the effective source strength and that the vertical Gaussian profile remains unchanged. In this derivation, the total activity has been conserved.

The reduced source strength, Q_{x_i}, as the result of deposition is calculated from the following equation (Slade 1968):

$$Q_{x_i} = Q_{0_i} \exp\left[- \frac{V_{d_j}}{\left(\frac{\pi}{2}\right)^{1/2} u_H} \int_0^x F(x)\, dx \right] , \qquad (3.20)$$

where

Q_{x_i} = depleted source strength of nuclide *i* at distance *x* (Ci),

Q_{0_i} = initial amount of radionuclide *i* released (Ci) [Equation 3.1],

$F(x)$ = Equation 3.21 or 3.22 (1/m), and

u_H = average wind speed at effective release height (m/s) [Equation 3.10].

At downwind distances not affected by the presence of a mixing layer,

$$F(x) = \frac{\exp\left(\frac{-H^2}{2\sigma_z^2}\right)}{\sigma_z} , \qquad (3.21)$$

where

H = effective release height (m) [Equation 3.2], and

σ_z = vertical dispersion coefficient [Equation 3.44].

At downwind distances where total mixing by the presence of a mixing layer can be assumed (Powell et al. 1979),

$$F(x) = \frac{1}{L} \quad , \tag{3.22}$$

where

L = mixing layer height sometimes referred to as lid height (m) [DMIX].

At downwind distances between the no-mixing (Equation 3.16) and total-mixing (Equations 3.17 and 3.18) conditions, $F(x)$ is determined by a linear combination of Equations 3.21 and 3.22. The integral expressions in Equation 3.20 are evaluated numerically in RISKIND with a Simpson's rule subroutine.

3.3.1.5.2 Wet Deposition. Radionuclides can also be removed from a plume by rain or snowfall. In wet deposition, the depletion mechanism of radionuclides is such that the plume is "washed out" by rain or snow. Thus, the wet deposition rate is dependent on the total amount of radioactivity contained in the plume, in contrast to dry deposition for which the depletion is closely related to the air concentration at ground level. The fraction of material removed per unit time by wet deposition is known as the "washout coefficient," V_w, and is defined as follows:

$$V_w = - \frac{1}{C_a} \frac{dC_a}{dt} \quad , \tag{3.23}$$

where

V_w = washout coefficient (1/s), and

C_a = local air concentration (Ci/m^3).

Calculated and measured values of the washout coefficient range from about 1.0×10^{-5} to 1.0×10^{-2} per second (Ritchie et al. 1978; McMahon and Dennison 1979). The value of the washout coefficient increases with an increasing rainfall rate and is linearly dependent on the rainfall rate:

$$V_w = W_C R \quad , \tag{3.24}$$

where

W_C = 1.0×10^{-3} (1/s)(mm/h)$^{-1}$ for stability classes A to D and 1.0×10^{-4} (1/s)(mm/h)$^{-1}$ for stability classes E and F [Ritchie et al. 1978], and

R = rainfall rate (mm/h) [RAIN].

The ground concentration in the precipitation region is given by (Slade 1968):

$$C_{WET_g}(i, x, y) = \frac{Q_{WET_{xi}} V_w}{\sqrt{2\pi}\ \sigma_y\ u_H} \exp\left(\frac{-y^2}{2\,\sigma_y^2}\right), \tag{3.25}$$

where

$C_{WET_g}(i,x,y)$ = initial ground concentration from wet deposition for nuclide i at location x, y after plume passage (Ci/m^2).

The depleted source strength from wet deposition, assuming a steady rainfall rate and wind speed is given by

$$Q_{WET_{x_i}} = Q_{0_i} \exp\left(-\frac{V_w\, x}{u_H}\right). \tag{3.26}$$

For low rainfall rates (i.e., a few millimeters per hour), Equations 3.24 and 3.25 are adequate. For high rainfall rates, the redistribution of the deposited radioactivity from surface runoff should be taken into account while evaluating the ground contamination from washed activity. Such conditions are not accounted for in RISKIND.

3.3.1.5.3 Dry and Wet Deposition. Dry deposition is always considered in RISKIND. When wet deposition is also considered, the depleted source strength at a distance x downwind becomes a function of both dry and wet deposition. The depleted source strength becomes a combination of Equations 3.20 and 3.26 and is calculated according to

$$Q_{x_i} = Q_{0_i} \exp\left\{-\left[\frac{V_w\, x}{u_H} + \frac{V_{d_j}}{\left(\frac{\pi}{2}\right)^{1/2} u_H} \int_0^x F(x)\, dx\right]\right\}. \tag{3.27}$$

Likewise, the initial ground concentration (Ci/m^2) from wet and dry deposition for nuclide i at location x, y after plume passage becomes

$$C_g(i,x,y) = C_{DRY_g}(i,x,y) + C_{WET_g}(i,x,y), \tag{3.28}$$

and can be written as

$$C_g(i, x, y) = \frac{Q_{xi}}{\sqrt{\pi}\ \sigma_y\ u_H}\left[\frac{V_w}{\sqrt{2}} + \frac{V_{d_i}}{\sqrt{\pi}\ \sigma_z} \exp\left(\frac{-H^2}{2\,\sigma_z^2}\right)\right] \exp\left(\frac{-y^2}{2\,\sigma_y^2}\right), \tag{3.29}$$

when the plume vertical distribution is not limited by a stable layer (Equation 3.16 holds), or as

$$C_g\,(i,x,y) = \frac{Q_{x_i}\,(V_w + V_{d_i}\,/\,L)}{\sqrt{2\pi}\,\sigma_y\,u_H}\exp\left(\frac{-y^2}{2\,\sigma_y^2}\right), \qquad (3.30)$$

when there is uniform mixing between the ground and the mixing layer (Equation 3.17 or 3.18 holds).

Use of the above methodologies allows the total activity of the plume to be conserved when estimating risks.

3.3.1.6 Mixing Height

The value of the mixing height (L) is either a direct input value (DMIX) for a user-specified weather condition or estimated from the annual average input values for morning and afternoon (Holzworth 1972). In the latter case, the mixing height is estimated from the following equation:

$$L = \begin{cases} 1.5\,L_{pm} & \text{for an extremely unstable atmosphere (stability class A)} \\ 0.5\,(L_{am} + L_{pm}) & \text{for a neutral atmosphere (stability class D)}, \end{cases} \qquad (3.31)$$

where

L_{am} = mean annual morning mixing height (m) [AMIX], and

L_{pm} = mean annual afternoon mixing height (m) [PMIX].

For other unstable situations (stability classes B and C), L is taken to be equal to L_{pm}. The mixing height does not apply to stable atmospheric conditions.

3.3.1.7 Meteorological Conditions

As presented in the previous sections, the dispersion model in RISKIND requires the following meteorological data:

1. Stability class (A through F),
2. Wind speed (m/s),
3. Mixing height (m) (for stability classes A through D),
4. Ambient temperature (K), and
5. Rainfall rate (mm/h).

Either a single stability class and wind speed can be used, or joint-frequency data on weather conditions over a period of time (e.g., annual data) can be input manually or read from a STAR format data file.

The atmospheric stabilities are classified into six categories (A, B, C, D, E, and F) in order of increasing stability on the basis of criteria established by Pasquill (1974). The dispersion equations in the models used are generic to all stability categories and empirical in nature. For each stability category, a set of dispersion coefficients, σ_y and σ_z, were derived for use in the equations.

For accidental releases at or near ground level, the values for σ_y and σ_z are initially calculated on the basis of the Pasquill-Gifford curves (Eimutis and Konicek 1972) and later adjusted for the initial dispersion geometry (Section 3.3.1.8) and buoyancy-induced dispersion (Section 3.3.1.9). The Pasquill-Gifford dispersion coefficients are calculated according to

$$\sigma'_y = (0.000246\,\sigma_\theta^2 + 0.00576\,\sigma_\theta + 0.066)\,x_{Yeff}^{0.9031}\ , \tag{3.32}$$

and

$$\sigma'_z = a\,x_{Zeff}^{b} + c\ . \tag{3.33}$$

Table 3.3 contains the values for the unitless dispersion parameters σ_θ, a, b, and c as a function of stability class. The variables x_{Yeff} and x_{Zeff} are defined below.

Briggs (1974) developed formulas for the dispersion coefficients on the basis of data collected from elevated releases:

$$\sigma'_y \text{ or } \sigma'_z = a\,x_{eff}\left(1+b\,x_{eff}\right)^c, \tag{3.34}$$

where

$$x_{Yeff} = x + x_{Yvirt}, \tag{3.35}$$

$$x_{Zeff} = x + x_{Zvirt}, \tag{3.36}$$

x_{Yeff} = effective receptor distance downwind from virtual point source for horizontal dispersion coefficient calculation (m),

$x_{y_{virt}}$ = distance from source location to virtual point source for horizontal dispersion coefficient calculation (m) [see Section 3.3.1.8 on initial dispersion geometry; Equation 3.39 for Pasquill-Gifford coefficients and Equation 3.41 for Briggs coefficients],

x_{Zeff} = effective receptor distance downwind from virtual point source for vertical dispersion coefficient calculation (m), and

TABLE 3.3 Pasquill-Gifford Dispersion Parameters for Ground-Level Releases

Applicable Range (downwind distance, m)	Stability Class	Coefficients			
		σ_θ	a	b	c
x > 1,000	A	25	0.00024	2.094	-9.6
	B	20	0.055	1.098	2.0
	C	15	0.133	0.911	0.0
	D	10	1.26	0.516	-13.0
	E	5	6.73	0.305	-34.0
	F	1.5	18.05	0.18	-48.6
100 ≤ x ≤ 1,000	A	25	0.00066	1.941	9.27
	B	20	0.0382	1.149	3.3
	C	15	0.113	0.911	0.0
	D	10	0.222	0.725	-1.7
	E	5	0.211	0.678	-1.3
	F	1.5	0.086	0.74	-0.35
x < 100	A	25	0.192	0.936	0.0
	B	20	0.156	0.922	0.0
	C	15	0.116	0.905	0.0
	D	10	0.079	0.881	0.0
	E	5	0.063	0.871	0.0
	F	1.5	0.053	0.814	0.0

Source: Data from Eimutis and Konicek (1972).

$x_{y_{vir}}$ = distance from source location to virtual point source for vertical dispersion coefficient calculation (m) [see Section 3.3.1.8 on initial dispersion geometry; Equation 3.40 for Pasquill-Gifford coefficients and Equation 3.42 for Briggs coefficients].

In addition, Briggs coefficients have been derived for rural and urban population zones. The urban values are also used in suburban population zone calculations in RISKIND. See Table 3.4 for values of *a*, *b*, and *c*.

3.3.1.8 Initial Dispersion Geometry

The initial dispersion of the puff at the source is modeled by using a virtual point source as implemented by Petersen and Lavdas (1986). The size of the source is first estimated in the

TABLE 3.4 Briggs Dispersion Coefficients for Elevated Releases

		σ_y					
		Rural			Urban		
Weather Conditions	Stability Class	a	b	c	a	b	c
Extremely unstable	A	0.22	0.0001	-0.5	0.32	0.0004	-0.5
Moderately unstable	B	0.16	0.0001	-0.5	0.32	0.0004	-0.5
Slightly unstable	C	0.11	0.0001	-0.5	0.22	0.0004	-0.5
Neutral	D	0.08	0.0001	-0.5	0.16	0.0004	-0.5
Moderately stable	E	0.06	0.0001	-0.5	0.11	0.0004	-0.5
Very stable	F	0.04	0.0001	-0.5	0.11	0.0004	-0.5

		σ_z					
		Rural			Urban		
Weather Conditions	Stability Class	a	b	c	a	b	c
Extremely unstable	A	0.20	0.0	0.0	0.24	0.001	0.5
Moderately unstable	B	0.12	0.0	0.0	0.24	0.001	0.5
Slightly unstable	C	0.08	0.0002	-0.5	0.20	0.0	0.0
Neutral	D	0.06	0.0015	-0.5	0.14	0.0003	-0.5
Moderately stable	E	0.03	0.0003	-1.0	0.08	0.00015	-0.5
Very stable	F	0.016	0.0003	-1.0	0.08	0.00015	-0.5

Source: Briggs (1974).

form of initial values for σ_y and σ_z. Since the dispersion equations are based on a point source model, these initial dispersion coefficient values are then used to back calculate the distance upwind from the source, which would correspond to an equivalent (virtual) point source. The distance that generates the initial value of a dispersion coefficient is called the virtual distance. The virtual distance is added to the distance of the receptor from the release before calculating the dispersion coefficients for that location, thereby adjusting for the initial size of the source.

For releases at high elevations, the initial dispersion usually has little influence on downwind concentrations. However, if the source is large enough or close enough to the ground, then the initial size of the release is important in determining ground-level concentrations near the source. For a cask near the ground, the initial horizontal dispersion coefficient is calculated according to (Martin 1979; Petersen and Lavdas 1986)

$$\sigma_{y_0} = L_{cask} / 4.3 \ , \tag{3.37}$$

where

σ_{y_0} = initial value for σ_y at the source location (m), and

L_{cask} = horizontal length of the shipping cask (m) [HSIZE].

The initial vertical dispersion parameter is estimated by (Martin 1979; Petersen and Lavdas 1986)

$$\sigma_{z_0} = 2\,R_{cask} \,/\, 2.15 \;, \tag{3.38}$$

where

σ_{z_0} = initial value for σ_z at the source location (m), and

R_{cask} = radius of the shipping cask (m) [RSIZE].

These initial dispersion parameters are then used to estimate the virtual source location. Rearranging Equations 3.32 and 3.33, the virtual distances for Pasquill-Gifford coefficients are calculated as

$$x_{Y_{virt}} = \left(\frac{\sigma_{y_0}}{0.000246\,\sigma_\theta^2 + 0.00576\,\sigma_\theta + 0.066} \right)^{1/0.9031} , \tag{3.39}$$

where

$x_{Y_{virt}}$ = virtual distance for σ_y (m),

and

$$x_{Z_{virt}} = \left(\frac{\sigma_{z_0} - c}{a} \right)^{1/b} , \tag{3.40}$$

where

$x_{Z_{virt}}$ = virtual distance for σ_z (m).

For Briggs dispersion coefficients (Equation 3.34), no simple analytical solution is available for solving x. A simple iterative method to reach convergence is used in RISKIND for estimating the virtual distances in this case. The equations used are

$$x_{Y_{virt}} = \frac{\sigma_{y_0}}{a\left(1 + b\,x_{Y_{virt}}\right)^c} , \tag{3.41}$$

and

$$x_{z_{vir}} = \frac{\sigma_{z_0}}{a\left(1 + b\,x_{z_{vir}}\right)^c} \quad . \tag{3.42}$$

This method of accounting for the cask size of a near-ground-level release gives reasonable concentration estimates at downwind distances greater than approximately five times the initial horizontal dimension of the cask.

3.3.1.9 Buoyancy-Induced Dispersion

Buoyancy-induced dispersion is considered in RISKIND because emitted plumes undergo a certain amount of growth during the plume-rise phase as a result of turbulent motions associated with plume release conditions and turbulent entrainment of ambient air. Pasquill (1976) suggests that this induced dispersion, σ_{zb}, can be approximated by the following equation:

$$\sigma_{zb} = \frac{\Delta h}{3.5} \quad , \tag{3.43}$$

where

σ_{zb} = buoyancy-induced vertical dispersion (m).

The effective dispersion coefficient used in RISKIND calculations can then be determined by adding variances such as

$$\sigma_z = \left(\sigma_{zb}^2 + \sigma_z'^2\right)^{1/2} \quad . \tag{3.44}$$

At the distance of final plume rise and beyond, σ_{zb} becomes constant.

Because the plume can be assumed to be symmetrical about its centerline in the initial growth phases of release, the calculation assumes that buoyancy-induced dispersion in the horizontal direction is equal to that in the vertical direction:

$$\sigma_{yb} = \frac{\Delta h}{3.5} \quad , \tag{3.45}$$

where

σ_{yb} = buoyancy-induced vertical dispersion (m).

This expression is combined with that for dispersion resulting from ambient turbulence, in the same manner described above for the horizontal direction, to give the vertical dispersion coefficient used in the RISKIND calculations for estimating air and ground concentrations:

$$\sigma_y = \left(\sigma_{yb}^2 + \sigma_y'^2\right)^{1/2} \quad . \tag{3.46}$$

In general, buoyancy-induced dispersion has little effect on maximum concentrations unless the release height is small compared with the plume rise. Also, buoyancy-induced dispersion is most effective in simulating concentrations near plume centerlines close to the source, where treating the emission as a point source confines the plume to a volume much smaller than the actual plume.

3.3.2 Environmental Pathway and Dosimetry Models

Two basic elements are necessary to assess human health hazards from released radioactivity. First, the concentrations of radioactive material in the surrounding environment must be determined. Second, the pathways of exposure that should be considered must be selected. Figure 3.2 shows the environmental pathways following an accidental release and the potential exposure modes. For an accidental release over a short duration, such as that considered in RISKIND, the concentrations of contaminants along the dispersive paths generally build up to a maximum value shortly after the release and decrease steadily thereafter.

Adequate prediction of health hazards to an individual depends on an accurate description of the time-dependent behavior of contaminants in the environment. A small change in a time constant can significantly affect the magnitude of exposure. Following an airborne release of relatively short duration, radioactive material becomes airborne as the "radioactive cloud" is dispersed and diluted by turbulent diffusion. When the cloud passes over an area, the people occupying that area may be exposed to radiation emanating from the cloud and may also inhale radioactive material suspended in air.

In RISKIND, exposure resulting from the initial passing plume is categorized as short-term because it is of relatively short duration, and the radioactive material is relatively concentrated. In addition to the exposure received from the passing plume, external exposure resulting from the loss of cask shielding may also contribute to short-term exposure. Section 3.3.2.1 describes modeling of short-term radiation exposure. Exposure to radionuclides depleted from the cloud is categorized as long-term because the ground-deposited contaminant may persist in the environment over a prolonged period of time following the initial release. In general, the radiological hazards to individuals tend to be lower from long-term exposures than short-term because the radionuclide concentrations in the environmental media are diluted further. However, the cumulative dose to the exposed individual over the long term could be potentially significant for cases in which no remediation is taken following an accident.

Several environmental pathways are identified for long-term exposures: exposure from the contaminated ground, inhalation of radioactive materials resuspended in the air, and ingestion of contaminated foodstuffs. In addition, initial deposition onto surface water bodies may also result in dose exposure via the drinking water pathway. Section 3.3.2.2 describes the models

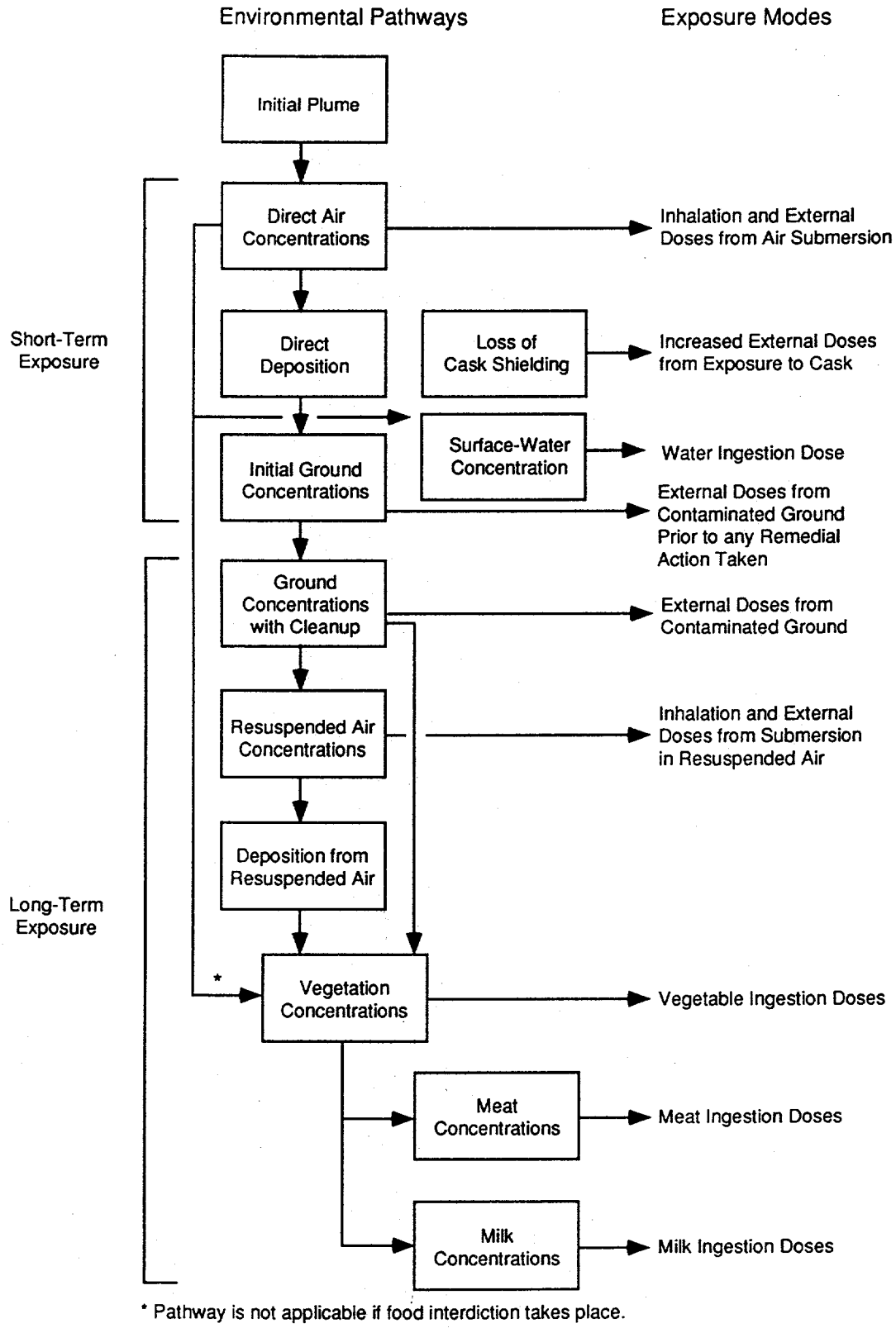

FIGURE 3.2 Environmental Pathways and Exposure Modes for a Spent Nuclear Fuel Cask Accident

used to calculate long-term environmental media concentrations. Once the radionuclide concentrations in the environmental media are determined, the doses to individuals can be calculated. Section 3.3.2.3 describes the modeling of the long-term radiation exposure.

Radiation doses are calculated only for individuals at each receptor location defined by the user. These receptor locations are normally defined to represent locations where potentially higher exposures are likely as the result of a release. The estimate of early health effects is dependent on the exposure information from short-term exposures; the estimate for latent health effects is dependent on the total dose from both short- and long-term exposures. A discussion of health effects models is presented in Section 4.

3.3.2.1 Short-Term Exposure

The model to calculate short-term radiation doses is described in this section. Such doses include external radiation from radionuclides in the passing cloud and radionuclides deposited on the ground, external exposure from loss of cask shielding, and internal radiation from inhaled radioactive material.

3.3.2.1.1 External Exposure from the Radioactive Cloud. External radiation doses received from a radioactive cloud are calculated as the product of the time-integrated air concentration and the cloud gamma DCF and take into account any shielding at the receptor location:

$$D(j)_{AirST} = SF(j)_{AirST}\ K_1 \sum_i \overline{C}_a(i,x,y)\ DCF_{Air}(i)\ , \qquad (3.47)$$

where

$D(j)_{AirST}$ = dose to receptor j from inhalation during plume passage (rem);

$DCF_{Air}(i)$ = dose conversion factor for air submersion for radionuclide i (Sv/Bq-s/m^3);

$\overline{C}_a(i,x,y)$ = time-integrated ground-level air concentration (Ci-s/m^3) [Equation 3.14 or 3.15];

K_1 = conversion factor, 3.7×10^{12} rem-Bq/Sv-Ci; and

$SF(j)_{AirST}$ = short-term shielding factor for air immersion: 0 = full shielding, 1 = no shielding (unitless) [set to the value in Table 3.5 as determined by ISHLT(j) (shelter type) for receptor j, which uses the cloudshine shielding factors].

The cloud DCFs are taken from *External Exposure to Radionuclides in Air, Water, and Soil*, EPA Federal Guidance Report No. 12 (FGR 12) (Eckerman and Ryman 1993).

TABLE 3.5 Shielding Values for Routine and Accident Exposures

	Shielding Factor		
Structure	Inhalation	Cloudshine	Groundshine
Outdoors	1.0	1.0	1.0
Frame house	1.0	0.9	0.4
Brick house	1.0	0.6	0.2
Office building	1.0	0.2	0.02
Car	1.0	1.0	0.5

Source: NRC (1975).

3.3.2.1.2 External Exposure from Ground-Deposited Radionuclides. A passing cloud of radioactive material can deposit its radioactive contents on the ground by dry and wet deposition, as described in Section 3.3.1.5. The deposited radioactive material can become a source of external radiation. The external exposure dose from radioactive material deposited on the ground is calculated by

$$D(j)_{GndST} = SF(j)_{GndST}\ K_2 \sum_i C_g(i,x,y)\ DCF_{Gnd}(i)\ T_{Ext}(j) \quad , \tag{3.48}$$

where

$D(j)_{GndST}$ = short-term external dose for receptor j from ground-deposited radionuclide i (rem);

$DCF_{Gnd}(i)$ = dose conversion factor for external radiation from the ground for radionuclide i (Sv/Bq-s/m^2);

K_2 = conversion factor, 1.332×10^{16} rem-Bq-s/Sv-Ci-h;

$SF(j)_{GndST}$ = short-term shielding factor for external ground radiation: 0 = full shielding, 1 = no shielding (unitless) [set to the value in Table 3.5 as determined by ISHLT(j) (shelter type) for receptor j, which uses the groundshine shielding factors]; and

$T_{Ext}(j)$ = short-term exposure time for receptor j at location x,y after plume passage (h) [TEXT(j)].

The DCFs used for this mode of exposure are also taken from EPA FGR 12 (Eckerman and Ryman 1993). Additional factors required are the time of exposure, $T_{Ext}(j)$, and a shielding factor, as appropriate, to account for any protective structures; see Table 3.5 for the shielding options provided by RISKIND.

3.3.2.1.3 External Exposure from Loss of Cask Shielding. Loss of cask shielding in a transportation accident may result in increased external exposure to the affected individuals. Such an event may involve, for example, the loss of neutron shielding in an accident involving fire, or the loss of gamma shielding because of the lead slump resulting from severe impact.

Doses from such accident exposures are modeled after Equation 2.5, routine dose to an individual during a shipment stop, and can be expressed as

$$D(j)_{ExtST} = SF_{ExtST} \left[M_g(k)\, \dot{D}_g(j) + M_n(k)\, \dot{D}_n(j) \right] T_{Ext}(j) \ , \qquad (3.49)$$

where

$D(j)_{ExtST}$ = short-term external dose for receptor j from the shipping cask (rem);

$\dot{D}_i(j)$ = dose rate (rem/h) from gamma (i = g) and neutron (i = n) radiation at the location of receptor j [Equation 2.1 where $r^2 = (x^2 + y^2)^{1/2}$];

SF_{ExtST} = shielding factor for external radiation at receptor location: 0 = full shielding, 1 = no shielding (unitless [set to the value in Table 3.5 as determined by ISHLT(j) (shelter type) for receptor j, which uses the groundshine shielding factors];

$M_g(k)$ = dose multiplication factor for gamma radiation due to loss of shielding (unitless) [SEXT(k,1) for accident response region k]; and

$M_n(k)$ = dose multiplication factor for neutron radiation due to loss of shielding (unitless) [SEXT(k,2) for accident response region k].

The only major difference between Equation 2.5 and Equation 3.49 is the addition of the dose multiplication factors for gamma and neutron radiation due to loss of shielding. The dose multiplication factors are the increased dose rates measured in multiples of the original external cask dose rates for incident-free conditions. Methods for calculating such factors can be based on estimates using the codes mentioned in Section 2.1.

3.3.2.1.4 Exposure from Inhaled Radionuclides. Individuals can be exposed to radiation by inhaling radionuclides. Although some of this inhaled material is immediately exhaled, a fraction is retained in the individual's body. The fraction retained depends on the particle size distribution, the radionuclide's solubility in body fluid, and the individual's breathing rate. The inhalation dose is calculated as follows:

$$D(j)_{InhST} = SF(j)_{InhST}\, K_3\, BR(j) \sum_i \overline{C}_a(i,x,y)\, DCF_{Inh}(i) \ , \qquad (3.50)$$

where

$D(j)_{InhST}$ = short-term inhalation dose for receptor j from radionuclide i (rem);

$DCF_{Inh}(i)$ = dose conversion factor for inhalation for radionuclide i (Sv/Bq);

$\overline{C}_a(i,x,y)$ = time-integrated ground-level air concentration (Ci-s/m^3) [Equation 3.14 or 3.15];

K_3 = conversion factor, 1.172×10^5 rem-Bq-yr/Sv-Ci-s;

$SF(j)_{InhST}$ = short-term shielding factor for inhalation: 0 = full shielding, 1 = no shielding (unitless) [set to the value in Table 3.5 as determined by ISHLT(j) (shelter type) for receptor j, which uses the inhalation shielding factors]; and

$BR(j)$ = breathing rate for receptor j (m^3/yr) [BRTIND(j)].

In RISKIND, all particle sizes are assumed to be respirable. The DCFs are taken from *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*, EPA Federal Guidance Report No. 11 (FGR 11) (Eckerman et al. 1988). The DCFs for each radionuclide were selected from the solubility class that would yield the highest effective dose equivalent.

3.3.2.2 Environmental Media Concentration Models

This section describes the models, equations, and data employed in the determination of the radionuclide concentrations in the environmental media following a release. Initial concentrations following passage of the radioactive cloud are derived. These concentrations are then integrated over the exposure period of interest for an individual to obtain the time-integrated concentrations used in the calculation of long-term doses (described in Section 3.3.2.3), that is, those doses resulting from the deposition and reconcentration of radionuclides in environmental media subsequent to the passing of the initial plume. These media include ground surface; resuspended contamination in air; and vegetation, meat, and milk. For convenience, symbols representing time-integrated media concentrations are capped with a bar [e.g., $\overline{C}_a(i,x,y)$]; symbols representing instantaneous concentrations are not capped.

Long-term environmental media concentrations are calculated as functions of the ground concentrations (Section 3.3.2.2.1) that result directly from deposition of radionuclides from the passing cloud and the amount of time that an individual is exposed to these concentrations. The ground concentrations related to these pathways can be calculated from the time-integrated air concentrations described in Section 3.3.1. Figure 3.2 shows the environmental pathways

following an accidental release and the exposure modes. Long-term concentrations in air are produced by ground disturbance, which causes resuspension of the deposited radionuclides as described in Section 3.3.2.2.2. Deposition of resuspended contamination is also considered in calculating accumulated concentrations in various types of vegetation, including hay and forage (animal-consumed vegetation). Section 3.3.2.2.3 covers the calculation of radionuclide concentrations in vegetation followed by the description of calculations for radionuclide concentrations in meat and milk in Section 3.3.2.2.4. Section 3.3.2.2.5 concludes with calculations for radionuclide concentrations in water.

3.3.2.2.1 Ground Surface Concentrations. Initial ground surface concentrations are calculated from time-integrated air concentrations arising directly from accidental releases (Section 3.3.1.5.3). The concentration of radionuclide i on a ground surface at time t following a release is related to the initial concentration as

$$C_g(i,x,y,t) = C_g(i,x,y)\left[\exp\left\{-\left[\lambda(i) + \lambda_g\right]t\right\}\right], \tag{3.51}$$

where

$C_g(i,x,y,t)$ = ground concentration of radionuclide i at receptor location x,y after time t following release (Ci/m^2),

$\lambda(i)$ = radioactive decay constant for radionuclide i (1/yr), and

λ_g = rate constant for environmental loss (1/yr) [0.693/PHALF]; PHALF is the removal half-life of any radionuclide from the soil.

The environmental loss rate constant λ_g is derived from an assumed half-life in the soil with respect to environmental availability. This parameter is used to account for loss through chemical binding during downward migration in soil and other environmental loss mechanisms such as wind or water erosion. It is assumed that this parameter applies to all radionuclides subject to ground deposition.

For long-term dose calculations, the time-integrated ground concentration is used. Equation 3.51 is integrated from the time of the accident ($t = 0$) to time T (yr) to cover the length of exposure:

$$\overline{C}_g(i,x,y,T) = C_g(i,x,y)\left[1 - \frac{\exp\left\{-\left[\lambda(i) + \lambda_g\right]T\right\}}{\lambda(i) + \lambda_g}\right], \tag{3.52}$$

where

$\overline{C}_g(i,x,y,T)$ = time-integrated ground concentration of radionuclide i at receptor location x,y at time T following a release (Ci-s/m^2), and

T = time following accidental release (yr) [YEVD].

3.3.2.2.2 Resuspended Air Concentrations. Resuspended air concentrations are calculated with a time-dependent resuspension factor, which, for deposits of age t years, is

$$R_{AtoG}(t) = \begin{cases} FI \exp\left(-\lambda_r t\right), & \text{for } t \le T_a \\ FE, & \text{for } t > T_a \end{cases}, \tag{3.53}$$

where

$R_{AtoG}(t)$ = ratio of resuspended air concentration to ground concentration for a ground concentration at time t yr (1/m);

FI = initial value of the resuspension factor for fresh deposits (1/m) [SUFI];

λ_r = resuspension decay constant (1/yr) [0.693/RSALF]; RSALF is the resuspension factor decay half-life;

FE = final value of the resuspension factor (1/yr) [SUFF]; and

T_a = time required for the resuspension factor to decrease from its initial to final value (yr); $t = T_a$ when

$$FE = FI \exp\left(-\lambda_r \; T_a\right) \tag{3.54}$$

and rearranging,

$$T_a = -\frac{1}{\lambda_r} \ln\left(\frac{FE}{FI}\right). \tag{3.55}$$

The formulation of the above expression for the resuspension factor is based on work in NRC (1974) and Anspaugh et al. (1974).

The resuspended air concentration may be estimated with the following equation:

$$C_r(i,x,y,t) = C_g(i,x,y,t) \; R_{AtoG}(t), \tag{3.56}$$

where

$C_r(i,x,y,t)$ = resuspended air concentration of radionuclide i at receptor location x,y after time t following release (Ci/m^3), and

$R_{AtoG}(t)$ = ratio of resuspended air concentration to ground concentration for a ground concentration at time t yr (1/m) [Equation 3.53].

This approach has been shown to predict results consistent with the recent data collected from Europe after the Chernobyl accident (International Atomic Energy Agency [IAEA] 1992).

The time-integrated resuspended air concentration is derived from Equation 3.56 and is found to be

$$\overline{C}_r(i,x,y,T) = \begin{cases} FI\, C_g(i,x,y)\left[1 - \dfrac{\exp\left\{-\left[\lambda(i) + \lambda_g + \lambda_r\right]T\right\}}{\lambda(i) + \lambda_g + \lambda_r}\right], & T \le T_a \\ FI\, C_g(i,x,y)\left[1 - \dfrac{\exp\left\{-\left[\lambda(i) + \lambda_g + \lambda_r\right]T_a\right\}}{\lambda(i) + \lambda_g + \lambda_r}\right] & \\ \quad + FE\left[\overline{C}_g(i,x,y,T) - \overline{C}_g(i,x,y,T_a)\right], & T > T_a \end{cases} \tag{3.57}$$

where

$\overline{C}_r(i,x,y,T)$ = time-integrated resuspended air concentration of radionuclide i at receptor location x,y at time T following a release (Ci-s/m^3).

3.3.2.2.3 Concentrations in Vegetation. Concentrations in vegetation may be the result of direct depositon from the initial passing plume (short-term) or of root uptake from soil and deposition of resuspended contamination (long-term). Therefore, these concentrations are derived from the previously derived air and ground concentrations. Ground concentrations are used to determine concentrations in vegetation that are the result of root uptake of soil radioactivity; air concentrations are used to determine concentrations in vegetation that are the result of foliar retention of deposited radioactivity. Two categories of vegetation are treated in RISKIND: vegetables consumed by humans and pasture grass (or hay) that is fed to animals that provide food for human consumption (NRC 1977a). The concentration on vegetation from the initial direct deposition from the passing radioactive cloud is expressed as (NRC 1977a)

$$C_{V_{dep}}(i,x,y) = \frac{\overline{C}_a(i,x,y)\, V_d(m)\, F_r\, E_{V_k} \exp\left(-\lambda_{V_w} T_{V_k}\right)}{Y_{V_k}}, \tag{3.58}$$

where

$C_{V_{dep}}(i,x,y)$ = vegetation concentration of radionuclide i at location x,y from direct deposition from the passing plume (Ci/kg),

$V_d(m)$ = deposition velocity for radionuclide type m (m/s) [VDEPNUC(m)],

F_r = fraction of deposition retained on the plant (unitless) [F_RETAIN],

E_{V_k} = fraction of foliar deposition reaching edible portions of vegetation type k (for human consumption or pasture grass for animal consumption) (unitless) [F_EDBL_HUM or F_EDBL_COW],

λ_{V_w} = decay constant for weathering losses (1/d) [DECAY_WEATHER],

T_{V_k} = time from accidental release to first harvest of vegetation type k (d) [T_HARVEST_HUM or T_HARVEST_COW], and

Y_{V_k} = yield density of vegetation type k (kg/m^2) [YIELD_HUM or YIELD_COW].

Equation 3.58 is used to calculate the radionuclide concentration in vegetation from the first harvest following an accidental release. If the initially contaminated vegetation is interdicted, this concentration would be zero.

The vegetation concentration over the long term resulting from ground concentration can be expressed by

$$C_{V_{lt}}(i,x,y,t) = \frac{C_g(i,x,y,t)\,B_V(i)}{\rho} + C_r(i,x,y,t)\,V_d(m)\,F_r\,E_{V_k}\left[1 - \frac{\exp\left(-\lambda_{V_w}\,t_{V_k}\right)}{Y_{V_k}\,\lambda_{V_w}}\right], \quad (3.59)$$

where

$C_{V_{lt}}(i,x,y,t)$ = long-term vegetation concentration of radionuclide i at receptor location x,y after time t following release (Ci/kg),

$C_g(i,x,y,t)$ = ground concentration of radionuclide i at receptor location x,y after time t following release (Ci/m^2) [Equation 3.51],

$B_V(i)$ = soil-to-plant transfer factor for radionuclide i (unitless),

$C_r(i,x,y,t)$ = resuspended air concentration of radionuclide i at receptor location x,y after time t following release (Ci/m^3) [Equation 3.56], and

t_{V_k} = time duration for growing season for vegetation type k (days) [T_GROW_HUM or T_GROW_COW].

The first term in Equation 3.59 represents the root uptake mechanism; the second term represents the resuspension and redeposition. The soil-to-plant transfer factors, $B_V(i)$, are listed in Table 3.6.

Starting with Equations 3.58 and 3.59, the time-integrated vegetation concentrations over the exposure period of interest are calculated as

$$\overline{C}_{V_k}(i,x,y,T) = \frac{\overline{C}_a(i,x,y)\, V_d(m)\, F_r\, E_{V_k}\, \exp\left(-\lambda_{V_w}\, T_{V_k}\right)}{Y_{V_k}} + \frac{\overline{C}_g(i,x,y,T)\, B_V(i)}{\rho} + \overline{C}_r(i,x,y,T)\, V_d(m)\, F_r\, E_{V_k}\left[1 - \frac{\exp\left(-\lambda_{V_w}\, t_{V_k}\right)}{Y_{V_k}\, \lambda_{V_w}}\right], \quad (3.60)$$

where

$\overline{C}_{V_k}(i,x,y,T)$ = time-integrated radionuclide i concentration in vegetation type k at location x,y at time T after an accidental release (Ci-s/kg).

3.3.2.2.4 Concentrations in Meat and Milk. Radionuclides deposited on hay or pasture grass can be ingested by animals whose meat or milk is consumed by man. The equation used to estimate radionuclide concentrations in meat is

$$\overline{C}_b(i,x,y,T) = \overline{C}_{V_a}(i,x,y,T)\, Q_a\, F_b(i) \quad , \quad (3.61)$$

where

$\overline{C}_b(i,x,y,T)$ = time-integrated concentration in meat (b) for radionuclide i at location x,y at time T after accidental release (Ci-s/kg),

$\overline{C}_{V_a}(i,x,y,T)$ = time-integrated radionuclide concentration in vegetation for animal consumption (hay or pasture grass) at location x,y at time T after accidental release (Ci-s/kg) [Equation 3.60],

Q_a = animal feed ingestion rate (kg/d) [QA], and

$F_b(i)$ = feed-to-meat transfer factor for radionuclide i (Ci/kg per Ci/d).

TABLE 3.6 Transfer Coefficients Applicable to Food Chain Pathways for Various Radionuclides

Index (i)	Element	Transfer Coefficients: Soil-to-Plant $B_v(i)$ (dimensionless)	Grass-to-Meat $F_b(i)$ (d/kg)	Grass-to-Milk $F_m(i)$ (d/L)
1	Hydrogen	4.8	1.2×10^{-2}	1.0×10^{-2}
2	Helium	0.0	0.0	0.0
3	Lithium	8.3×10^{-4}	1.0×10^{-2}	5.0×10^{-2}
4	Beryllium	4.2×10^{-4}	1.0×10^{-3}	1.0×10^{-4}
5	Boron	1.2×10^{-1}	8.0×10^{-4}	2.7×10^{-3}
6	Carbon	5.5	3.1×10^{-2}	1.2×10^{-2}
7	Nitrogen	7.5	7.7×10^{-2}	2.2×10^{-2}
8	Oxygen	1.6	1.6×10^{-2}	2.0×10^{-2}
9	Fluorine	6.5×10^{-4}	1.5×10^{-1}	1.4×10^{-2}
10	Neon	1.4×10^{-1}	2.0×10^{-2}	2.0×10^{-2}
11	Sodium	5.2×10^{-2}	3.0×10^{-2}	4.0×10^{-2}
12	Magnesium	1.3×10^{-1}	5.0×10^{-3}	1.0×10^{-2}
13	Aluminum	1.8×10^{-4}	1.5×10^{-3}	5.0×10^{-4}
14	Silicon	1.5×10^{-4}	4.0×10^{-5}	1.0×10^{-4}
15	Phosphorous	1.1	4.6×10^{-2}	2.5×10^{-2}
16	Sulfur	5.9×10^{-1}	1.0×10^{-1}	1.8×10^{-2}
17	Chlorine	5.0	8.0×10^{-2}	5.0×10^{-2}
18	Argon	0.0	0.0	0.0
19	Potassium	3.7×10^{-1}	1.2×10^{-2}	1.0×10^{-2}
20	Calcium	3.6×10^{-2}	4.0×10^{-3}	8.0×10^{-3}
21	Scandium	1.1×10^{-3}	1.6×10^{-2}	5.0×10^{-6}
22	Titanium	5.4×10^{-5}	3.1×10^{-2}	5.0×10^{-6}
23	Vanadium	1.3×10^{-3}	2.3×10^{-3}	1.0×10^{-3}
24	Chromium	2.5×10^{-4}	2.4×10^{-3}	2.2×10^{-3}
25	Manganese	2.9×10^{-2}	8.0×10^{-4}	2.5×10^{-4}
26	Iron	6.6×10^{-4}	4.0×10^{-2}	1.2×10^{-3}
27	Cobalt	9.4×10^{-3}	1.3×10^{-2}	1.0×10^{-3}
28	Nickel	1.9×10^{-2}	5.3×10^{-3}	6.7×10^{-3}
29	Copper	1.2×10^{-1}	8.0×10^{-3}	1.4×10^{-2}
30	Zinc	4.0×10^{-1}	3.0×10^{-2}	3.9×10^{-2}
31	Gallium	2.5×10^{-4}	1.3	5.0×10^{-5}
32	Germanium	1.0×10^{-1}	2.0×10^{-1}	5.0×10^{-4}
33	Arsenic	1.0×10^{-2}	2.0×10^{-3}	6.0×10^{-3}
34	Selenium	1.3	1.5×10^{-2}	4.5×10^{-3}
35	Bromine	7.6×10^{-1}	2.6×10^{-2}	5.0×10^{-2}

TABLE 3.6 (Cont.)

Index (i)	Element	Transfer Coefficients: Soil-to-Plant $B_v(i)$ (dimensionless)	Grass-to-Meat $F_b(i)$ (d/kg)	Grass-to-Milk $F_m(i)$ (d/L)
36	Krypton	0.0	0.0	0.0
37	Rubidium	1.3×10^{-1}	3.1×10^{-2}	3.0×10^{-2}
38	Strontium	1.7×10^{-2}	6.0×10^{-4}	8.0×10^{-4}
39	Yttrium	2.6×10^{-3}	4.6×10^{-3}	1.0×10^{-5}
40	Zirconium	1.7×10^{-4}	3.4×10^{-2}	5.0×10^{-6}
41	Niobium	9.4×10^{-3}	2.8×10^{-1}	2.5×10^{-3}
42	Molybdenum	1.2×10^{-1}	8.0×10^{-3}	7.5×10^{-3}

Source: NRC (1977a)

The corresponding equation to estimate radionuclide concentrations in milk is

$$\overline{C}_m\,(i,x,y,T) = \overline{C}_{V_a}\,(i,x,y,T)\,Q_a\,F_m(i)\ , \tag{3.62}$$

where

$\overline{C}_m\,(i,x,y,T)$ = time-integrated concentration in milk (m) for radionuclide i at location x,y at time T after accidental release (Ci-s/kg),

$\overline{C}_{V_a}\,(i,x,y,T)$ = time-integrated radionuclide concentration in vegetation for animal consumption (hay or pasture grass) at location x,y at time T after accidental release (Ci-s/kg) [Equation 3.60], and

$F_m(i)$ = feed-to-milk transfer factor for radionuclide i (Ci/kg per Ci/d).

3.3.2.2.5 Concentrations in Drinking Water. Surface water contamination can result from the deposition of radionuclides onto the water bodies that serve as potential sources of drinking water. Contamination may also occur by rain washoff and runoff from contaminated land areas. In RISKIND, the drinking water pathway considered is via fresh surface water, which could occur within a short period (e.g., a week) following an accidental release. Other water pathways requiring a longer period — such as irrigation of farmland, water ingestion by animals that serve as food sources (meat or milk), and ingestion of aquatic food — are not included in the current version of RISKIND.

The calculation of doses from drinking water is based on a model that requires the deposition of radionuclides onto the water body, individual water consumption rates, duration of water consumption from the contaminated water body, and water treatment efficiency. In the current version of RISKIND, all materials deposited onto the water body are assumed to be thoroughly mixed with portions of or all of the water body. The removal of radionuclides by sedimentation is not considered, thus yielding a conservative estimate of the radionuclide concentrations in water.

The initial radionuclide concentration in a drinking water body from deposition from the passage of the radioactive cloud is estimated as

$$C_w(i,x,y) = \frac{Amount}{Volume} = \frac{C_g(i,x,y)\,A'_w(x,y)}{A_w(x,y)\,W_d(x,y)} = \frac{C_g(i,x,y)\,F_a(x,y)}{W_d(x,y)} \quad , \tag{3.63}$$

where

$C_w(i,x,y)$ = initial water concentration from wet and dry deposition for nuclide i at location x, y after plume passage (Ci/m^3);

$C_g(i,x,y)$ = initial areal (ground) concentration from wet and dry deposition for nuclide i at location x,y after plume passage (Ci/m^2) [Equation 3.29 or 3.30];

$A'_w(x,y)$ = area of water body at location x,y subject to contaminant deposition from the passing puff (m^2);

$A_w(x,y)$ = area of water body at location x,y (m^2);

$W_d(x,y)$ = effective mixing depth of the water body at location x,y (m) [WBDYD(j) for receptor j];

$F_a(x,y)$ = fraction of the water body at location x,y covered by the passing puff, assumes puff travels the full distance across the water body in the downwind direction (unitless), where

$$F_a(x,y) = \begin{cases} 1\,, \text{ if } F_w(x,y) \geq 1 \\ F_w(x,y)\,, \text{ if } F_w(x,y) < 1\,, \end{cases} \tag{3.64}$$

and

$$F_w(x,y) = \frac{\sqrt{2\pi}\,\sigma_y}{W_c(x,y)}\;; \tag{3.65}$$

σ_y = horizontal dispersion coefficient [Equation 3.46]; and

$W_c(x,y)$ = crosswind width of the water body at location x,y (m) [WBDYW(j) for receptor j].

At time t following an accidental release, the drinking water radionuclide concentration is estimated as

$$C_w(i,x,y,t) = \frac{C_g(i,x,y)\, F_a(x,y)\left(1 - E_w\right) \exp\left\{-\left[\lambda(i) + \lambda_w(x,y)\right] t\right\}}{W_d(x,y)}, \qquad (3.66)$$

where

$C_w(i,x,y,t)$ = radionuclide i concentration in water body at location x,y at time t after puff passage (Ci/m^3);

E_w = water treatment efficiency, fraction of contamination removed by water treatment facilities before use (0 = no contamination removed, 1 = all contamination removed) [TREATM];

$\lambda(i)$ = radioactive decay constant for radionuclide i (1/yr).

$\lambda_w(x,y)$ = water exchange rate for water body at location x,y (1/yr) [WEXCG(j) for receptor j]; and

Equation 3.66 is derived from Equation 3.63 by including the efficiency of water treatment systems for removing the contamination and accounting for the concentration dependencies on radionuclide decay and dilution. For dose calculations, the time-integrated drinking water concentration is calculated from Equation 3.66 as

$$\overline{C}_w(i,x,y,T) = \frac{C_g(i,x,y)\, F_a(x,y)\left(1 - E_w\right)\left(1 - \exp\left\{-\left[\lambda(i) + \lambda_w(x,y)\right] T\right\}\right)}{W_d(x,y)\left[\lambda(i) + \lambda_W(x,y)\right]}, \qquad (3.67)$$

where

$\overline{C}_w(i,x,y,T)$ = time-integrated radionuclide i concentration in water body at location x,y at time T after puff passage (Ci-yr/m^3), and

T = time following accidental release (yr) [YEVD].

3.3.2.3 Long-Term Dose Models

The long-term dose from a given release is calculated by integrating the dose over a period of T years following the release and using the time-integrated media concentrations developed in Section 3.3.2.2. Doses to individuals can be calculated for all known significant pathways: inhalation; external exposure to air and ground contamination; and ingestion of vegetables, meat, and milk. Internal doses from inhalation and ingestion pathways are calculated with DCFs. Because radionuclides taken into the body via ingestion or inhalation will continue to irradiate the body as long as they exist and are retained by the body, these internal DCFs

represent the committed dose (ICRP 1977), that is, the dose integrated over an interval of 50 years.

3.3.2.3.1 External Doses from Resuspended Air Concentrations. External radiation doses received from resuspended air concentrations are the product of the time-integrated resuspended air concentrations, the cloud gamma DCF, and shielding considerations:

$$D(j)_{AirLT} = SF(j)_{AirLT}\, K_1 \sum_i \overline{C}_r(i,x,y,T)\, DCF_{Air}(i) \quad , \tag{3.68}$$

where

$D(j)_{AirLT}$ = dose to receptor j from long-term external radiation exposure from resuspended contamination (rem);

$SF(j)_{AirLT}$ = long-term shielding factor for air immersion for receptor j: 0 = full shielding, 1 = no shielding (unitless), where

$$SF(j)_{AirLT} = OF_{out}(j) + OF_{in}(j)\, SF_{kAir}(j) \quad ; \tag{3.69}$$

$OF_{out}(j)$ = fraction of time spent outdoors by receptor j (unitless) [OCUPF(j,1)];

$OF_{in}(j)$ = fraction of time spent indoors by receptor j (unitless) [OCUPF(j,2)];

$SF_{kAir}(j)$ = shielding factor afforded receptor j by shelter type k for air immersion [set to the value in Table 3.5 as determined by LSHLT(k)];

K_1 = conversion factor, 3.7×10^{12} rem-Bq/Sv-Ci;

$\overline{C}_r(i,x,y,T)$ = time-integrated ground-level air concentration (Ci-s/m^3) [Equation 3.57]; and

$DCF_{Air}(i)$ = dose conversion factor for air submersion for radionuclide i (Sv/Bq-s/m^3).

The cloud DCFs used by RISKIND are those published in FGR 12 (Eckerman and Ryman 1993).

3.3.2.3.2 External Exposure from Ground-Deposited Radionuclides. Radioactively contaminated ground provides a long-term source of gamma radiation for individuals residing near contamination. For long-term exposure, the external doses from radioactive material deposited on the ground are calculated as the product of the time-integrated ground concentrations, the ground DCFs, and shielding considerations:

$$D(j)_{GndLT} = SF(j)_{GndLT}\, K_1 \sum_i \overline{C}_g(i,x,y,T)\, DCF_{Gnd}(i) \quad , \tag{3.70}$$

where

$D(j)_{GndLT}$ = dose to receptor j from long-term external radiation exposure from ground contamination (rem);

$SF(j)_{GndLT}$ = long-term shielding factor for external ground radiation for receptor j: 0 = full shielding, 1 = no shielding (unitless), where

$$SF(j)_{GndLT} = OF_{out}(j) + OF_{in}(j)\, SF_{kGnd}(j) \ ; \qquad (3.71)$$

$SF_{kGnd}(j)$ = shielding factor afforded receptor j by shelter type k for external ground radiation [set to the value in Table 3.5 as determined by LSHLT(k)];

$\overline{C}_g(i,x,y,T)$ = time-integrated ground concentration of radionuclide i at receptor location x,y at time T following a release (Ci-s/m^2) [Equation 3.52]; and

$DCF_{Gnd}(i)$ = dose conversion factor for external radiation from the ground for radionuclide i (Sv/Bq-s/m^2).

The ground DCFs used in RISKIND are also from FGR 12 (Eckerman and Ryman 1993).

3.3.2.3.3 Inhalation Doses from Resuspended Air Concentrations. Long-term inhalation doses are calculated using the time-integrated resuspended air concentrations, individual receptor breathing rates, 50-year committed inhalation DCFs from FGR 11 (Eckerman et al. 1988), and shielding factors. The equation used is

$$D(j)_{InhLT} = SF(j)_{InhLT}\, K_3\, BR(j) \sum_i \overline{C}_r(i,x,y,T)\, DCF_{Inh}(i) \ , \qquad (3.72)$$

where

$D(j)_{InhLT}$ = dose to receptor j from long-term inhalation of resuspended contamination (rem);

$SF(j)_{InhLT}$ = long-term shielding factor for resuspended contaminant inhalation for receptor j: 0 = full shielding, 1 = no shielding (unitless), where

$$SF(j)_{InhLT} = OF_{out}(j) + OF_{in}(j)\, SF_{kInh}(j) \ ; \qquad (3.73)$$

$SF_{kInh}(j)$ = shielding factor afforded receptor j by shelter type k for inhalation [set to the value in Table 3.5 as determined by LSHLT(k)];

K_3 = conversion factor, 1.172×10^5 rem-Bq-yr/Sv-Ci-s;

$BR(j)$ = breathing rate for receptor j (m^3/yr) [BRTIND(j)]; and

$DCF_{Inh}(i)$ = dose conversion factor for inhalation for radionuclide i (Sv/Bq).

3.3.2.3.4 Ingestion Doses from Agricultural Products. Ingestion doses are calculated for vegetables, meat, and milk on the basis of the time-integrated concentrations derived in Sections 3.3.2.2.3 and 3.3.2.2.4. The 50-year committed ingestion DCFs used in RISKIND are those in FGR 11 (Eckerman et al. 1988).

Vegetable ingestion doses are calculated by

$$D(j)_{Veg} = DF\ U_V\ CF_V\ K_4\ \sum_i \overline{C}_{V_h}(i,x,y,T)\ DCF_{Ing}(i)\ , \tag{3.74}$$

where

$D(j)_{Veg}$ = dose to receptor j from ingestion of contaminated vegetables (rem);

DF = decontamination factor, that is, the fraction of contamination remaining on vegetation after food preparation at time of consumption (unitless) [DFACT];

U_V = human consumption rate of vegetables (kg/d) [XIN(1)];

CF_V = fraction of consumed vegetables that are contaminated (unitless), [PFIN(1)];

K_4 = conversion factor, 4.282×10^7 rem-Bq-d/Sv-Ci-s;

$\overline{C}_{V_h}(i,x,y,T)$ = time-integrated radionuclide i concentration in vegetation for human consumption at location x,y at time T after an accidental release (Ci-s/kg) [Equation 3.60]; and

$DCF_{Ing}(i)$ = dose conversion factor for ingestion for radionuclide i (Sv/Bq).

Doses from meat ingestion are calculated by

$$D(j)_{Meat} = U_b\ CF_b\ K_4\ \sum_i \overline{C}_b(i,x,y,T)\ DCF_{Ing}(i)\ , \tag{3.75}$$

where

$D(j)_{Meat}$ = dose to receptor j from ingestion of contaminated meat (rem);

U_b = human consumption rate of meat (kg/d) [XIN(2)];

CF_b = fraction of consumed meat that is contaminated (unitless) [PFIN(2)]; and

$\overline{C}_b(i,x,y,T)$ = time-integrated concentration in meat for radionuclide i at location x,y at time T after accidental release (Ci-s/kg) [Equation 3.61].

The dose to an individual from milk ingestion is given by

$$D(j)_{Milk} = U_m \, CF_m \, K_4 \sum_i \overline{C}_m(i,x,y,T) \, DCF_{Ing}(i), \tag{3.76}$$

where

$D(j)_{Milk}$ = dose to receptor j from ingestion of contaminated milk (rem);

U_m = human consumption rate of milk (kg/d) [XIN(3)];

CF_m = fraction of consumed milk that is contaminated (unitless) [PFIN(3)];

K_4 = conversion factor, 4.282×10^7 rem-Bq-d/Sv-Ci-s;

$\overline{C}_m(i,x,y,T)$ = time-integrated concentration in milk (m) for radionuclide i at location x,y at time T after accidental release (Ci-s/kg) [Equation 3.62]; and

$DCF_{Ing}(i)$ = dose conversion factor for ingestion for radionuclide i (Sv/Bq).

3.3.2.3.5 Ingestion Doses from Drinking Water. The dose to an individual from drinking contaminated surface water is calculated by

$$D(j)_{Water} = U_w \, CF_w \, K_5 \sum_i \overline{C}_w(i,x,y,T) \, DCF_{Ing}(i) \ , \tag{3.77}$$

where

$D(j)_{Water}$ = dose to receptor j from ingestion of contaminated water (rem);

U_w = human consumption rate of water (L/d) [XIN(5)];

CF_w = fraction of consumed water that is contaminated (unitless) [PFIN(5)];

K_5 = conversion factor, 1.351×10^{12} rem-Bq-d-m^3/Sv-Ci-yr-L;

$\overline{C}_w(i,x,y,T)$ = time-integrated radionuclide i concentration in water body at location x,y at time T after puff passage (Ci-yr/m^3) [Equation 3.67]; and

$DCF_{Ing}(i)$ = dose conversion factor for ingestion for radionuclide i (Sv/Bq).

The total long-term ingestion dose to an individual for an exposure period of T years following an accidental release is obtained by summing the vegetable, meat, milk, and water ingestion doses per the following equation:

$$D(j)_{Ing} = D(j)_{Veg} + D(j)_{Meat} + D(j)_{Milk} + D(j)_{Water} , \quad (3.78)$$

where

$D(j)_{Ing}$ = Dose to receptor j from ingestion of contaminated food and water (rem).

3.3.2.3.6 Analysis of Weather Uncertainty on Individual Doses. Weather conditions and their frequency of occurrence at a site can be characterized by site-specific wind-rose data. These data are in joint-frequency form, that is, the fraction of time the wind is blowing at a given wind speed in a given stability category for each of six average wind speed groups and six Pasquill weather stability categories.

When the risk over all weather conditions is selected, the uncertainty of the effect of weather conditions during an accident on the calculated individual dose consequences is estimated by constructing a cumulative probability distribution of dose values by using seasonal or annual joint-frequency data for a given region. This probabilistic dose distribution is then used to determine the "median" (50% weather probability) and reasonable "maximum" (95% weather probability) dose values for each receptor of interest when the joint frequency wind speed/stability class options are used. The 50% weather probability dose value calculated for a receptor is one that is not exceeded approximately 50% of the time (50% of the time a higher dose would be expected). Similarly, the 95% weather probability dose value calculated for a receptor is one that is not exceeded 95% of the time (5% of the time a higher dose would be expected).

3.4 POPULATION DOSE MODEL

A population dose model was developed for RISKIND to assess the potential collective doses to the exposed population as the result of a release associated with a radioactive material transportation accident. The population dose model implemented in RISKIND calculates the total collective dose based on the average individual doses and the distribution of doses in the exposed population within the specific area of interest. The same weather uncertainty

calculations discussed in Section 3.3.2.3.6 for individual risks can be selected for population risks also.

To calculate the distribution of radiation doses to the exposed population from a release, the areas and magnitudes of air and ground concentrations in the downwind direction are needed. This information is calculated with the equations developed for atmospheric transport in Section 3.3.1 for determining individual receptor concentrations. Section 3.4.1 gives the approach implemented in RISKIND for estimating the area and concentration. The collective dose models are based on those for individual receptors and are described in Sections 3.4.2 and 3.4.3. Section 3.4.4 discusses the auxiliary PAG calculations performed in RISKIND to estimate soil cleanup levels that would result in doses below the suggested limits.

3.4.1 Contaminated Areas and Concentration Isopleths

In Section 3.3.1, contaminant radionuclide concentrations in the environmental media were calculated for specific receptor locations. For a population dose calculation, it is necessary and more expedient to determine concentrations on a broader scale and to portion the affected area into isopleths on the basis of air and ground concentrations. Because of the assumptions made in the air transport models, air and ground concentration isopleths will coincide in space (not magnitude) when there is no wet deposition. However, the location of the isopleths is calculated separately for the air and ground concentrations since their locations will not coincide if rainfall is present (greater than 0 mm/h).

Beginning at the accident location, air and ground concentrations will generally increase to a maximum and then decrease as the distance downwind increases. Where the maximum concentrations occur strongly depends on the effective release height and atmospheric conditions at the time of release. In RISKIND, up to 20 isopleths in the direction downwind of the release at the time of the accident are calculated from a nearest distance, x_{min}, up to a maximum distance, x_{max}, as specified by the user (see Figure 3.3).

The first step in determining the isopleths is to find the maximum concentration between x_{min} [XPZ(1)] and x_{max} [XPZ(2)] that will occur along the plume centerline ($y = 0$). A variation of Brent's method (Press 1986) is used to find the maximum concentrations; Equation 3.14 or 3.15 can be used for air concentrations and Equation 3.29 or 3.30 for ground concentrations. The surrounding contour (C_1) for the innermost isopleth is then defined by a concentration value $\sqrt{10}$ smaller than the maximum concentration. The contour for ground-level air concentrations where no mixing with the stable layer has occurred is a rearrangement of Equation 3.14 and is given by

$$y_a(x) = \pm \sigma_y \left[2 \ln \left(\frac{Q_{x_i}}{\pi \sigma_y \sigma_z u_H \overline{C}_a(i,x,y,t)} \right) - \frac{H^2}{\sigma_z^2} \right]^{1/2} \qquad (3.79)$$

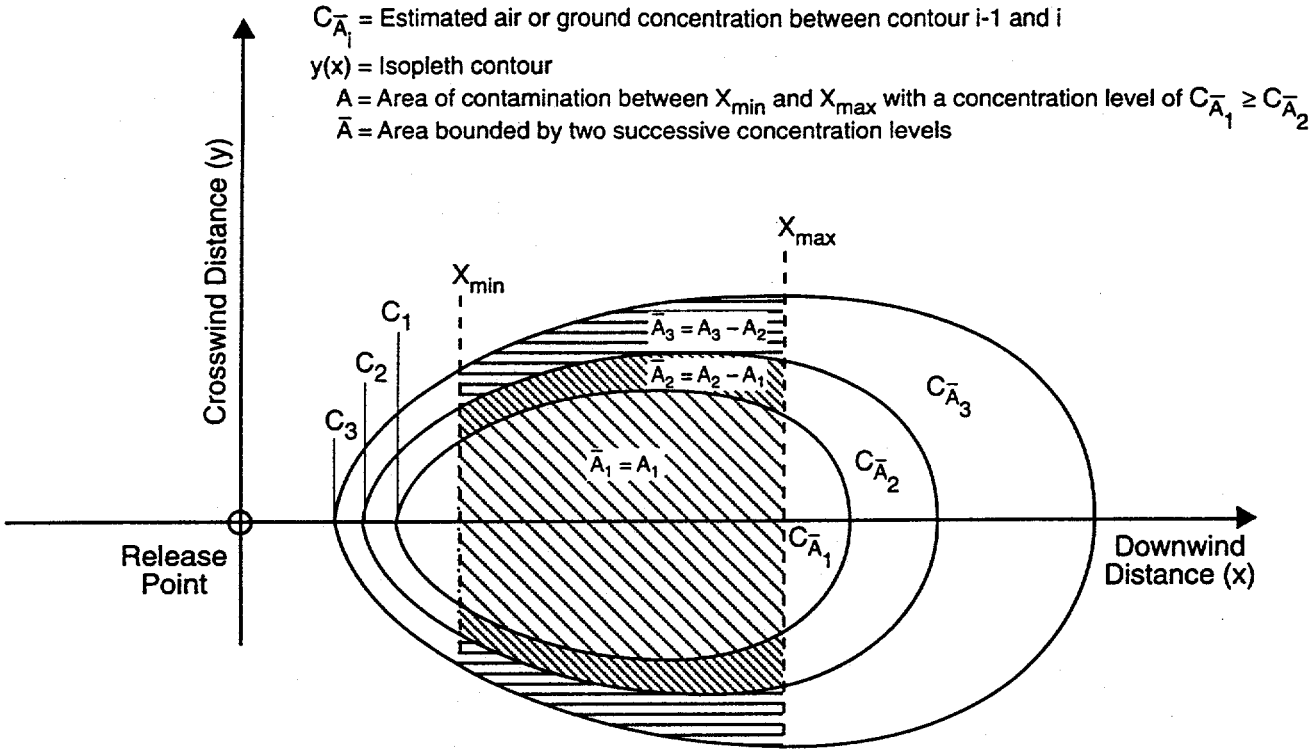

FIGURE 3.3 Areas of Estimated Air or Ground Concentration Contours for Population Dose Calculation

between x_{min} and x_{max}. If the puff is limited by a stable layer and mixing has occurred, the contour is derived from Equation 3.15 and given by

$$y_a(x) = \pm \sigma_y \left[2 \ln \left(\frac{Q_{x_i}}{\sqrt{2\pi}\, \sigma_y\, u_H\, L\, \overline{C}_a(i,x,y,t)} \right) \right]^{1/2} . \qquad (3.80)$$

Similarly, for ground concentration isopleths, the isopleth contour will be given by

$$y_g(x) = \pm \sigma_y \left(2 \ln \left\{ \frac{Q_{x_i}}{\sqrt{\pi}\, \sigma_y\, u_H\, C_g(i,x,y)} \left[\frac{V_w}{\sqrt{2}} + \frac{V_{dep}}{\sqrt{\pi}\, \sigma_z} \exp\left(\frac{-H^2}{2\,\sigma_z^2} \right) \right] \right\} \right)^{1/2} \qquad (3.81)$$

for the no-mixing condition (from Equation 3.29), or by

$$y_g(x) = \pm \sigma_y \left\{ 2 \ln \left[\frac{Q_{x_i} \left(V_w + V_{dep} / L \right)}{\sqrt{2\pi}\, \sigma_y\, u_H\, C_g(i,x,y)} \right] \right\}^{1/2} , \qquad (3.82)$$

if the plume is limited by the stable layer (from Equation 3.30) and mixing has occurred. The total area of contamination within the isopleth contour for a given ground or air concentration is then

$$A = 2 \int_{X_{min}}^{X_{max}} y(x)\, dx \quad , \tag{3.83}$$

where $y(x)$ is given by Equation 3.79, 3.80, 3.81, or 3.82.

Now that the innermost isopleth and its surrounding contour, which defines the area of maximum concentration, have been defined, the next larger isopleth is defined in a similar manner. A contour (C_2) is defined, by using a concentration value of $\sqrt{10}$ smaller than the previous contour, and so on, until the number of specified isopleths is achieved (maximum of 20):

$$C_i = \sqrt{10}\, C_{i-1} \quad , \tag{3.84}$$

where

C_i = air or ground concentration for the ith isopleth contour.

The isopleth areas are calculated from the total areas within the isopleth contours by

$$\overline{A}_i = A_i - A_{i-1} \quad , \tag{3.85}$$

where

$\overline{A}_i$ = isopleth area (area between concentration contours C_i and C_{i-1}) (m^2),

A_i = total area within contour i for isopleth i where i ranges from 1 for the innermost isopleth to NISOPL (number of isopleths) for the outermost isopleth [Equation 3.83], and

$\overline{A}_1$ = (the area for the innermost isopleth) is determined directly by using Equation 3.83.

The air and ground concentration values to be used for each isopleth are determined from the isopleth contours by using the geometric mean

$$C_{\overline{A}_i} = \sqrt{C_i\, C_{i-1}} \quad , \tag{3.86}$$

where

$C_{\overline{A}_i}$ = ground or air concentration of interest for the area $\overline{A}_i$.

For the innermost isopleth,

$$C_{\overline{A}_1} = \sqrt{C_1\, C_{max}} \quad , \tag{3.87}$$

where

C_{max} = maximum ground or air concentration within x_{min} and x_{max}.

For dose calculations, the number of persons present in each isopleth is given by

$$P_i = PD\,\overline{A}_i \ , \tag{3.88}$$

where

PD = population density (persons/km^2) [POPD].

3.4.2 Short-Term Exposure

For short-term exposures, the dose to an individual in each isopleth from inhalation and external radiation is calculated according to the methodology in Section 3.3.2.1 for individual doses by using the isopleth concentration values discussed in Section 3.4.1. The dose to each isopleth is determined by multiplying the total individual dose in each by the number of persons in the respective isopleth. The total collective population dose is obtained by summing over all isopleths.

3.4.2.1 External Exposure from the Radioactive Cloud

The external radiation dose to an individual in isopleth j from the passing radioactive cloud is calculated as

$$D_{AirST}(j) = SF_{AirST}\,K_1 \sum_i C_{\overline{A}_{ij}}\,DCF_{Air}(i) \ , \tag{3.89}$$

where

$D_{AirST}(j)$ = short-term external cloudshine (immersion) dose to an individual in isopleth j (rem);

SF_{AirST} = short-term shielding factor for air immersion: 0 = full shielding, 1 = no shielding (unitless), where

$$SF_{AirST} = OF_{outST} + OF_{inST}\,SF_{Air} \ ; \tag{3.90}$$

OF_{outST} = short-term fraction of population outdoors (unitless) [1 - RFIE];

OF_{inST} = short-term fraction of population indoors (unitless) [RFIE];

SF_{Air} = shielding factor afforded by various shelter types from cloudshine for different people, where

$$SF_{Air} = \sum_k FP_k\,SF_{kAir} \ ; \tag{3.91}$$

FP_k = fraction of indoor population afforded shielding by shelter type k [WSHLT(k)];

SF_{kAir} = shielding factor for shelter type k for cloudshine, 0 = full shielding, 1 = no shielding (unitless) [Table 3.5];

K_1 = conversion factor, 3.7×10^{12} rem-Bq/Sv-Ci;

$C_{\bar{A}_{ij}}$ = time-integrated ground-level air concentration for radionuclide i in isopleth j (Ci-s/m^3) [Equation 3.86 in conjunction with Equation 3.14 or 3.15]; and

$DCF_{Air}(i)$ = dose conversion factor for air submersion for radionuclide i (Sv/Bq-s/m^3).

3.4.2.2 External Exposure from Ground-Deposited Radionuclides

The external dose to an individual in isopleth j from ground contamination following an accidental release is calculated as

$$D_{GndST}(j) = SF_{GndST}\, T_{Ext}\, K_2 \sum_i C_{\bar{A}_{ij}}\, DCF_{Gnd}(i) \ , \tag{3.92}$$

where

$D_{GndST}(j)$ = short-term external groundshine dose to an individual in isopleth j (rem);

SF_{GndST} = short-term shielding factor for external ground radiation: 0 = full shielding, 1 = no shielding (unitless), where

$$SF_{GndST} = OF_{outST} + OF_{inST}\, SF_{Gnd} \ ; \tag{3.93}$$

SF_{Gnd} = shielding factor afforded by various shelter types from groundshine for different people, where

$$SF_{Gnd} = \sum_k FP_k\, SF_{kGnd} \ ; \tag{3.94}$$

SF_{kGnd} = shielding factor for shelter type k for groundshine: 0 = full shielding, 1 = no shielding (unitless) [see Table 3.5];

T_{Ext} = short-term exposure time after plume passage (h) [HTEXP];

K_2 = conversion factor, 1.332×10^{16} rem-Bq-s/Sv-Ci-h;

$C_{\bar{A}_{ij}}$ = initial ground concentration from wet and dry deposition for radionuclide i in isopleth j after plume passage (Ci/m^2) [Equation 3.86 in conjunction with Equation 3.29 or 3.30]; and

$DCF_{Gnd}(i)$ = dose conversion factor for external radiation from the ground for radionuclide i (Sv/Bq-s/m^2).

3.4.2.3 Exposure from Inhaled Radionuclides

The inhalation dose to an individual in isopleth j from the passing radioactive cloud is calculated as

$$D_{InhST}(j) = SF_{InhST}\, K_3\, BR \sum_i C_{\bar{A}_{ij}}\, DCF_{Inh}(i) \quad , \tag{3.95}$$

where

$D_{InhST}(j)$ = short-term inhalation dose to an individual in isopleth j (rem);

SF_{InhST} = short-term shielding factor for inhalation: 0 = full shielding, 1 = no shielding (unitless), where

$$SF_{InhST} = OF_{outST} + OF_{inST}\, SF_{Inh} \quad ; \tag{3.96}$$

SF_{Inh} = shielding factor afforded by various shelter types from inhalation for different people, where

$$SF_{Inh} = \sum_k FP_k\, SF_{kInh} \quad ; \tag{3.97}$$

SF_{kInh} = shielding factor for shelter type k for inhalation: 0 = full shielding, 1 = no shielding (unitless) [Table 3.5];

K_3 = conversion factor, 1.172×10^5 rem-Bq-yr/Sv-Ci-s;

BR = individual breathing rate for population calculations (m^3/yr) [BRTPOP];

$C_{\bar{A}_{ij}}$ = time-integrated ground-level air concentration for radionuclide i in isopleth j (Ci-s/m^3) [Equation 3.86 in conjunction with Equation 3.14 or 3.15]; and

$DCF_{Inh}(i)$ = dose conversion factor for inhalation for radionuclide i (Sv/Bq).

3.4.2.4 External Exposure from Loss of Cask Shielding

The shielding on the shipping cask may be compromised in an accident, resulting in increased levels of radiation. The collective dose is calculated for an annular region from x_{min} [XPZ(1)] to x_{max} [XPZ(2)] about the cask location in a manner similar to that for routine stops (Equation 2.6). The dose is calculated by

$$D_{caskST} = 2\pi\, PD\, SF_{GndST}\, T_{Ext} \int_{x_{min}}^{x_{max}} \left[SL_g\, \dot{D}_g(r) + SL_n\, \dot{D}_n(r) \right] r\, dr \quad , \tag{3.98}$$

where

D_{caskST} = short-term external dose to population around the shipping cask following an accident (person-rem);

PD = population density (persons/km^2) [POPD];

SF_{GndST} = short-term shielding factor for external ground radiation: 0 = full shielding, 1 = no shielding (unitless) [Equation 3.93];

T_{Ext} = short-term exposure time after plume passage (h) [HTEXP];

$\dot{D}_i(r)$ = dose rate from gamma (i = g) or neutron (i = n) radiation at a distance r meters from the cask surface (rem/h) [Equation 2.2];

SL_i = shielding loss factor for gamma (i = g) or neutron (i = n) radiation from the cask, an integral multiple of the original routine dose rate [SEXT(i)];

x_{min} = minimum distance from the cask surface (m) [XPZ(1)]; and

x_{max} = maximum distance from the cask surface (m) [XPZ(2)].

The total short-term dose to the collective population is the external dose from the shipping cask plus the sum of the doses over all isopleths, which in turn is the sum of the individual dose for each exposure pathway in a given isopleth times the number of persons in that isopleth.

$$PDOSE_{ST} = \sum_j P_j \left[D_{AirST}(j) + D_{GndST}(j) + D_{InhST}(j) \right] + D_{CaskST} , \qquad (3.99)$$

where

$PDOSE_{ST}$ = collective dose from short-term exposure to an accidental release (person-rem).

3.4.3 Long-Term Exposure

For long-term exposures, the dose to an individual in each isopleth from inhalation and external radiation is calculated according to the methodology in Section 3.3.2.3 for individual doses by using the isopleth concentration values discussed in Section 3.4.1. The ingestion dose model described in Section 3.4.3.4 is similar to that used for individuals but is a societal dose model and is based on the amount of contaminated food produced. The dose to each isopleth is determined by multiplying the total individual dose (excluding the ingestion dose) in each isopleth by the number of persons in the respective isopleth and then adding the ingestion dose for that isopleth. The total collective population dose is obtained by summing over all isopleths.

3.4.3.1 External Doses from Resuspended Air Concentrations

Long-term exposure to external radiation from resuspended air concentrations for an individual in isopleth j is calculated according to

$$D_{AirLT}(j) = SF_{AirLT}\, K_1 \sum_i C_{\overline{A}_{ij}}\, DCF_{Air}(i) \ , \tag{3.100}$$

where

$D_{AirLT}(j)$ = long-term external cloudshine (immersion) dose to an individual in isopleth j (rem);

SF_{AirLT} = long-term shielding factor for air immersion: 0 = full shielding, 1 = no shielding (unitless), where

$$SF_{AirLT} = OF_{out} + OF_{in}\, SF_{Air} \ ; \tag{3.101}$$

OF_{out} = long-term fraction of population outdoors (unitless) [OCUPF(1,1)];

OF_{in} = long-term fraction of population indoors (unitless) [OCUPF(1,2)];

SF_{Air} = shielding factor afforded by various shelter types from cloudshine for different people, where

$$SF_{Air} = \sum_k FP_k\, SF_{kAir} \ ; \tag{3.102}$$

K_1 = conversion factor, 3.7×10^{12} rem-Bq/Sv-Ci;

$C_{\overline{A}_{ij}}$ = time-integrated ground-level resuspended air concentration for radionuclide i in isopleth j (Ci-s/m^3) [Equation 3.86 in conjunction with Equation 3.57]; and

$DCF_{Air}(i)$ = dose conversion factor for air submersion for radionuclide i (Sv/Bq-s/m^3).

3.4.3.2 External Exposure from Ground-Deposited Radionuclides

The long-term dose to an individual in isopleth j from ground-deposited radionuclides is given by

$$D_{GndLT}(j) = SF_{GndLT}\, K_1 \sum_i C_{\overline{A}_{ij}}\, DCF_{Gnd}(i) \ , \tag{3.103}$$

where

$D_{GndLT}(j)$ = long-term external groundshine dose to an individual in isopleth j (rem);

SF_{GndLT} = long-term shielding factor for external ground radiation: 0 = full shielding, 1 = no shielding (unitless), where

$$SF_{GndLT} = OF_{out} + OF_{in}\, SF_{Gnd} \quad ; \tag{3.104}$$

SF_{Gnd} = shielding factor afforded by various shelter types from groundshine for different people, where

$$SF_{Gnd} = \sum_{k} FP_k\, SF_{kGnd} \quad ; \tag{3.105}$$

K_1 = conversion factor, 3.7×10^{12} rem-Bq/Sv-Ci;

$C_{\bar{A}_{ij}}$ = time-integrated ground concentration for radionuclide i in isopleth j (Ci-s/m^2) [Equation 3.86 in conjunction with Equation 3.52]; and

$DCF_{Gnd}(i)$ = dose conversion factor for external radiation from the ground for radionuclide i (Sv/Bq-s/m^2).

3.4.3.3 Inhalation Doses from Resuspended Air Concentrations

The long-term inhalation dose from resuspended air concentrations to an individual in isopleth j is calculated by

$$D_{InhLT}(j) = SF_{InhLT}\, K_3\, BR \sum_{i} C_{\bar{A}_{ij}}\, DCF_{Inh}(i) \quad , \tag{3.106}$$

where

$D_{InhLT}(j)$ = long-term inhalation dose to an individual in isopleth j (rem);

SF_{InhLT} = long-term shielding factor for inhalation: 0 = full shielding, 1 = no shielding (unitless), where

$$SF_{InhLT} = OF_{out} + OF_{in}\, SF_{Inh} \quad ; \tag{3.107}$$

SF_{Inh} = shielding factor afforded by various shelter types from inhalation for different people, where

$$SF_{Inh} = \sum_{k} FP_k\, SF_{kInh} \quad ; \tag{3.108}$$

K_3 = conversion factor, 1.172×10^5 rem-Bq-yr/Sv-Ci-s;

BR = individual breathing rate for population calculations (m^3/yr) [BRTPOP];

$C_{\overline{A}_{ij}}$ = time-integrated resuspended ground-level air concentration for radionuclide i in isopleth j (Ci-s/m^3) [Equation 3.86 in conjunction with Equation 3.57]; and

$DCF_{Inh}(i)$ = dose conversion factor for inhalation for radionuclide i (Sv/Bq).

3.4.3.4 Ingestion Dose Model

Unlike the other population dose models, the ingestion dose model is based on the societal dose concept. The total collective dose from ingestion pathways is calculated on the basis of regional agricultural productivity rather than the local population because the total radioactive contamination in the food determines the potential collective doses. Because all food may not be consumed locally, ingestion population doses are calculated by using the following procedures.

The annual productivity (kg/km^2-yr) of each food category (vegetables, meat, and milk) is assigned by the user; these productivity values can be either site-specific data or the default state average values. For each nested isopleth, the mean radionuclide concentrations in each food type are calculated by using the approach in Section 3.3.2.2. The values are then multiplied by the farm production rate and the farm area to find the total radioactive contamination in each food for each area (A_j). Collective doses are then determined by assuming that either all or some fraction of the food produced in the contaminated region of interest is eventually consumed.

First, the total amount of radioactive contamination in each food type is calculated according to

$$Q_f(i,j) = K_6\, G_f\, \overline{A}_j\, F_{farm}\, UF_f\, C_{\overline{A}_{ij}} \quad , \tag{3.109}$$

where

$Q_f(i,j)$ = gross content of radionuclide i produced in isopleth j in food type f, where f represents v for vegetables, b for meat, and m for milk (Ci);

K_6 = conversion constant, $1/(3.156 \times 10^7$ s/yr);

G_f = farm production rate of food type f (kg/yr-km^2) [GVEGE, GMEAT, or GMILK];

$\overline{A}_j$ = area encompassed by isopleth j (km^2) [Equation 3.85];

F_{farm} = fraction of land that is farmland (unitless) [FARM];

UF_f = fraction of contaminated food type f produced that is consumed by humans (unitless) [UF(f)]; and

$C_{\bar{A}_{fj}}$ = time-integrated concentration of radionuclide i in food type f in isopleth j (Ci-s/kg) [Equation 3.86 in conjunction with Equation 3.60, 3.61, or 3.62].

Next, the dose from each food category is calculated for each isopleth. The societal dose from vegetables grown in isopleth j is calculated as

$$PDOSE_{Veg}(j) = DF\,K_1 \sum_i Q_v(i,j)\,DCF_{Ing}(i) \quad , \tag{3.110}$$

where

$PDOSE_{Veg}(j)$ = societal dose from ingestion of contaminated vegetables produced in isopleth j (person-rem);

DF = decontamination factor, that is, fraction of contamination remaining on vegetation after food preparation at time of consumption (unitless) [DFACT];

K_1 = conversion factor, 3.7×10^{12} rem-Bq/Sv-Ci;

$Q_v(i,j)$ = gross content of radionuclide i produced in isopleth j in vegetables (Ci) [Equation 3.109]; and

$DCF_{Ing}(i)$ = dose conversion factor for ingestion for radionuclide i (Sv/Bq).

The societal dose from meat products is calculated as

$$PDOSE_{Meat}(j) = K_1 \sum_i Q_b(i,j)\,DCF_{Ing}(i) \quad , \tag{3.111}$$

where

$PDOSE_{Meat}(j)$ = societal dose from ingestion of contaminated meat grown in isopleth j (person-rem); and

$Q_b(i,j)$ = gross content of radionuclide i produced in isopleth j in meat (Ci) [Equation 3.109].

The societal dose from milk products is calculated as

$$PDOSE_{Milk}(j) = K_1 \sum_i Q_m(i,j)\,DCF_{Ing}(i) \quad , \tag{3.112}$$

where

$PDOSE_{Milk}(j)$ = societal dose from ingestion of contaminated milk produced in isopleth j (person-rem); and

$Q_m(i,j)$ = gross content of radionuclide i produced in isopleth j in milk (Ci) [Equation 3.109].

If water ingestion for a population analysis is specified, water ingestion doses are calculated in a manner similar to that for individuals in Section 3.3.2.3.5. The only real difference is the multiplication of the individual dose by the number of persons drinking from a specific water body.

$$PDOSE_{Water}(k) = P_{Water}(k)\, U_w\, K_5 \sum_i \overline{C}_w(i,x,y,T)\, DCF_{Ing}(i) \quad , \tag{3.113}$$

where

$PDOSE_{Water}(k)$ = dose to receptors from ingestion of contaminated water from water body k (person-rem);

$P_{water}(k)$ = number of persons drinking from water body k [POPW(k)];

U_w = human consumption rate of water (L/d) [XING(5)];

K_5 = conversion factor, 1.351×10^{12} rem-Bq-d-m^3/Sv-Ci-yr-L;

$\overline{C}_w(i,x,y,T)$ = time-integrated radionuclide i concentration in water body at location x,y at time T after puff passage (Ci-yr/m^3) [Equation 3.67]; and

$DCF_{Ing}(i)$ = dose conversion factor for ingestion for radionuclide i (Sv/Bq).

The total ingestion dose is given by the summation over the food categories in each isopleth, added to the sum over all water bodies selected:

$$PDOSE_{Ing} = \sum_j \{[PDOSE_{Veg}(j) + PDOSE_{Meat}(j) + PDOSE_{Milk}(j)]\} + \sum_j PDOSE_{Water}(k) \quad , \tag{3.114}$$

where

$PDOSE_{Ing}$ = societal ingestion dose following an accidental release (person-rem),

j = index over isopleths, and

k = index over water bodies.

In turn, the total collective long-term dose is the sum of all pathways over all isopleths, plus the societal ingestion dose and is calculated as

$$PDOSE_{LT} = \sum_j P_j \left[D_{AirLT}(j) + D_{GndLT}(j) + D_{InhLT}(j)\right] + PDOSE_{Ing} , \quad (3.115)$$

where

$PDOSE_{LT}$ = collective dose from long-term exposure to an accidental release (person-rem).

Finally, the total collective population dose (person-rem) is calculated as the sum of the doses from short- and long-term exposures:

$$PDOSE = PDOSE_{ST} + PDOSE_{LT} . \quad (3.116)$$

3.4.4 Protective Action Guidelines

The EPA has published suggested PAGs dealing with exposure to accidental radioactive releases (EPA 1991). These guidelines deal with the early (short-term) and later (long-term) phases following an accidental release. Early phase considerations are not implemented in RISKIND because forewarning (i.e., time to mitigate potential exposure) of an accidental transport-related release may not be likely. On the other hand, cleanup of soil contamination to safer levels might be a viable solution over the long term. On the basis of a PAG value input by the user, the program will estimate the maximum soil concentrations necessary to maintain radiation exposure over the long term at the PAG limit. These concentrations are calculated to give the user an assessment of the amount of cleanup necessary to achieve the specified PAG limit, not for analyzing mitigative cleanup actions.

RISKIND performs an auxiliary set of calculations for a given population isopleth if an average individual in that isopleth were to receive a long-term dose greater than the user-specified PAG over the course of the specified exposure time [YEVD]. Calculations are then performed to determine the maximum contaminant ground concentrations allowable that will still meet the PAG limit. A second table of isopleth ground concentration values after cleanup is listed in the program output for comparison with the levels calculated following release. Short-term and water ingestion doses are not considered in the calculations.

4 HEALTH EFFECTS MODELS

This section discusses the health effects models and parameters used in RISKIND. Potential early health effects from acute, short-term high dose rate exposures from a hypothetical severe accident scenario are addressed, as well as the latent health effects from short- and long-term low dose rate exposures incurred during routine transport or from potential accident events.

Early health effects are nonstochastic effects that are associated with the degree of radiation trauma received by such vital body organs as the bone marrow, the lungs, or the gastrointestinal (GI) tract (Evans et al. 1985; Abrahamson et al. 1989, 1991). These effects exhibit a nonlinear, threshold relationship with dose and are typically measured in acute lethality. Absorbed dose is used for assessing the early health effects. Section 4.1 describes the method for estimating the absorbed doses and assessing early health effects.

Latent health effects, on the other hand, are stochastic effects where the chance of contracting such an effect increases with the radiation dose received by the organs. Stochastic health effects exhibit a linear, nonthreshold relationship with dose (National Research Council 1990) and are typically measured in cancer incidence, cancer fatality, or genetic effects. Because of the assumed linear relationship with dose, latent health effects are conveniently related to the dose (in terms of effective dose equivalent) by simple health effects conversion factors (ICRP 1991) described in Section 4.2.

4.1 EARLY EFFECTS

A health effects model was developed for early (acute) effects of short-term exposure to radiation from transportation accidents involving radioactive materials. The model applies to hypothetical accident conditions in which individuals would be exposed to relatively large doses in a short period of time. The early effects estimated are fatalities that might occur within the first year after radiation exposure. The model is based on the NRC health effects study (Evans et al. 1985; Abrahamson et al. 1989, 1991). The fatalities modeled are the result of injury to the (1) bone marrow (hematopoietic syndrome), (2) GI tract (GI syndrome), and (3) lungs (pulmonary syndrome). Dose responses for basic first aid and more extensive medical treatment are provided. Also, options are available for bounding model parameters at three estimation levels — lower, central (assumed to be the most realistic), and upper — to compensate for uncertainty associated with the model.

Two basic categories of acute dose are considered: brief and protracted. Brief dose is due to sudden exposure during the short-term period immediately following an accidental release. The brief dose includes the dose received from inhalation within the first 24 hours of a release, as well as the external dose due to external gamma rays from a passing radioactive cloud, the radionuclide-contaminated ground surface, or loss of cask shielding. Protracted dose is the

dose due to internal exposure from inhaled radionuclides during the short-term period, up to one year from the time of release. For radiation exposure resulting from SNF transportation accidents, the first dose category is usually not as significant as the second because SNFs generally contain a significant portion of radionuclides that can potentially deliver internal doses over a longer period of time after intake.

4.1.1 Dose and Dose Rate Estimation

For the health risk calculation, radiation dose refers to the average absorbed dose (units of rad or Gy, 1 Gy = 100 rad) to the specific organ of interest. Dose rate refers to the average absorbed dose rate to the target organ of interest over a given time period from external and inhalation exposure. The early effects of exposure are generally associated only with relatively high radiation dose rates $\gtrsim$ 0.06 Gy/h); the severity of these effects diminishes with lower dose levels. This dose-response relationship implies a dose threshold below which no early effects are apparent.

4.1.1.1 Absorbed Dose

The radiation trauma, that is, physical damage, induced by high dose rates can be quantified in terms of the absorbed dose. The doses estimated in Sections 2 and 3 are in terms of the effective dose equivalent (units of Sv or rem, 1 Sv = 100 rem), which considers both physical and biological factors. The effective dose equivalent is a weighted average of organ dose equivalents. The dose equivalent is estimated by multiplying the absorbed dose by a weighting factor, referred to as the quality factor (Q, International Commission on Radiation Units and Measurements 1993), since some types of radiation are more destructive than others. The quality factor takes into account the relative biological effectiveness (RBE) of different radiation types and energies. Weighting factors of 1, 10, and 20 are recommended by the ICRP (1991) for gamma, neutron, and alpha radiation, respectively. Therefore, an absorbed dose of 1 rad from gamma radiation is equivalent to an equivalent dose of 1 rem; an absorbed dose of 1 rad from neutron radiation is equivalent to an equivalent dose of 10 rem.

As discussed in the following subsections, the methodology for estimating some absorbed doses will be similar to that used in Section 3. However, organ-specific dose DCFs are used in place of the effective DCFs, and the estimated dose is then adjusted by using the suggested Q weighting factors, if the dose is a result of alpha or neutron radiation.

4.1.1.2 External Exposure

The brief external doses to the three target organs can be calculated according to Equations 3.47 and 3.48 in Section 3 for radioactive cloud and contaminated ground exposure, respectively, by substituting organ-specific DCFs (Eckerman and Ryman 1993) for whole body

DCFs. The dose rates to each organ are calculated by dividing the individual organ doses by the short-term exposure time used in Equations 3.47 and 3.48. For exposure from loss of cask shielding, the equivalent dose to each organ is calculated according to Equation 3.49. The neutron radiation portion of the dose is adjusted by the weighting factor of 10 to obtain the absorbed dose. The dose rate is calculated by dividing the absorbed dose by the time of exposure [$T_{ext}(j)$].

4.1.1.3 Inhalation Exposure

Currently, no published DCFs are available for the target organs and specific time intervals of interest for estimating early effects from accidental radionuclide exposure from inhalation. The shortest time period for which DCFs are available is 1 year for selected target organs, as derived by Dunning (1986). A simplified method is used in RISKIND to interpolate doses and dose rates from Dunning's 1-year DCFs to factors for shorter, specified periods of time.

The inhalation dose rate to a target organ (and therefore the resulting dose) following an acute radionuclide exposure may be related to the rate of clearance or the retention function of the body. The radionuclide metabolic model and model parameters have been described in various sections of ICRP Publication 30 (ICRP 1979-1982). The ICRP model assumes that radionuclide retention in the lungs and other organs can be represented by either a single or linear combination of up to five exponential functions, except for the alkaline earth elements (calcium, strontium, barium, and radium). For these elements, a combination of exponential and power functions were considered more appropriate (ICRP 1972).

In RISKIND, as in the ICRP model, retention of radionuclides in all organs or tissues is assumed to be a single or linear combination of exponential functions. For the alkaline earth elements, the retention in the body over the first 365 days following exposure is represented by the sum of two exponential functions. This expression is constructed from a least-squares fit of the retention data given in ICRP Publication 20 (ICRP 1972). The retention function for any radionuclide in one of the three target organs is given by a single exponential function ($j = 1$) or a linear combination of exponential functions ($j > 1$) of the form

$$R\ (i,k,t) = \sum_j a(i,j,k) \exp\left\{ - \left[\lambda_b\ (i,j,k) + K_6\ \lambda(i)\right] t\right\}, \qquad (4.1)$$

where

$R(i,k,t)$ = retention of radionuclide i in organ k after time t (unitless);

$a(i,j,k)$ = fraction of radionuclide i originally absorbed in subcompartment j of organ k (unitless) [Tables 4.1 and 4.2], where

$$\sum_j a(i,j,k) = 1 \qquad (4.2)$$

$\lambda_b(i,j,k)$ = biological removal constant for radionuclide i in subcompartment j of organ k, $0.693/T_b(i,j,k)$ (1/d) [Tables 4.1 and 4.2 for values of $T_b(i,j,k)$];

K_6 = conversion constant, 1/365.25 (yr/d);

$\lambda(i)$ = radioactive decay constant for radionuclide i (1/yr); and

t = time since exposure (d);

The retention parameters for the lungs and bone marrow are given in Tables 4.1 and 4.2, respectively. The dose rate and dose to each part of the GI tract (i.e., stomach, small intestine, upper large intestine, and lower large intestine [LLI]) are a function of the radionuclide residence period and the quantity absorbed from the gut into the blood pool. Of the four parts of the GI tract, the LLI is considered to be the critical section because it has the longest transit time. The retention function for the GI tract consists of one exponential [$a(i,1,3) = 1$] that uses a biological half-life of 0.75 days [$\lambda_b(i,1,3)$], which corresponds to a mean residence time of 18 hours in the LLI.

TABLE 4.1 Retention Parameters for the Lungs for Each Translocation Class

	Translocation Class Y		Translocation Class W		Translocation Class D	
Subcompartment (j)	Fraction Absorbed [a(i,j,1)][a]	Biological Half-Life [T_b(i,j,1)][b] (days)	Fraction Absorbed [a(i,j,1)]	Biological Half-Life [T_b(i,j,1)] (days)	Fraction Absorbed [a(i,j,1)]	Biological Half-Life [T_b(i,j,1)] (days)
1	0.6	500	0.6	50	1	0.5
2	0.4	1	0.4	1		

[a] a = fraction of radionuclide originally absorbed in subcompartment of the lungs.

[b] T_b = biological half-life of radionuclide in subcompartment j of the lungs.

Source: ICRP (1972).

TABLE 4.2 Retention Parameters for Bone Marrow Dose Calculations

	Subcompartment 1		Subcompartment 2		Subcompartment 3		Subcompartment 4	
Element	Fraction Absorbed [a(i,1,2)[a]]	Biological Half-Life [T_b(i,1,2)[b] (days)]	Fraction Absorbed [a(i,2,2)]	Biological Half-Life [T_b(i,2,2) (days)]	Fraction Absorbed [a(i,3,2)]	Biological Half-Life [T_b(i,3,2) (days)]	Fraction Absorbed [a(i,4,2)]	Biological Half-Life [T_b(i,4,2) (days)]
H	1	0	0	0	0	0	0	0
Be	1	0	0	0	0	0	0	0
C	1	40	0	0	0	0	0	0
N	1	0	0	0	0	0	0	0
F	1	0	0	0	0	0	0	0
Na	1	10	0	0	0	0	0	0
P	1	0	0	0	0	0	0	0
S	0.75	20	0.25	2,000	0	0	0	0
Cl	1	10	0	0	0	0	0	0
Ca	0.5	6.9	0.5	1,650	0	0	0	0
Sc	0.1	5	0.9	1,500	0	0	0	0
Cr	0.62	6	0.38	80	0	0	0	0
Mn	1	0	0	0	0	0	0	0
Fe	1	2,000	0	0	0	0	0	0
Co	0.6	6	0.2	60	0.2	800	0	0
Ni	1	1,200	0	0	0	0	0	0
Cu	1	40	0	0	0	0	0	0
Zn	0.3	20	0.7	400	0	0	0	0
Se	0.1	3	0.4	30	0.5	160	0	0
Br	1	10	0	0	0	0	0	0
Kr	1	0	0	0	0	0	0	0
Rb	1	44	0	0	0	0	0	0
Sr	0.78	3	0.22	963	0	0	0	0
Y	1	36,500	0	0	0	0	0	0
Zr	1	7	0	0	0	0	0	0
Nb	0.5	6	0.5	200	0	0	0	0
Mo	0.1	1	0.9	50	0	0	0	0
Tc	1	1.6	0	3.7	0	22	0	0
Ru	0.15	0.3	0.35	8	0.3	35	0.2	1,000
Rh	0.15	0.3	0.35	8	0.3	35	0.2	1,000
Pd	1	15	0	0	0	0	0	0
Ag	0.1	3.5	0.9	50	0	0	0	0
Cd	1	2.5	0	0	0	0	0	0
In	1	36,500	0	0	0	0	0	0
Sn	0.2	4	0.2	25	0.6	400	0	0
Sb	0.95	5	0.05	100	0	0	0	0
Te	1	20	0	0	0	0	0	0
I	1	0	0	0	0	0	0	0
Cs	0.1	2	0.9	110	0	0	0	0
Ba	0.92	0.9	0.09	592	0	0	0	0
La	1	3,500	0	0	0	0	0	0
Ce	1	3,500	0	0	0	0	0	0
Pr	1	3,500	0	0	0	0	0	0
Nd	1	3,500	0	0	0	0	0	0
Pm	1	3,500	0	0	0	0	0	0
Sm	1	3,500	0	0	0	0	0	0
Eu	1	3,500	0	0	0	0	0	0
Gd	1	3,500	0	0	0	0	0	0
Tb	1	3,500	0	0	0	0	0	0
Ho	1	3,500	0	0	0	0	0	0
Tm	1	3,500	0	0	0	0	0	0
Hf	1	7	0	0	0	0	0	0
Ta	0.5	4	0.5	100	0	0	0	0
W	1	0	0	0	0	0	0	0
Re	0.75	1.6	0.2	3.7	0.05	22	0	0

TABLE 4.2 (Cont.)

Element	Subcompartment 1		Subcompartment 2		Subcompartment 3		Subcompartment 4	
	Fraction Absorbed [a(i,1,2)[a]]	Biological Half-Life [T_b(i,1,2)[b] (days)]	Fraction Absorbed [a(i,1,2)]	Biological Half-Life [T_b(i,1,2) days)]	Fraction Absorbed [a(i,1,2)]	Biological Half-Life [T_b(i,1,2) days)]	Fraction Absorbed [a(i,1,2)]	Biological Half-Life [T_b(i,1,2) days)]
Pb	0.8	12	0.18	180	0.02	10,000	0	0
Bi	0.6	0.6	0.4	5	0	0	0	0
Po	1	50	0	0	0	0	0	0
Rn	1	0	0	0	0	0	0	0
Ra	0.92	1.3	0.08	413	0	0	0	0
Ac	1	36,500	0	0	0	0	0	0
Th	1	700	0	0	0	0	0	0
Pa	1	36,500	0	0	0	0	0	0
U	1	6	0	0	0	0	0	0
Np	1	36,500	0	0	0	0	0	0
Pu	1	18,200	0	0	0	0	0	0
Am	1	18,200	0	0	0	0	0	0
Cm	1	18,200	0	0	0	0	0	0
Cf	1	18,200	0	0	0	0	0	0

[a] a = fraction of radionuclide originally absorbed in subcompartment of the bone marrow.

[b] T_b = biological half-life of radionuclide in subcompartment of the bone marrow.

Source: ICRP (1972).

The dose received from a given radionuclide in the target organ over a period of time will be proportional to the time-integrated retention function:

$$\overline{R}(i,k,t) = \sum_j \frac{a(i,j,k)\left\{1 - \exp\left(-\left[\lambda_b(i,j,k) + K_6\,\lambda(i)\right]t\right)\right\}}{\lambda_b(i,j,k) + K_6\,\lambda(i)}, \tag{4.3}$$

where

$\overline{R}(i,k,t)$ = time-integrated retention of radionuclide i in organ k after time t (unitless).

For any particular organ k and radionuclide i, the ratio of time-integrated doses, $D(i,k,t_1)$ and $D(i,k,t_2)$, for time periods t_1 and t_2 following exposure is given by

$$\frac{D(i,k,t_1)}{D(i,k,t_2)} = \frac{\overline{R}(i,k,t_1)}{\overline{R}(i,k,t_2)} = \frac{\sum_j \dfrac{a(i,j,k)\left(1 - \exp\left\{-\left[\lambda_b(i,j,k) + K_6\,\lambda(i)\right]t_1\right\}\right)}{\lambda_b(i,j,k) + K_6\,\lambda(i)}}{\sum_j \dfrac{a(i,j,k)\left(1 - \exp\left\{-\left[\lambda_b(i,j,k) + K_6\,\lambda(i)\right]t_2\right\}\right)}{\lambda_b(i,j,k) + K_6\,\lambda(i)}}. \tag{4.4}$$

Rearranging results in

$$D(i,k,t_1) = D(i,k,t_2) \frac{\sum_j \frac{a(i,j,k)\left(1 - \exp\left\{-\left[\lambda_b(i,j,k) + K_6\,\lambda(i)\right] t_1\right\}\right)}{\lambda_b(i,j,k) + K_6\,\lambda(i)}}{\sum_j \frac{a(i,j,k)\left(1 - \exp\left\{-\left[\lambda_b(i,j,k) + K_6\,\lambda(i)\right] t_2\right\}\right)}{\lambda_b(i,j,k) + K_6\,\lambda(i)}} , \quad (4.5)$$

where

$D(i,k,t_1)$ = acute absorbed dose from radionuclide i to target organ k from time period of interest t_1 (rad); and

$D(i,k,t_2)$ = acute absorbed dose from radionuclide i to target organ k from time period of interest t_2; in RISKIND, t_2 is set to 1 year and the 1-year dose equivalent conversion factors for the target organs given by Dunning (1986), who used a quality factor of 20 for alpha radiation, are used to estimate the acute inhalation according to Equation 3.50 (rad). A weighting factor of 1/20 is used to reduce the dose for those radionuclides emitting alpha radiation to obtain the absorbed dose.

Once the dose to the target organ is determined, the average dose rate to the target organ is calculated as

$$DR(i,k,t_1) = \frac{D(i,k,t_1)}{t_1} , \quad (4.6)$$

where

$DR(i,k,t_1)$ = average dose rate to target organ k during time period of interest t_1 (rad/d).

As described in Section 4.1.2, the dose rate is used in the determination of the lethality risk.

In the above calculations, t_1 and t_2 are assumed to be functions of radionuclide i and target organ k where

$$t_2(i,k) = \begin{cases} 365 \text{ days}, & \text{if } \frac{1}{\lambda_m(i,j,k)} > 365 \text{ days} \\ \frac{1}{\lambda_m(i,j,k)}, & \text{if } \frac{1}{\lambda_m(i,j,k)} < 365 \text{ days} . \end{cases} \quad (4.7)$$

For brief exposures,

$$t_1(i,k) = \begin{cases} 1 \text{ day}, & \text{if } \dfrac{1}{\lambda_m(i,j,k)} > 1 \text{ day} \\ \dfrac{1}{\lambda_m(i,j,k)}, & \text{if } \dfrac{1}{\lambda_m(i,j,k)} < 1 \text{ day} \end{cases} . \tag{4.8}$$

For protracted exposures,

$$t_1(i,k) = \begin{cases} TP(k), & \text{if } \dfrac{1}{\lambda_m(i,j,k)} > TP(k) \\ \dfrac{1}{\lambda_m(i,j,k)}, & \text{if } \dfrac{1}{\lambda_m(i,\mathrm{j},\mathrm{k})} < TP(k) \end{cases} , \tag{4.9}$$

where

$TP(k)$ = time periods of exposure of 30, 365, and 7 days, respectively, for organs (k), bone marrow, lungs, and GI tract; and

$\lambda_m(i,j,k)$ = minimum decay constant (longest half-life) of radionuclide i from all subcompartments j from organ k (1/d); minimum value of $\lambda_b(i,j,k)$ over all j.

4.1.2 Lethality Risk

In this section, the term lethality risk represents the probability of fatality from an incurred radiation dose. A hazard-function approach is used to derive fatality risk estimates for effects in the three target organs of the body and to determine the total risk resulting from exposure of these organs. The lethality is calculated from the cumulative hazard H (Evans et al. 1985; Abrahamson et al. 1989). The general expression used for the lethality hazard is the following two-parameter Weibull function:

$$H_A(k) = \ln(2)\, X(k)^V , \tag{4.10}$$

where

$H_A(k)$ = lethality hazard for organ k (unitless);

$$X(k) = \frac{D(k)}{D_{50}(k)} ; \tag{4.11}$$

$D(k)$ = acute dose to organ k, sum of pathway doses (external radiation from passing radioactive cloud, contaminated ground, and loss of cask shielding; and time-integrated dose from inhalation) (Gy);

$D_{50}(k)$ = median lethal dose, dose to organ k that produces the effect of interest in 50% of the population at risk (Gy) [Table 4.3]; and

V = shape parameter [Table 4.3]:

The lethality risk is then related to H_A by the expression (Abrahamson et al. 1989, 1991)

$$Lethality\ risk(k) = 1 - \exp\,[-H_A(k)]\ , \tag{4.12}$$

where

Lethality risk(k) = risk of lethality from organ k.

The total lethality risk from all acute effects considered is calculated by summing the cumulative hazards for each lethal mode of injury, that is, the hematopoietic syndrome (bone marrow), the gastrointestinal syndrome (intestines), and the pulmonary syndrome (lungs). The estimated lethality risk from these three competing injuries can be calculated as follows (Abrahamson et al. 1989, 1991):

$$Lethality\ risk = 1 - \exp\{-[\,H_A(bone) + H_A(lung) + H_A(GI)]\}. \tag{4.13}$$

Application of this method is based on the calculation of $X(k)$, which is the dose to organ k normalized to the D_{50} value (the dose that is expected to cause death in 50% of the persons receiving such a dose). Ideally, $X(k)$ would be calculated according to (Abrahamson et al. 1989)

$$X(k) = \int_0^t \frac{\dot{D}(k)}{D_{50}\left(\dot{D}(k)\right)}\,dt\ , \tag{4.14}$$

where $\dot{D}(k)$ is the instantaneous absorbed dose rate to organ k at time t, and the D_{50} value is dependent on the dose rate. The exact form of Equation 4.15 cannot be used because of the lack of data for D_{50} values. A simplified fixed parameter approach is used in the NRC health effects study (Abrahamson et al. 1989, 1991). In this approach, the model parameter D_{50} is assumed to change only when the dose rate enters specific ranges. Two dose rate categories are defined: brief high dose rates (> 0.06 Gy/h) and protracted long-term dose rates (≤ 0.06 Gy/h). Protracted exposures are treated as less effective than brief exposures. Table 4.3 lists the D_{50} values used in the calculations for specific dose rates for the three target organs.

In RISKIND, $X(k)$ is approximated by an expression of the form (Abrahamson et al. 1989)

$$X(k) = \frac{D_B(k)}{D_{50,\,B}} + \frac{D_P(k)}{D_{50,\,P}}\ , \tag{4.15}$$

TABLE 4.3 Early Effects Model Parameters

Target Organ [a]	Dose Rate (Gy/h)	Median Lethal Dose (D_{50}, Gy)			Shape Parameter (V)			Threshold (X = 0.5)		
		Central	Lower	Upper	Central	Lower	Upper	Central	Lower	Upper
Bone marrow (minimum treatment)	>10	3	2.5	3.5	6	4	8	1.5	1.2	1.8
	1	3.1	2.5	3.7	6	4	8	1.6	1.3	1.9
	0.1	3.7	3.1	4.3	6	4	8	1.9	1.6	2.2
	0.05	4.4	3.6	5.2	6	4	8	2.2	1.8	2.6
	0.01	10	8	12	6	4	8	5	4	6
Pulmonary	100	10	8	12	12	12	12	5	4	6
	10	15	10	20	12	12	12	7	5	9
	1	40	20	60	12	12	12	20	10	30
	0.5	70	40	100	12	12	12	40	20	60
	0.1	310	160	460	12	12	12	160	80	230
	0.05	610	310	910	12	12	12	310	160	460
GI tract	> 0.06	15	10	20	10	10	10	8	5	10
	< 0.06	35	25	50	10	10	10	18	13	25

[a] Multiply dose values by 1.5 or 2 for supportive treatment for bone marrow or pulmonary calculations, respectively. Brief exposure: dose received within the first day following initial exposure. Protracted exposure: dose received from inhalation within the first 30 days for bone marrow, 365 days for lungs, and 7 days for GI tract.

Source: Abrahamson et al. (1989, 1991).

where

$D_B(k)$ = dose to target organ k during the brief exposure time (Gy),

$D_P(k)$ = dose to target organ k during the protracted exposure time (Gy),

$D_{50,B}$ = D_{50} value for target organ k for dose rate during brief exposure time (Gy), and

$D_{50,P}$ = D_{50} value for target organ k for dose rate during protracted exposure time (Gy).

A threshold effect is assumed to be operative, and the value for $X(k)$ is set to 0.0 if the calculated value from Equation 4.15 is less than 0.5 (Abrahamson et al. 1989, 1991). Exposure due to external gamma rays from the passing radioactive cloud, the radionuclide-contaminated ground surface, and loss of cask shielding is evaluated for the brief exposure period that is considered to be the short-term exposure time [TEXT(j) for individuals or HEXT for population calculations]. Exposure from inhaled radionuclides is included in the brief dose by using an exposure time of

24 hours. The protracted dose is calculated from the exposure from inhaled radionuclides for periods of 30, 365, and 7 days, respectively, for the bone marrow, lungs, and GI tract.

4.1.3 Dose Response

Two types of dose responses are used for modeling the levels of medical treatment: minimal and supportive. Minimal treatment assumes that no extraordinary means of medical treatment are administered outside of basic first aid. Depending on the affected organ(s), supportive treatment includes such measures as hospitalization with state-of-the-art antibiotic therapy, blood transfusions, electrolyte replacement, and intravenous feeding. If supportive medical treatment is considered [ITREAT = 1], the D_{50} values used by RISKIND (Table 4.3) are increased by a factor of 1.5 for bone marrow and 2 for pulmonary calculations (Abrahamson et al. 1989).

4.2 LATENT EFFECTS

Latent effects may result from cumulative exposures, including the short- and long-term exposures discussed in Section 3. As a conservative measure, no credit is given for exposures resulting in acute fatalities, and the entire cumulative dose received is used in estimating the latent health effects. Three latent health effects are considered in RISKIND: (1) nonfatal cancer occurrence, (2) fatal cancer occurrence, and (3) genetic effects manifested in the exposed individual's descendants.

The latent effects are calculated with dose-to-health risk conversion factors (Table 4.4) suggested by the ICRP (ICRP 1991). Two sets of conversion factors are provided, one for occupational workers and the other, with higher values, for the general public. Workers are assumed to be in better physical condition and, therefore, better able to tolerate exposure to radiation than the population as a whole.

As was the case with the early effects, higher dose rates are more effective in inducing adverse effects. The ICRP (ICRP 1991) recommends that the health risk conversion factors be doubled for equivalent doses resulting from absorbed doses greater than or equal to 20 rad (20 rem for gamma exposure), when the dose rate is greater than or equal to 10 rad/h. RISKIND doubles the risk conversion factors in Table 4.4 when the estimated cumulative dose exceeds 20 rem per individual, regardless of the dose rate. This approach may overestimate the health effects when the dose exceeds 20 rem. It will, however, account for situations where higher dose rates occur in the short-term, and the cumulative exposure includes a long-term component at relatively low dose rates.

TABLE 4.4 Latent Effects Health Risk Conversion Factors

Exposed Population	Fatal Cancers per Person-Rem	Nonfatal Cancers per Person-Rem	Genetic Effects per Person-Rem
Occupational workers	4.0×10^{-4}	8.0×10^{-5}	8.0×10^{-5}
General public	5.0×10^{-4}	1.0×10^{-4}	1.3×10^{-4}

Source: ICRP (1991).

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APPENDIX A:

DESCRIPTION OF RADIONUCLIDE INVENTORY DATABASE FOR SPENT NUCLEAR FUELS

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APPENDIX A: DESCRIPTION OF RADIONUCLIDE INVENTORY DATABASE FOR SPENT NUCLEAR FUELS A-5

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TABLE

A.1 Sample Radionuclide Inventory A-6

APPENDIX A:

DESCRIPTION OF RADIONUCLIDE INVENTORY DATABASE FOR SPENT NUCLEAR FUELS

A radionuclide inventory database specific to spent nuclear fuels was derived from the computerized databases developed by Oak Ridge National Laboratory (ORNL) (Notz et al. 1987; DOE 1992). These databases were developed for the U.S. Department of Energy (DOE), Office of Civilian Radioactive Waste Management (OCRWM), to establish reference characteristics of radioactive waste materials that may be accepted by DOE for emplacement in the mined geologic disposal system developed under the Nuclear Waste Policy Act of 1982.

The inventory data applicable to spent fuels have been generated by the ORIGEN2 computer code (Croff 1980) and are contained in the Light-Water Reactor (LWR) Radiological Quantities Database of DOE (DOE 1992). Specifically, the radioactivity, given in curies per metric ton of initial heavy metal (Ci/MTIHM), is provided for a detailed list of radionuclides for significant activation- and fission-product nuclides as well as actinides. The inventory data are compiled according to reactor type, fuel burnup, and fuel cooling period. Two reference LWRs were used, a pressurized-water reactor (PWR) (Westinghouse) and a boiling-water reactor (BWR) (General Electric).

For application to the RISKIND code described in the main body of this report, a somewhat condensed inventory database was compiled from the DOE database. This condensed database contains inventory information for all isotopes contributing more than 0.01% to the total inventory data. The burnup levels are 10,000, 20,000, 30,000, 40,000, 50,000, and 60,000 MWd/MTIHM for the PWRs, and 7,500, 15,000, 22,500, 30,000, 40,000, and 50,000 MWd/MTIHM for the BWRs. The cooling periods selected were 1, 2, 3, 5, 10, 15, 20, 30, 50, 100, 200, 300, and 500 years. A sample of such inventory data is given in Table A.1.

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TABLE A.1 Sample Radionuclide Inventory (Variations in Radioactivity for Significant Activation- and Fission-Product Nuclides as a Function of Time Since Discharge) [a]

Isotope [b]	Concentration (Ci/MTIHM) at Time Since Discharge							
	1 yr	5 yr	10 yr	20 yr	30 yr	50 yr	100 yr	500 yr
Hydrogen-3	7.03×10^{2}	5.62×10^{2}	4.25×10^{2}	2.42×10^{2}	1.38×10^{2}	4.50×10^{1}	0.0	0.0
Carbon-14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.13
Iron-55	2.50×10^{3}	8.61×10^{2}	2.27×10^{2}	0.0	0.0	0.0	0.0	0.0
Cobalt-60	7.29×10^{3}	4.31×10^{3}	2.23×10^{3}	5.99×10^{2}	1.61×10^{2}	0.0	0.0	0.0
Nickel-59	0.0	0.0×	0.0	0.0	0.0	0.0	0.0	2.50
Nickel-63	4.12×10^{2}	4.00×10^{2}	3.85×10^{6}	3.57×10^{2}	3.31×10^{2}	2.85×10^{2}	1.96×10^{2}	9.60
Selenium-79	0.0	0.0	0.0	0.0	0.0	0.0	0.0	$3\,70 \times 10^{-1}$
Krypton-85	8.03×10^{3}	6.20×10^{3}	4.49×10^{3}	2.35×10^{3}	1.23×10^{3}	3.38×10^{2}	1.33×10^{1}	0.0
Strontium-89	5.24×10^{3}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Strontium-90	6.56×10^{4}	5.96×10^{4}	5.29×10^{4}	4.17×10^{4}	3.29×10^{4}	2.04×10^{4}	6.21×10^{3}	4.56×10^{-1}
Yttrium-90	6.56×10^{4}	5.96×10^{4}	5.29×10^{4}	4.17×10^{4}	3.29×10^{4}	2.04×10^{4}	6.22×10^{3}	4.56×10^{-1}
Yttrium-91	1.36×10^{4}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zirconium-93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.92
Zirconium-95	2.84×10^{4}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Niobium-93m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.82
Niobium-94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.09×10^{-1}
Niobium-95	6.38×10^{4}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Technetium-99	0.0	0.0	0.0	0.0	0.0	1.21×10^{1}	1.21×10^{1}	1.21×10^{1}
Ruthenium-103	2.25×10^{3}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ruthenium-106	2.36×10^{5}	1.51×10^{4}	4.84×10^{2}	0.0	0.0	0.0	0.0	0.0
Rhodium-103m	2.03×10^{3}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rhodium-106	2.36×10^{5}	1.51×10^{4}	4.84×10^{2}	0.0	0.0	0.0	0.0	0.0
Silver-110m	1.15×10^{3}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tin-119m	2.04×10^{3}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tin-123	4.92×10^{2}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tin-126	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.82×10^{-1}
Antimony-125	1.10×10^{4}	4.03×10^{3}	1.15×10^{3}	9.43×10^{1}	0.0	0.0	0.0	0.0
Antimony-126m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.82×10^{-1}
Tellurium-125m	2.67×10^{3}	9.83×10^{2}	2.81×10^{2}	0.0	0.0	0.0	0.0	0.0
Tellurium-127	1.25×10^{3}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tellurium-127m	1.28×10^{3}	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE A.1 (Cont.)

Isotope[b]	Concentration (Ci/MTIHM) at Time Since Discharge							
	1 yr	5 yr	10 yr	20 yr	30 yr	50 yr	100 yr	500 yr
Cesium-134	9.43×10^{4}	2.46×10^{4}	4.58×10^{3}	1.59×10^{2}	0.0	0.0	0.0	0.0
Cesium-135	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.55×10^{-1}
Cesium-137	9.19×10^{4}	8.38×10^{4}	7.47×10^{4}	5.93×10^{4}	4.70×10^{4}	2.96×10^{4}	9.33×10^{3}	9.04×10^{-1}
Barium-137m	8.70×10^{4}	7.93×10^{4}	7.07×10^{4}	5.61×10^{4}	4.45×10^{4}	2.80×10^{4}	8.83×10^{3}	8.55×10^{-1}
Cerium-141	6.10×10^{2}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cerium-144	4.19×10^{5}	1.19×10^{4}	1.38×10^{2}	0.0	0.0	0.0	0.0	0.0
Praseodymium-144	4.19×10^{5}	1.19×10^{4}	1.38×10^{2}	0.0	0.0	0.0	0.0	0.0
Praseodymium-144m	5.03×10^{3}	1.43×10^{2}	0.0	0.0	0.0	0.0	0.0	0.0
PM-147	9.89×10^{4}	3.44×10^{4}	9.17×10^{3}	6.53×10^{2}	4.65×10^{1}	0.0	0.0	0.0
Samarium-151	3.55×10^{2}	3.44×10^{2}	3.31×10^{2}	3.06×10^{2}	2.84×10^{2}	2.43×10^{2}	1.65×10^{2}	7.60
Europium-154	7.04×10^{3}	5.10×10^{3}	3.41×10^{3}	1.52×10^{3}	6.79×10^{2}	1.36×10^{2}	0.0	0.0
Europium-155	4.31×10^{3}	2.46×10^{3}	1.22×10^{3}	3.03×10^{2}	7.48×10^{1}	0.0	0.0	0.0
Thorium-234	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.19×10^{-1}
Protactinum-233	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.32×10^{-1}
Protactinium-234m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.19×10^{-1}
Uranium-234	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.84
Uranium-238	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.19×10^{-1}
Neptunium-237	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.32×10^{-1}
Neptunium-239	0.0	0.0	0.0	0.0	0.0	1.40×10^{1}	1.40×10^{1}	1.35×10^{1}
Plutonium-238	2.06×10^{3}	2.03×10^{3}	1.95×10^{3}	1.81×10^{3}	1.67×10^{3}	1.43×10^{3}	9.64×10^{2}	4.30×10^{1}
Plutonium-239	3.20×10^{2}	3.20×10^{2}	3.20×10^{2}	3.20×10^{2}	3.20×10^{2}	3.20×10^{2}	3.19×10^{2}	3.16×10^{2}
Plutonium-240	4.46×10^{2}	4.47×10^{2}	4.47×10^{2}	4.47×10^{2}	4.48×10^{2}	4.47×10^{2}	4.45×10^{2}	4.27×10^{2}
Plutonium-241	1.13×10^{5}	9.31×10^{4}	7.31×10^{4}	4.52×10^{4}	2.79×10^{4}	1.07×10^{4}	9.61×10^{2}	0.0
Plutonium-242	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.50

TABLE A.1 (Cont.)

Isotope[b]	Concentration (Ci/MTIHM) at Time Since Discharge							
	1 yr	5 yr	10 yr	20 yr	30 yr	50 yr	100 yr	500 yr
Americium-241	3.07×10^{2}	9.61×10^{2}	1.61×10^{3}	2.51×10^{3}	3.04×10^{3}	3.51×10^{3}	3.55×10^{3}	1.88×10^{3}
Americium-242	0.0	0.0	0.0	0.0	0.0	0.0	9.01	1.45
Americium-242m	0.0	0.0	0.0	0.0	0.0	0.0	9.05	1.46
Americium-243	0.0	0.0	0.0	0.0	0.0	1.40×10^{1}	1.40×10^{1}	1.40×10^{1}
Curium-242	7.48×10^{3}	0.0	0.0	0.0	0.0	0.0	7.45	1.20
Curium-244	1.43×10^{3}	1.22×10^{3}	1.01×10^{3}	6.89×10^{2}	4.70×10^{2}	2.18×10^{2}	3.22×10^{1}	0.0
TOTAL	2.11×10^{6}	5.19×10^{5}	3.59×105	2.56×10^{5}	1.94×10^{5}	1.16×10^{5}	3.73×10^{4}	2.75×10^{3}

[a] Discharge from a 33,000-MWd/MTIHM PWR.

[b] Nuclides contributing greater than 0.01% are listed.

Source: DOE (1992).

APPENDIX B:

METHOD FOR ADJUSTING CASK EXTERNAL DOSE RATES RELATIVE TO CASK DIMENSIONS

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FIGURE

B.1 Schematic Diagram Correlating Doses to Cask Dimensions B-6

APPENDIX B:

METHOD FOR ADJUSTING CASK EXTERNAL DOSE RATES RELATIVE TO CASK DIMENSIONS

This appendix describes a method developed for adjusting the cask external dose rates when different cask dimensions are used in place of a reference cask.

B.1 FORMULATION

In this method, the radiation source from the cask is approximated by a uniform surface-source cylinder characterized by a radius R and length L and a surface source strength S_a, as shown in Figure B.1. For a receptor P located at a distance r from the centerline of the cask (Figure B.1), the radiation (neutron or gamma) flux f at the receptor can be calculated by (Jaeger 1968)

$$\phi(r) = \frac{2S_a R}{R+r} F(\psi, k) \ , \tag{B.1}$$

where

$$\psi = \tan^{-1}\left(\frac{L/2}{r-R}\right) , \tag{B.2}$$

$$k = \frac{2(rR)^{1/2}}{(r+R)} \ , \text{and} \tag{B.3}$$

$$F(\psi,k) = \int_0^{\psi} \left(1 - k^2 \sin^2\theta\right)^{-1/2} d\theta \ , \tag{B.4}$$

where ψ is the angle subtended by the centerline and the edge of the cask, as viewed by the receptor (Figure B.1); L equals the length of the cask; R equals the radius of the cask; and r equals the distance of the receptor measured from the center of the cask.

B.2 DOSE RATE CONVERSION

In the above calculations, it is assumed that the dose rate is directly proportional to the flux at the receptor. If K_0 is the flux-to-dose-rate conversion factor, then the dose rate at receptor P is approximated by

$$\dot{D}(r) = K_0 \ \Phi(r) \ . \tag{B.5}$$

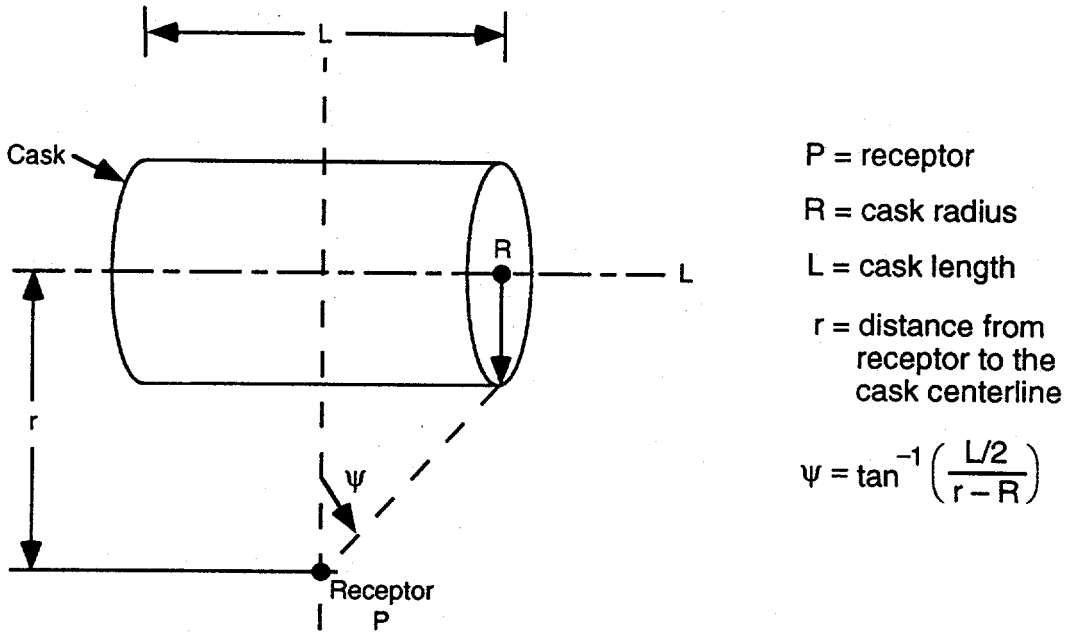

FIGURE B.1 Schematic Diagram Correlating Doses to Cask Dimensions

If $\dot{D}_0(r)$ represents the dose rate at r for the reference cask with dimensions R_0 and L_0, and $\dot{D}_1(r)$ represents the dose rate at r for a new cask with dimensions R_1 and L_1, the adjusted dose rate will be $\dot{D}_1$ because of the dimension changes. The dose rates at the reference distance (D, 1 m or 2 m) for both casks are assumed to be equal to the dose rate input by the user. The reference distance includes the offset of the cask's outer surface from the transport vehicle outer lateral surface. From Equation B.1, the following equations can be derived:

$$\dot{D}_0\,(R_0 + D) = \frac{S_{a0}\,R_0\,K_0}{(2R_0 + D)}\,F\left(\psi_{0D}, k_{0D}\right) \tag{B.6}$$

and

$$\dot{D}_1\,(R_1 + D) = \frac{S_{a1}\,R_1\,K_0}{2R_1 + D}\,F\,(\psi_{1D}, k_{1D})\ , \tag{B.7}$$

where

$$\psi_{0D} = \tan^{-1}\left(L_0 / 2D\right)\ , \tag{B.8}$$

$$\psi_{1D} = \tan^{-1}\left(L_1 / 2D\right)\ , \tag{B.9}$$

$$k_{0D} = \frac{2\left[\left(R_0 + D\right) R_0\right]^{1/2}}{\left(2R_0 + D\right)}\ , \text{and} \tag{B.10}$$

$$k_{1D} = \frac{2\left[\left(R_1 + D\right) R_1\right]^{1/2}}{\left(2R_1 + D\right)} , \tag{B.11}$$

where ψ and k are evaluated at the reference distance from the surfaces of the two casks.

Thus, the dose rate at a distance d from the surfaces of the two casks is

$$\dot{D}_0\left(d + R_0\right) = \frac{S_{a0}\, R_0\, K_0}{d + 2R_0}\, F\left(\psi_0, k_0\right) \tag{B.12}$$

and

$$\dot{D}_1\left(d + R_1\right) = \frac{S_{a1}\, R_1\, K_0}{d + 2R_1}\, \mathrm{F}\left(\psi_1, k_1\right) , \tag{B.13}$$

where

$$\psi = \tan^{-1}\left(\frac{L_0}{2d}\right) , \tag{B.14}$$

$$\psi_1 = \tan^{-1}\left(\frac{L_1}{2d}\right) , \tag{B.15}$$

$$k_0 = \frac{2\left[\left(R_0 + d\right) R_0\right]^{1/2}}{\left(2R_0 + d\right)} , \text{ and} \tag{B.16}$$

$$k_1 = \frac{2\left[\left(R_1 + d\right) R_1\right]^{1/2}}{\left(2R_1 + d\right)} . \tag{B.17}$$

B.3 DOSE RATE ADJUSTMENT

By using the relationship of S_{a0} and S_{a1} from Equations B.6 and B.7, $\dot{D}_0\left(R_0+D\right) = \dot{D}_1\left(R_1+D\right)$, and substituting Equations B.12 and B.13, the ratio $Q(d)$ of the dose rates at a distance d meters from the surfaces of the two casks becomes

$$Q(d) = \frac{\dot{D}_1\left(d + R_0\right)}{\dot{D}_0\left(d + R_1\right)} \tag{B.18}$$

$$Q(d) = \frac{\left(2R_0 + d\right)}{\left(2R_1 + d\right)} \times \frac{F\left(\psi_1, k_1\right)}{F\left(\psi_0, k_0\right)} \times \frac{\left(2R_1 + D\right)}{\left(2R_0 + D\right)} \times \frac{F\left(\psi_{0D}, k_{0D}\right)}{F\left(\psi_{1D}, k_{1D}\right)} . \tag{B.19}$$

The ratio $Q(d)$ depends on the reference cask dimensions, R_0 and L_0, and the new cask dimensions, R_1 and L_1. The ratio $Q(d)$ can be used to adjust the dose rates obtained from

Equation 2.1 due to changes in cask dimensions. That is, the adjusted dose rate $\dot{D}_1(d)$ for a receptor at a distance d meters from the cask surface can be obtained by

$$\dot{D}_1(d) = \dot{D}_0(d)\, Q(d) \quad , \tag{B.20}$$

where $\dot{D}_0(d)$ is the known dose rate for the reference cask, and $Q(d)$ is the dose-rate ratio obtained from Equation B.19.

APPENDIX B REFERENCE

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APPENDIX C:

METHOD FOR SCREENING RADIONUCLIDES

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APPENDIX C:

METHOD FOR SCREENING RADIONUCLIDES

Spent nuclear fuels (SNFs) are usually irradiated in nuclear reactors for many hundreds of hours before they are removed for refueling. Thus, even after years of cooling, the spent fuels may still contain several hundred different radionuclides. Because it is necessary to limit the number of nuclides for each assessment when using RISKIND (up to 100 nuclides), and because not all of these radionuclides are radiologically significant in the environment, selecting radionuclides of potential importance becomes an essential task. With careful screening, the number of nuclides selected can be reduced to a manageable size without sacrificing accuracy in dose calculations. This appendix describes the process used to select radionuclides for dose calculations.

C.1 KEY PARAMETERS

The relative importance of the various radionuclides contained in SNFs is evaluated by considering (1) the quantity of each radionuclide present, (2) the fraction of each radionuclide that would be released to the atmosphere during an accident, and (3) the various exposure pathway-dependent factors. The latter includes soil-to-vegetation transfer factors, vegetation-to-meat and -milk transfer factors and human and animal food ingestion rates; the dose conversion factors for each exposure pathway; and the radionuclide decay constant and weathering removal parameter that determines how long deposited radioactive material remains on the ground. Only key parameters that are the most important in determining the relative radiological impacts to humans are considered.

The quantity of each radionuclide present in the spent fuel is dependent on characteristics such as fuel burnup, type of reactor (pressurized-water reactor [PWR] or boiling-water reactor [BWR]), and age of fuel (cooling time). Oak Ridge National Laboratory (ORNL) has compiled a spent fuel radionuclide database (Notz et al. 1987) with the ORIGEN2 code (Croff 1980). The results of the ORNL data compilation are given in the U.S. Department of Energy (DOE) report *Characteristics of Potential Repository Wastes* (DOE 1992). In RISKIND, the radionuclide source term in the spent fuel, $Q(i)$, is calculated on the basis of the user's input values for fuel burnup, type of reactor, and age of fuel.

The amount of a radionuclide that can be released to the atmosphere during an accident is usually represented by the release fraction of the total source inventory in the cask. Because the amount of radioactivity that could be released to the atmosphere is highly dependent on the severity of the accident, accurate calculation of doses requires that this value be determined for each accident scenario. In the RISKIND code, the screening process is calculated for each of the 20 cask response regions defined in the U.S. Nuclear Regulatory Commission (NRC) modal

study (Lawrence Livermore National Laboratory [LLNL] 1987). For convenience, radionuclides are grouped by physical and chemical behavior: particulates; ruthenium, cesium, and iodine isotopes; and noble or inert gases. The release parameters for these five types of radionuclides have been discussed in Section 3.2 of this document.

C.2 PATHWAY CONSIDERATIONS

In RISKIND, three pathways that would lead to human exposure following atmospheric release of radionuclides are used to determine the relative health hazards of one radionuclide versus others in the shipping cask. The first pathway (I) is the short-term exposure from air immersion and inhalation during plume passage; it is used to determine the relative importance of nuclides in causing individual doses from the passing plume. The second pathway (II) is the long-term external radiation exposure from contaminated ground; it is used to screen each nuclide's relative importance with respect to the long-term hazard of residing on the contaminated land. The third pathway (III) is the long-term internal radiation exposure from ingestion of contaminated foods; it is used to screen each nuclide relative to the hazard from eating or drinking contaminated food products and water.

C.3 SCREENING PARAMETERS

The dose received from pathway I at a particular location from radionuclide i can be expressed as

$$DI(i) = \sum_{j=1,2} DFI(i,j)\, Q(i)\, RS(i)\, \overline{C}_a(i) \quad , \tag{C.1}$$

where

$DI(i)$ = dose from pathway I (short-term) exposure for radionuclide i;

$DFI(i,j)$ = appropriate dose conversion factor for radionuclide i, exposure pathway j;

j = 1, for inhalation; j = 2, for air immersion;

$Q(i)$ = source inventory of radionuclide i;

$RS(i)$ = expected fraction of radionuclide i released to the atmosphere; and

$\overline{C}_a(i)$ = time-integrated air concentration factor at a reference location for radionuclide i, $\overline{C}_a(i)$ is assumed to be independent of radionuclide i, i.e., $\overline{C}_a(i) = \overline{C}_a$.

The relative importance of a radionuclide for pathway I exposure is calculated as

$$FI(i) = \frac{DI(i)}{\sum_i DI(i)} \quad . \tag{C.2}$$

Equation C.2 can be expressed as

$$FI(i) = \frac{\sum_{j=1,2} Q(i)\, RS(i)\, DFI(i,j)}{\sum_i \sum_{j=1,2} Q(i)\, RS(i)\, DFI(i,j)} \quad . \tag{C.3}$$

The dose received from pathway II (long-term external exposure from ground contamination) can be written as

$$DII(i) = DFII(i)\overline{C}_g(i) \tag{C.4}$$

$$\overline{C}_g(i) = Q(i)\, RS(i)\, \overline{C}_a(i)\, V_d(i)\, TG(i) \quad , \tag{C.5}$$

where

$DII(i)$ = dose from external exposure to ground contamination for radionuclide i;

$DFII(i)$ = dose conversion factor for ground external exposure;

$\overline{C}_g(i)$ = time-integrated ground concentration for radionuclide i;

$TG(i)$ = $\left[1 - \exp\left(-\lambda_g(i)\, T\right)\right] / \lambda_g(i)$; (C.6)

$V_d(i)$ = deposition velocity for radionuclide i;

$\lambda_g(i)$ = effective removal constant, including radioactive decay and weathering, for radionuclide i; and

T = total time period for ground external exposure (default: 50 yr).

The relative radiation hazard of a radionuclide from pathway II exposure is calculated as

$$FII(i) = \frac{DII(i)}{\sum_i DII(i)} \quad . \tag{C.7}$$

Explicitly,

$$FII(i) = \frac{Q(i)\ RS(i)\ V_d(i)\ DFII(i)\ TG(i)}{\sum_i Q(i)\ RS(i)\ V_d(i)\ DFII(i)\ TG(i)} \quad . \tag{C.8}$$

Pathway III accounts for long-term food ingestion. The amount of radioactivity ingested over time through the food pathway is difficult to assess. A simplified approach is used for screening purposes. The dose received from ingestion of food is approximated by estimating radionuclides in foodstuff via root uptake mechanisms from soil. The dose received from pathway III is approximated by

$$DIII(i) = DFIII(i)\ S_v(i)\left[F1(i) + F2(i) + F3(i)\right]\bar{C}_g(i) \tag{C.9}$$

$$F1(i) = F_b(i)\ Q_a\ U_b/\rho \tag{C.10}$$

$$F2(i) = F_m(i)\ Q_a\ U_m/\rho \tag{C.11}$$

$$F3(i) = 0.5\ U_v/\rho \ , \tag{C.12}$$

where

$DIII(i)$ = ingestion dose factor for pathway III exposure;

$DFIII(i)$ = ingestion dose conversion factor for radionuclide i;

$S_v(i)$ = soil-to-vegetation transfer factor for radionuclide i;

$F_b(i)$ = meat transfer factor for radionuclide i;

$F_m(i)$ = milk transfer factor for radionuclide i;

U_b, U_m, U_v = human food ingestion rate for meat, milk, and vegetables, respectively;

Q_a = animal pasture ingestion rate for meat cattle and milk cows; and

ρ = vegetation yield density of pastureland or a vegetable garden.

The relative importance of radionuclide i for pathway III exposure can be expressed by

$$FIII(i) = \frac{DIII(i)}{\sum_i DIII(i)} \quad . \tag{C.13}$$

Explicitly,

$$FIII(i) = \frac{DFIII(i)\, Q(i)\, RS(i)\, V_d(i)\, S_v(i) \left[F1(i) + F2(i) + F3(i)\right] TG(i)}{\sum_i DFIII(i)\, Q(i)\, RS(i)\, V_d(i)\, S_v(i) \left[F1(i) + F2(i) + F3(i)\right] TG(i)} . \quad (C.14)$$

The radionuclide selection criterion in RISKIND is based on the calculated relative importance of the values of $FI(i)$, $FII(i)$, and $FIII(i)$. The screening procedure is such that radionuclides are selected as

$$FI(i) > S, \text{ or } FII(i) > S, \text{ or } FIII(i) > S \ , \quad (C.15)$$

where S is the radionuclide selection criterion (default: 0.01, or 99%). In using RISKIND, the radionuclide selection process follows the procedures described above until the total number of selected nuclides exceeds the prescribed limit of 100. If the number of nuclides selected exceeds this limit, it is recommended that the user change the input value of S to a smaller value so that the dose calculation will cover the whole range of nuclides in the spent fuel. By selecting an appropriate S value, the number of radionuclides considered can be reduced while maintaining a high degree of accuracy in the calculated results.

The resulting impacts, which are estimated by RISKIND with the radionuclides selected with a particular value of the radionuclide selection criterion, will not exactly match the accuracy specified by the criterion. The selection criterion is only an approximate value since the radionuclides are selected on the basis of general principles and not on the actual calculations used. To ensure a given accuracy, the selection criterion should be set to a lower value. For example, S should be set to 0.001 (99.9%) to ensure that 99% of the estimated dose is reported.

APPENDIX C REFERENCES

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APPENDIX D:

METHOD FOR ESTIMATING THE SPALLATION OF CRUD MATERIAL

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APPENDIX D:

METHOD FOR ESTIMATING THE SPALLATION OF CRUD MATERIAL

This appendix describes the method used to estimate the amount of crud material that could be released from a shipping cask during a transportation accident. The method follows that described in a recent Sandia National Laboratory report by Sandoval et al. (1991). During shipment, crud may spall from the rods, become airborne in the cask cavity, and be released to the environment should a leak path develop in the cask containment system. Because of the sparsity of experimental data on (1) crud activity levels, (2) crud spallation fractions from the fuel rods, and (3) the resulting particle size distributions of the spalled crud necessary for estimating airborne fractions, the results presented in Sandoval et al. (1991) are of limited use and are upper bound estimates. Further experimental and analytical analyses are required for a more accurate prediction of crud release.

D.1 CHARACTERISTICS OF CRUD

Crud is a mixture of reactor primary cooling system corrosion products that have deposited on fuel rod surfaces. These deposits contain neutron-activated nuclides and may also contain fissile particles and fission products. Limited studies suggest that deposits on assembly skeletons are similar to, if not the same, as on the fuel rods themselves.

Two types of crud are observed. Some crud can be easily removed from the fuel rod with a soft brush. This flocculent form is the dominant one found on boiling-water reactor (BWR) fuel rods and was noted to constitute approximately 65% of the crud samples removed from a set of BWR fuel rods (Asay and Blok 1978). This easily removed crud is mostly hematite (Fe_2O_3), generally of a porous, hydrated nature. The other form of crud is more tenacious, usually found on pressurized-water reactor (PWR) fuel rods, and is not readily removed from the fuel rods. This latter form is composed of crystalline oxides, mainly a nickel-substituted spinel ($Ni_xFe_{3-x}O_4$). These two types of crud usually develop in layers and may form a sandwich-like structure. The differences between the two types of fuel rods have been attributed to different oxygen levels in the primary coolant water of the two reactor types (Strasser et al. 1985). Rods currently being discharged from reactors tend to have less crud than before because of better control of the reactor coolant chemistry. Even in the past, most fuel rods were visually observed to have little or no crud. Those rods without visual crud deposits are expected to have a thin crud film, because iron has been detected on the surface of some fuel rods without visual amounts of crud. Table D.1 summarizes the general characteristics of crud found on BWR and PWR fuel rods.

TABLE D.1 General Crud Characteristics[a]

Feature	PWR	BWR
Color	Gray, reddish orange, brown, tan, black, reddish brown	Orange, brown, reddish brown
Thickness		
Maximum[b]	4 mil	10 mil
Average[c]	<1 mil	1 to 3 mil
Peak to average axial variation	≈2	≈2
Chemical composition		
Major elements	Ni, Fe, Cr	Ni, Fe, Cr, Cu
Ni/Fe ratio	<1	<<<1 or >1
Structure	$Ni_xFe_{3-x}O_4$	Fe_2O_3, NiO
Axial variation	≈2	≈2
Radioactivity		
Maximum observed Co-60 (μCi/cm^2)	140	1,250
Range of Co-60 (μCi/cm^2)[d]	0.1 to 140	11 to 1,250
Major component after 10 years	Co-60	Co-60

[a] Co = cobalt, Cr = chromium, Cu = copper, Fe = iron, Fe_2O_3 = hematite, Ni = nickel, $Ni_xFe_{3-x}O_4$ = nickel-substituted spinel, and NiO = nickel oxide.

[b] Maximum thickness measured on any rod regardless of location.

[c] Average of all the maximum thicknesses measured.

[d] Maximum densities observed.

Source: Sandoval et al. (1991).

D.2 CRUD INVENTORY

The total crud inventory inside a shipping cask is the product of the total surface area of the fuel rods and the crud surface activity density. The total surface area of the fuel rods inside a cask is a function of the cask design, the number of fuel assemblies, and the type of fuel. Table D.2 presents the total surface area of the cask cavity and the number and type of fuel rods normally shipped in currently used casks. The default value for cask cavity surface area used in RISKIND is for the NLI-1/2 truck cask or for the IF-300 rail cask, depending on the transportation mode selected.

TABLE D.2 Current Cask and Fuel Assembly Design Parameters[a]

Cask Type	Fuel Type	V (m^3)	A_t (m^2)	N_a
NLI-1/2	PWR	0.155	39.0	1
NLI-1/2	BWR	0.129	26.7	2
TN-8[b]	PWR	0.151	37.0	3
TN-9[b]	BWR	0.070	13.6	7
NAC-1/NFS-4	PWR	0.257	39.5	1
NAC-1/NFS-4	BWR	0.268	27.2	2
IF-300	PWR	2.32	251.6	7
IF-300	BWR	2.34	209.5	18
NLI-10/24	PWR	3.27	357.4	10
NLI-10/24	BWR	3.27	227.6	24

[a] V = void volume of loaded cask; A_t = total surface area of cask cavity, including fuel rods; and N_a = number of assemblies that can be shipped in cask.

[b] TN-8 has three compartments; TN-9 has seven compartments; values given are per compartment.

Source: Sandoval et al. (1991).

The crud surface activity density, as discussed in Sandoval et al. (1991), is a function of fuel type, fuel age, isotope composition, and reactor system chemistry. Sufficient data are not available to completely specify the crud activity characteristics for each type of fuel. Therefore, the conservatively estimated average maximum surface activity densities measured on the fuel rods and tabulated in Sandoval et al. (1991) are used by RISKIND for estimating the total crud inventory in a cask. Table D.1 lists the range of crud activity densities found on spent fuel rods. Because these density values are the maximums found on the fuel rods analyzed, many rods will have substantially lower values, particularly since most rods in the studies analyzed were chosen because of abnormal operating conditions, poor water chemistry, or heavy visual deposits of crud. In addition, the average activity density for a given fuel rod will be much less than the reported maximum spot density. Axially averaged values of 18 and 235 $\mu Ci/cm^2$ for PWR and BWR maximum spot densities of 140 and 1,250 $\mu Ci/cm^2$, respectively, are used as defaults in RISKIND.

The surface activity value input to RISKIND is adjusted by the decay of cobalt-60, according to the age of the fuel in the cask at the time of the accident. It is assumed that the total crud activity can be attributed to cobalt-60 because it accounts for 99% of the activity at 8 years from fuel discharge for PWR fuel, and 98% of the activity at 5 years from fuel discharge for

BWR fuel. The other isotopes commonly found in crud material are not considered because of their small concentrations after the initial few years following discharge, primarily because of their short half-lives (Table D.3). However, if fresh spent fuel is considered, isotopes such as cobalt-58 and manganese-54 should be considered. Table D.4 lists maximum activity densities measured for the different isotopes on both BWR and PWR fuel rods. Again, these are maximum spot densities on fuel rods with quantifiable amounts of crud material. The majority of fuel rods will contain much lower levels of crud.

D.3 CRUD RELEASE

The maximum amount of crud-borne activity that could be released to the environment because of a breach in the integrity of the shipping cask is the total crud inventory in the cask. For crud to be released, it must spall from the fuel rods, remain airborne, and pass through a leak path (breach in the cask confinement) to the environment.

Crud can spall from the fuel rods as a result of mechanical force on the rods or from expansion of the rods from heating (i.e., a fire). Because of insufficient data on crud particle spallation due to impact- or shock-related force on the cask during transport, spallation fractions of 1.0 were conservatively assumed by Sandoval et al. (1991) for all impact-related releases. Such a value may significantly overestimate the amount spalled from PWR fuel rods where the more tenacious form of crud dominates. In RISKIND, a spallation fraction of 1.0 is also assumed for all levels of mechanical loads above 0.2% strain because of lack of data. A spallation fraction of 0.15 was estimated as the upper bound for crud particle spallation fractions for the regulatory fire accident condition (30-minute exposure to a fire of approximately 1,100 K [1,500°F]). This value is assumed for all levels of thermal loads above a 530 K (500°F) lead midlayer thickness temperature. Table D.5 gives the default values of the spallation fraction assumed for the 20 accident response regions.

If crud is to be released during a transportation accident, it must remain airborne once it has spalled off the fuel rods in order to pass through a potential leak path to the environment. The ability of the crud to remain airborne once it has spalled from the fuel rods depends on its particle size distribution. Very little information is available for crud particle size distribution on BWR fuel and none is available for PWR fuel. No data are available on the particle size distribution of the spalled crud. In RISKIND, all of the spalled crud material is conservatively assumed to be released to the environment for all U.S. Nuclear Regulatory Commission (NRC) modal study response regions (Lawrence Livermore National Laboratory [LLNL 1987]) except region R(1,1), for which no release is assumed because no leak path has been identified (see Section 3.1). A number of attenuation mechanisms can significantly mitigate this source term. These include deposition and gravitational settling of the particulates during transport from their point of origin to a breach point in the shipping package, the mode and duration of the driving

TABLE D.3 Radionuclides Found in Crud[a]

Parent	Radionuclide	Half-Life, $t_{1/2}$ (days)
Cr-50	Cr-51	27.7
	Nb-95	35
Fe-58	Fe-59	44.6
	Sb-124	60.2
	Zr-95	64
Ni-58	Co-58	70.8
	Sn-113	115
Zn-64	Zn-65	244
Fe-54	Mn-54	312
	Sb-125	996
Co-59	Co-60	1,935

[a] Mn = manganese, Nb = niobium, Sb = antimony, Sn = tin, Zn = zinc and Zr = zirconium.

Source: Sandoval et al. (1991).

TABLE D.4 Maximum Radioisotope Activity Density (corrected to fuel discharge)

Reactor	Co-50	Co-60	Mn-54	Cr-51	Fe-59	Zr-95	Sb-125	Zn-65
PWR (μCi/cm^2)								
Yankee Rowe	1,400	140	380	240	300			
B&W Reactors [ZI78]	400	100		170	30	1		
Oconee 1	42	10	2					
Point Beach 1	13	2	2	16	2			
Benzau 1	215	16	13	391	25			
Zion 1 EOC-3 Grid 6/7	346	73	43	127	25	36		
H. B. Robinson		19	1					
BWR (μCi/cm^2)								
Peach Bottom		11	5					
Monticello	21	350	57		48	58		121
Tsuruga		1,250	625					
Millstone 1	63	595	85	35	87			25
GE Reactors	50	180	90	80				

Source: Sandoval et al. (1991).

TABLE D.5 Spallation Values for NRC Modal Study Cask Response Regions

Response Region	Spallation Fraction	Response Region	Spallation Fraction
1	0.15	11	1
2	1	12	1
3	1	13	0.15
4	1	14	1
5	0.15	15	1
6	1	16	1
7	1	17	0.15
8	1	18	1
9	0.15	19	1
10	1	20	1

force that affects such transport, and the possibility that the spalled crud particles themselves could plug the leak path.

APPENDIX D REFERENCES

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APPENDIX E:

METHOD FOR ESTIMATING CASK RESPONSE FROM USER-SPECIFIED ACCIDENT SCENARIOS

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APPENDIX E:

METHOD FOR ESTIMATING CASK RESPONSE FROM USER-SPECIFIED ACCIDENT SCENARIOS

In a shipping accident involving spent nuclear fuel, mechanical or thermal cask response, or both, can be generated and the cask can be damaged. The response depends on many factors described in the modal study of the U.S. Nuclear Regulatory Commission (Lawrence Livermore National Laboratory [LLNL] 1987). Such factors include the mechanical loadings generated by the accident impact velocity and the object that is struck and, in the event of a fire, the thermal loadings generated by flame temperature and duration of the fire. This appendix describes the subroutine implemented in RISKIND to determine the magnitude of the cask response on the basis of user-specified accident scenarios. The subroutine incorporates the parameters developed for the reference casks in the modal study. Because the response can be different for various cask designs subjected to the same accident conditions, reevaluation of the cask response may be necessary for a more accurate assessment of the potential radiation hazards when cask designs significantly different from those of the reference casks are involved. In the modal study, an analytical method based on various computer codes was used to estimate cask responses. These computer codes have been benchmarked or validated against experimental data.[1]

Two representative cask designs were developed in the modal study (LLNL 1987): one for truck shipments and the other for rail shipments of spent fuel. The configurations of these representative casks are shown in Figure E.1 for a truck cask and Figure E.2 for a rail cask. The truck cask is designed to allow for transport of a single pressurized-water reactor (PWR) fuel assembly; the rail cask capacity is 21 PWR fuel assemblies. Detailed descriptions of the designs are provided in the modal study (LLNL 1987).

The cask response state during an accident is categorized in terms of the magnitude of the mechanical and thermal loads that could be received by a spent fuel cask. Both loads generate response states for a cask that could result in damage to the cask and the release of radioactive material. Because specific mechanical and thermal loading conditions can affect the cask under a variety of accident conditions, identifying the loading parameters is an essential task.

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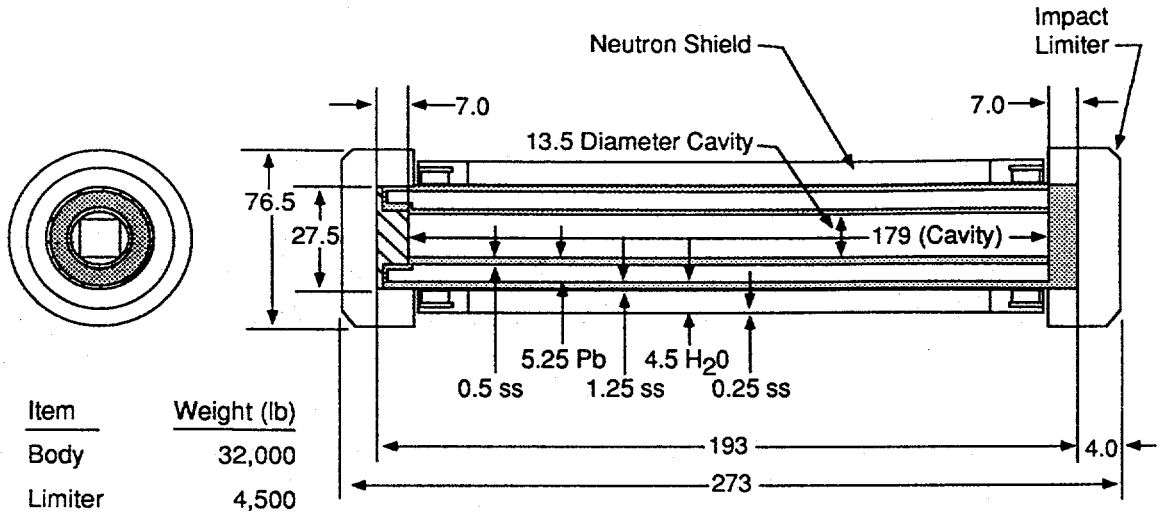
[1] The RISKIND program uses SI units (km/h and K) in the user interface for consistency across all models. However, the model and algorithms in the modal study (LLNL 1987) use units of mph for speed and °F for temperature to determine the accident response region. Both sets of units are provided in this appendix for the user's convenience.

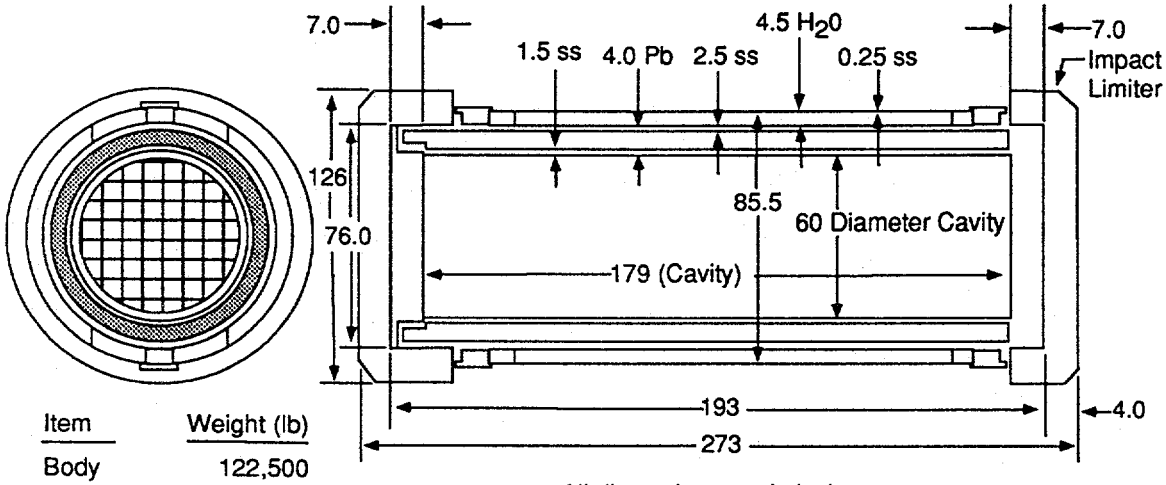


Item	Weight (lb)
Body	32,000
Limiter	4,500
Contents	2,500
	39,000

All dimensions are in inches.

Pb = Lead
H_2O = Water
SS = Stainless Steel

FIGURE E.1 Representative Truck Cask Design Used for Dynamic Structural and Thermal Response Studies (Source: Modified from LLNL 1987)



Item	Weight (lb)
Body	122,500
Limiter	22,500
Contents	52,000
	197,000

All dimensions are in inches.

Pb = Lead
H_2O = Water
SS = Stainless Steel

FIGURE E.2 Representative Rail Cask Design Used for Dynamic Structural and Thermal Response Studies (Source: Modified from LLNL 1987)

E.1 MECHANICAL LOADS

The dominant mechanical loads have been identified as the forces on the cask caused by impact with a surface or hard object. Three major accident parameters have been identified that affect the cask mechanical response and may cause damage: (1) impact velocity, (2) orientation of the cask, and (3) hardness of the object impacted.

The impact velocity depends on the relative velocity of the cask and the angle of impact with respect to the object impacted. The relative velocity is the velocity of the cask relative to the impact object at the time of impact. The impact angle (α) is the angle between the cask velocity (direction along which the cask is traveling) and the plane of the surface struck. The impact velocity can be calculated as

$$\textit{Impact velocity} = \textit{Cask velocity} \times \sin \alpha \ . \qquad \text{(E.1)}$$

The cask orientation angle (β) is the angle between the cask's longitudinal axis and the impact surface; Figure E.3 shows the interrelationship of these accident parameters. The impact on a surface with a 0° cask orientation constitutes a sidewise impact, whereas a 90° cask orientation constitutes an endwise impact.

The object hardness is the hardness of the object impacted during the accident. Four increasing levels of object hardness are categorized in the modal study (LLNL 1987): very soft (water), soft (tillable soil), medium (hard soil/soft rock), and unyielding (hard rock).

The strain on the inner shell of the shipping cask was selected as the single parameter in the modal study (LLNL 1987) to characterize mechanical load response states. The relationships between the strain and various accident parameters such as cask velocity, impact angle, cask orientation, and object hardness were investigated extensively. Three discrete levels of maximum strain on the inner shell were used to relate ranges of response states and mechanical loads to potential radiological hazards: 0.2% (elastic), 2% (plastic), and 30% (plastic) strain at the inner shell. The relationship between strain and impact velocity has been developed for various object hardnesses and cask orientations. The impact velocities required to reach the three discrete levels of maximum strain on the inner shell for the representative truck and rail casks are given in Table E.1. By using the bounding impact velocities for various cask orientations and impact surfaces, the response regions for the representative truck and rail casks can be determined by interpolation for any combination of impact velocity, cask orientation, and impact hardness.

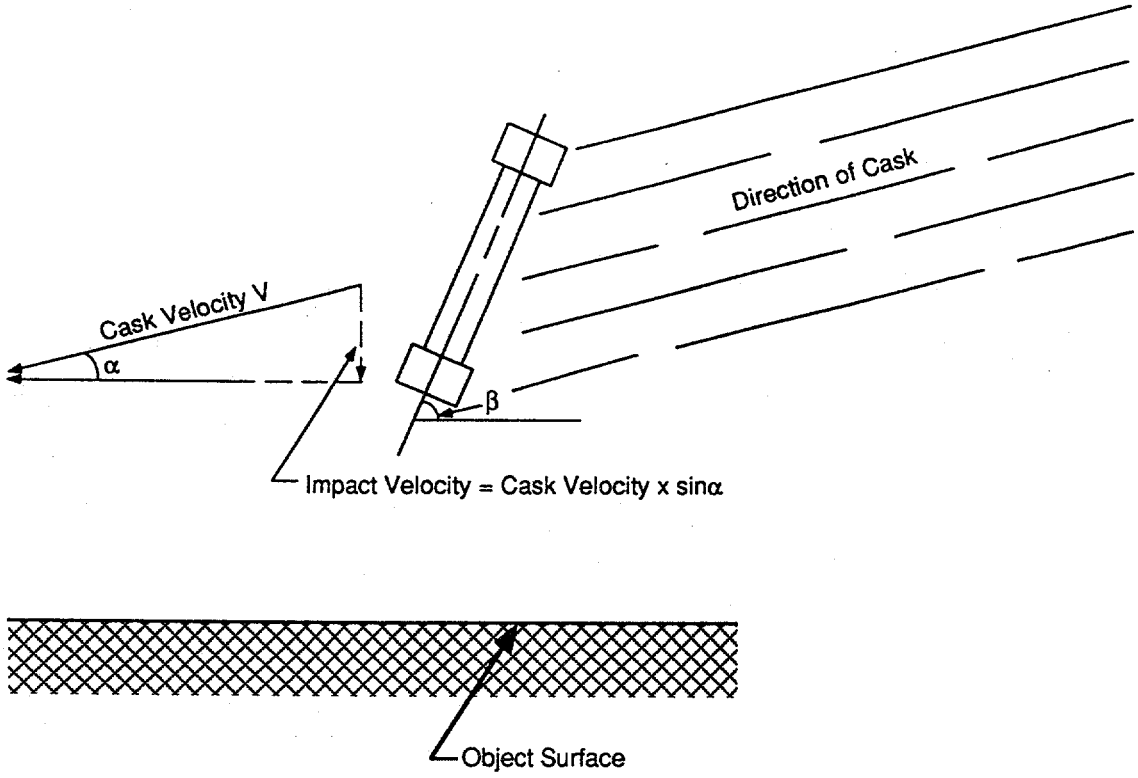


FIGURE E.3 Three Impact Loading Parameters Considered in the Response Analysis for Impacts on Surfaces (Modified from LLNL 1987, Figure 2.1)

E.2 THERMAL LOADS

The temperature at the midlayer thickness of the lead shield (lead is the material assumed for the reference cask) was selected in the modal study as the appropriate parameter for characterizing thermal load response states. This temperature can be related to three accident parameters: fire duration, fire location, and flame temperature. Fire duration is the duration of the fire during the accident. Flame temperature, which usually ranges from 1,030 to 1,590 K (1,400 to 2,400°F), is dependent on the burning materials and the amount of oxygen present in the flame. Fire location is determined by the relative distance from the fire to the cask. Fire location has been found to be an important factor in determining the thermal load. The heat load received by the cask can decrease by a factor of 4 for a fire 6 m (20 ft) from the cask, compared with the heat load for an engulfing fire.

For casks with lead shielding, four discrete temperature response levels — 530, 590, 616, and 839 K (500, 600, 650, and 1,050°F) — are used to characterize the ranges of thermal response states and, therefore, the release potentials. The fire durations required to reach these four response states for a 1,200 K (1,700 F) engulfing fire were estimated in the modal study (LLNL 1987). Table E.2 shows the results of the required fire durations for the 1,200 K

TABLE E.1 Impact Velocities Required to Attain 0.2%, 2%, and 30% Strain Levels for Objects Impacted in Highway and Railway Accidents

Accident Type/ Object Hardness	Impact Velocity (km/h) at Various Strain Levels and Orientation Angles								
	0.2% Strain at Three Angles			2% Strain at Three Angles			30% Strain at Three Angles		
	0°	45°	90°	0°	45°	90°	0°	45°	90°
Highway									
Unyielding	51.5 (32)	56.3 (35)	61.1(38)	82.1 (51)	78.8 (49)	74.0 (46)	>241(>150)	182 (113)	122 (76)
Median	51.5 (32)	56.3 (35)	61.1(38)	82.1 (51)	78.8 (49)	74.0 (46)	241(>150)	241 (>150)	241(>150)
Soft	51.5(32)	933 (58)	135 (84)	82.1 (51)	163 (101)	241(>150)	241(>150)	241 (>150)	241(>150)
Very soft	67.6 (42)	>241(>150)	61.1 (38)	94.9 (59)	241(>150)	103 (64)	241(>150)	241 (>150)	241(>150)
Railway									
Unyielding	88.5 (55)	75.6 (47)	61.1 (38)	116 (72)	(96.5) 60	77.2 (48)	241(>150)	206 (128)	169 (105)
Median	88.5 (55)	75.6 (47)	61.1 (38)	116 (72)	(96.5) 60	77.2 (48)	241(>150)	206 (128)	169 (105)
Soft	88.5 (55)	75.6 (47)	64.4 (40)	116 (72)	111 (69)	105 (65)	241(>150)	241 (>150)	241(>150)
Very soft	88.5 (55)	>241(>150)	61.1 (38)	116 (72)	241(>150)	96.5 (60)	241(>150)	241 (>150)	241(>150)

[a] In the modal study (LLNL 1987), 150 mph (241 km/h) is defined as the maximum credible velocity. Numbers in parentheses indicate mph.

Source: LLNL (1987).

(1,700°F) engulfing fire to reach the four lead midlayer thickness temperatures. The response states for fires that deviate from the 1,200 K (1,700°F) engulfing fire were examined in the modal study; the approach developed in that study to extrapolate the fire duration results estimated for the 1,200 K (1,700°F) engulfing fire is presented in the following paragraphs.

TABLE E.2 Fire Duration Required to Reach the Four Levels of Lead Midlayer Thickness Temperatures for a 1,200 K (1,700°F) Engulfing Fire

Temperature		Duration (h)	
(K)	(°F)	Truck Cask	Rail Cask
530	500	1.1	1.2
590	600	1.4	1.8
616	650	2.1	2.7
839	1,050	3.3	5.1

Source: LLNL (1987).

For a given fire scenario, the thermal response represented by the lead midlayer thickness temperature can be related to the fire duration, flame temperature, and fire location. The general equation developed in the modal study to extrapolate the thermal response of the 1,200 K (1,700°F) engulfing fire to any other fire scenario is expressed as

$$d_F(t,l) = \delta(t)\,\delta(l)\,d_F(1{,}700°\text{F}) \quad , \tag{E.2}$$

where $d_F(t,l)$ is the fire duration corresponding to a lead midlayer thickness temperature (°F) for flame temperature t and fire location l. The temperature multiplication factor, $\delta(t)$, is used to estimate the relative fire duration required for a flame temperature t to match a 1,200 K (1,700°F) fire on the basis of thermal response measured in terms of lead midlayer thickness temperature. Values of $\delta(t)$ provided in the modal study are given in Table E.3. The distance multiplication factor, $\delta(l)$, is used to extrapolate the results of thermal response computed for the engulfing fire (distance $l = 0$) to the away-from-the-cask fire (distance = l). For the representative truck cask, $\delta(l)$ is expressed as

$$\delta(l) = 0.78 \exp(0.7732 + 0.06287\,l) \quad \textit{for} \quad l > 1.5 \text{ ft.} \tag{E.3}$$

For the representative rail cask, $\delta(l)$ is expressed as

$$\delta(l) = 0.78 \exp(0.62874 + 0.08471\,l) \quad \textit{for } l > 4 \text{ ft.} \tag{E.4}$$

E.3 DETERMINATION OF RESPONSE REGIONS

Cask responses during a transportation accident depend on the containment vessel strain and the lead midlayer thickness temperature. The potential responses have been partitioned into 20 response regions $R(i,j)$ (i = 1,2,3,4; j = 1,2,3,4,5) consisting of the combination of four structural response regions and five thermal response regions, as shown in Table E.4.

TABLE E.3 Heat Flux Factors for Flame Temperatures (engulfing fire)

Flame Temperature, t		
K	(°F)	δ(t)
1,030	1,400	1.72
1,090	1,500	1.43
1,140	1,600	1.21
1,200	1,700	1.0
1,260	1,800	0.86
1,310	1,900	0.73
1,370	2,000	0.64
1,420	2,100	0.56
1,480	2,200	0.49
1,530	2,300	0.44
1,590	2,400	0.39

Source: LLNL (1987).

TABLE E.4 Response Regions Categorized by Vessel Strain and Lead Midlayer Thickness Temperature

Structural Response		Thermal Response	
Region (i)	Condition	Region (j)	Condition
1	< 0.2% strain	1	< 530 K (500°F) lead midlayer thickness temperature
2	0.2% to 2% strain	2	530 to 590 K (500 to 600°F) lead midlayer thickness temperature
3	2% to 30% strain	3	590 to 616 K (600 to 650°F) lead midlayer thickness temperature
4	> 30% strain	4	616 to 839 K (650 to 1,050°F) lead midlayer thickness temperature
		5	> 839 K (1,050°F) lead midlayer thickness temperature

To determine an appropriate response region [$R(i,j)$], the user must provide the following input parameters:

- Mechanical load accident parameters:
  - Cask velocity,
  - Impact angle,
  - Cask orientation, and
  - Hardness of the impacted object;
- Thermal load accident parameters:
  - Fire duration,
  - Flame temperature, and
  - Fire location with respect to the cask.

The flow diagram to relate the accident parameters to the appropriate response region is given in Figure E.4. All of the threshold or bounding accident parameters used in this algorithm follow those provided in the modal study (LLNL 1987). For accident parameters that are not equal to the threshold values, linear interpolation between the two bounding values is assumed to be appropriate.

APPENDIX E REFERENCE

Lawrence Livermore National Laboratory, 1987, *Shipping Container Response to Severe Highway and Railway Accident Conditions*, NUREG/CR-4829, UCID-20733, prepared by Lawrence Livermore National Laboratory, Livermore, Calif., for U.S. Nuclear Regulatory Commission, Washington, D.C., Feb.

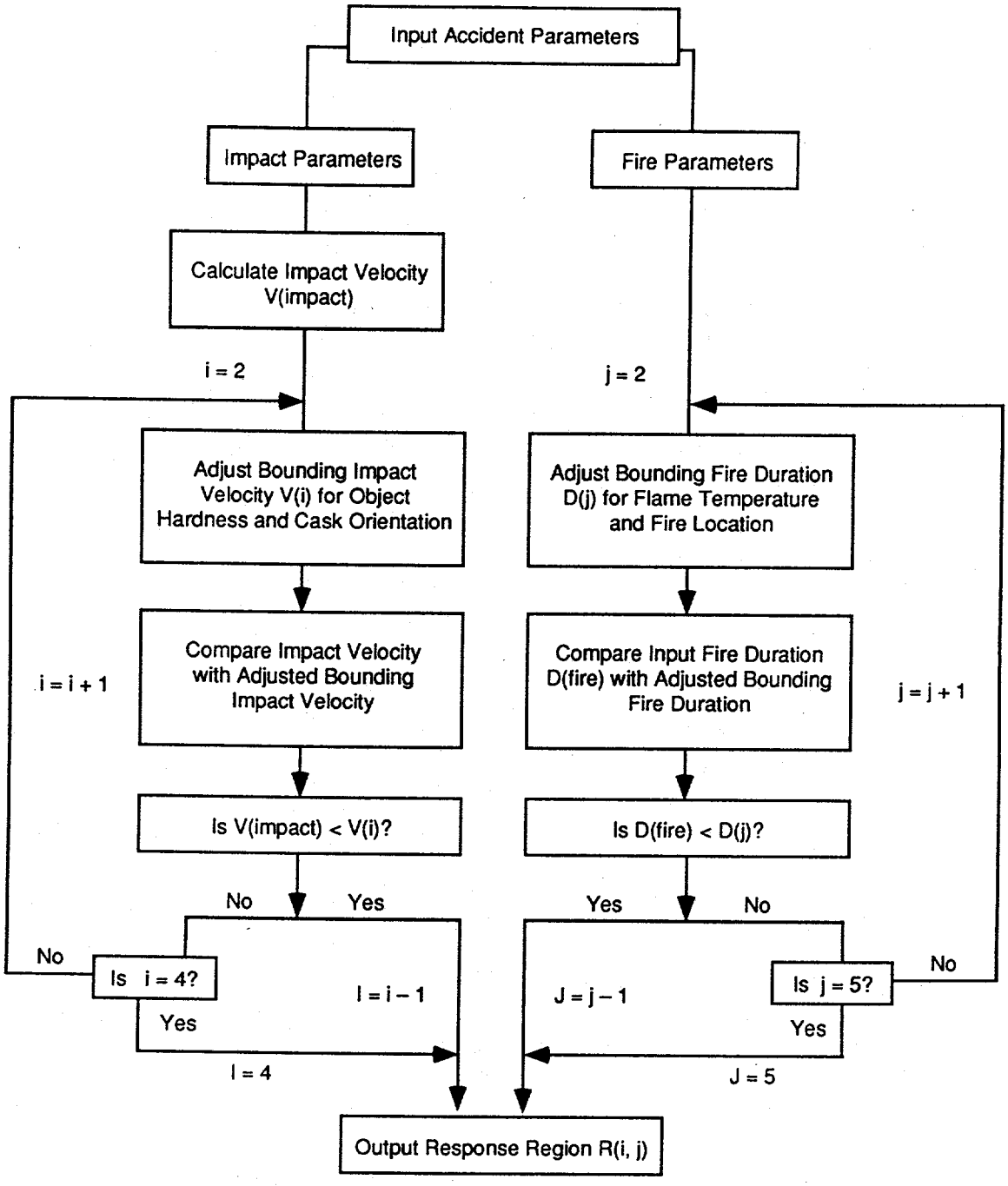


FIGURE E.4 Flow Diagram Used in RISKIND to Determine Cask Response Regions

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PROGRAM STRUCTURE

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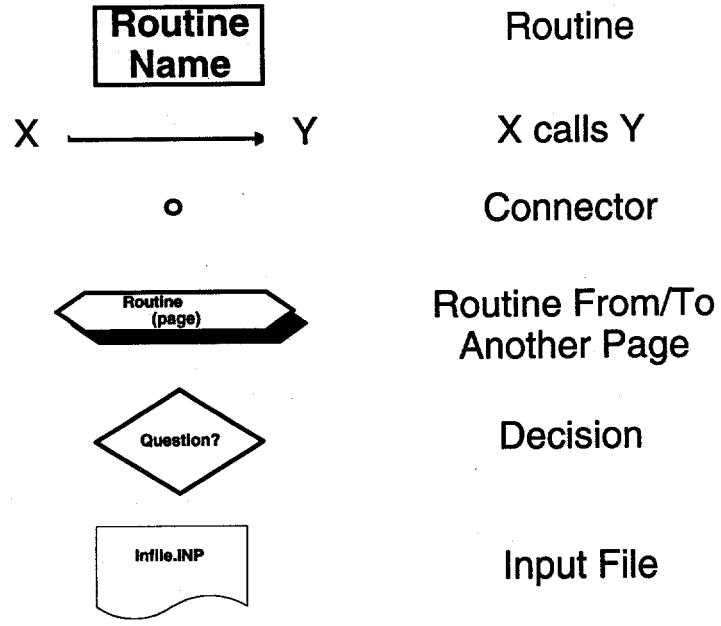
APPENDIX F:

PROGRAM STRUCTURE

This appendix provides information related to the program structure and data transfer used in RISKIND. RISKIND is a Windows™ application with the user interface written in Microsoft VISUAL BASIC™ 3.0.[1] The remainder of the RISKIND program, the calculation and output subroutines and utility function modules, is written in Lahey FORTRAN 5.01.[2] Data transfer is performed through subroutine calls and labeled common blocks.

F.1 HIERARCHY

The key below and Figures F.1 through F.10 illustrate the structure of the major FORTRAN RISKIND subroutines. These diagrams represent calling sequences and major branching of a RISKIND calculation. Descriptions of the subroutines are given in Table F.1.



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[1] Microsoft Corporation, 1993, Microsoft Visual Basic 3.0, Redmond, Wash.

[2] Lahey Computer Systems, Inc., Lahey 5.01, Incline Village, Nev.

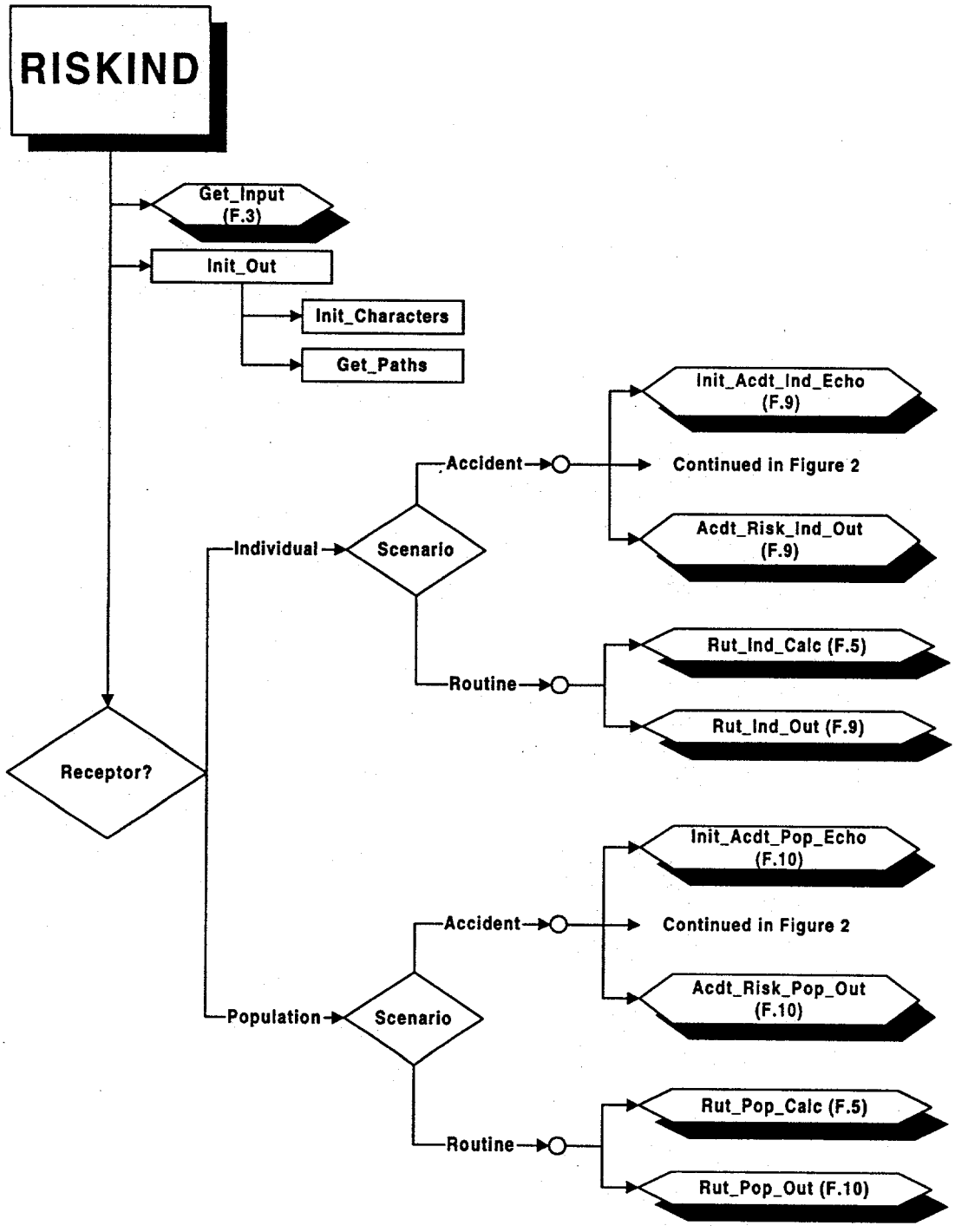

FIGURE F.1 Root Structure for RISKIND Calculations

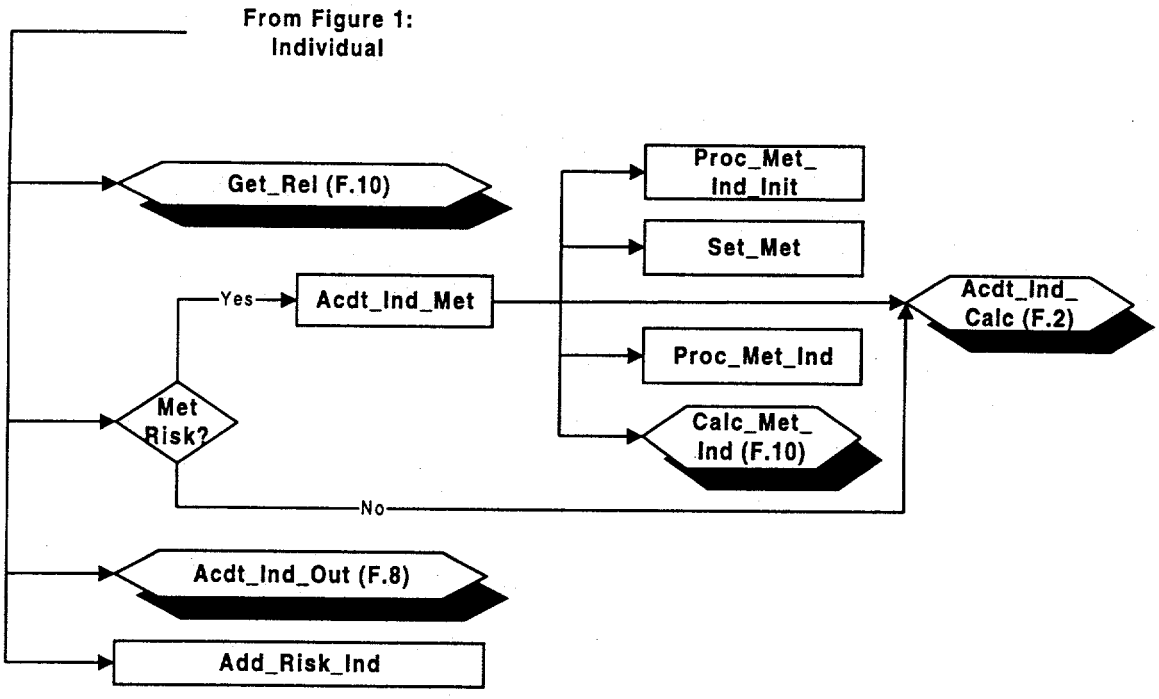

FIGURE F.2a Individual Accident Scenario Processing

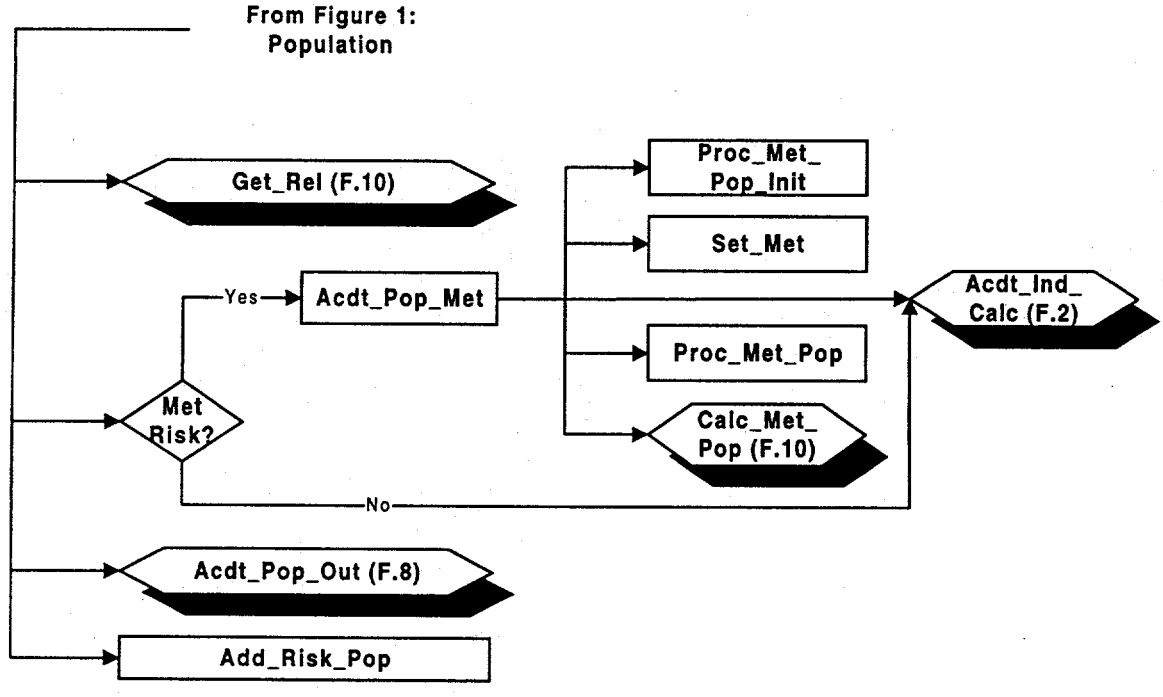

FIGURE F.2b Population Accident Scenario Processing

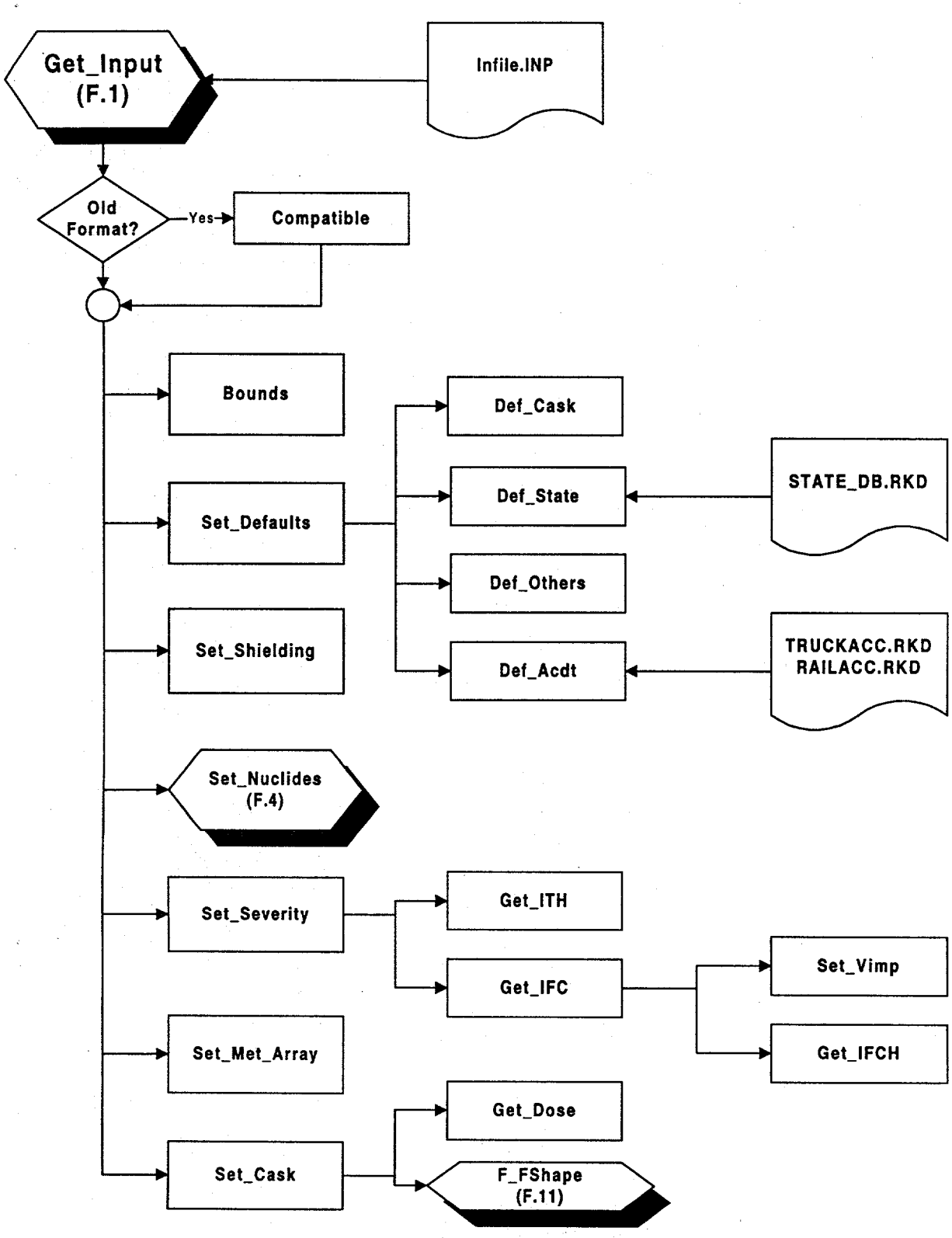

FIGURE F.3 Structure for the Get_Input Subroutine

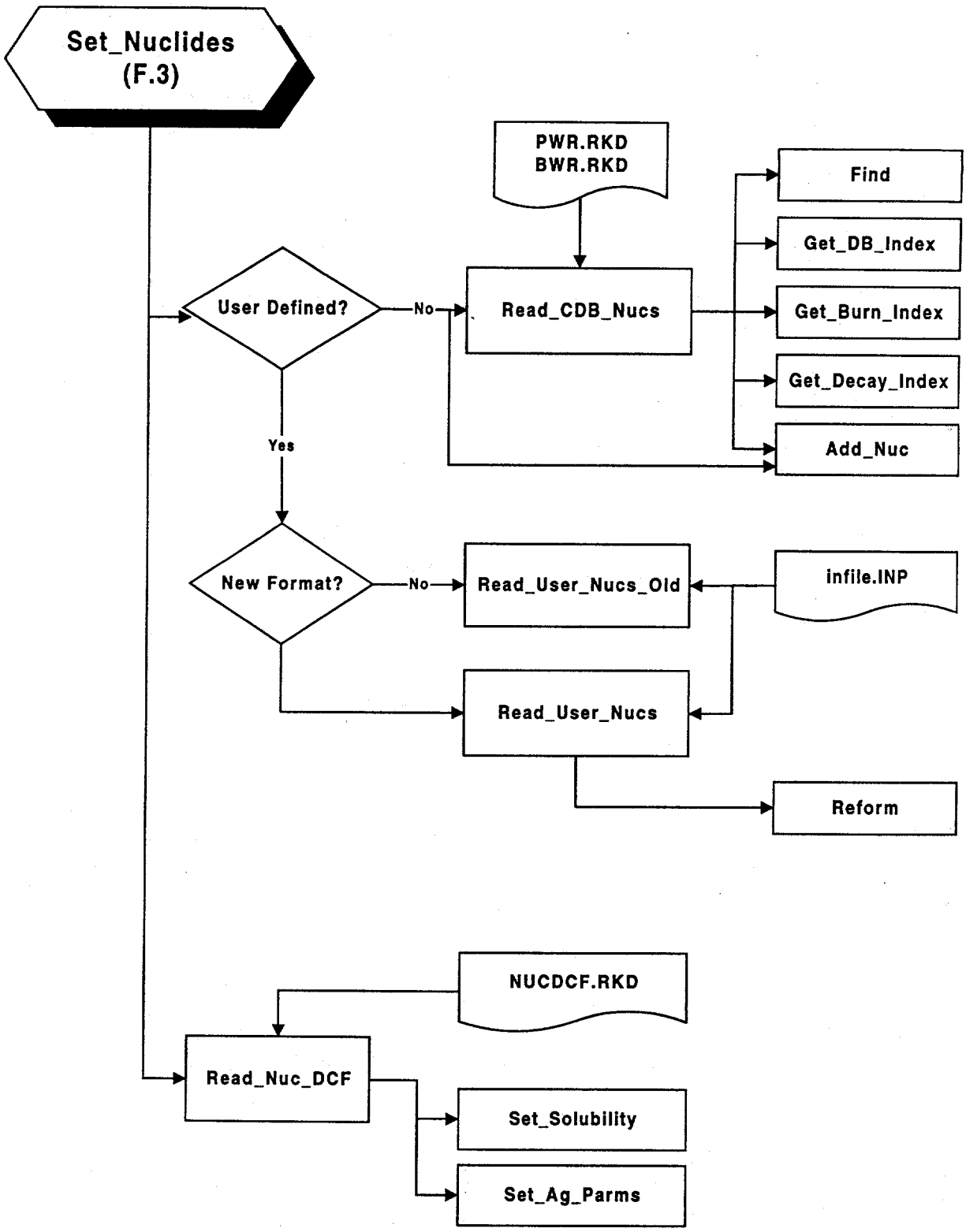

FIGURE F.4 Structure for the Set_Nuclides Subroutine

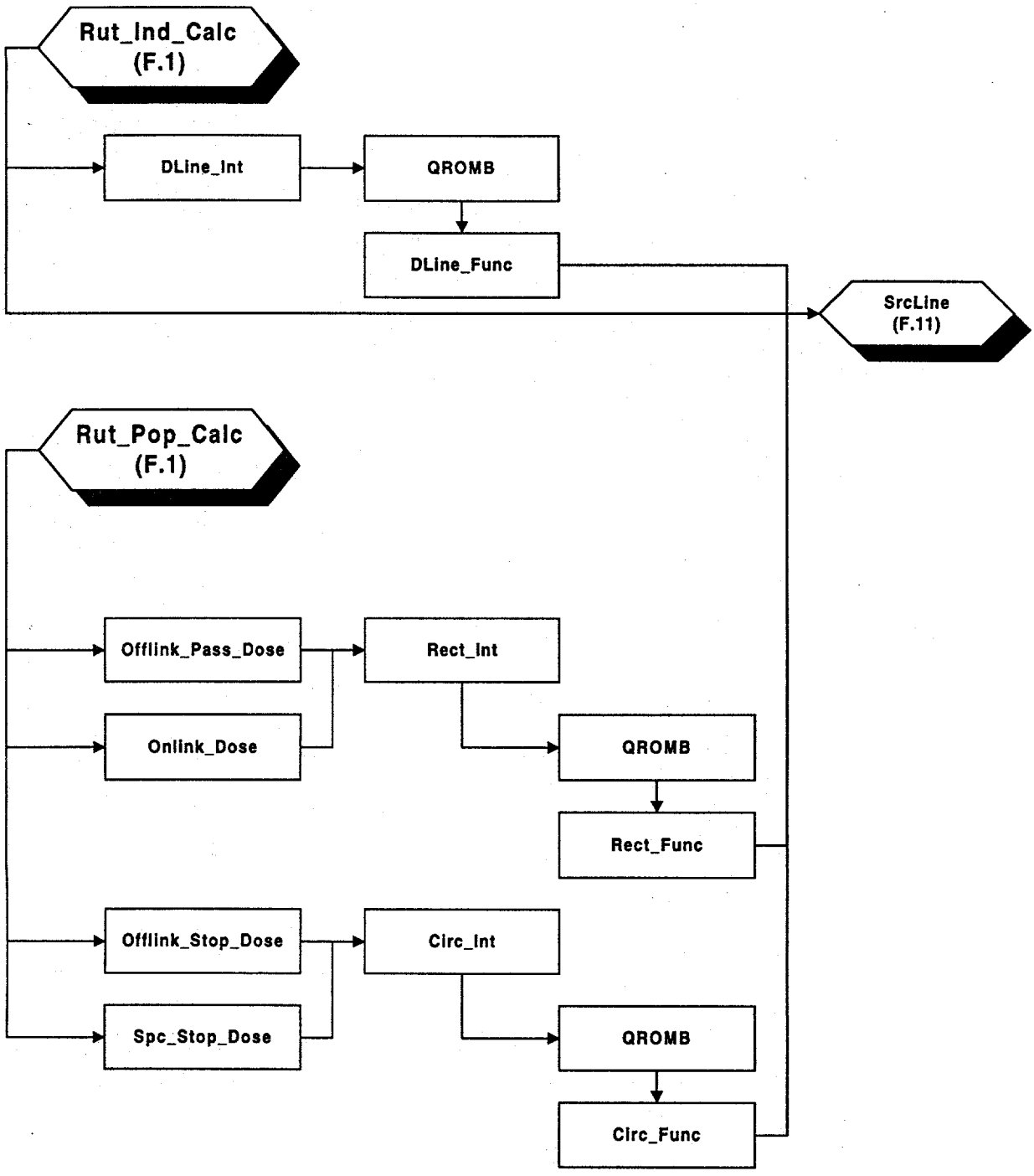

FIGURE F.5 Structure for Routine Calculations

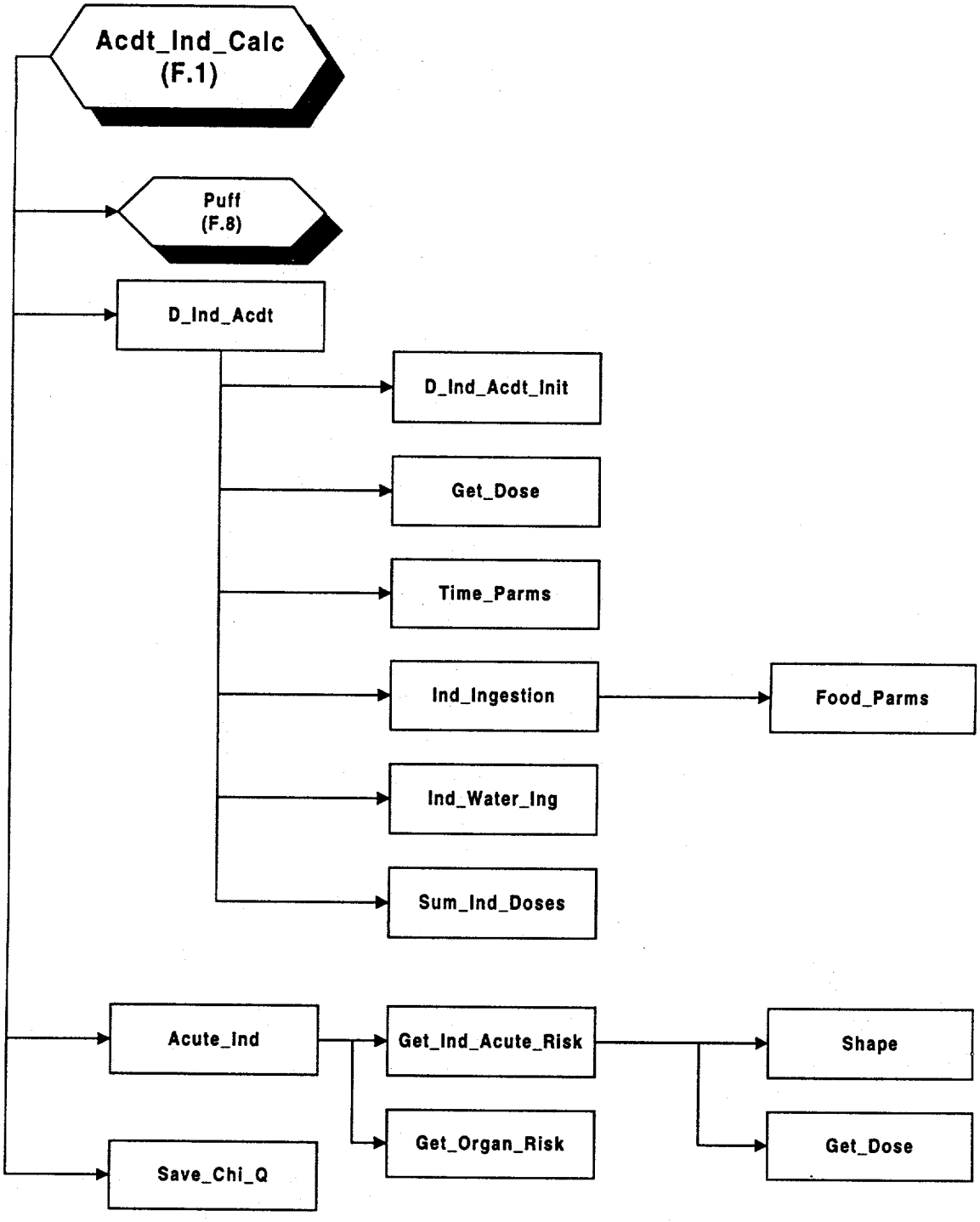

FIGURE F.6 Structure for Individual Accident Calculations

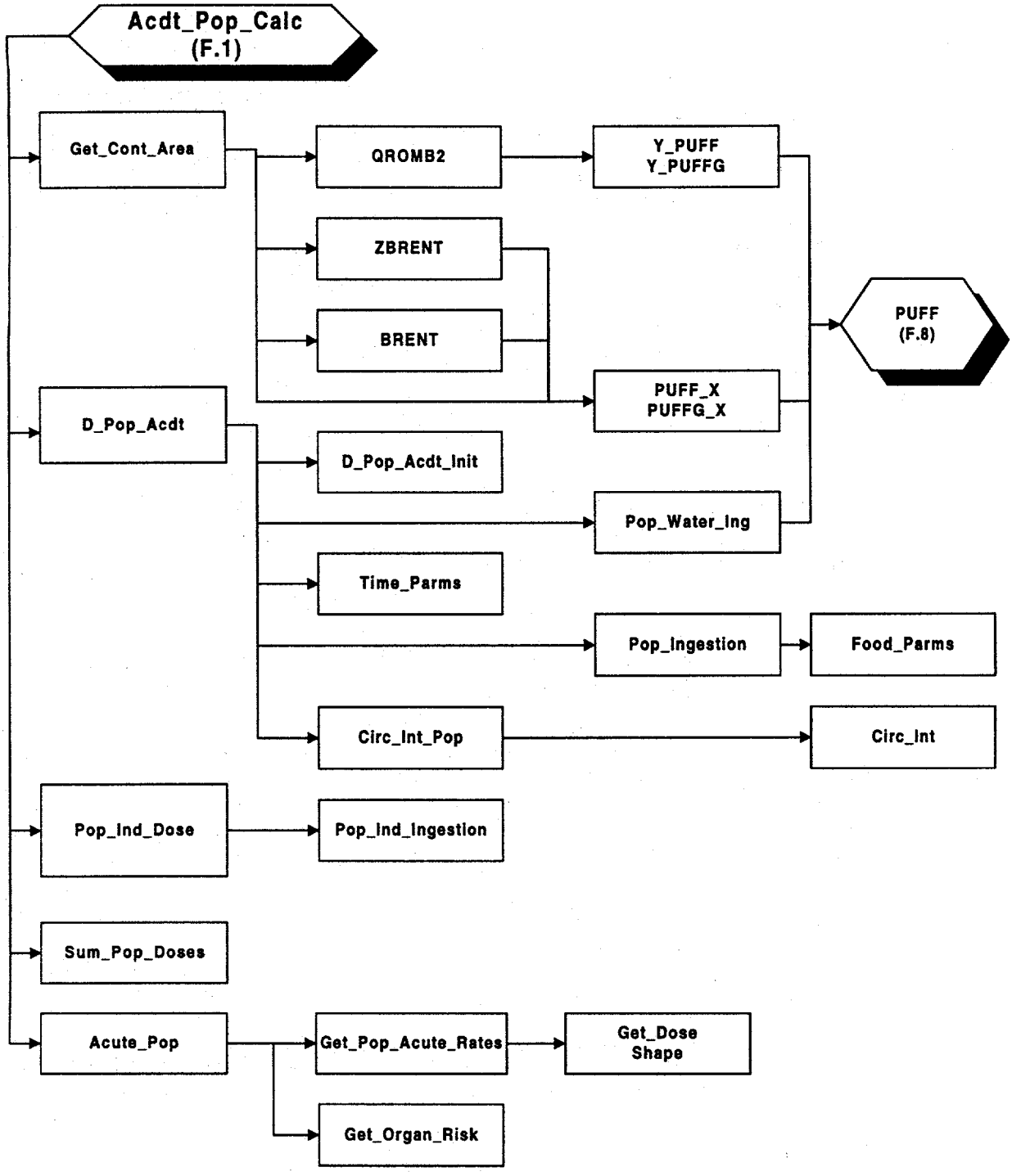

FIGURE F.7 Structure for Population Accident Calculations

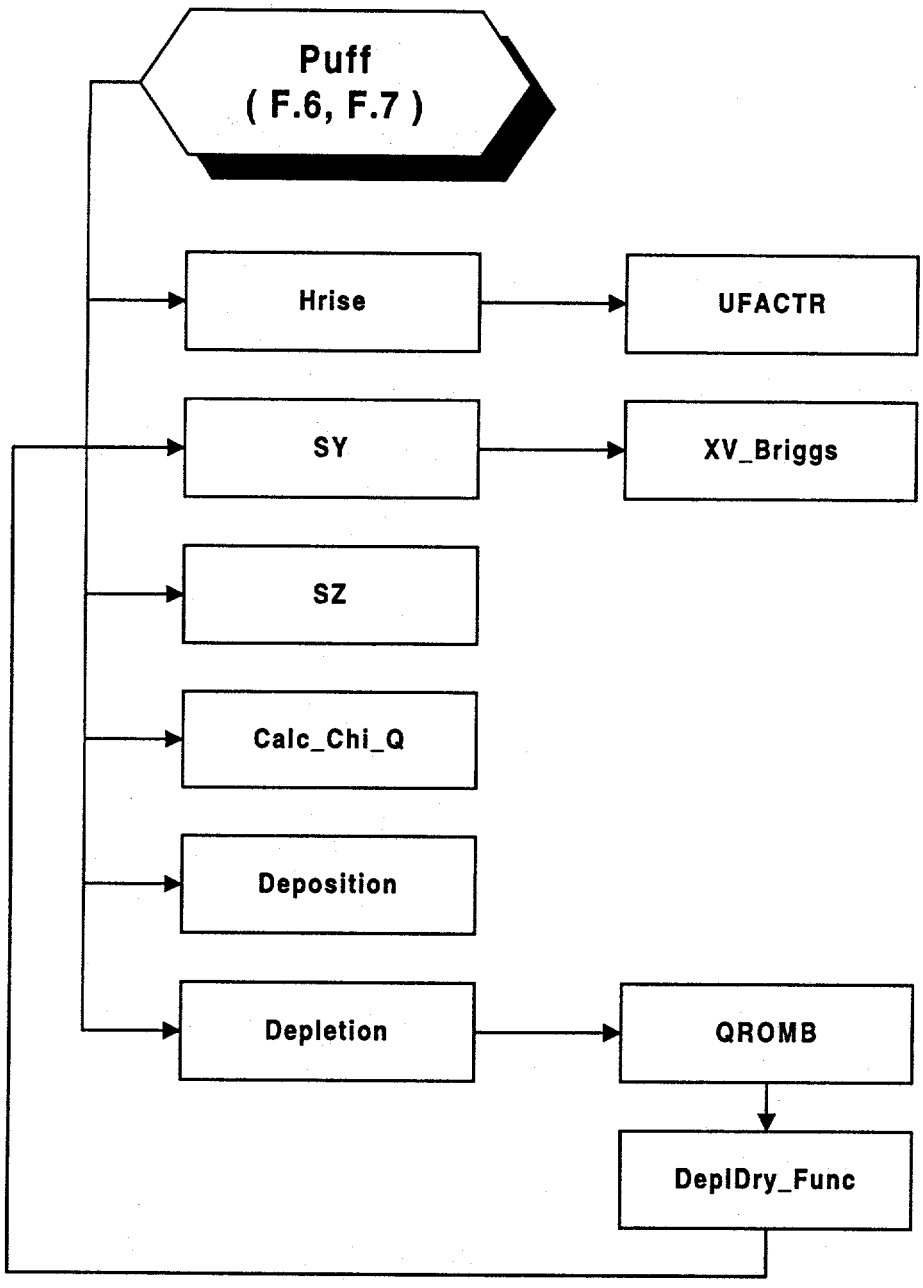

FIGURE F.8 Structure for Puff Dispersion Calculations

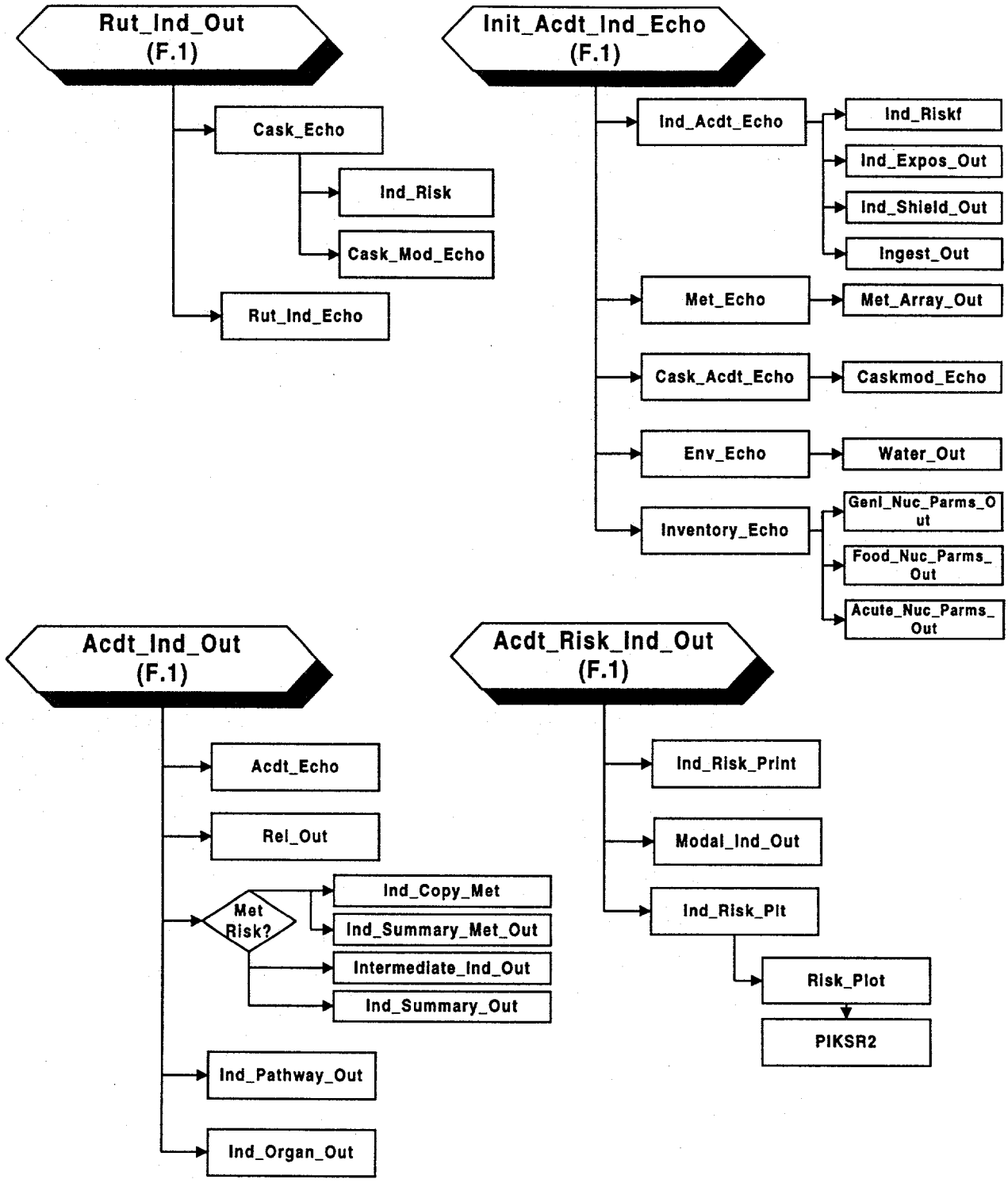

FIGURE F.9 Individual Output Routines

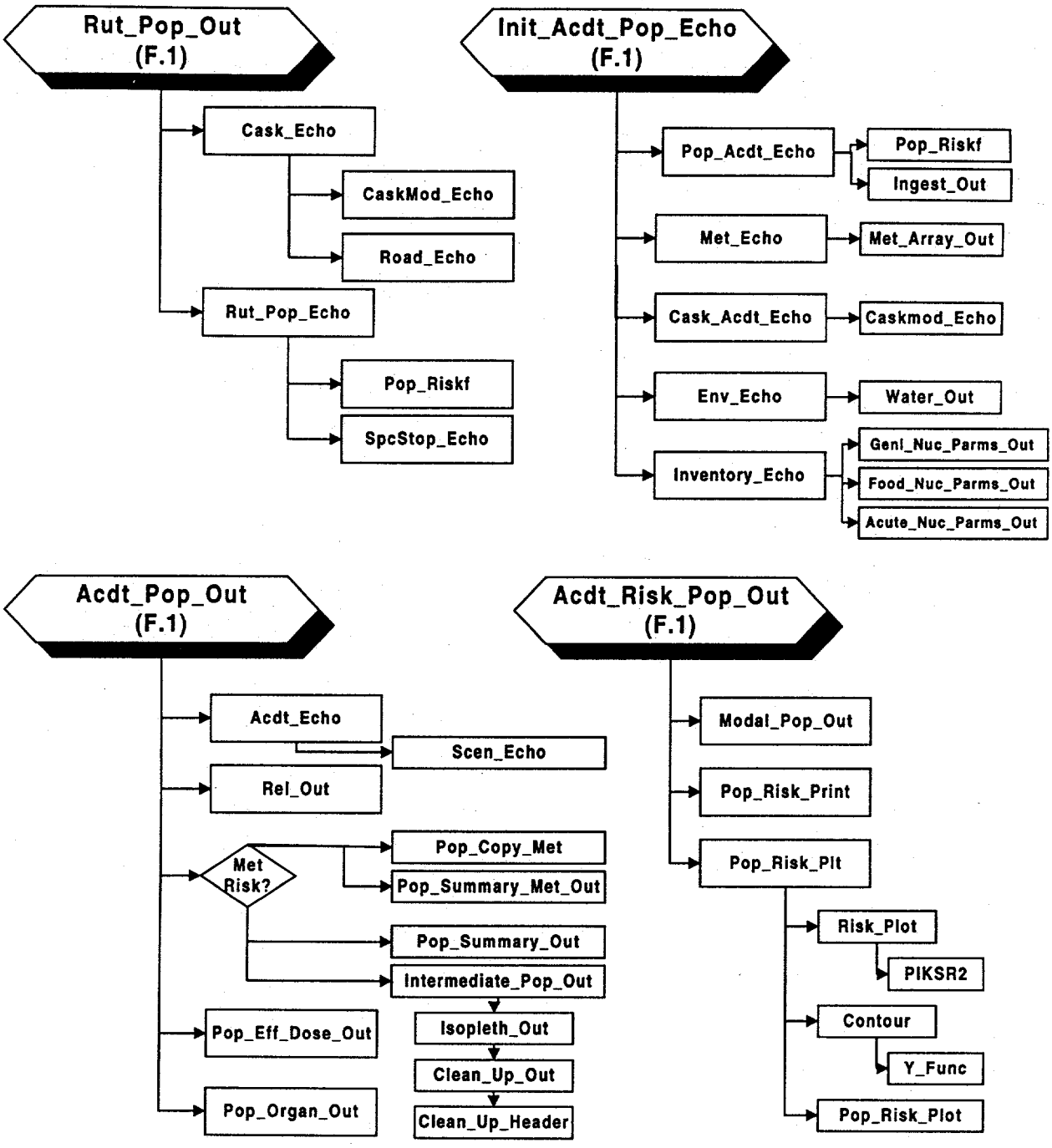

FIGURE F.10 Population Output Routines

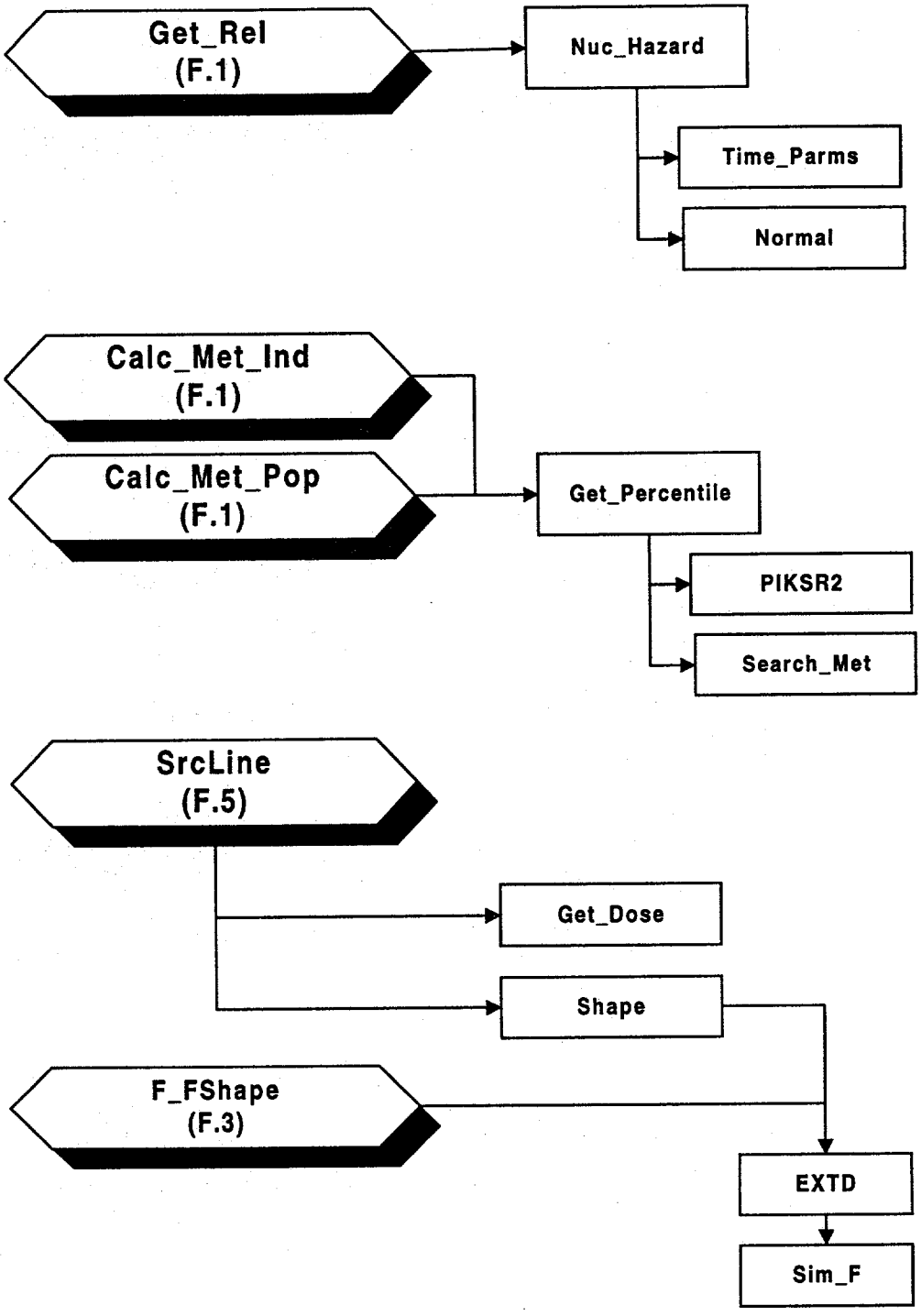

FIGURE F.11 Miscellaneous Routines

TABLE F.1 Descriptions of Major RISKIND Subroutines

ACDT_ECHO	Echoes accident input to the output file after calculations
ACDT_IND_CALC	Performs individual accident calculations for given stability class and wind speed
ACDT_IND_MET	Performs individual accident calculations over all meteorological conditions
ACDT_IND_OUT	Writes single individual accident results to the output file
ACDT_POP_CALC	Performs population accident calculations for given stability class and wind speed
ACDT_POP_OUT	Writes single population accident results to the output file
ACDT_POP_MET	Performs population accident calculations over all meteorological conditions
ACDT_RISK_IND_OUT	Writes individual accident risks to the output file
ACDT_RISK_POP_OUT	Writes population accident risks to the output file
ACUTE_IND	Calculates individual acute doses and effects
ACUTE_NUC_PARMS_OUT	Writes radionuclide parameters to the output file
ACUTE_POP	Calculates population acute doses and effects
ADD_NUC	Adds a radionuclide record to the inventory list
ADD_RISK_IND	Keeps track of individual risk calculation
ADD_RISK_POP	Keeps track of population risk calculation
BOUNDS	Checks the input data for bounds of application
BRENT	Search routine from Numerical Methods
CALC_CHI_Q	Finds the Chi/Q
CALC_MET_IND	Determines the meteorological risks for individual calculations
CALC_MET_POP	Determines the meteorological risks for population calculations
CASK_ACDT_ECHO	Echoes cask accident parameters to the output file
CASK_ECHO	Echoes cask input parameters to the output file
CASKMOD_ECHO	Writes cask modification parameters to output file
CIRC_FUNC	Circular integral for external cask dose
CIRC_INT	Circular integral for external cask dose
CIRC_INT_POP	Circular integral for population external cask dose
CLEAN_UP_HEADER	Writes header for cleanup of isopleths
CLEAN_UP_OUT	Writes cleanup results
COMPATIBLE	Makes previous version input data compatible with current version
CONTOUR	Plots isopleth contours
D_IND_ACDT	Calculates the pathway doses at a given individual location
D_IND_ACDT_INIT	Initializes individual accident doses
D_POP_ACDT	Calculates population pathway doses

TABLE F.1 (Cont.)

DEF_ACDT	Sets accident data-dependent defaults
DEF_CASK	Sets cask data-dependent defaults
DEF_OTHERS	Sets other data-dependent defaults
DEF_STATE	Sets state data-dependent defaults
DEPLDRY_FUNC	Dry depletion function
DEPLETION	Calculates depletion
DEPOSITION	Calculates deposition
DLINE_FUNC	Line integral for external dose
DLINE_INT	Calculates the dose at a specific point from a passing shipment
ENV_ECHO	Echoes environmental parameters to the output file
F_FSHAPE	Final limiting value of the shape factor at far distances
FIND	Finds radionuclide in database
FOOD_NUC_PARMS_OUT	Writes nuclide ingestion parameters
FOOD_PARMS	Calculates ingestion parameters
GENL_NUC_PARMS_OUT	Writes general nuclide parameters
GET_BURN_INDEX	Calculates spent fuel burnup index
GET_CONT_AREA	Finds isopleths in population accident scenario
GET_DB_INDEX	Calculates the spent fuel database index
GET_DOSE	Calculates external dose from cask
GET_IFC	Calculates strain response index
GET_IFCH	Intermediate strain response calculation
GET_IND_ACUTE_RATES	Calculates individual acute rate
GET_INPUT	Reads input data and sets input-dependent defaults
GET_ITH	Calculates thermal response index
GET_ORGAN_RISK	Calculates organ health effects risks
GET_PATHS	Sets pathway logical variables
GET_POP_ACUTE_RATES	Calculates acute rates for population problem
GET_REL	Gets release parameters
HRISE	Calculates effective release height from plume rise
IND_ACDT_ECHO	Echoes input to output file for individual accident calculations
IND_COPY_MET	Stores individual results from specific meteorological condition
IND_EXPOS_OUT	Writes individual exposure parameters
IND_INGESTION	Calculates individual dose from food ingestion
IND_ORGAN_OUT	Writes organ-specific individual dose and health effects to the output file
IND_PATHWAY_OUT	Writes individual dose breakdown by pathway

TABLE F.1 (Cont.)

IND_RISK_PLT	Plots the individual risk distribution
IND_RISK_PRINT	Writes individual risks
IND_SHIELD_OUT	Writes individual shielding parameters
IND_SUMMARY_MET_OUT	Writes summary average, 50%, and 95% doses and health effects to the output file
IND_SUMMARY_OUT	Writes summary of the estimated individual dose and health effects to the output file
IND_WATER_ING	Calculates individual dose from water ingestion
INGEST_OUT	Writes ingestion results
INIT_ACDT_IND_ECHO	Echoes input to output file for individual accident calculations
INIT_ACDT_POP_ECHO	Echoes input to output file for population accident calculations
INIT_CHARACTERS	Initializes output variables
INIT_OUT	Initializes the output file
INTERMEDIATE_IND_OUT	Writes intermediate individual results
INTERMEDIATE_POP_OUT	Writes puff calculations to the output file
INVENTORY_ECHO	Echoes the radionuclide inventory to the output file
ISOPLETH_OUT	Writes isopleth results
MET_ARRAY_OUT	Writes met conditions
MET_ECHO	Echoes meteorological input to the output file
MODAL_IND_OUT	Writes individual modal study consequence/risk to the output file
MODAL_POP_OUT	Writes population modal study consequence/risk to the output file
OFF-LINK_PASS_DOSE	Calculates the off-link incident-free population dose for both sides of the route
ON-LINK_DOSE	Calculates the on-link incident-free population dose
PIKSR2	Sorts routine from Numerical Recipes
POP_ACDT_ECHO	Echoes input to output file for population accident calculations
POP_COPY_MET	Stores population results from a specific met condition
POP_EFF_DOSE_OUT	Writes detailed pathway dose analysis for the population to the output file
POP_IND_DOSE	Estimates the doses to individuals within the isopleths
POP_IND_INGESTION	Calculates individual ingestion dose in population problem
POP_INGESTION	Calculates population dose from ingestion
POP_ORGAN_OUT	Writes organ-specific population dose and health effects to the output file
POP_RISK_PLT	Plots the population risk distribution
POP_RISK_PRINT	Writes population risk
POP_RISKF	Gets the appropriate dose-to-risk conversion factor
POP_SUMMARY_MET_OUT	Writes summary average, 50%, and 95% doses and health effects to the output file

TABLE F.1 (Cont.)

POP_SUMMARY_OUT	Writes summary of the estimated population dose and health effects to the output file
POP_WATER_ING	Calculates the population dose from water ingestion
PROC_MET_IND	Processes the results after each set of stability class and wind speed calculations
PROC_MET_IND_INIT	Initializes individual problem for meteorological risks
PROC_MET_POP	Processes the results after each set of stability class and wind speed calculations
PROC_MET_POP_INIT	Initializes population problem for met risks
PUFF	Calculates puff parameters at specific location
QROMB	Integration routine from Numerical Recipes
READ_CDB_NUCS	Reads Characteristic Database nuclide list
READ_NUC_DCF	Reads nuclide dose conversion factors
READ_USER_NUCS	Reads user-supplied nuclide list
READ_USER_NUCS_OLD	Reads old format of user-supplied nuclide list
RECT_FUNC	Rectangular function for external dose calculations
RECT_INT	Rectangular integral for external population dose calculations
REFORM	Reformats nuclide name
REL_OUT	Writes release characteristics to the output file
RISK_PLOT	Plots the risk
ROAD_ECHO	Writes the road parameters
RUT_IND_CALC	Performs incident-free individual calculations
RUT_IND_ECHO	Writes parameters for individual routine problem
RUT_IND_OUT	Echoes input and writes output for incident-free individual calculations
RUT_POP_CALC	Performs incident-free population calculations
RUT_POP_ECHO	Echoes input and writes output for incident-free population calculations
RUT_POP_OUT	Writes output for incident-free population calculations
SAVE_CHI_Q	Saves intermediate calculations
SCEN_ECHO	Writes the scenario parameters
SET_AG_PARMS	Sets the agricultural parameters
SET_CASK	Sets the cask normalization factor for 2-m dose rate
SET_DEFAULTS	Sets NAMELIST input-dependent defaults
SET_MET	Sets meteorological conditions
SET_MET_ARRAY	Sets the met array for met risk calculations
SET_NUCLIDES	Gets the nuclide information and the dose conversion factors
SET_SEVERITY	Calculates the accident severity region
SET_SHIELDING	Sets shielding/time factors
SET_SOLUBILITY	Sets nuclide solubility

TABLE F.1 (Cont.)

SET_VIMP	Sets velocity of impact parameters
SHAPE	Calculates the shape factor for the external dose from the cask
SPC_STOP_DOSE	Calculates the population incident-free doses at specified stops
SPCSTOP_ECHO	Writes population-specified stop doses to the output file
SRCLINE	Calculates the external dose rate at a specific distance from the shipment
SUM_IND_DOSES	Sums the individual doses
SUM_POP_DOSES	Sums the population doses
SY	Calculates the horizontal dispersion
SZ	Calculates the vertical dispersion
TIME_PARMS	Calculates time-integrated parameters
UFACTR	Adjusts wind velocity as a function of height
WATER_OUT	Writes doses from water ingestion
XV_BRIGGS	Corrects dispersion for initial dispersion
ZBRENT	Root-finding routine from Numerical Recipes

F.2 COMMON BLOCKS

Many of the data transfers among subroutines are handled through labeled common blocks. RISKIND uses 13 common blocks, which are described in Table F.2.

TABLE F.2 Common Blocks Used in RISKIND

Block	Description
ACUTCOEF	Parameters for acute model
BOUNDS	Data for bounds checking
EFFECTS	Parameters for health effects
IND_ACDT	Storage and passing of individual accident consequence results
IND_INTE	Storage of intermediate individual calculations
IND_RISK	Storage and passing of individual accident risks
IND_RUT	Storage and passing of individual incident-free results
INPUT	RISKIND NAMELIST input data
NUCLIDES	Storage and passing of radionuclide input data and release calculations
OUTCHAR	Maintenance of output character and page number
POP_ACDT	Storage and passing of population accident consequence results
POP_RISK	Storage and passing of population accident risks
POP_RUT	Storage and passing of population incident-free results

APPENDIX G:

DATA INPUT PREPARATION

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APPENDIX G:

DATA INPUT PREPARATION

The RISKIND computer code runs on an IBM (or compatible) microcomputer with a Windows™ 3.1 operating system. A hard drive and a math coprocessor (80387 or higher) are required. The RISKIND code consists of two major components:

1. RISKVB.EXE — The Windows™ interface program that is written in Visual Basic 3.0.[1] This module handles all user interaction with RISKIND. The user may input and edit the specific parameters necessary for a particular analysis. Input files may be created or retrieved, modified, and saved. The interface program executes RISKIND.EXE (see below) once the user is satisfied with the input selections. The resulting output, both plot graphics and text output, may then be viewed.

2. RISKIND.EXE — A Fortran (Lahey F77L 5.01[2]) program that performs the radiological calculations on the basis of the input files created with RISKVB.EXE and generates the output files for RISKIND. RISKIND.EXE may be run separately in a DOS 3.1 or higher operating system. This latter mode of operation allows the radiological analysis to be performed in the absence of the Windows™ operating environment and facilitates the processing of numerous input files in a batch mode (may be executed from a user-developed DOS batch file).

G.1 INSTALLATION AND OPERATION OF RISKIND

The RISKIND code is available on two 1.44-megabyte (MB) 3.5-in. diskettes. After inserting Disk 1 into the floppy disk drive (A:, or the appropriate drive designation for your machine), installation of RISKIND can be accomplished by double-clicking on A:\SETUP.EXE, while in the File Manager, or by typing "A:\SETUP.EXE" into the command line box under "Run.." in the File menu of either the Program Manager or File Manager. The user will be given a prompt for the directory to be used on the hard drive (default: C:\RISKIND), and installation will continue automatically from that point. The RISKIND code and supporting data files will occupy approximately 5 MB of disk space once expanded and installed. The README.TXT text file in the default directory contains last minute program documentation and a list of the program files that should now reside on the hard drive.

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[1] Microsoft Corporation, 1993, Microsoft Visual Basic 3.0, Redmond, Wash.

[2] Lahey Computer Systems, Inc., 1991, Lahey 5.01, Incline Village, Nev.

The RISKIND program can be started by double-clicking on the RISKIND icon in the RISKIND group under Windows™. As mentioned previously, the calculational portion of RISKIND (RISKIND.EXE) can be run separately in DOS by typing RISKIND MYINPUT.INP at the system prompt while in the default RISKIND directory, where MYINPUT.INP is the user input file. This second mode of operation permits batch processing of multiple input files and provides a method for performing the radiological calculations if the Windows™ operating environment is not available. However, the user-friendly interface and the plot graphics are not available in this second mode.

Available options in the RISKIND windows may be selected by using the mouse or the tab key for moving forward through the selections and Shift-tab for moving backward through selections. The buttons in the various windows available for performing certain actions can be "pressed" (activated) by one of three methods: (1) a mouse click while the mouse arrow is over the button, (2) pressing the Enter key on the keyboard when the button has the input focus (button label is circled), or (3) pressing a hot key (the underlined letters in the different menu items) while the Alt key is depressed. A hot key also corresponds to the underlined letter in the button labels.

G.2 INPUT REQUIREMENTS AND DATA ENTRY

The user interface to RISKIND consists of a main menu and window and numerous subwindows for problem definition (Figure G.1). The situation to be assessed is defined in terms of input variables that are set through user interaction with the various windows and their options. The input thus generated is collected and stored in an ASCII text file following the FORTRAN NAMELIST format. This file is then used for input to the FORTRAN program RISKIND.EXE, which performs the numerical calculations. The NAMELIST input parameters and their descriptions are discussed in the subsections that follow. Section G.3.2 provides a list of these variables. As an aid to the user who may wish to later edit the input file directly, the variable name used for each input item is listed in parentheses in capital letters next to the corresponding selection in an input window. It is highly recommended that only very experienced users of the code who are aware of the interdependencies of the input parameters edit the input file with a text editor. Input files from the previous release of RISKIND can be run without modification.

Output files retain the name of the input file with a change in the filename extension to "*.OUT." With the user interface, modifications to input files are not automatically saved to disk unless specifically directed through the use of the Save Input item of the File menu discussed in Section G.2.2. However, modified input files may be run without being saved; the input file will be saved to disk with the "*.MOD" file extension and then executed. Input files from the previous release of RISKIND can be run without modification, but the user should check the input parameters first since new parameters have been added to the input.

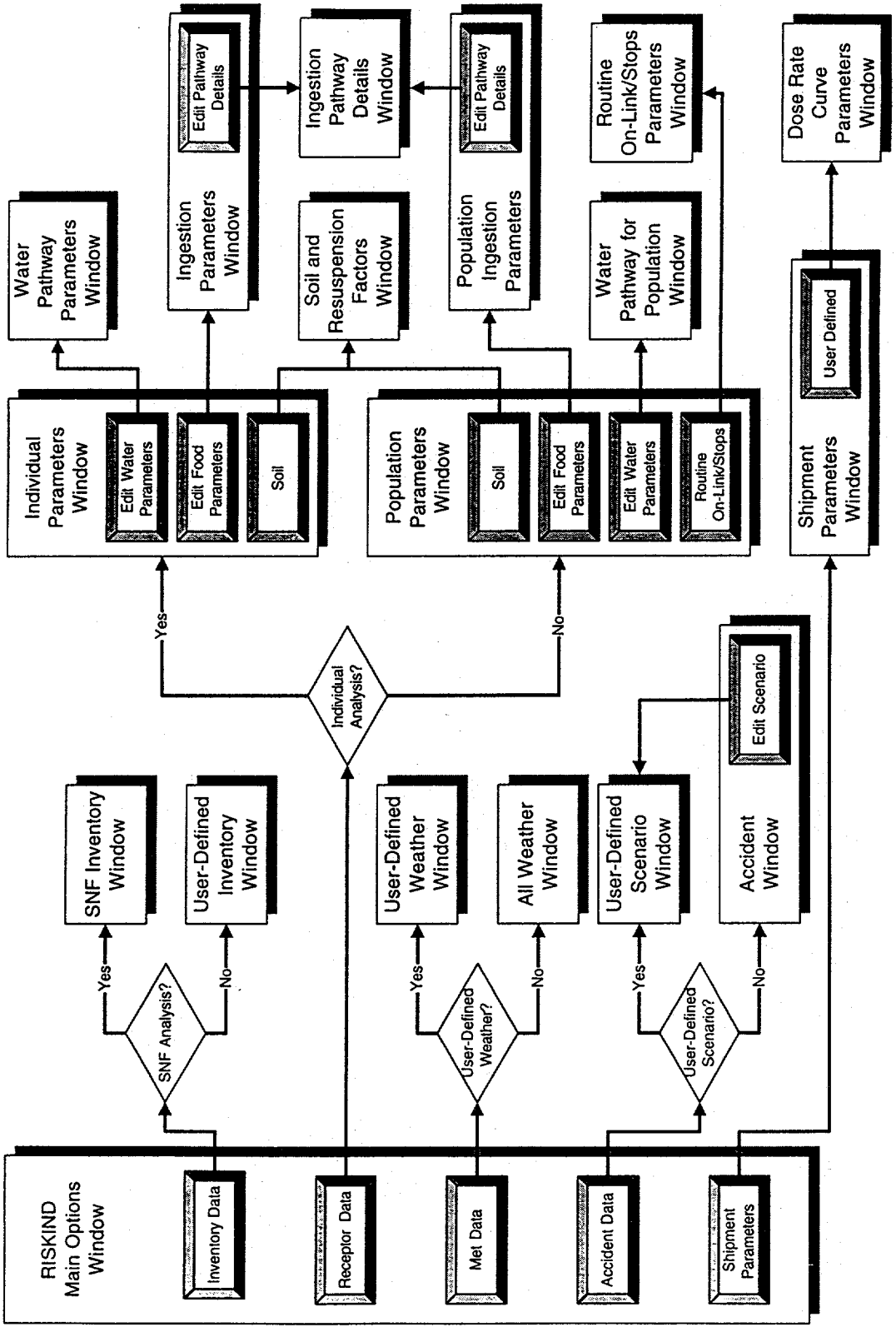

FIGURE G.1 RISKIND Window Access Diagram

The default problem for RISKIND is loaded automatically from the DEFAULT.RKD input file at the startup of RISKIND. This is a read-only file and should not be removed from the default directory. It may be replaced with a default file more appropriate to the user's needs if desired. Any replacements must be made when the RISKIND program is not running.

RISKIND, Version 1, has bounds checks on the input parameters. Both the user interface and the run-time portions of the program perform the same checks. The user interface checks parameters when an input file is loaded from disk and when entered by the user and will prompt for suitable input if a parameter is found to be out of bounds. The run-time portion of the code will give a warning message and terminate calculations if a parameter is found to be out of bounds.

G.2.1 Scenario Definition

The situation to be analyzed is defined by the major input options in the main input window (Figure G.2), thus giving the user an overall summary of the problem definition. The window also provides quick access to more detailed problem-specific information for some of the major input options through a button press, which brings up other input windows with parameters grouped by function. The scenario is defined by a series of simple questions reflecting the input options on the main screen. What is being shipped (Inventory Options)? How is it being shipped (Transportation Mode)? Who is affected (Receptor/Population Zone)? How will normal transportation of the material affect the receptor(s) (Scenario)? What happens if there is an accident (Scenario/Accident Scenarios)? To aid the user in setting up an analysis, those input parameters not pertinent to the selected options are not available for input from the user interface.

RISKIND is designed to estimate the impacts associated with the transportation of radioactive materials at the local level. The user is able to model most credible situations involving a truck or rail transport vehicle. This level of detail and versatility requires many location-specific input parameters, some of which may not be readily available. The default data provided with RISKIND help alleviate this problem. However, it is the user's responsibility to ensure that the input data used are the best available and appropriate for the situation to be analyzed. Much of the default data in RISKIND consists of average values that may be unreasonable for a specific location and scenario.

G.2.1.1 Input Options

Inventory — RISKIND contains an internal spent nuclear fuel (SNF) database for estimating boiling-water reactor (BWR) and pressurized-water reactor (PWR) commercial fuel shipment inventories on the basis of the fuel's history. Appendix A contains a description of the database used. Pressing the Inventory Data button when the Spent Fuel option is selected will

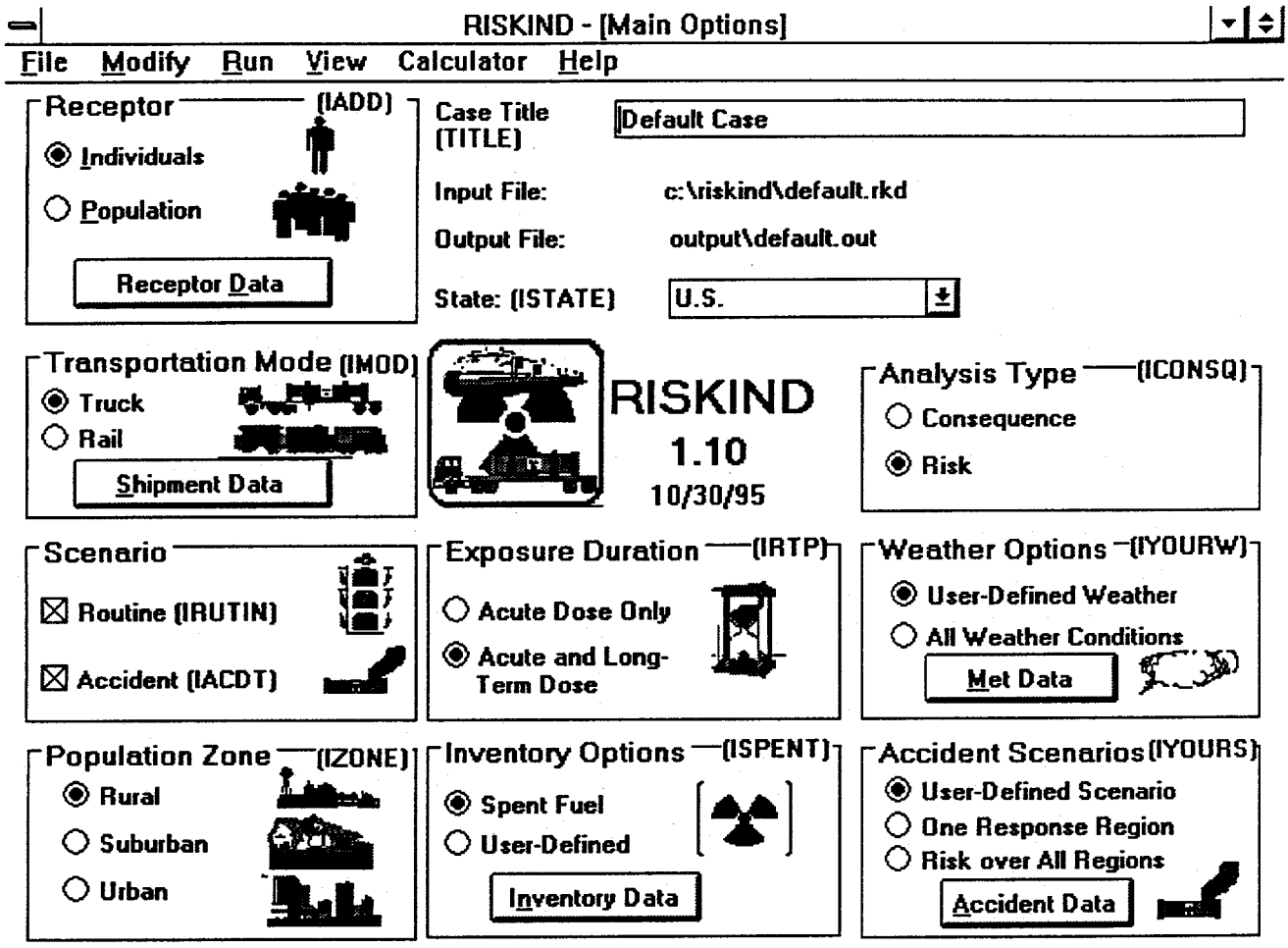

FIGURE G.2 Main Input Window

bring up the SNF Inventory window containing the input parameters required for determining the SNF composition (discussed later in Section G.2.5.1). If the User-Defined option is selected, the Inventory Data button accesses the User Inventory window where the user may select a custom inventory of radionuclides for shipments of nonstandard SNF or other types of radioactive materials.

Transportation Mode — When necessary, most SNF is shipped by truck or rail and sometimes by barge. RISKIND has the option of truck or rail transport. This option affects default values assigned to input parameters such as cask size, accident rates, vehicle speed, and other route characteristics. The Shipment Data button accesses the Shipment Parameters window that contains input for shipping cask and local route characteristics.

Receptor — RISKIND can estimate transportation impacts to specific individual receptors (up to a maximum of 20) with unique attributes in a single analysis, or impacts to a population subgroup defined by a specific area relative to the radioactive materials shipment.

The appropriate selection is made with the radio buttons in the Receptor box. Pressing the Receptor Data button accesses either the Individual Parameters window or the Population Parameters window. These windows contain specific location and receptor attribute input parameters.

Population Zone — RISKIND recognizes three population zones: rural, suburban, and urban. This option affects default values assigned to route parameters such as accident rates, transport vehicle speed, and traffic density. Impacts from ingestion of contaminated foodstuffs following an accidental release can only be selected if the rural population zone is selected. Food is not expected to be grown in suburban and urban areas to any significant extent.

Scenario — Impacts can be analyzed for routine (incident-free) transport of radioactive material, transport under accident conditions, or both. Impacts from routine transport are the result of exposure of the receptors to external radiation emanating from the shipment as it either passes by en route or while it is stopped at a location such as a refueling area. A routine impacts analysis will be conducted if the Routine checkbox is selected. Likewise, an accident analysis will be conducted for the same receptor(s) if the Accident checkbox is selected. Potential accident impacts will be assessed, as discussed below, on the basis of severity of the accident (Accident Scenarios), the weather conditions at the time of accident (Weather Options), and the exposure duration of the receptor(s) (Exposure Duration). Either an accident consequence or risk can be estimated (Analysis Type).

Accident Scenario — The accident scenario ultimately determines how much of the shipment inventory is released to the environment. As discussed in Section 3 and in Appendix E, 20 default response regions constitute the entire range of accident severities possible for a SNF cask given that an accident has occurred. Selection of the User-Defined Scenario option allows the user to input the accident conditions at the time of accident after pressing the Accident Data button. The release characteristics will then be given by the response region determined by the methodology developed in the U.S. Nuclear Regulatory Commission (NRC) modal study (LLNL 1987) as described in Appendix E. As an alternative, the user may directly select the response region after selecting the One Response Region option or may elect to estimate the risk when considering the spectrum of accident severities over all regions (Risk Over All Regions option). This latter option is not available if the Analysis Type is set to Consequence.

Weather Options — After radioactive material is released to the environment from an accident, the material is dispersed to the surrounding receptor locations by atmospheric turbulence. The input for weather conditions at the time of accident can be accessed by using the Met Data button if the User-Defined Weather option is selected. If analyzing the risks for a potential accident and the weather conditions at the time are uncertain, a risk estimate over all weather conditions can be calculated by selecting the All Weather Conditions option. This latter option is not available if the Analysis Type is set to Consequence.

Exposure Duration — Immediately following an accident, persons in the vicinity may be exposed to the passing radioactive cloud released (inhalation and external radiation) and possibly to increased external radiation levels from the shipment itself, because of containment failure. This short-term exposure generally lasts only a few hours at most, since emergency measures will be taken as soon as possible after the accident to minimize exposure to the general public. Persons exposed might be motorists stopped in traffic at the accident scene, workers in nearby businesses, or persons attempting to rescue accident victims before the arrival of emergency response teams. The Acute Dose Only option directs RISKIND to estimate only this short-term dose. However, other persons living near the accident scene could be exposed to external radiation from the deposited radioactive ground contamination and resuspended contamination, as well as receiving internal exposure from ingesting contaminated foods and inhaling resuspended contamination over the long term (years). The Acute and Long-Term Dose option directs the program to estimate doses from both the short- and long-term exposures.

Analysis Type — What if an accident occurred nearby? is a common question regarding SNF transportation. The impacts following such a postulated accident would be the consequence of the accident as if it had occurred. Selecting the Consequence option sets the program to estimate the effects from a given accident scenario occurring under a single set of defined conditions (i.e., fixed accident severity and weather conditions). On the other hand, many persons are also interested in the risk to themselves or their community rather than the consequence from a potential SNF transportation accident. The risk factors all of the probabilities into the sum of all potential consequences (risk = probability $\times$ consequence). Selecting the Consequence option automatically sets the accident rate and the probabilities for the accident response region and weather condition to 1. If the total risk is to be estimated, the probability of an accident occurring in conjunction with the probability weighted consequences for every possible combination of accident response region and weather condition is estimated (i.e., 20 response regions $\times$ 6 weather stability categories $\times$ 6 wind speeds = 720 consequences combined with their probabilities of occurrence). Selecting the Risk option permits the user to run such an analysis. A constrained risk analysis may also be conducted. Someone may wish to know what the accident risk would be for a given set of weather conditions over all response regions, or the risk over all weather conditions for a given accident severity. Therefore, a full or partial risk analysis is only fully defined once the Risk option is selected and the appropriate choices made in the Weather Options and Accident Scenarios boxes.

G.2.2 Main Menu

The main menu across the top of the screen is available to the user while the RISKIND main window and many of the subwindows are displayed. Table G.1 lists the options and their functions. As is standard for most Windows™ programs, the main menu can be accessed either through the use of a mouse or by pressing the Alt key to activate the menu bar. Hot keys or the arrow keys may be used for traversing the menu and making a selection once the menu is activated.

TABLE G.1 RISKIND Main Menu Options

Menu Item	Sub-Menu Item	Function
File	Read Input	Reads user-specified input file into memory.
	Save Input	Saves the current version of the input data in a file using the current input file name.
	Save Input As	Saves the current version of the input data in a file using a different input file name.
	EXIT	Terminates the RISKIND program and returns to Windows™.
Modify	Receptor	Duplicates the Receptor Data button in the main window and accesses the Individual or Population Parameters window.
	Shipment	Duplicates the Shipment Data button in the main window and accesses the Shipment Parameters window.
	Inventory	Duplicates the Inventory Data button in the main window and accesses the SNF Inventory or the User-Defined Inventory window.
	Meteorology	Duplicates the Met Data button in the main window and accesses the Defined Meteorology or the All Weather window.
	Accident	Duplicates the Accident Data button in the main window and accesses the Accident window.
Run		Performs the radiological calculations with the current input data.
View	Last Report	Permits viewing of the last output file generated by RISKIND.
	Plots	Plots data from the last set of calculations performed with RISKIND. If applicable, the user may select from among risk, air concentration isopleth, and ground concentration isopleth plots.
	Any File	Permits viewing of any ASCII text file.
	Images	Turns images displayed in the main window on or off. Screen redraws of the main window may be substantially faster on slower computers with the images turned off.
Calculator		Brings up the Windows™ calculator from the Accessories group for quick calculations.
Help	Contents	Lists topics (input parameters) available from user help.
	References	Brings up the reference list for the default input parameter values.
	Diagrams	Accesses submenu of available help diagrams for additional explanation of selected input parameters.
	About RISKIND	Displays general information about RISKIND.

G.2.3 Receptor Data

G.2.3.1 Individual

The Individual Parameters window (Figure G.3) is brought up by pushing the Receptor Data button on the main window when individual receptors are selected. Up to 20 individuals may be specified for a single run of the program. Individuals may be added or deleted by using the buttons at the bottom of the window.

General Information — The General Information box has a droplist box for selecting the desired individual. Also present is the user name or label given to that specific individual (XNAME), the individual's breathing rate (BRTIND), and a choice of dose-to-risk conversion factors for use in the health effects calculations (INDTYPE).

The default breathing rate of 8,000 m^3/yr is that suggested for an average adult in NRC Regulatory Guide 1.109 (NRC 1977a), as recommended by the International Commission on Radiological Protection (ICRP 1975). Regulatory Guide 1.109 also suggests a breathing rate of 3,700 m^3/yr for children. Unless a receptor is engaged in strenuous activity prior to an accident, the individual's breathing rate is expected to be near the average. A summary of breathing rate information relating to age and physical activity can be found in Snyder et al. (1994).

The Health Risk Factors option allows the user to select among the dose-to-health risk conversion factors for estimating latent health effects. The effects estimated are the number of nonfatal cancer cases per person-rem, the number of fatal cancers per person-rem, and the number of adverse genetic effects per person-rem. Cancer incidence and fatalities are determined over the lifetime of the exposed population. Genetic effects occur in descendants of the exposed population. For individual receptors, these latent health results represent the probability of occurrence for the dose received. The conversion factors used in RISKIND are those recommended by the ICRP (ICRP 1991). Two conversion factor options are available, one for workers and another for the general public. The factors used for workers are slightly lower than those for the general public because the worker population is expected to be in better physical condition. Table 4.4 lists the values used. If a receptor receives more than a 20-rem dose, the risk conversion factors are doubled to account for the better effectiveness of higher dose rates for creating lasting adverse effects (ICRP 1991). Table G.2 compares cancer fatality and genetic effect studies.

Shielding — Exposure is reduced when a receptor is sheltered from radioactive sources such as a passing radioactive materials shipment or ground contamination. RISKIND provides a set of default shielding factors for a variety of shelter types and sources. These shielding factors are listed in Table 3.5 and on-screen and are from the Reactor Safety Study (NRC 1975). These factors are conservative values for a given source and shelter type: 1 represents no shielding,

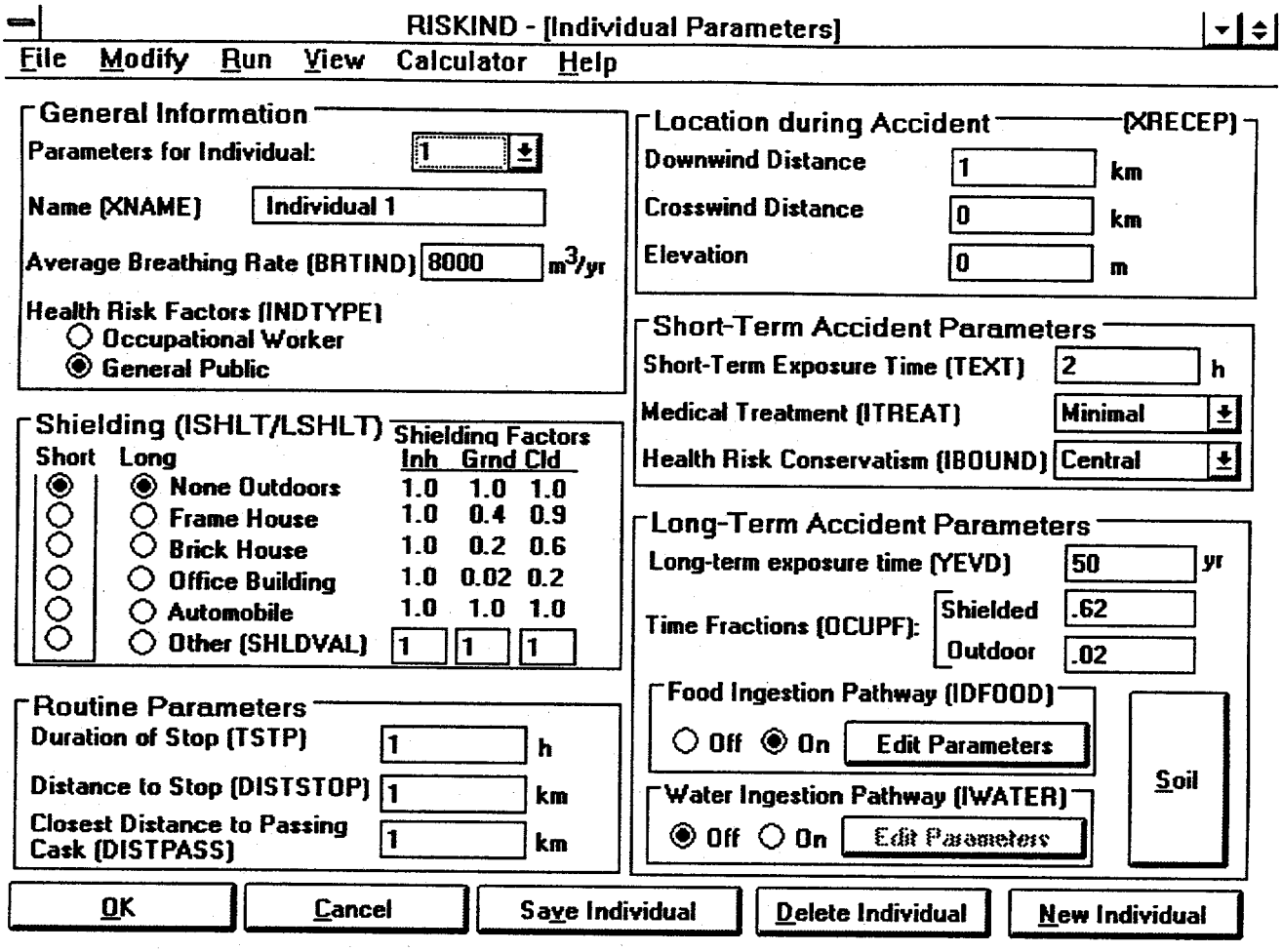

FIGURE G.3 Individual Parameters Window

TABLE G.2 Estimated Lifetime Cancer Mortalities and Genetic Effects

Source of Estimate	Lifetime Cancer Fatalities per 10^6 person-rem	Genetic Effects per Generation per 10^6 person-rem
National Research Council (1990)	790	110-200
UNSCEAR (1986)	700-1,100	119
ICRP (1991)	500	130
EPA (1989b)	390	260

0 represents complete shielding. For external radiation, the shielding provided by a particular structure depends on its construction materials and thickness, location with respect to the receptor and the radioactive source, and the energy of the radiation. For inhalation doses, open windows and the efficiency of ventilation systems at removing airborne contamination must be considered. Because a number of considerations must be taken into account, the user is provided with an option for entering a custom value for each source type if data are available for a particular situation. The short-term value (ISHLT) is used for routine shipment doses (ground source term factor) and for calculations of short-term accident exposure during plume passage immediately following an accident. The long-term value (LSHLT) is used for the long-term accident exposure calculations and is only available when accident calculations are specified.

Routine Parameters — For each individual routine shipment calculation, two doses are estimated, one for the dose received as the shipment passes by the receptor, and the other for the shipment at a fixed location relative to the receptor. A separate distance input is present for each of the two dose calculations (DISTPASS and DISTSTOP). An exposure time input is also needed for the stop calculation (TSTP).

Location during Accident — This box provides the input for situating the individual receptor with respect to the potential accident location (XRECEP) for the calculation of radioactive contamination levels. Only values greater than or equal to zero are acceptable input, because the elevation of the receptor is used in the adjustment of the plume height when considering elevated terrain downwind of the accident site (Section 3.3.1.1.2). If a receptor is located at a lower elevation than the accident site, the accident can be modeled as an elevated release for situations such as an accident on or near a bridge.

Short-Term Accident Parameters — For short-term accident calculations, the exposure time (TEXT) is needed for determining the dose received from external radiation from loss of cask shielding and deposited ground contamination. To estimate any acute health effects, the user may select the level of medical treatment received and the level of conservatism used in the acute dose model described in Section 4. Medical treatment options (ITREAT) are minimal and supportive. Minimal treatment refers to only the administration of basic first aid for any type of physical trauma. Supportive treatment directly counteracts radiation damage through such measures as hospitalization with state-of-the-art antibiotic therapy, blood transfusions, electrolyte replacement, and intravenous feeding. Because of the scarcity of data and some differences in opinion, the acute health effects model (Abrahamson et al. 1989, 1991) incorporates three sets of fixed parameters (IBOUND) for estimating acute effects; one for estimating upper bound responses, another for central estimates, and a third for lower bound estimates. Generally, the central estimates should be selected, unless the user is thoroughly familiar with the model and has reason to use the lower or upper bound estimates.

Long-Term Accident Parameters — Input is provided for the long-term exposure time (YEVD), which has a default of 50 years. This value is taken from the most restrictive of

U.S. Environmental Protection Agency (EPA) long-term protective action guidelines (PAGs), which is a maximum of 5 rem in 50 years (EPA 1991). When considering residential receptors, the average residence time at one location could be used. For the United States, the average time a typical homeowner lives in a house is approximately 9 years; 90% of homeowners live in the same house for 30 years or less (EPA 1989a).

The fractions of the long-term exposure spent indoors (shielded) and outdoors (not shielded) at the individual location are also input (OCUPF). The sum of these two must be less than or equal to 1, but are not required to equal 1 since a portion of the time may be spent at some other location such as work or home. The default values are based on the average time spent at home (EPA 1989a).

Long-term parameters related to the inhalation of resuspended radioactivity, food ingestion, and water intake can be accessed through their respective buttons in this box. The ingestion and water pathways can be turned on or off by selecting the appropriate radio buttons. The ingestion pathway can only be turned on if the population zone is set to rural in the main program window.

G.2.3.2 Population

The Population Parameters window (Figure G.4) is brought up by pushing the Receptor Data button on the main window when population receptors are selected. The Routine On-Link/Stops Parameters button is active in this window if routine calculations are selected. This button brings up the input window of the same name (Figure G.5) that contains input for the population on-link (sharing the transportation route with the shipment) and stops doses.

General Information — The area within the nearest distance (XPZ[1]) and maximum distance (XPZ[2]) to the shipment route is used for both routine shipment and accident calculations. In combination with the distance traveled input (SHIPDIST), a rectangular area is defined and is used for the routine off-link dose estimate calculations. For accident calculations, the area under consideration is defined by the radioactive cloud dimensions in addition to the nearest and farthest distances from the route. The number of people exposed under routine and accident conditions is determined by the affected area and population density (POPD). The population density may be input directly by the user or a state average population density (1990 census) may be selected (DOC 1992). The default population density is the average for rural population zones in the United States (NRC 1977b). If the state average option is selected, the state selected in the main program window determines the average value.

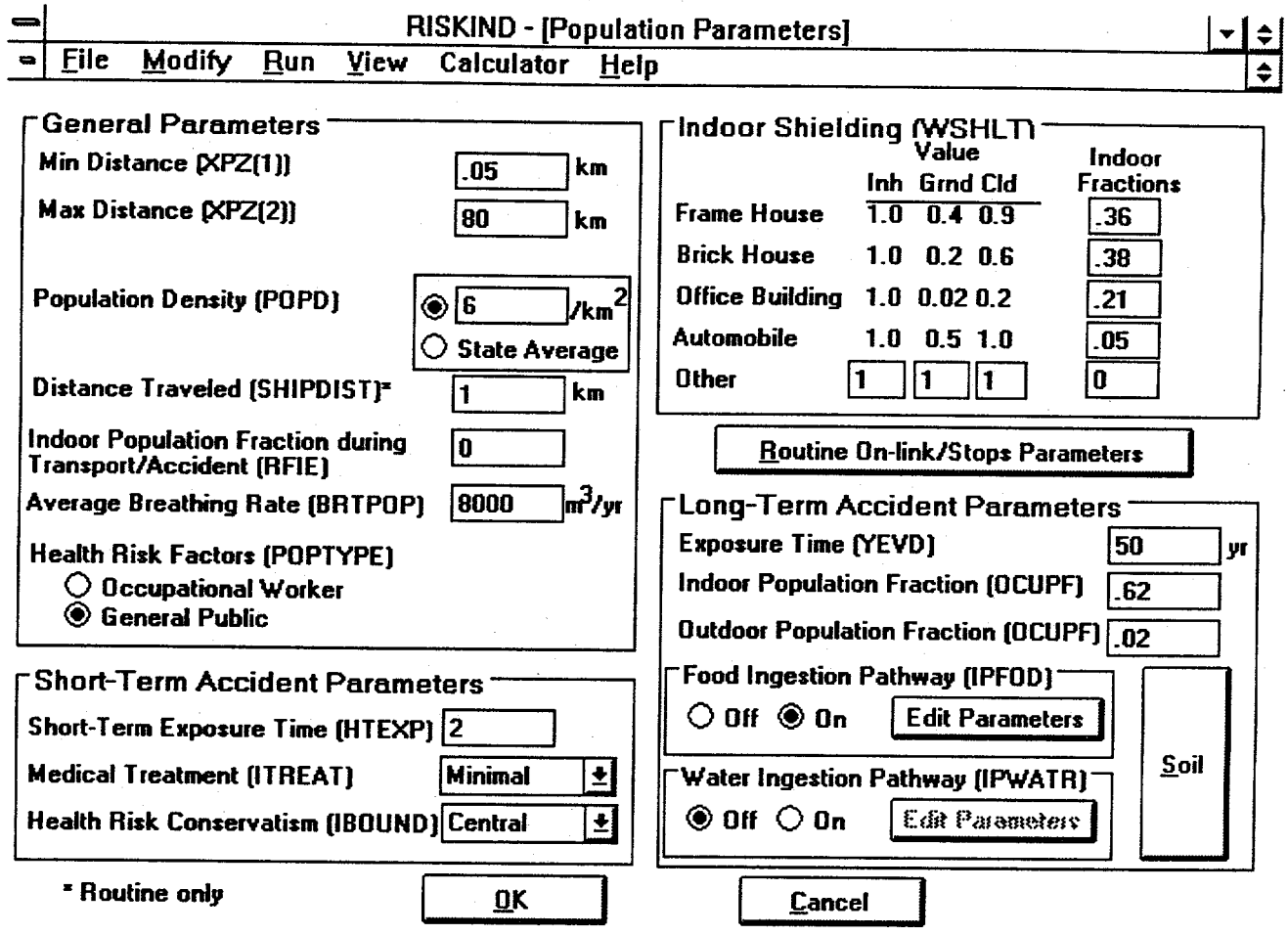

FIGURE G.4 Population Parameters Window

Breathing rates (BRTPOP) and health risk factors (POPTYPE) are discussed in Section G.2.3.1. The indoor population fraction input (RFIE) applies to both routine shipment and accident conditions. The fraction of the population indoors at the time of an accident is given by this input; the shielding is determined by the Indoor Shielding box parameters. The remaining fraction of the population is assumed to be outdoors and unshielded.

Indoor Shielding — The same shielding factors discussed in Section G.2.3.1 are available for population calculations. They are applied slightly differently since a group of persons is involved. For the persons assumed to be indoors, the indoor fractions (WSHLT) relate to the distribution of the indoor population among the different shielding types. Thus, the indoor fractions must sum to 1. This shielding distribution applies to both routine and accident conditions (short- and long-term).

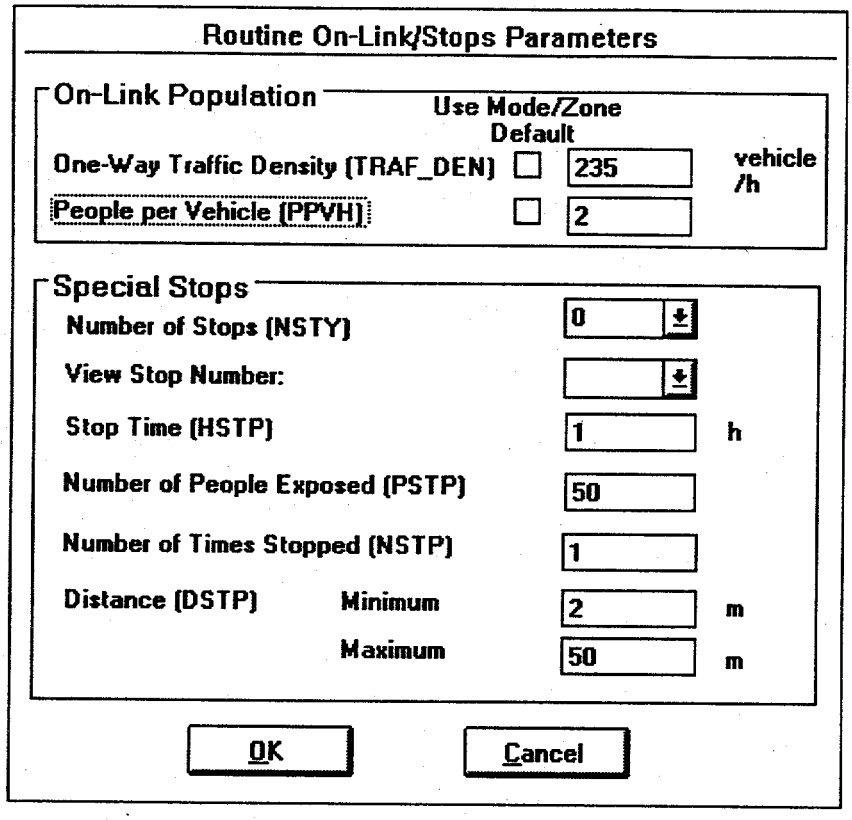

FIGURE G.5 Routine On-Link/Stops Parameters Window

Short-Term Accident Parameters — These input parameters are the same as those discussed in Section G.2.3.1.

Long-Term Accident Parameters — These input parameters are the same as those discussed in Section G.2.3.1.

On-Link Population — Persons sharing the transportation route traveling in the same and opposing directions to a radioactive materials shipment are denoted as the on-link population. Their exposure is dependent on the one-way traffic density (TRAF_DEN) and the number of persons per vehicle (PPVH). The default one-way traffic density of 235 vehicles per hour is per lane for truck transport and is derived from the one-way traffic density in rural zones of 470 vehicles per hour (NRC 1977b), assuming two lanes of travel in each direction. The default value of two persons per vehicle is for truck transport (Neuhauser and Kanipe 1992).

Special Stops — Up to 10 special stops for assessing doses to population subgroups can be input (NSTY). The number of times stopped at such a location (NSTP), the stop time (HSTP), and the number of persons exposed (PSTP) must be input for each of these stop types. The dose calculated for such a stop assumes that the number of persons exposed is distributed

evenly about an annular ring defined by minimum and maximum distances (DSTP) from the shipment.

G.2.3.3 Soil and Resuspension Factors

The Soil and Resuspension Factors window (Figure G.6) is accessed by pressing the Soil button in either the Individual Parameters or Population Parameters windows.

Soil — The soil removal half-life (PHALF) is used in the calculation of long-term ground contamination levels, applies to all radionuclides, and accounts for environmental loss mechanisms in that the radionuclide becomes unavailable for ingestion pathways or resuspension into the air. Such mechanisms include chemical reaction with other soil constituents and wind and water erosion. The RISKIND default value of 50 years is that used in the EPA CAP88-PC program (Parks 1992).

The soil cleanup level input (PAG) is the long-term dose value used by RISKIND for determining cleanup levels for population problems (Section 3.4.4). The value specifies the maximum permissible dose to an individual over the long-term exposure period (YEVD) discussed in Section G.2.3.1.

The EPA has published suggested PAGs dealing with exposure to accidental radioactive releases (EPA 1991). These guidelines deal with the early (short-term) and later (long-term) phases following an accidental release. The early phase is defined as "the period beginning at the projected (or actual) initiation of a release and extending to a few days later, when deposition of airborne materials has ceased and enough information has become available to permit reliable decisions about the need for longer term protection" (EPA 1991). Early phase considerations are not considered in RISKIND because forewarning (i.e., time to mitigate potential exposure) of an accidental transport-related release is not likely, and cleanup is not a short-term mitigative action. Short-term mitigative actions include washing exposed skin and changing clothing, seeking shelter, and evacuation, depending on the situation at hand.

The most restrictive of the longer term guidelines suggests a limit of 5 rem to a single individual over a 50-year exposure period. If the exposure to a single individual in a given population isopleth exceeds the PAG value over the specified time (default for YEVD is 50 years), RISKIND will perform an extra set of calculations for that isopleth to determine the approximate ground concentrations necessary after cleanup needed to stay within the PAG limit. This determination "reduces" the dose from inhalation of resuspended material, groundshine, and ingestion. Short-term doses and water ingestion are not considered in the calculations.

Resuspension Factor — Estimates of resuspended air concentrations for the long-term inhalation and external cloudshine exposure pathways are based on the work in NRC (1974) and Anspaugh et al. 1974 (Equation 3.57). The decay time (RSALF) is the half-life used for

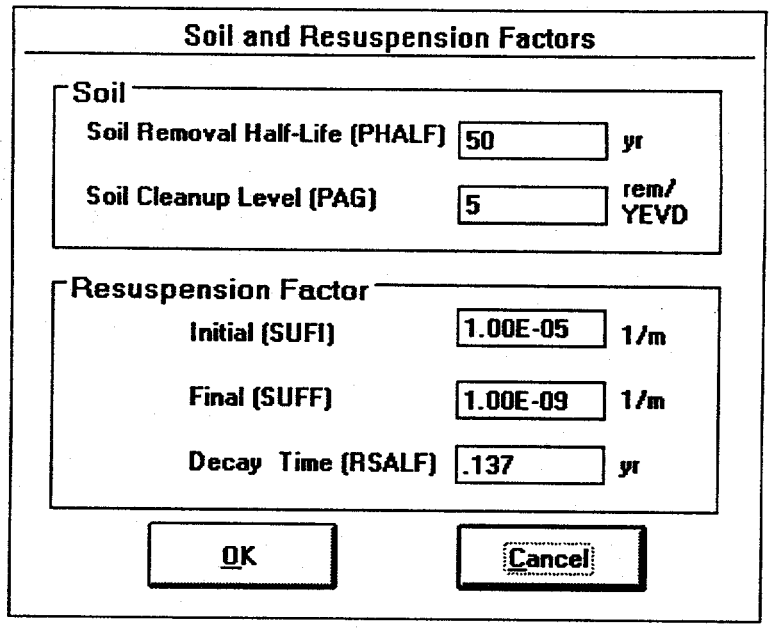

FIGURE G.6 Soil and Resuspension Factors Window

computing the resuspension decay constant (ln 2/RSALF) in the resuspension factor. The resuspension factor has an initial value (SUFI) that decays over a period of time, depending on RSALF (Equation 3.55), and a final value (SUFF) that remains constant over further periods of time. The RISKIND default values used for RSALF, SUFI, and SUFF were taken from NRC (1974).

G.2.3.4 Ingestion

Individual — The Ingestion Parameters window (Figure G.7) is accessed by pressing the Ingestion button in the Individual Parameters window if the ingestion pathway is activated (IDFOOD = 1).

An option is available for throwing away the initially contaminated foodstuffs (IACFOD). If this option is chosen, deposition of radionuclides directly onto vegetation from the initial plume passage is not considered; only vegetation contamination from the root-uptake mechanism and later deposition from resuspended material are taken into account. If not interdicted, initially contaminated foodstuffs are assumed to be consumed at a constant rate over a one-year period following harvest.

The vegetation decontamination factor (DFACT) accounts for external washing of vegetables before consumption. The default value of 0.5 was taken from Parks (1992). Minimum and maximum values of 0.15 and 0.75 have been suggested in Snyder et al. (1994) for iodine on leafy vegetables and fruits.

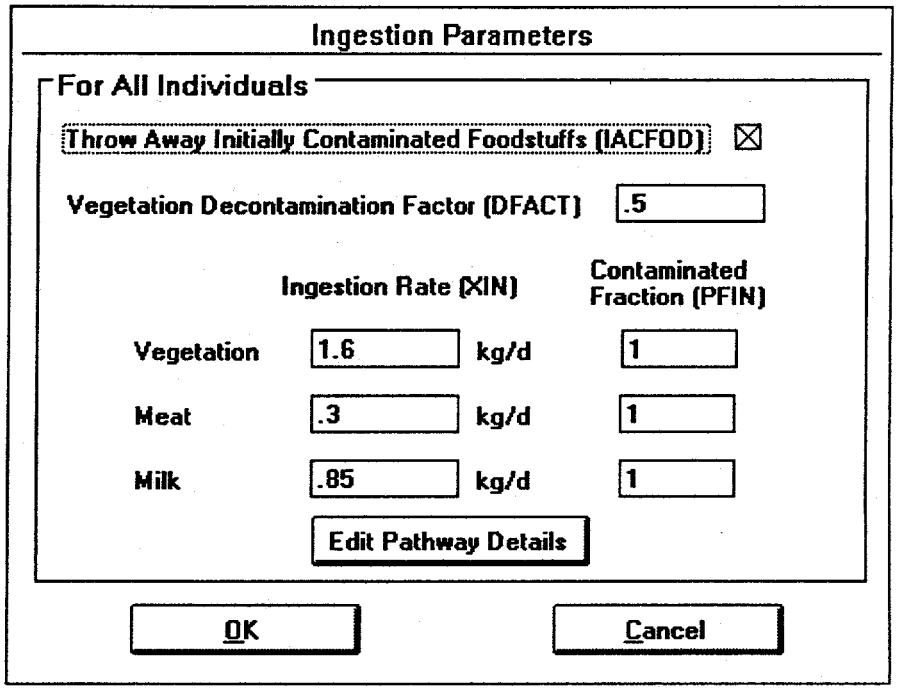

FIGURE G.7 Ingestion Parameters Window

RISKIND considers ingestion of three food types: vegetables, meat, and milk. The default individual ingestion rates (XIN[1 to 3], Table G.3) are taken from NRC Regulatory Guide 1.109 (NRC 1977a). Vegetables includes fruits, vegetables, and grains; meat includes beef and poultry; and milk includes milk and milk by-products. The fraction of contaminated food of each food type eaten (PFIN[1 to 3]) is used to represent that fraction of the food that was grown locally in the contaminated area. The remaining fraction accounts for noncontaminated food that was imported from other regions.

The Ingestion Pathway Details window (Figure G.8) is brought up by pressing the button of the same name in the Ingestion Parameters window. This window contains the input parameters specific to crop contamination. The fraction of contamination that is retained on plants from airborne deposition (F_RETAIN) has a default value of 0.2 (NRC 1977a) for particulates. Activity deposited on plant surfaces decreases over time due to weathering processes. The rate constant used to model these processes (DECAY_WEATHER) has a default value of 0.0495/day, which corresponds to a 14-day half-life (NRC 1977a). Half-lives for weathering processes are typically in the range of 1 to 35 days (Snyder et al. 1994). Radionuclide contaminant concentrations in vegetation result from root uptake from the soil as well as from direct deposition. The effective soil density (EFF_SOIL_DEN) is used in the root uptake calculations. The default value of 240 kg/m^2 is based on a 15-cm plow layer (NRC 1977a).

TABLE G.3 Default Ingestion Rate Values

Food Type	Individual Calculations	Population Calculation
Vegetation (kg/d)	1.6	0.52
Meat (kg/d)	0.30	0.26
Milk (kg/d)	0.85	0.30

Source: NRC (1977a).

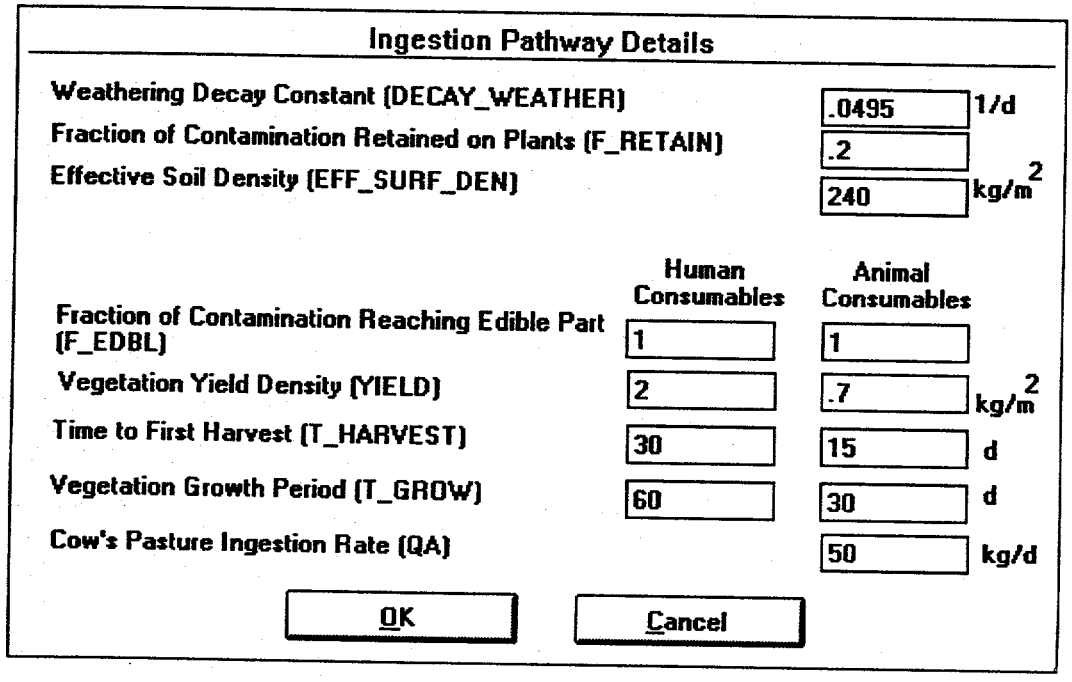

FIGURE G.8 Ingestion Pathway Details Window

Following the model in NRC Regulatory Guide 1.109 (NRC 1977a), two types of vegetation are considered in RISKIND: one for human consumption (fruits, grains, and vegetables) and the other for animal consumption (pasture grass or hay). The time to first harvest following an accidental release for each type (T_HARVEST_HUM or T_HARVEST_COW) is set to half the value given for the normal growing season (vegetation growth period, T_GROW_HUM or T_GROW_COW), since there is no way of predicting the time of an accident. The default growing periods are 60 and 30 days, respectively, for human-consumed vegetation and animal-consumed vegetation with yield densities (YIELD_HUM and YIELD_COW) of 2 and 0.7 kg/m^2 (NRC 1977a), respectively. Most crops have a minimum growing season of about 90 days or less (Kennedy and Strenge 1992). The animal's pasture ingestion rate (QA) is also taken from NRC (1977a).

Population — The ingestion dose for population calculations is a societal dose based on the assumption that all food grown in the contaminated area is eaten, but not necessarily by those living in the local area. The window for population input (Figure G.9) has added parameters for the fraction of land used for farming (FARM) and land productivity for vegetables (GVEGE), meat (GMEAT), and milk (GMILK). These variables have average state-dependent default values (Saricks et al. 1989) specified by the state selected in the RISKIND main window. Vegetable production values in Saricks et al. (1989) include a variety of vegetables, fruits, and grains. Meat production values include beef, pork, poultry, and eggs. Milk production is for the entire amount of milk produced annually. All production values were calculated by using the percentage of land in farms for each state. Production values will be underestimated if the user employs data based on the entire land area for a state or the region of interest. If all food is not assumed to be consumed by humans, the UF(i) input parameter may be reset from 1 to the fraction of each food type *i* produced that is consumed by humans.

With the exception of the vegetation yield density for humans (replaced by GVEGE), all other input remains the same for population ingestion input as for individual ingestion input. Individual food consumption rates and contaminated fractions input are retained for a separate individual estimate to be used in the PAG comparison for each ground concentration isopleth.

G.2.3.5 Water Consumption

The Water Pathway Parameters window (Figure G.10 or G.11 for individual or population, respectively) is accessed by pressing the Edit Parameters button in the Water Ingestion Pathway box in the Individual Parameters or Population Parameters window.

The water pathway option is a simple model intended only for use with relatively small surface water bodies used as drinking water supplies. The water bodies are characterized by their depth and width dimensions (WBDYD and WBDYW) and their exchange rates (WEXCG). The

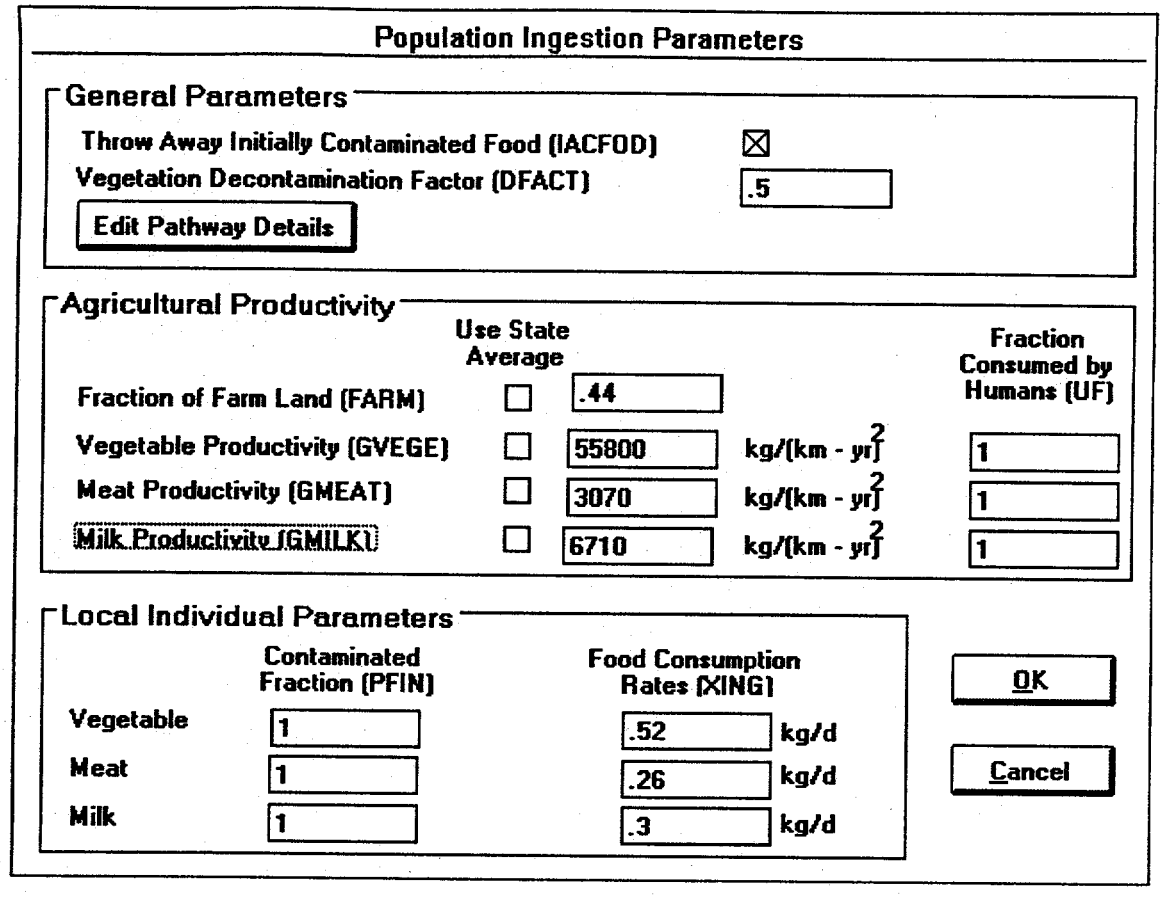

FIGURE G.9 Population Ingestion Parameters Window

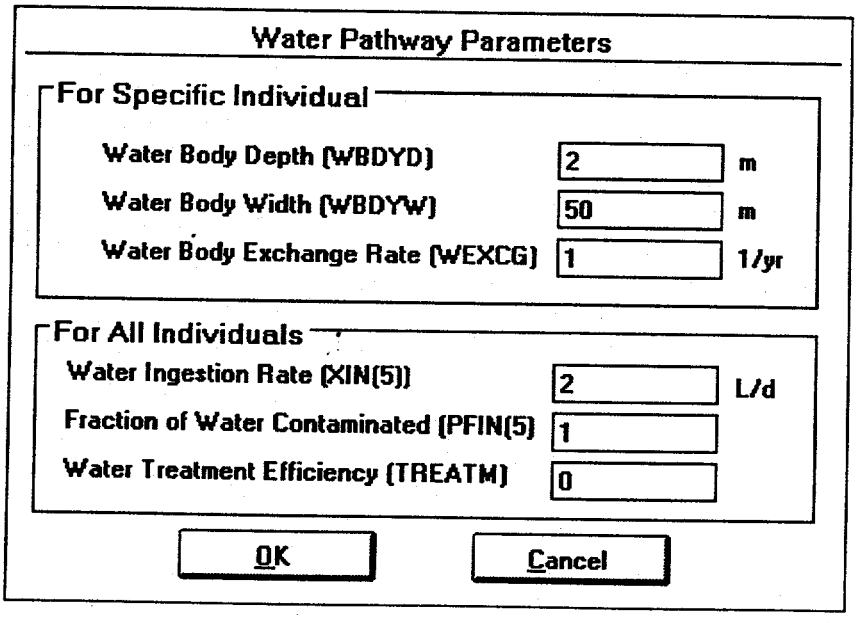

FIGURE G.10 Water Pathway Parameters Window

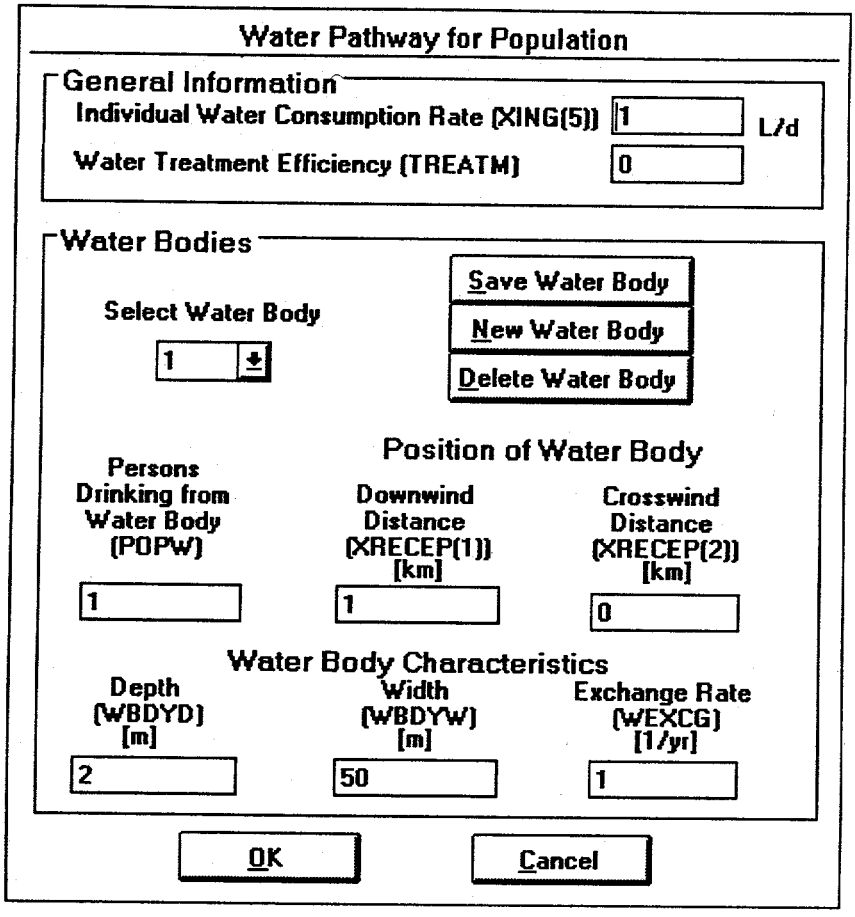

FIGURE G.11 Water Pathway for Population Window

exchange rates should be based on the amount of average water in the system and its replenishment with uncontaminated water from rivers or underground sources. Consumption of the water is characterized by the individual consumption rate (XIN[5] or XING[5]) and the water treatment efficiency (TREATM) of the water delivery system. A treatment efficiency of 0 represents no treatment; an efficiency of 1 represents complete decontamination.

For individual receptor estimates, the drinking water body is assumed to be at the location of each individual; the fraction of water consumed by the individual that is from the local contaminated source (PFIN[5]) is also input. For population estimates, up to 20 water bodies may be specified, each characterized by location (XRECEP[1,j], XRECEP[2,j]) and the number of persons drinking from it. The sole source of drinking water is assumed to be the contaminated water body for population calculations.

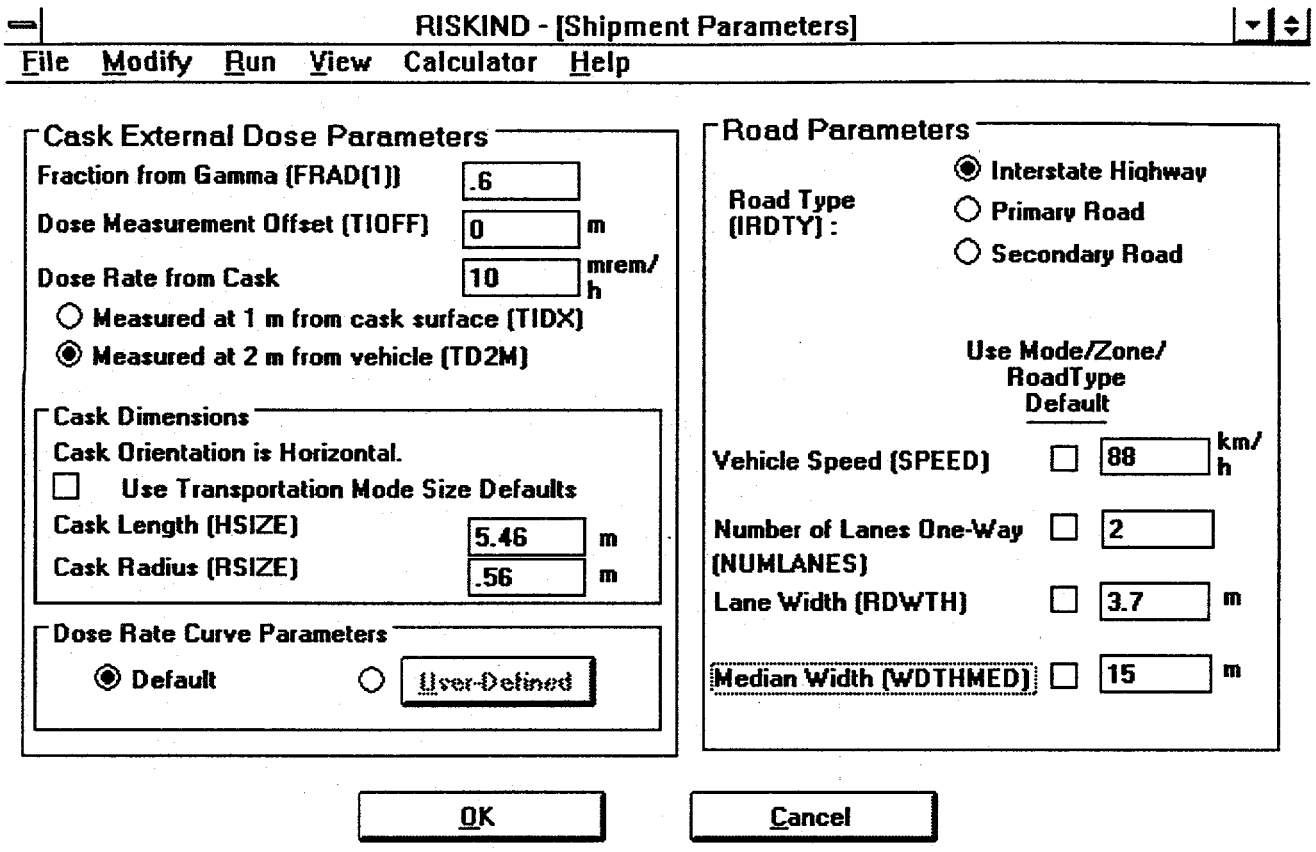

FIGURE G.12 Shipment Parameters Window for Truck Transportation Mode

G.2.4 Shipment Parameters

User input for the shipping cask external dose rate variables and route data are contained in the Shipping Parameters window (Figures G.12 and G.13), which is accessed by pressing the Shipment Data button in the main RISKIND window.

G.2.4.1 Cask External Dose Parameters

The shipping cask length (HSIZE) and width (RSIZE) input parameters are used in both routine and accident calculations. For routine calculations, these parameters are used to adjust the dose rate from the cask, according to the cask's size, by using the method in Appendix B if the shape factor option is selected (discussed below). The fraction of the external dose rate due to gamma radiation is specified with FRAD(1); the balance is assumed to come from neutron radiation. For accident calculations, the cask dimensions are used to estimate the initial size of the radioactive cloud at the release (accident) point according to the method described in Section 3.3.1.8. Table G.4 lists a number of cask types and their characteristics. The default dimensions of the cask are taken from the study used to estimate the default dose rate curves

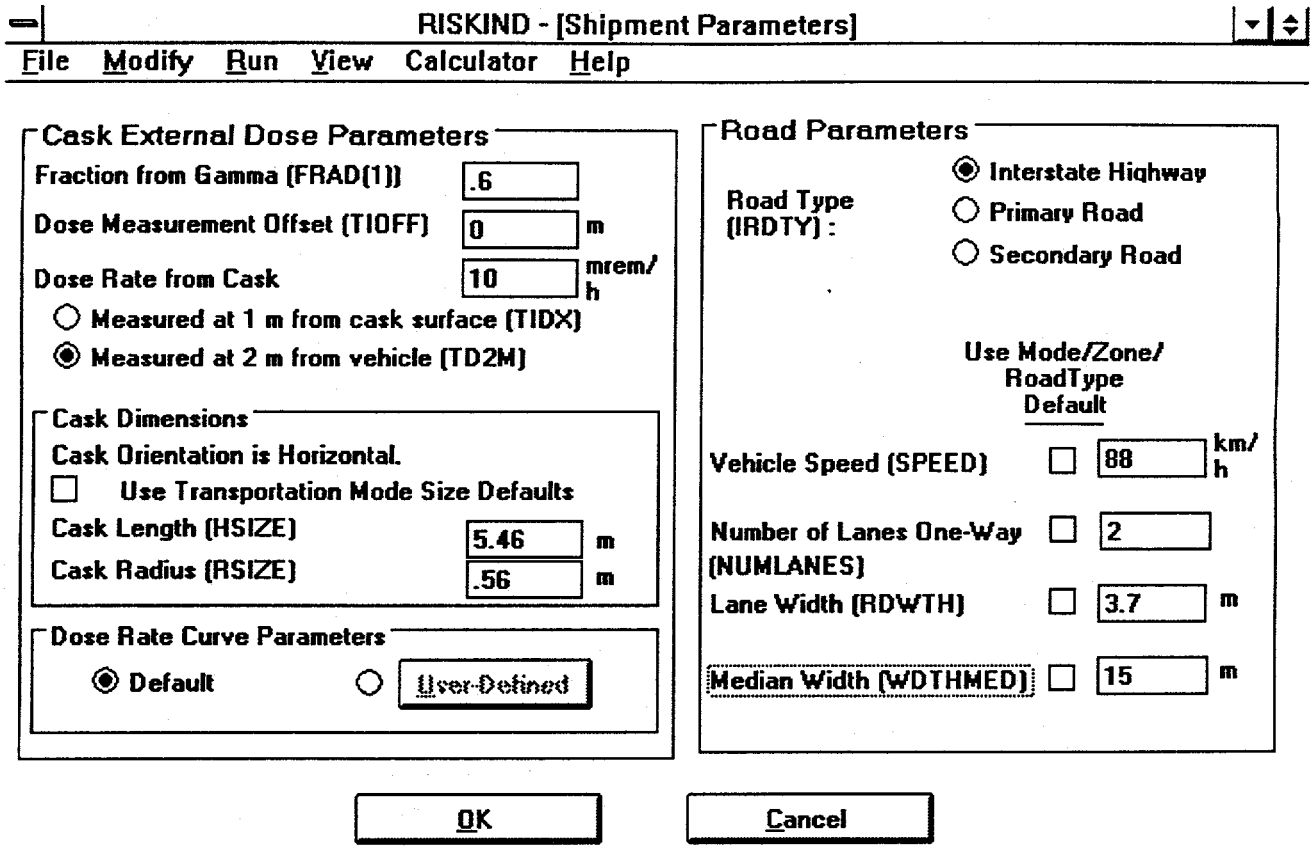

FIGURE G.13 Shipment Parameters Window for Rail Transportation Mode

(Chen and Yuan 1988). If the Use Transportation Mode Size Defaults box is checked, the cask dimensions used in the NRC modal study (LLNL 1987) will be used.

Several improvements have been made since the original release of RISKIND. First, the user input dose rate from the cask can be measured at 1 m from the cask (the only previous option) or 2 m from the transport vehicle, the distance for the regulatory check.[3] Second, another input parameter has been added (TIOFF) to account for the distance from the cask surface to the lateral plane of the transport vehicle from where the regulatory check is made. Previously, the cask surface was assumed to coincide with the outside surface of the transport vehicle. This assumption required that the distance to the cask surface rather than that to the vehicle be used in cases in which the distance from the cask surface to the outside vehicle surface was significant compared to the distance from the receptor to the transport vehicle. All input distances still reference the lateral plane of the vehicle. Old RISKIND input files will run correctly because the default value for the offset distance is set to 0 m. The third improvement to the code is that the

[3] The 10 mrem/h limit at 2 m is according to the specifications of the *Code of Federal Regulations*, Title 10, Part 71 (NRC 1994b), and Title 49, Part 173, (DOT 1994).

TABLE G.4 Comparison of Preliminary Design Characteristics of DOE Initiative I and NRC Modal Study SNF Transportation Casks

Cask Type	GA-4 Cask (truck)	GA-9 Cask (truck)	BR-100 Cask (rail/ barge)	BR-100 Cask (rail/ barge)	NRC Modal Study (truck)	NRC Modal Study (rail)	MPC Conceptual Design (rail)	MPC Conceptual Design (rail)
Fuel type	PWR	BWR	PWR	BWR	PWR	PWR	PWR	BWR
Number of fuel assemblies	4	9	21	52	1	21	21	40
Initial uranium weight (MTU/cask)	1.69	1.59	8.89	9.19	0.46	8.89	10.3	8.0
Length (m)	4.77	5.03	5.13	5.13	6.93	6.93	5.29	5.29
Radius (cm)	50.48	50.48	104.1	104.1	46.4	109	108.6	108.6
Fuel burnup (MWd/MTU)	35,000	30,000	35,000	30,000	33,000	33,000	40,000	40,000
Cooling time (yr)	10	10	10	10	5	5	10[a]	10[a]
Maximum initial enrichment (wt% uranium-235)	4.5	4.5	4.5	4.5	-[b]	-	3.75	3.75
Fraction of gamma radiation[c]	0.83	0.83	0.60	0.48	-	-	-	-
Fraction of neutron radiation[c]	0.17	0.17	0.40	0.52	-	-	-	-

[a] Five years for storage, 10 years for transport.

[b] A hyphen indicates that data are not available

[c] Dose rate fractions estimated at 2 m from the centerline of the casks.

Sources: LLNL (1987), Babcock and Wilcox (1990), General Atomics (1990), and DOE (1994).

default cask external dose rate curves for gamma and neutron radiation now fit empirically to a single equation (Equation 2.2) that can be used to fit any dose rate curve; the curve coefficients may be specified by the user if pertinent dose rate data are available.

G.2.4.2 Dose Rate Curve Parameters

The User-Defined button in the Dose Rate Curve Parameters box accesses the window (Figure G.14) for changing the dose rate curve coefficients (ACOEFU) if the user wishes to use dose rate curves specific to the shipping package and contents. The dose rate curves were developed by using the energy spectrum from a "typical" commercial SNF cask (Chen and Yuan 1988). Nonstandard types of SNF or other radioactive materials can have a much different energy spectrum. The user may also wish to turn off the shape factor correction, that is, the

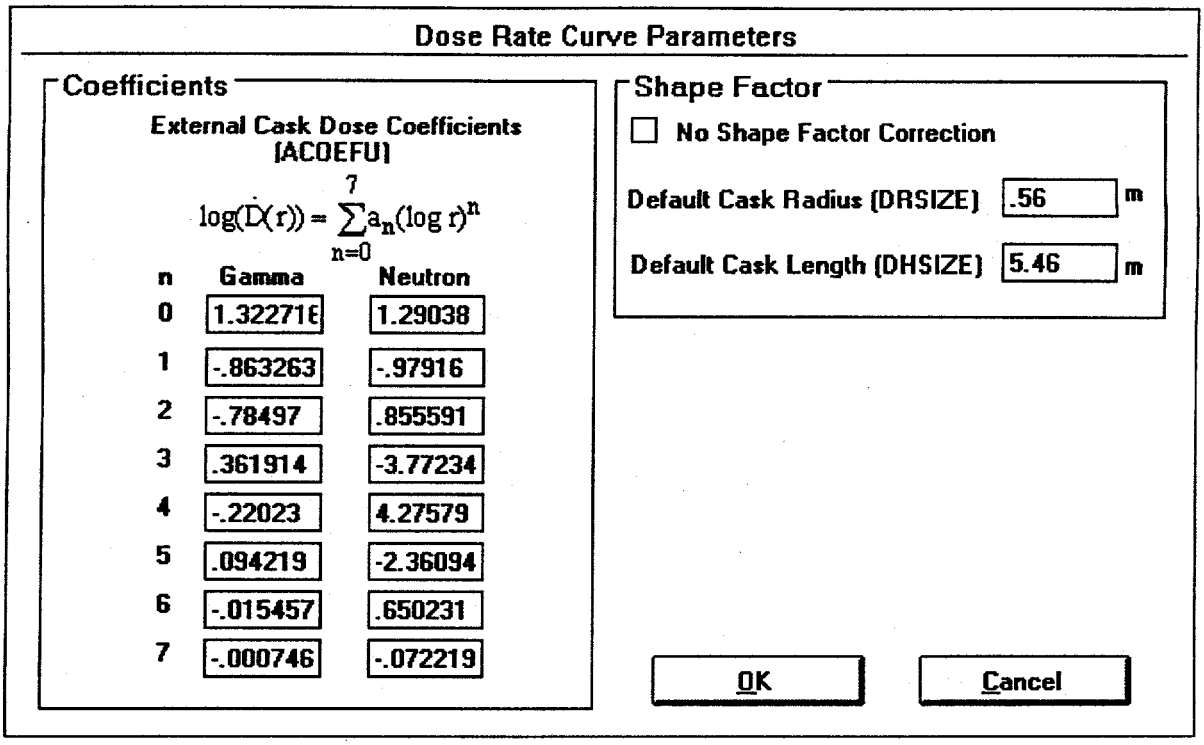

FIGURE G.14 Dose Rate Curve Parameters Window

check box in the Shape Factor box, if using a custom dose rate curve, or change the dimensions of the default cask length (DHSIZE) and radius (DRSIZE) to coincide with the new curve(s). The shape factor correction in RISKIND adjusts the dose rate for the user cask on the basis of a cylindrical surface source configuration, which has the dimensions of the default cask. See Appendix B for details. Table G.5 lists example dose rates and doses received from a GA-4 truck cask.

G.2.4.3 Road Parameters

The road type (IRDTY) input parameter is used in determining a number of data-dependent defaults that include accident rate (ACTA), vehicle speed (SPEED), number of lanes one-way for truck transport or the number of parallel tracks for rail transport (NUMLANES), lane width (RDWTH), and median width for truck transport or track spacing for rail transport (WDTHMED). Tables G.6 and G.7 give the data-dependent values.

The SPEED default is used for estimating routine passing doses to individual and population receptors for both truck and rail transport. It is not available for input when only accident calculations have been specified. The NUMLANES, RDWTH, and WDTHMED parameters are only used for routine population on-link calculations (Section 2.3). For truck

TABLE G.5 Sample of External Dose Information Based on the DOE Initiative I GA-4 Truck Cask[a,b] for a PWR

Interval	Distance (m)	Dose Rate, $\dot{D}$ (mrem/h)	Dose from Passing Shipment, D (mrem)	Population Dose at Stops D_{ps} (person-mrem/h)	Off-Link Population Dose, D_{off} (person-mrem/km)
1	1	2.16E+01	1.15E-01	0.00E+00	0.00E+00
2	2	1.00E+01	8.25E-02	1.33E-04	1.01E-04
3	3	5.68E+00	6.33E-02	2.49E-04	1.69E-04
4	4	3.64E+00	5.08E-02	3.48E-04	2.26E-04
5	5	2.52E+00	4.22E-02	4.33E-04	2.70E-04
6	6	1.84E+00	3.60E-02	5.07E-04	3.12E-04
7	7	1.41E+00	3.12E-02	5.73E-04	3.46E-04
8	8	1.10E+00	2.75E-02	6.32E-04	3.76E-04
9	9	8.89E-01	2.45E-02	6.84E-04	3.95E-04
10	10	7.31E-01	2.21E-02	7.32E-04	4.21E-04
11	12	5.17E-01	1.83E-02	8.17E-04	4.59E-04
12	14	3.83E-01	1.56E-02	8.89E-04	4.92E-04
13	16	2.95E-01	1.34E-02	9.52E-04	5.22E-04
14	18	2.33E-01	1.18E-02	1.01E-03	5.47E-04
15	20	1.88E-01	1.05E-02	1.06E-03	5.70E-04
16	25	1.19E-01	8.04E-03	1.16E-03	6.15E-04
17	30	8.15E-02	6.44E-03	1.25E-03	6.50E-04
18	35	5.87E-02	5.31E-03	1.31E-03	6.79E-04
19	40	4.41E-02	4.46E-03	1.37E-03	7.04E-04
20	45	3.41E-02	3.81E-03	1.42E-03	7.25E-04
21	50	2.70E-02	3.30E-03	1.47E-03	7.43E-04
22	60	1.80E-02	2.55E-03	1.54E-03	7.71E-04
23	70	1.26E-02	2.04E-03	1.60E-03	7.94E-04
24	80	9.23E-03	1.66E-03	1.65E-03	8.12E-04
25	90	6.97E-03	1.37E-03	1.69E-03	8.28E-04
26	100	5.40E-03	1.15E-03	1.72E-03	8.40E-04
27	200	8.39E-04	2.95E-04	1.92E-03	9.00E-04
28	300	2.23E-04	1.02E-04	1.99E-03	9.17E-04
29	400	7.23E-05	3.96E-05	2.01E-03	9.25E-04
30	500	2.59E-05	1.65E-05	2.03E-03	9.27E-04
31	600	9.88E-06	7.32E-06	2.03E-03	9.28E-04
32	700	3.95E-06	3.54E-06	2.03E-03	9.29E-04
33	800	1.64E-06	1.94E-06	2.03E-03	9.29E-04
34	900	7.06E-07	1.25E-06	2.04E-03	9.29E-04
35	1000	3.14E-07	9.78E-07	2.04E-03	9.29E-04

[a] It is assumed that the fraction of the gamma dose (f_g) is equal to 0.83, that the fraction of the neutron dose (f_n) is equal to 0.17, and that the shielding factor is equal to 1. The dose rate is assumed to be the regulatory limit, that is, 10 mrem/h at 2 m from the surface of a GA-4 truck cask.

[b] The dose information contains $\dot{D}$ = dose rate (Equation 2.1), D = dose from passing vehicle (Equation 2.8), D_{ps} = population dose at stops (Equation 2.6) for population density of 1 person/km^2, and D_{off} = off-link population dose (Equation 2.12) for population density of 1 person/km^2 for a distance of 1 km from 30 to 1,000 m on one side of the route. The vehicle speed (V) is assumed to be 1 km/h.

TABLE G.6 Default Route Values for Truck Transportation

Road Type	Population Zone	Vehicle Speed [SPEED] (km/h)	Lane Width [RDWTH] (m)	Number of Lanes in One Direction [NUMLANES]	Median Width [WDTHMED] (m)	One-Way Traffic Density [TRAF_DEN] (Vehicles/h)
Interstate	Rural	88	3.7	2	15	235
	Suburban	88	3.7	2	5	390
	Urban	88	3.7	3	3	930
Primary	Rural	80	3.7	1	0	235
	Suburban	64	3.7	1	0	390
	Urban	48	3.7	2	0	930
Secondary	Rural	72	3.4	1	0	235
	Suburban	48	3.7	1	0	390
	Urban	40	3.7	1	0	930

TABLE G.7 Default Route Values for Rail Transportation

Population Zone	Vehicle Speed [SPEED] (km/h)	Number of Parallel Tracks [NUMLANES]	One-Way Traffic Density [TRAF_DEN] (Vehicles/h)
Rural	64	1	1
Suburban	40	1	5
Urban	24	1	5

transport, SNF shipments are required to use the interstate highway system as much as possible, with some restrictions. Over 90% of the interstate highway system consists of four-lane highways (FHWA 1991) two lanes in each direction (NUMLANES default). The majority of all roads in the United States have lanes that are 12 ft (3.7 m) wide; a few have widths of 9, 10, or 11 ft (2.7, 3.0, or 3.4 m). Median widths vary with population zone and road type and are typically smaller in urban areas where space is at a premium; also, speeds in urban areas may be lower than in rural areas. For rail transport, the route type designations of Total Rail and Mainline Only are used solely for determining default accident rates (Section G.2.6.1). Total Rail includes accidents that occur in rail yards, while Mainline Only excludes rail yard accidents. Track width is not useful for determining the potential location of receptors in a passing railcar for rail transport. A typical railcar width of 3 m (AAR 1974) is used as the rail analogue to the lane width in on-link dose calculations.

G.2.5 Radionuclide Inventory

Depending on the selection in the Inventory Options box in the RISKIND main window, the Inventory Data button on the RISKIND main screen brings up spent fuel parameters (Figure G.15) or a user list of radionuclides and amounts (Figure G.16). The old version of RISKIND had inventories available for commercial BWR or PWR spent fuel. RISKIND, Version 1, maintains this option and also provides for a user-defined inventory.

G.2.5.1 SNF Inventory

The SNF Inventory window (Figure G.15) provides the input parameters used in RISKIND for characterizing the radionuclide inventory for a SNF shipment. Appendix A contains the SNF database description.

Spent Fuel Specifications — Spent fuel is characterized according to its type (RTYPE), BWR or PWR; the burnup (BURNUP), which is a measure of the amount of energy obtained from the fuel; its cooling time (TFUEL), which is the length of time since the fuel has been removed from the reactor; and the amount of uranium initially present (UMT). The majority of SNF assemblies discharged annually from reactors have a burnup near the default value of 35,000 MWd/MTIHM (EIA 1995). Burnups greater than 40,000 and 60,000 MWd/MTIHM for BWR and PWR fuel, respectively, are rare. For cooling times, as of the end of 1993, approximately 40% of BWR spent fuel and 50% of PWR spent fuel in storage were discharged prior to 1986 [EIA 1995]. Shipping casks are licensed by the NRC with restrictions on fuel burnup and cooling time. Most casks are not licensed to ship fuel that has a cooling time less than one year (NRC 1994a).

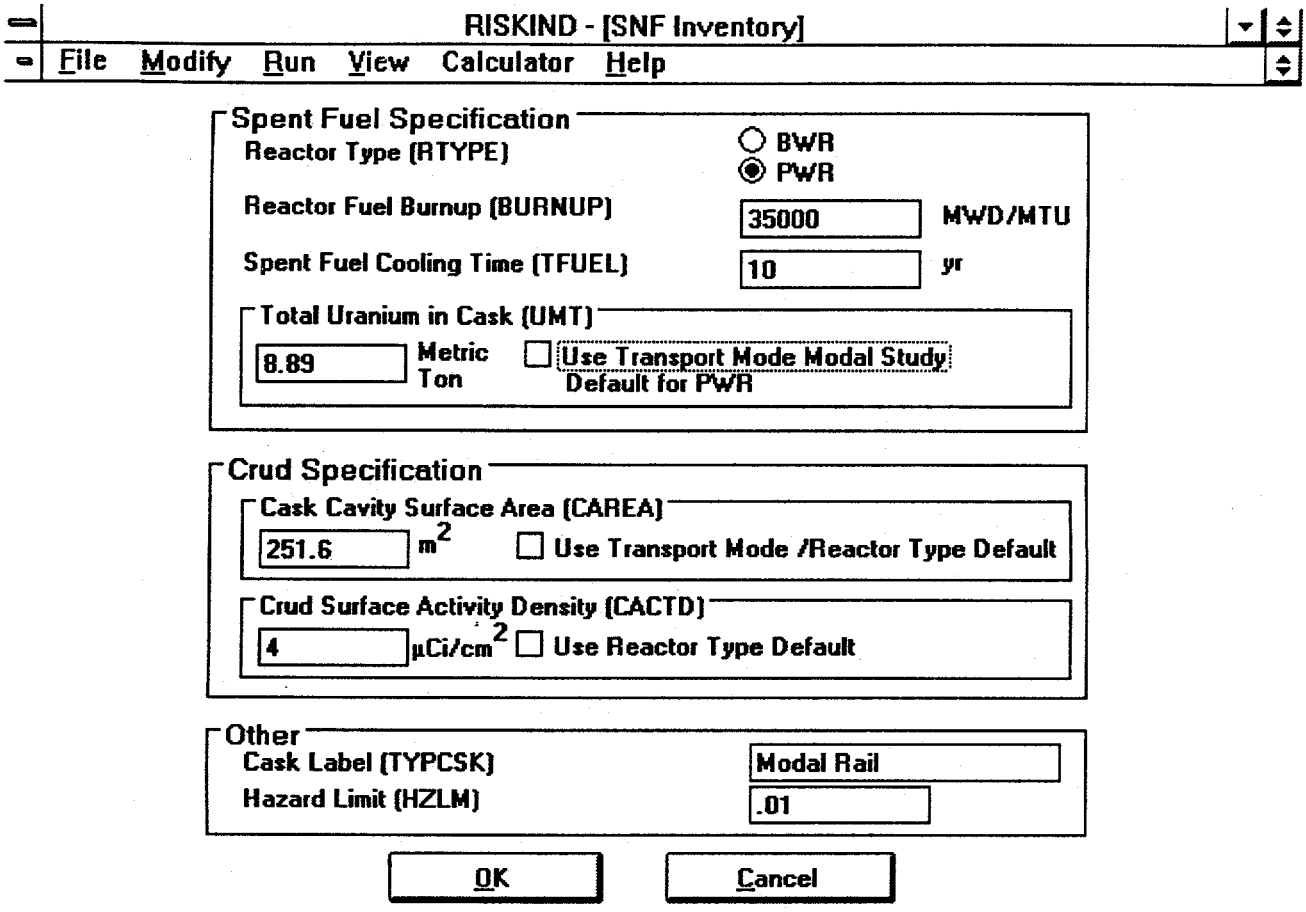

FIGURE G.15 Spent Nuclear Fuel Inventory Window

A typical fuel assembly contains approximately 0.45 (PWR) or 0.20 (BWR) metric tons of uranium (MTU) [EIA 1995]. The total amount of uranium in the shipping cask is the amount per assembly multiplied by the number of assemblies in the cask. Table G.4 contains information on the amount of uranium in a number of different cask types. The default value for UMT is taken from the NRC modal study (LLNL 1987) for the given transportation mode if the default box is checked.

Crud Specifications — In RISKIND, the amount of radioactive material available for release from a SNF shipping cask is considered to be from two sources. The first is the SNF itself, as discussed above, and the second is the crud material, which primarily consists of reactor coolant corrosion products that have deposited on the fuel rods and assemblies. Crud contains mostly neutron-activated nuclides and may also contain fissile materials and fission products. During shipment, crud may spall (break away) from the rods, become airborne in the cask cavity, and be released to the environment should a leak path develop in the cask containment system. The spalling can be caused by impact, vibration, abrasion, or thermal changes. The amount of spalled crud that may be released depends on the crud's adhesion to the fuel rods and assemblies

and its particle size distribution. The amount of crud plated on the spent fuel varies considerably and depends on plant operating conditions and the water chemistry of the reactor and storage pool. The amount of crud material in a cask and the fraction that could be spalled from the rods and assemblies during an accident are estimated on the basis of the method described in a recent Sandia National Laboratories report (Sandoval et al. 1991). The approach used is discussed further in Appendix D, which also contains representative internal cask surface areas and bounding case activity densities. The activity estimated to be in the crud is assumed to be from cobalt-60 and is incorporated in the estimated SNF inventory listed in the RISKIND output.

Other — Other input parameters for SNF inventories are the user-defined label (TYPCSK) and the hazard limit (HZLM). The hazard limit is a radionuclide selection criterion applied to three pathways to reduce the number of radionuclides being considered. Its application is discussed in Appendix C. The radionuclides that are estimated to cause approximately 99% of the potential risk are selected when HZLM = 0.01, the default value. Setting the hazard limit to 0 selects all radionuclides.

G.2.5.2 User-Defined Inventory

The User-Defined Inventory window (Figure G.16) provides the necessary input for defining a custom radionuclide inventory, that is, an inventory for a nonstandard SNF shipment or other type of radioactive material shipment. As was the case for the SNF inventory window discussed above, inputs are provided for a user-defined label and the hazard limit.

RISKIND currently contains a database of 211 radionuclides. Up to 100 radionuclides may be selected for a single analysis. The radionuclides presently selected for an analysis appear with their specified inventory amount and their radionuclide type (category) in the Inventory box. RISKIND recognizes five radionuclide types, which are described in Section G.2.6.

The addition of a radionuclide from the list is accomplished by selecting the desired radionuclide in the Radionuclide droplist box, specifying the appropriate inventory amount in the Amount box, and selecting the radionuclide's type in the Nuclide Type box if the default category is not appropriate for the current application. By pressing the Enter button, the radionuclide is added to the inventory list.

The amount or type of a radionuclide already entered can be edited by selecting the radionuclide in the Inventory list. The radionuclide will be removed from the list and placed in the Edit Inventory box. The radionuclide is then returned to the list, after the appropriate corrections have been made, by pressing the Enter button in the Edit Inventory box. Removal of the item from the list is accomplished according to the same procedure used to get the radionuclide into the Edit Inventory box. A radionuclide's removal from the list is permanent unless it is re-entered from the Edit Inventory box by using the Enter button.

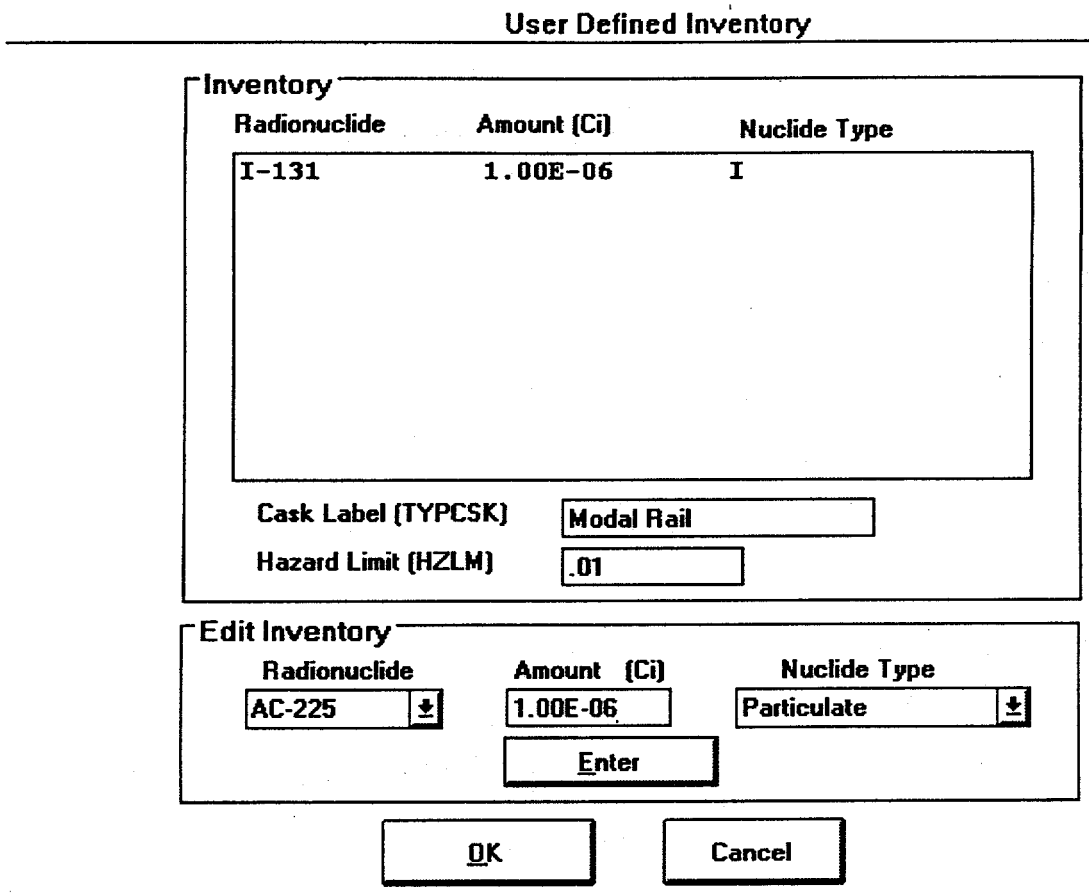

FIGURE G.16 User-Defined Inventory Window

G.2.6 Accident Parameters

Twenty accident response regions constitute the default in RISKIND and correspond to the regions defined in the NRC modal study (LLNL 1987). Stammer et al. (1990) have characterized accident events on the basis of actual or potential situations that result in levels of structural and thermal response, such that at least one event is defined for each of the 20 response regions. The NRC (Lahs 1987) has also provided the predicted cask response to a number of selected historical accident events.

In RISKIND, Version 1, the user is also able to define a custom set of regions (maximum of 20) and the associated input parameters to suit the analysis at hand. The Accident Scenarios box in the main RISKIND window allows the user to choose among defining the accident parameters necessary for estimating the region to use; selecting a particular region to use for the analysis, such as for a consequence analysis; or selecting all regions for a risk analysis.

G.2.6.1 One or All Response Region(s)

The Accident Data button in the main RISKIND window brings up the Accident window (Figure G.17) if one or all response regions is (are) selected.

Accident Specification — If risk calculations are to be performed, the accident rate input (ACTA) for the region under study is provided. The user should use the appropriate site-specific value if it is available or may choose to use a default value based on the state, population zone, and road type for truck transport. For the rail transport mode, the default accident rates are dependent on state and route type. These accident rates are taken from Saricks and Kvitek (1994) and listed in Table G.8. The truck accident rates are for commercial inter-state carriers using heavy combination tractor-trailer rigs. The rail accident rates are for commercial freight trains.

The release height (HS) is the physical release height of escaped material above the ground from an accident. This value could be the cask height or road height, unless other information is available. The default value of 1 m is the approximate height above ground of a cask on a tractor-truck trailer or railcar.

RISKIND, Version 1, makes the dispersion coefficients and the number of concentration isopleths available to the user. The Pasquill-Gifford coefficients were developed from data on ground level releases (Eimutis and Konicek 1972); the Briggs coefficients are based on data from elevated releases. However, Briggs suggests that his coefficients are not appropriate for (effective) release heights much higher than 100 m (Briggs 1974). The original release of RISKIND automatically used the Pasquill-Gifford coefficients for releases less than 30 m in height and Briggs coefficients for releases greater than 30 m in height. Users can now select the original implementation on the basis of the effective release height or choose the desired coefficients to be used on the basis of the situation being analyzed.

Air and ground radionuclide concentration isopleths are calculated for population analyses. For individual analyses, air and ground concentrations are estimated at the actual location of each receptor. The number of isopleths droplist input (NISOPL) appears only for population runs. The difference in concentration between isopleths is maintained as the $\sqrt{10}$, starting at the location of maximum concentration. Thus, the estimated concentration drops by an order of magnitude every second isopleth while moving outward from the area of maximum concentration. A minimum of 4 and a maximum of 20 isopleths may be specified. Ten isopleths (five orders of magnitude) generally cover enough area to include any significant impact. A warning message will appear if isopleth NISOPL+1 would increase the impacts by more than 1%.

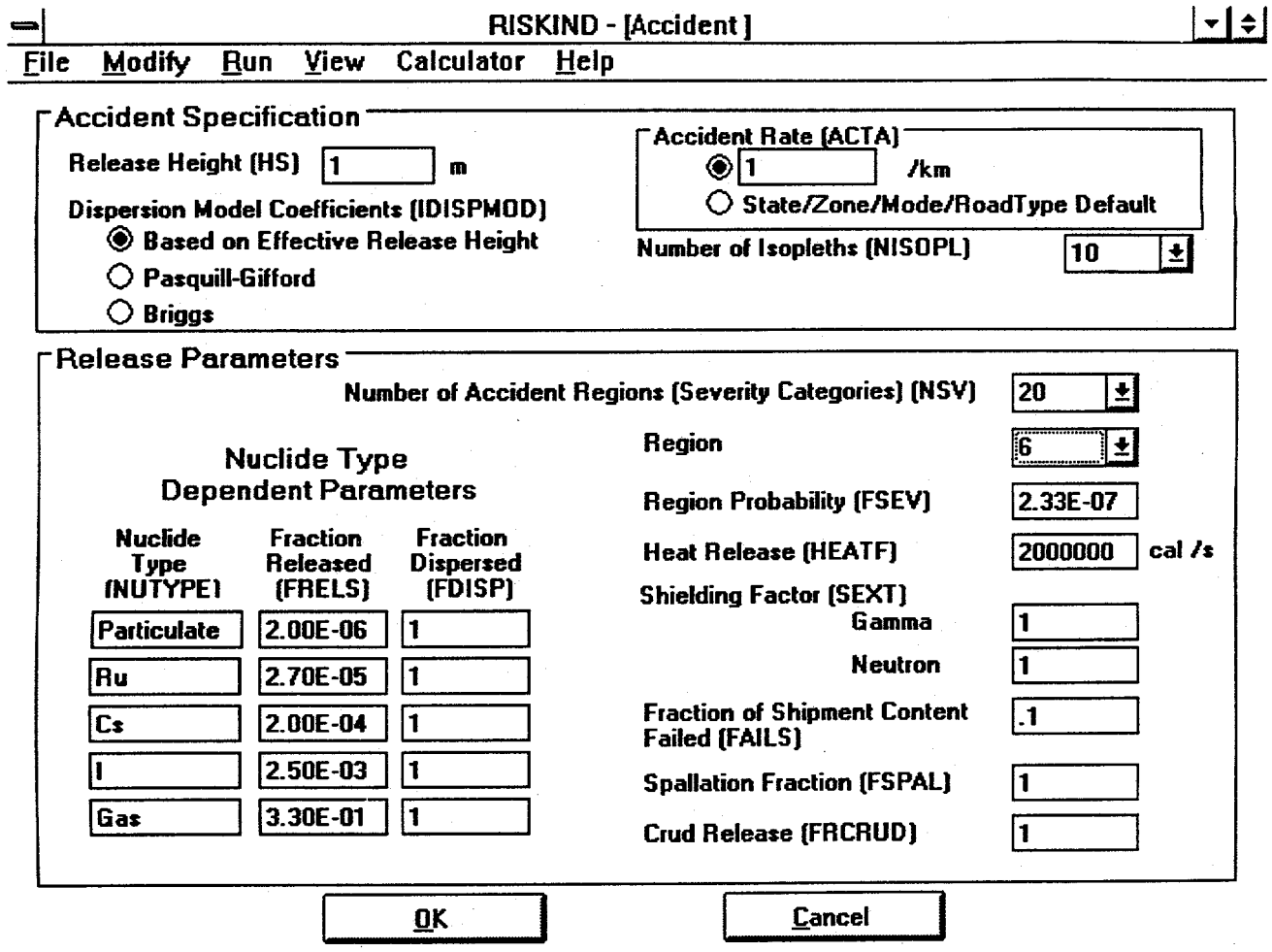

FIGURE G.17 Accident Window

Release Parameters — The Release Parameters box contains the relevant input for defining an accident response region, that is, the conditional probability and the released and dispersed fractions of the SNF and crud inventories. The fraction released (FRELS) and dispersed (FDISP) of the SNF inventory are given for five radionuclide types with different physical characteristics: particulates, vapors (ruthenium, cesium, and iodine), and gases (LLNL 1987). Because this categorization may not be appropriate for a shipment inventory other than SNF, RISKIND, Version 1, allows the user to redefine the radionuclide type labels (NUTYPE) as well as the values for release and dispersion. A maximum of five radionuclide types is allowed. The user may also switch the type for a particular radionuclide in the User-Defined Inventory window (Section G.2.5.2), and, therefore, account for different speciations of the same radionuclide under different conditions. The radionuclide categorization also affects the deposition velocity for individual calculations (Section G.2.7.1).

TABLE G.8 Default Accident Rates for Truck and Rail Transportation

	Truck (accidents/shipment-km)				Rail (accidents/railcar-km)	
	Interstate					
State	Rural	Suburb/Urban	Primary	Secondary	Total	Mainline Only
AL	1.26E-07	4.68E-07	5.16E-07	3.96E-07	4.80E-08	2.75E-08
AZ	1.60E-07	2.71E-07	2.12E-07	1.45E-07	1.75E-08	1.30E-08
AR	1.73E-07	4.82E-07	4.69E-07	6.84E-07	6.78E-08	3.54E-08
CA	1.64E-07	1.92E-07	1.15E-07	2.22E-07	5.10E-08	2.51E-08
CO	2.76E-07	6.28E-07	4.11E-07	4.42E-07	1.73E-08	1.02E-08
CT	4.60E-07	2.67E-07	2.56E-07	9.09E-07	2.83E-07	1.01E-07
DE	0.00E+00	2.56E-07	7.35E-07	4.81E-07	1.77E-07	1.11E-07
FL	1.21E-07	2.25E-07	3.73E-07	6.33E-07	4.02E-08	2.21E-08
GA	1.65E-07	4.87E-07	6.15E-07	4.04E-07	6.44E-08	2.84E-08
ID	2.30E-07	1.73E-07	4.93E-07	2.29E-07	7.01E-08	4.14E-08
IL	1.76E-07	8.75E-07	6.40E-07	1.78E-07	1.07E-07	2.97E-08
IN	1.92E-07	4.58E-07	4.72E-07	2.80E-07	4.64E-08	1.93E-08
IA	1.78E-07	3.54E-07	4.03E-07	1.24E-07	1.47E-07	7.16E-08
KS	2.04E-07	4.48E-07	5.11E-07	1.38E-07	3.61E-08	1.75E-08
KY	1.46E-07	5.13E-07	5.74E-07	8.80E-07	4.48E-08	2.44E-08
LA	1.30E-07	3.54E-07	3.53E-07	2.39E-07	1.24E-07	4.28E-08
ME	2.44E-07	9.03E-07	5.44E-07	2.28E-07	3.78E-07	1.85E-07
MD	3.95E-07	3.08E-07	3.56E-07	1.24E-06	5.62E-08	2.58E-08
MA	6.47E-07	1.42E-07	3.43E-07	4.61E-06	1.16E-07	4.97E-08
MI	1.59E-07	3.16E-07	2.68E-07	8.10E-08	1.65E-07	7.19E-08
MN	2.06E-07	2.66E-07	4.19E-07	2.16E-07	8.48E-08	3.16E-08
MS	1.19E-07	2.01E-07	4.48E-07	6.50E-08	1.15E-07	8.51E-08
MO	1.78E-07	5.18E-07	5.36E-07	2.49E-07	5.28E-08	2.56E-08
MT	2.52E-07	1.00E-06	5.38E-07	1.02E-07	1.73E-08	1.10E-08
NE	1.77E-07	6.97E-07	3.62E-07	9.90E-08	4.63E-08	2.56E-08
NV	1.57E-07	6.33E-07	4.35E-07	3.17E-07	3.23E-08	2.19E-08
NH	1.39E-07	2.20E-08	4.36E-07	3.33E-07	2.15E-07	1.72E-07
NJ	7.65E-07	2.77E-07	6.80E-07	9.69E-07	1.24E-07	4.82E-08
NM	1.92E-07	9.64E-07	4.77E-07	1.22E-06	9.40E-09	6.60E-09
NY	2.93E-07	5.69E-07	3.16E-07	9.48E-07	8.32E-08	4.30E-08
NC	2.28E-07	5.92E-07	5.17E-07	6.37E-07	5.70E-08	2.27E-08
ND	9.90E-08	4.40E-07	1.99E-07	4.00E-08	2.41E-08	1.80E-08
OH	2.27E-07	3.16E-07	4.42E-07	1.10E-06	4.73E-08	2.12E-08
OK	1.47E-07	3.76E-07	3.61E-07	1.73E-07	4.66E-08	2.72E-08
OR	2.20E-07	3.99E-07	4.17E-07	1.63E-07	1.25E-07	5.77E-08
PA	3.60E-07	3.02E-07	7.21E-07	7.92E-07	4.38E-08	2.69E-08
RI	1.98E-07	2.27E-07	1.37E-07	1.67E-06	1.05E-06	0.00E+00
SC	1.83E-07	3.13E-07	6.27E-07	2.27E-07	5.11E-08	3.31E-08
SD	2.09E-07	8.57E-07	3.94E-07	1.49E-07	1.02E-07	9.09E-08
TN	1.48E-07	7.97E-07	5.56E-07	6.26E-07	5.59E-08	1.88E-08
TX	1.56E-07	2.74E-07	2.78E-07	1.09E-07	7.12E-08	3.16E-08
UT	2.41E-07	2.52E-07	3.70E-07	5.00E-07	5.78E-08	2.31E-08
VT	1.38E-07	0.00E+00	6.30E-07	6.80E-07	1.52E-07	1.16E-07
VA	2.54E-07	2.63E-07	4.67E-07	5.03E-07	4.35E-08	1.91E-08

TABLE G.8 (Cont.)

	Truck (accidents/shipment-km)				Rail (accidents/railcar-km)	
	Interstate					
State	Rural	Suburb/Urban	Primary	Secondary	Total	Mainline Only
WA	2.50E-07	1.61E-07	2.62E-07	7.30E-08	3.49E-08	1.44E-08
WV	3.10E-07	2.95E-07	1.17E-06	7.87E-07	9.61E-08	7.42E-08
WI	1.74E-07	5.29E-07	2.80E-07	3.24E-07	1.65E-07	7.66E-08
WY	3.42E-07	2.98E-07	3.41E-07	3.70E-07	3.10E-08	1.97E-08
US	2.03E-07	3.58E-07	3.94E-07	3.48E-07	5.57E-08	2.66E-08

Source: Saricks and Kvitek (1994).

The amount of inventory released to the atmosphere is characterized by how many rods fail; how much of the inventory in the failed rods is released to the cask cavity; and finally, how much of the released material in the cask cavity is dispersed to the environment through a compromised cask containment system. The fraction of the shipment content failed (FAILS) is the fraction of failed spent fuel rods in a SNF cask. It can be used for the fraction of failed packages in a multiple package shipment of other radioactive materials. The default values are from the NRC modal study (LLNL 1987). The fraction released (FRELS) is the fraction of the SNF inventory released from failed rods to the cask cavity. However, it can be used as the fraction released from the shipping package for other radioactive material shipments. Default values are from the NRC modal study (LLNL 1987). The dispersed fraction (FDISP) is the fraction of the released SNF inventory dispersed to the atmosphere as a respirable aerosol for the given accident response region. Default values are based on the NRC modal study (LLNL 1987).

The number of accident regions input (NSV) is only available if the risk over all regions was selected in the Accident Scenarios box in the main window. The default value taken from the NRC modal study is 20. Up to 20 accident regions may be defined for a custom set of accident severity categories, such as the 8 defined in NUREG-0170 (NRC 1977b). The conditional probability for a given accident response region (FSEV) is only available if a risk analysis was specified in the main RISKIND window. These default values were also taken from the NRC modal study (LLNL 1987).

The heat flux generated for an accident response region (HEATF) is used to determine the effective release height of the radioactive cloud from buoyant plume rise (Section 3.3.1.1.1). The default values are somewhat subjective and will vary with the particular aspects of an accident; especially on wind speed, the amount of diesel fuel or other combustible available for combustion, and whether or not fuel tanks were ruptured. Accidents not involving fire were given a small default heat flux (500 cal/s) to account for the thermal properties of the SNF

assemblies. For perspective, a 2×10^6 cal/s heat flux corresponds to a burn rate of approximately 1 gal/min on the basis of a heat content of 1.07×10^{-4} cal/g and a density of 11.3 kg/gal (CRC 1970) for diesel fuel.

If a SNF inventory was specified, input for the shielding factor (SEXT), spallation fraction (FSPAL), and crud release (FRCRUD) are provided. The shielding factor is the multiple increase of the original cask external dose rate due to loss of shielding in an accident such as lead slump in some casks as a result of fire. The default values are set to 1 for lack of data. This input option is made available for situations in which some information is available on the external dose rate following an accident. The spallation fraction and crud release input are discussed in Appendix D. The default values are taken from Sandoval et al. (1991).

G.2.6.2 User-Defined Scenario

The Defined Accident Scenario window (Figure G.18) is accessed through the Accident Data button on the main window, if a user-defined scenario is selected. This window provides the necessary input for determining the accident response region to which an accident scenario belongs. The rationale used in RISKIND for this determination is taken from the NRC modal study (LLNL 1987) and is provided in Appendix E.

Impact Parameters — The input variables required are the cask impact velocity (VCASK), impact angle (ALPHA), orientation angle (BETA), and impact object hardness (IHARD) for the impact parameters. The default cask velocity is set to 65 km/h because approximately half of all truck accidents occur in the 51-84 km/h range, and 32% occur within approximately the same range for rail (NRC 1974). The NRC modal study also limited this value to a maximum of 241 km/h (150 mph), since it was argued that greater speeds for SNF shipments are not credible. Default values of 90° for the impact and orientation angles (head-on collision) and an unyielding value for impact object hardness were chosen to provide the most conservative results. The impact object hardness values are representative of water (very soft), tillable soil (soft), hard soil/soft rock (medium), and hard rock (unyielding) (LLNL 1987).

Fire Parameters — Fire-related parameters include the flame temperature (TFLAME), fire duration (DFIRE), and fire location relative to the shipping cask (FLOCA). The default flame temperature was given a value of 1,350 K, since approximately 70% of fires expected in transportation accidents will not achieve temperatures more than 1,350 K (LLNL 1987). Approximately 75-80% of expected truck/truck and truck/train accident fires and 75% of rail accident fires are expected to last 0.75 hours (the RISKIND default) or less (LLNL 1987). The default fire location is set to that for an engulfing fire (0 m).

When data input to the Defined Accident Scenario window is completed, clicking on the OK button will save this data internally and bring up the Scenario Category window (Figure G.19), which will display the accident response region selected on the basis of the above

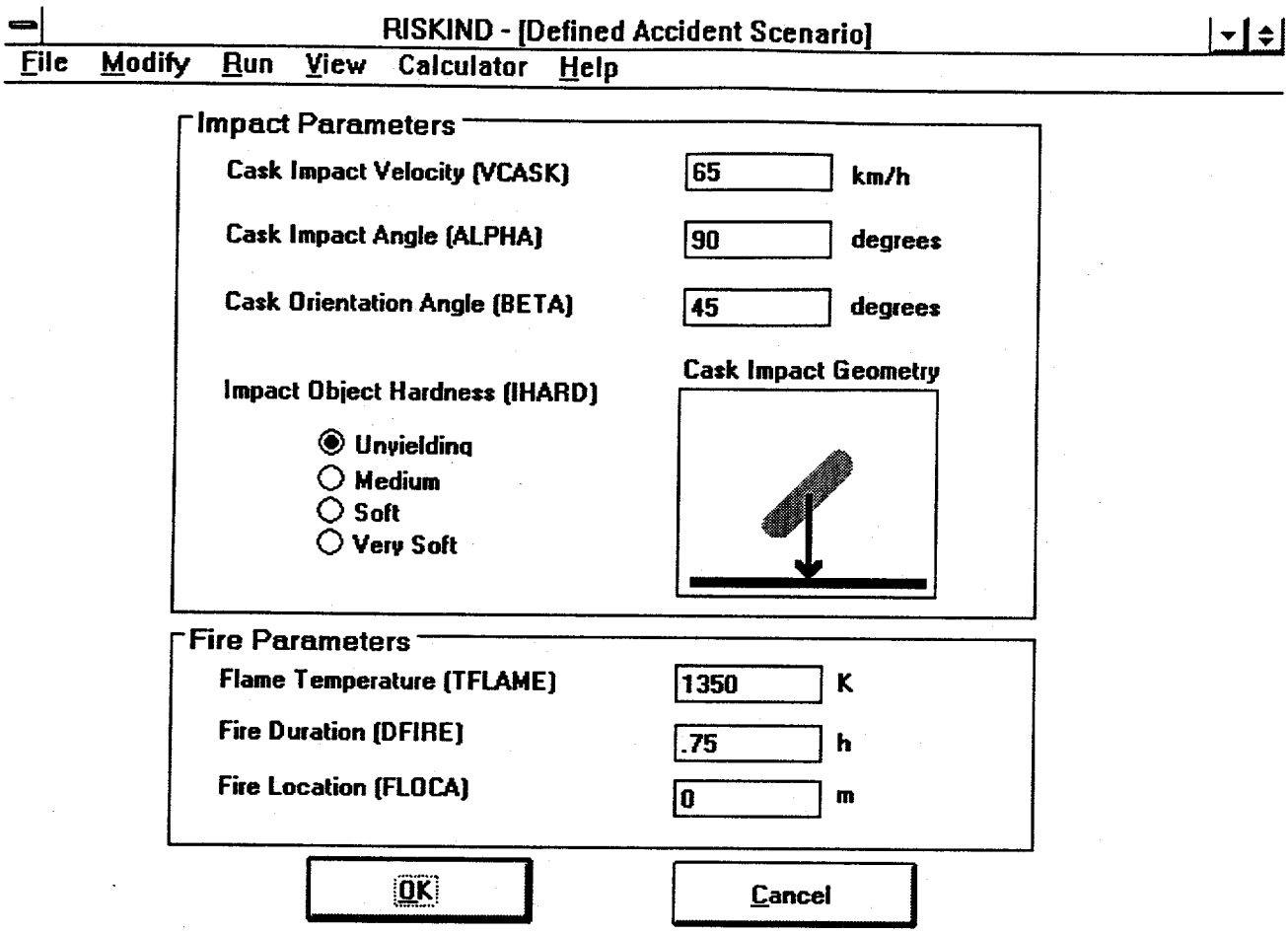

FIGURE G.18 Defined Accident Scenario Window

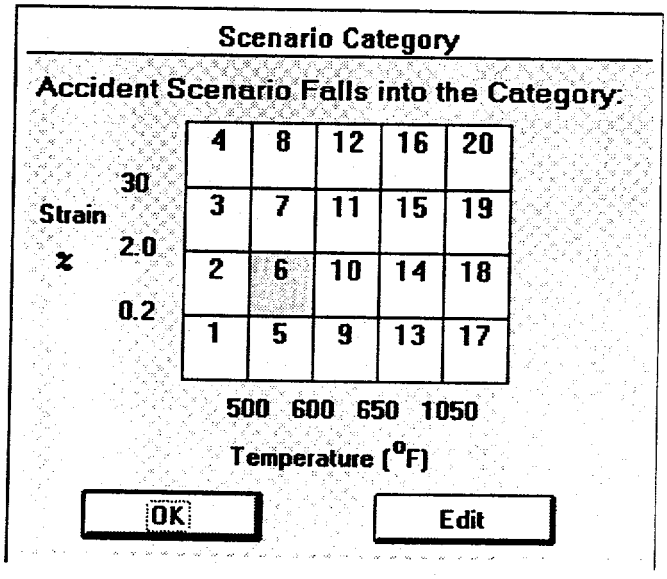

FIGURE G.19 Scenario Category Window

user input. Pressing the OK button on the Scenario Category window puts the user in the Accident window, which has a button (Edit Accident Scenario) for returning to the Defined Accident Scenario window; the Edit button puts the user back into the Defined Accident Scenario window.

G.2.7 Meteorological Parameters

Calculations may be performed by using one set of weather conditions (i.e., one stability class and wind speed) for a consequence assessment, or calculations may be performed over all possible combinations of stability classes and wind speeds ($6 \times 6 = 36$) for a probabilistic risk assessment.

G.2.7.1 User-Defined Weather

In the main RISKIND window, the User-Defined Weather selection in the Weather options box displays the Defined Meteorology window (Figure G.20), when the Met Data button is pressed.

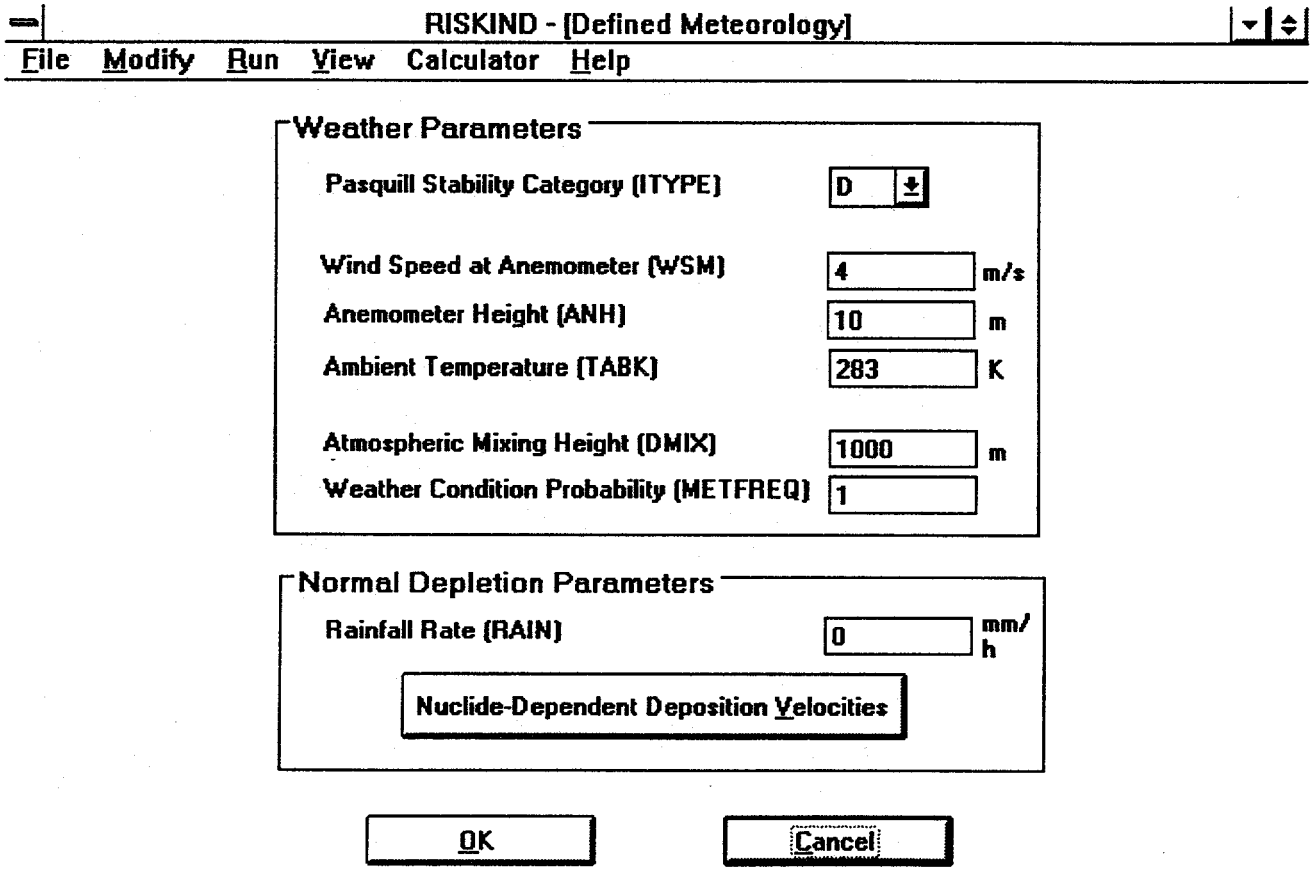

FIGURE G.20 Defined Meteorology Window

Weather Parameters — The primary weather parameters required by the Gaussian puff dispersion model used in RISKIND are the Pasquill weather stability category (ITYPE) and the wind speed at the effective release height. The wind speed at the effective release height is estimated on the basis of wind speed (WSM) measured at a given anemometer height (ANH). The D stability category is the default in RISKIND since neutral stability classes are, on average, prevalent about 50% of the time across the United States (Doty et al. 1976). A default wind speed of 4 m/s was selected because the 4.47 m/s wind speed category in most STability ARray (STAR) data has the highest frequency of occurrence. A standard height for wind speed measurements is 10 m (NRC 1972).

The ambient outside temperature (TABK) is used for plume rise estimates and has a default value of 283 K (Parks 1992). The atmospheric mixing height (DMIX) is assumed to reflect the rising radioactive puff, if the puff reaches that height, causing a total vertical mixing condition of the puff between the ground and mixing height. The default value of 1,000 m is taken from Parks (1992). Depending on the time of day, season of the year, and location in the United States, the mixing height can range from tens of meters to greater than 4,000 m above ground level (Holzworth 1972). The probability of the weather condition occurring (METFREQ) as defined with the above parameters is only available when a risk analysis is selected in the main RISKIND window.

Normal Depletion Parameters — The radioactive cloud released during an accident is gradually depleted due to dry and wet deposition (Section 3.3.1.5.3). For dry deposition, the deposition velocity of each radionuclide determines how fast the radionuclide settles out of the passing radioactive cloud in depletion calculations and how much contamination is deposited on the ground. Many measurements of dry deposition velocity have been reported by McMahon and Dennison (1979) and Sehmel (1980). Values for particulates range over several orders of magnitude and depend on meteorological conditions, surface conditions, particle size, and nuclide types. Values will tend to be higher over some areas of farmland with taller crops, wooded areas, and suburban/urban areas. Table G.9 presents the deposition velocity range for various particulate radionuclides. Separate deposition velocities for the cesium, iodine, ruthenium, and particulate radionuclide types may be used in RISKIND for estimating individual receptor impacts.

Pressing the Nuclide-Dependent Deposition Velocities button brings up the window with the same name (Figure G.21), where the deposition velocities (VDEPNUC) may be input. For population impact calculations, only one deposition velocity is used; the input (VDEP) replaces the Nuclide-Dependent Deposition Velocities button on the Defined Meteorology window. The default for all deposition velocities, except for inert gases (= 0), is a conservative value of 0.01 m/s. As with all other input parameters in RISKIND, whenever possible, the user should use the best available data for the specific situation being analyzed and not rely on the default values provided with the program.

TABLE G.9 Deposition Velocity Data Summary for Particulate Radionuclides

Depositing Material	Deposition Velocity (cm/s)	Deposition Surface
Barium	0.001 - 0.006	Grass
Strontium	0.002 - 0.01	Grass
Radium	0.05 - 0.5	Tank
Plutonium	3.2 - 7.3	Tray
Cesium-137	0.09 ± 0.06	Water
	0.04 ± 0.05	Soil
	0.2 - 0.05	Grass
Ruthenium-103	2.3 ± 1.0	Water
	0.1 ± 0.2 - 0.6 ± 0.4	Soil
	0.02 - 0.8	Grass
Zirconium-95, Niobium-95	5.7 ± 3.4	Water
	2.9 ± 2.7	Soil
Beryllium-7	0.6 - 5.3	Ocean with rain
Tellurium-127, Tellurium-129	0.7 ± 1.3	Sticky paper

Source: Sehmel (1980).

The rainfall rate (RAIN) is used to estimate depletion due to wet deposition. The default value of 0 mm/h assumes no rainfall during the accident. The wet deposition model in RISKIND is only appropriate for rainfall rates on the order of a few mm/h. Higher rainfall rates lead to water runoff, which is not considered. Runoff occurs in urban areas during rainfall rates approximately greater than 3 mm/h; extremely heavy rains such as those at 25 mm/h may not produce runoff in agricultural areas that were not previously saturated with water to some extent (Ritchie et al. 1978).

G.2.7.2 All Weather Conditions

The All Weather window (Figure G.22) replaces the Defined Meteorology window discussed above, when the risk over all weather conditions is selected in the main window. The

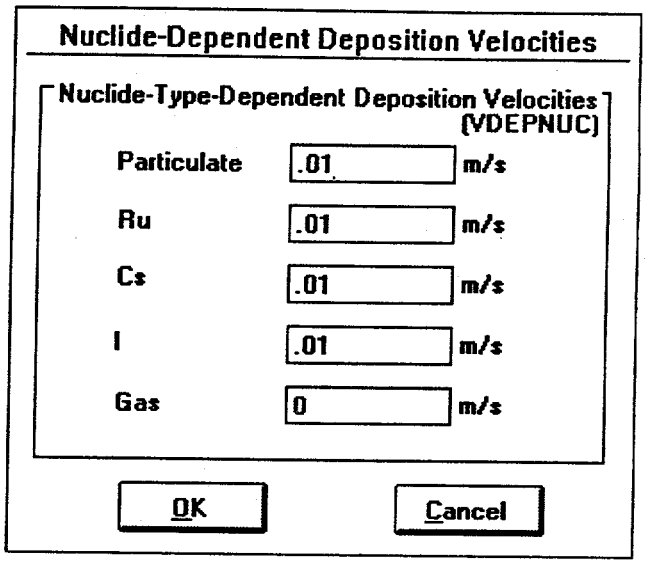

FIGURE G.21 Nuclide-Dependent Deposition Velocities Window

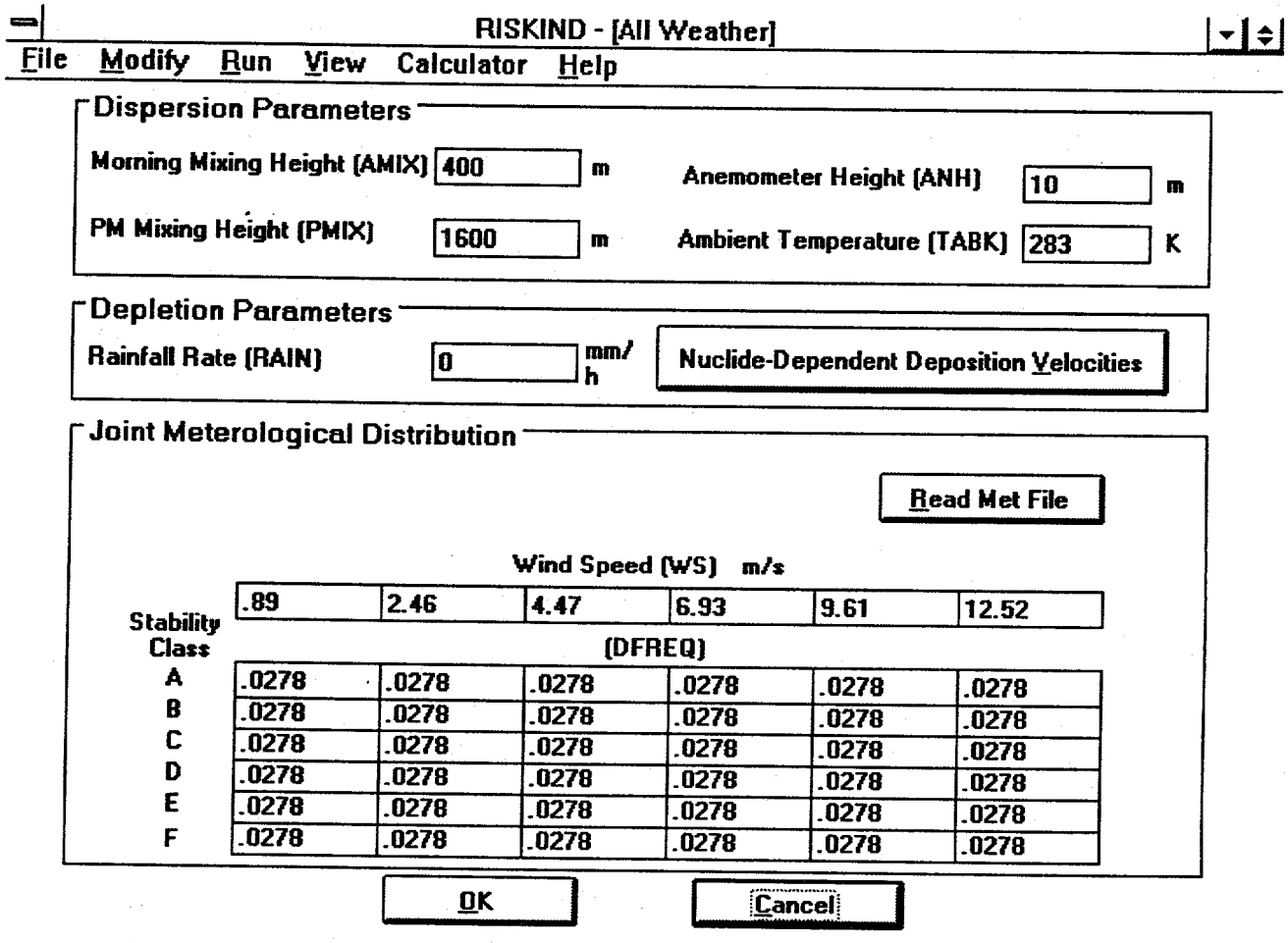

FIGURE G.22 All Weather Window

weather input selections discussed above are present except that input for the AM (AMIX) and PM (PMIX) mixing heights, rather than one mixing height, is requested. Daily, annual, and seasonal averages of mixing heights for different regions of the United States can be found in Holzworth (1972).

The major addition in this window is the Joint Frequency Distribution box. RISKIND recognizes the six Pasquill stability categories (A through F) and has provisions for up to six wind speed categories. The user may enter the fraction (not percentage) of time the wind is blowing in each stability category for each wind speed directly or may read a STAR data file to obtain the information.

An added feature in RISKIND, Version 1, is the ability to import STAR weather data. To give the user initial data for an assessment, over 200 weather data files in STAR format from the National Oceanic and Atmospheric Administration are provided for the 48 contiguous states. These data are a superset of those currently used by the CAP88-PC code (Parks 1992). The EPA developed the code for demonstrating compliance with radionuclide emission standards (EPA 1989b) that DOE facilities are required to use. STAR files may be added to RISKIND by placing the appropriate file in the METFILES subdirectory and adding the file name to the list in the STARSET2.TXT file in the METFILES subdirectory. The STAR file must have a *.STR file name extension because this extension is appended to the name in the STARSET2.TXT file when RISKIND goes to find the STAR file. Because of local variations in the weather, it is strongly recommended that site-specific weather data, if available, be used for any final risk analysis.

The risk calculation for a specific compass direction may be chosen, or the data for the 16 directions can be collapsed to a 6×6 joint frequency array for a nondirectional risk estimate. The Read Met File button brings up the corresponding window (Figure G.23) where the user may make the appropriate selection. The user may choose a specific direction for the weather data if a consequence assessment is being performed, or may choose to do a nondirectional assessment. The program will check the summation of the joint frequency input and warn the user if a total summation of 1.0 ± 0.01 is not achieved.

G.3 USER HELP

Help on RISKIND input parameters is available on-line and in this appendix.

G.3.1 On-Line Help

Access to on-line help is available through the Help submenu at the right of the main menu bar.

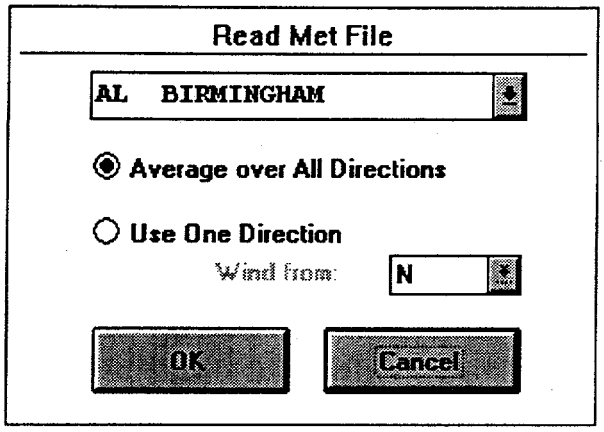

FIGURE G.23 Read Met File Window

G.3.1.1 Input Parameter Definitions

Access to on-line help for parameter definitions is available through the Contents item under the Help submenu at the right of the main menu bar, or by pressing the F1 function key while the parameter of interest has the input focus and is the one being edited. In either case, the RISKIND Help window (Figure G.24) is displayed. Five text boxes provide (1) a definition or explanation for the parameter and any default dependencies on other input, (2) the name of the input window where the user may modify the parameter, (3) the valid input range for the parameter recognized by RISKIND, (4) the RISKIND default value for the parameter, and (5) the equation(s) listed in the main text of the manual where the parameter is used.

Both the user interface and run-time portions of the program perform the same validity checks on the input parameters to make certain that all parameters are within the acceptable ranges for the program. Calculations are not performed, and an error message is issued if a parameter is found to be out of bounds.

G.3.1.2 References

References to information contained in the input parameter definitions can be listed through the References item under the Help submenu or by pressing the References button on the RISKIND Help window.

G.3.1.3 Help Diagrams

A number of diagrams can be accessed that depict various input parameters so that the user can better understand their use. Figure G.25 shows an example of the help diagrams available to the user. Help diagrams are brought up through the Diagrams submenu under the Help submenu.

G.3.2 Variable List and Definitions

Table G.10 contains a list of all RISKIND input variables and their definitions. These definitions may also be found in on-line help.

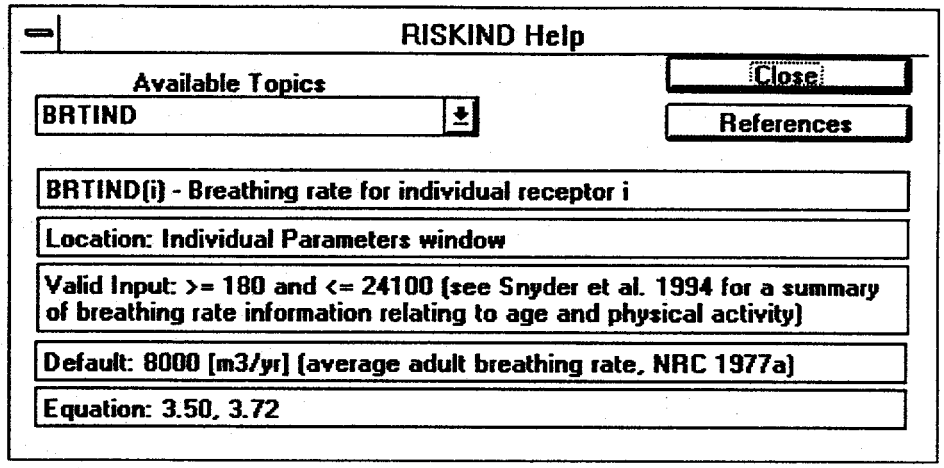

FIGURE G.24 RISKIND Help Window

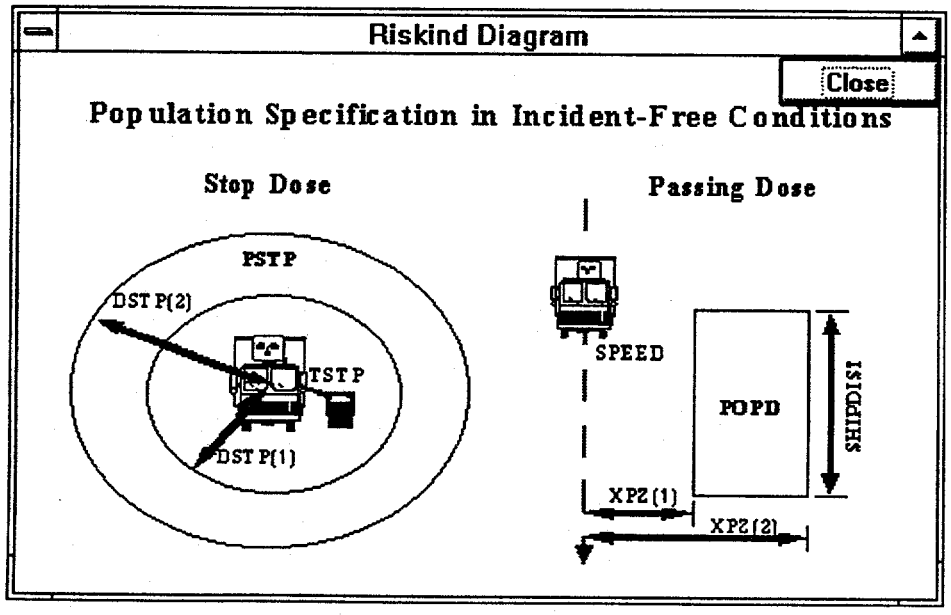

FIGURE G.25 RISKIND Help Diagram

TABLE G.10 Input Parameters

Input Parameter	Description
&INDATA	FORTRAN NAMELIST data delimiter input string for RISKIND. The NAMELIST format is used in FORTRAN programs as a method for data input.
ACOEFU(j,k)	User-defined coefficients for estimating the external dose from the shipping package. These values used only if Cask Coefficients are enabled by check box (IACOEF =1) in the Shipment Parameters window. The dose is calculated according to log (*Dose rate*) = Σ *ACOEF(j,k)* $\times$ (log [*r*]) ^ (j – 1), where *k* is the type of dose (1: gamma; 2: neutron), and *j* is the index for summation (1 through 8). Location: Dose Rate Curves Parameters window. Valid Input: Any double precision real number. Defaults: See Table 2.1 in the RISKIND manual. Equation: 2.2.
ACTA	Accident probability per kilometer traveled for risk calculation. Location: Accident window. Data-Dependent Defaults: If the default checkbox is checked (ACTA is set to -1), the value corresponding to the currently selected state, transportation mode, route type, and population zone is used (ISTATE, IMOD, IRDTY, IZONE, respectively). These values are maintained in the TRUCKACC.RKD and RAILACC.RKD data files for truck and rail accident rates, respectively, as taken from Saricks and Kvitek (1994). Valid input: > 0 and $\leqq$ 1, –1 for data-dependent default. Default: 1 [/km] (set for a consequence calculation). Equation:
ALPHA	Cask impact angle (degrees) for user-defined accident scenario. The impact angle is the angle between the cask velocity (the direction along which the cask is traveling) and the plane of the surface struck. Location: Defined Accident Scenario window. Valid Input: 0 to 90. Default: 90 [degrees] (head-on collision). Equation: E.1.
AMIX	Annual average morning mixing height. The average of AMIX and PMIX (annual afternoon mixing height) is used to determine the mixing height for calculations involving Pasquill stability class D weather. Location: All Weather window. Valid Input: > 0 and $\leqq$ 5,000 (mixing heights can range from a few tens of meters to > 4,000 m [Holzworth 1972]). Default: 400 [m] (annual average morning mixing heights range from approximately 300 to 800 m, the majority of the areas in the United States have values in the 300 to 500 m range [Holzworth 1972]). Equation: 3.15 to 3.18, 3.30. 3.31.

TABLE G.10 (Cont.)

Input Parameter	Description
ANH	Anemometer height. The height at which the value for wind speed (WSM) is measured. Location: All Weather or Defined Meteorology window, depending on the weather option selected. Valid Input: > 0 and ≦ 200 (>200 m is approximately where the wind speed power law, used in the effective wind speed and release height calculations, starts to breakdown Hanna et al. [1982]). Default: 10.0 [m] (standard meteorological instrumentation height [e.g., see NRC 1972]. Equation: 3.10.
BETA	Cask orientation angle (degrees). The orientation angle is the angle between the cask's longitudinal axis and the impact surface. Location: Defined Accident Scenario window. Valid Input: 0 to 90. Default: 90 [degrees] (end-on collision). Equation: Determines impact velocity using lookup Table E.1.
BRTIND(i)	Breathing rate for individual receptor *i*. Location: Individual Parameters window. Valid Input: ≧ 180 and ≦ 24,100 (see Snyder et al. [1994] for a summary of breathing rate information relating to age and physical activity). Default: 8,000 [m^3/yr] (average adult breathing rate [NRC 1977a]). Equation: 3.50, 3.72.
BRTPOP	Average individual breathing rate for population risk estimates. Location: Population Parameters window. Valid Input: ≧ 180 and ≦ 24,100 (see Snyder et al. [1994] for a summary of breathing rate information relating to age and physical activity). Default: 8,000 [m^3/yr] (average adult breathing rate [NRC 1977a]). Equation: 3.95, 3.106.
BURNUP	Reactor fuel burnup. Location: SNF Inventory window. Valid Input: 0 to 60,000 (no commercial PWR or BWR assemblies discharged to date have a burnup greater than 60,000 [EIA 1995]). Default: 35,000 [MWd/MTIHM] (the majority of assemblies discharged annually have a burnup near this value [EIA 1995]). Equation: Used with lookup table of DOE SNF database described in Appendix A.
CACTD	Crud surface activity density of cask for spent fuel inventories. Location: SNF Inventory window. Data-Dependent Default : Defaults are dependent on fuel type (RTYPE). Valid Input: > 0 and ≤ 1,500 (the maximum observed has been 1,250 for BWR fuel [Sandoval et al. 1991]) Default: 4 or 350 [μCi/cm^2] (average maximum values for PWR and BWR fuels, respectively [Sandoval et al. 1991]) Equation: Multiplied by CAREA, FSPAL, FRCRUD, and crud inventory to get cobalt-60 source term to add to SNF inventory releases.

TABLE G.10 (Cont.)

Input Parameter	Description
CAREA	Total surface area of cask cavity, including fuel for spent fuel inventories. Location: SNF Inventory window. Data-Dependent Default: Defaults dependent on fuel type and transportation mode (RTYPE, IMOD). Valid Input: > 0 and ≤ 500 (the larger licensed rail casks have surface areas < 400 [Sandoval et al. 1991]) Default: [m^2] Truck - 39.0 (PWR), 26.7 (BWR); Rail - 251.6 (PWR), 209.5 (BWR). (Values are for the NLI-1/2 truck and IF-300 rail casks [Sandoval et al. 1991]). Equation: Multiplied by CACTD, FSPAL, FRCRUD, and crud inventory to get cobalt-60 source term to add to SNF inventory releases.
DECAY_ WEATHER	Weathering decay constant for loss of contamination from vegetation due to weathering processes. Location: Ingestion Pathway Details window. Valid Input: 0.693 to 0.0198 (ln 2/1 to ln 2/35, based on information in Snyder et al. [1994]). Default: 0.0495 [1/d] (ln 2/14 d NRC [1977a]). Equation: 3.58, 3.59, 3.60.
DFACT	Decontamination factor. Fraction of initially deposited contamination remaining on human-consumed vegetation after washing. Location: Ingestion Parameters or Population Ingestion Parameters window, depending on receptor option selected. Valid Input: 0 to 1. Default: 0.5 (Parks 1992). Equation: 3.74, 3.110.
DFIRE	Fire duration for user-defined accident scenario. Location: Defined Accident Scenario window. Valid Input: 0 to 100 (a portion of a train not involving spent fuel derailed and burned for over four days near Livingston, Louisiana in 1982; modal study [LLNL 1987]). Default: 0.75 [h] (approximately 75 to 80% of expected truck/truck and truck/train accident fires and 75% of rail accident fires will last 0.75 h or less, NRC modal study [LLNL 1987]). Equation: E.2.
DFREQ(i,j)	Fractional frequency of occurrence for each of the *j* (1 to 6) average wind-speed classes for each of the *i* (1 to 6) atmospheric stability classes. Used when estimating risk over meteorological conditions. Location: All Weather window. Valid Input: 0 to 1 for each entry (the sum of all entries should total 1, unless only one direction was specified). Default: 36*0.0278 (uniform distribution). Equation: Multiplied by impact estimated by using atmospheric stability *i* and wind speed *j* to estimate the risk for that weather condition.

TABLE G.10 (Cont.)

Input Parameter	Description
DHSIZE	User-defined reference cask length for shape factor correction when Dose Rate Curve Parameters are enabled (IACOEF = 1) and Shape Factor Correction is still used (ISHPF = 0). Location: Dose Rate Curves Parameters window. Valid Input: > 0 and ≦ 25 (a limiting value would be a railcar loaded with waste packages and treated as a single source for routine risk calculations; the useful length of some railcars exceeds 20 m [AAR 1974). Default: 5.46 [m] (cask size used for developing the routine dose rate curves [Chen and Yuan 1988]). Equation: B.8, B.14.
DISTPASS(i)	Nearest distance of individual receptor *i* to the passing shipment. Location: Individual Parameters window. Valid Input: 0.001 to 80.0 (routine doses beyond 1 km are generally insignificant; the maximum input distance used here is to maintain consistency with accident calculations). Default: 1.0 [km] (unit distance). Equation: 2.7 to 2.11.
DISTSTOP(i)	Distance of individual receptor *i* from the stopped shipment. Location: Individual Parameters window. Valid Input: 0.001 to 80.0 (routine doses beyond 1 km are generally insignificant; the maximum input distance used here is to maintain consistency with accident calculations). Default: 1.0 [km] (unit distance). Equation: 2.5.
DMIX	Mixing height for user-defined weather. Location: Defined Meteorology window. Valid Input: > 0 and ≦ 5,000 (mixing heights can range from a few tens of meters to > 4,000 m [Holzworth 1972]). Default: 1,000 [m] (Parks 1992). Equation: 3.15 to 3.18, 3.30, 3.80, 3.82.
DRSIZE	User-defined reference cask radius for shape factor correction when Dose Rate Curve Parameters are enabled (IACOEF = 1) and Shape Factor Correction is still used (ISHPF = 0). Location: Dose Rate Curves Parameters window. Valid Input: > 0 and ≦ 5 (a limiting value would be a railcar loaded with waste packages and treated as a single source for routine risk calculations; the useful height of some railcars exceeds 3 m [AAR 1974]). Default: 0.56 [m] (cask size used for developing the routine dose rate curves [Chen and Yuan 1988]). Equation: B.6, B.10, B.12, B.16, B.18, B.19.

TABLE G.10 (Cont.)

Input Parameter	Description
DSTP(i,j)	Annular exposure region radii of each population stop type *j* for routine population calculations. A maximum of 10 independent stop types may be defined (NSTY = 10 maximum); each type is defined by the area bounded by a minimum and maximum radii. (*i* = 1: minimum radius; *i* = 2: maximum radius). Location: Routine On-Link/Stops Parameters window. Valid Input: 1 to 80,000 (routine doses beyond 1,000 m are generally insignificant; the maximum input distance used here is to maintain consistency with accident calculations). Default: (1,*j*) = 2, (2,*j*) = 90 [m] (based on a study by Madsen and Wilmot [1982] for truck transport for an average truck stop; values for rail transport will depend on the size of the rail yard and surrounding countryside). Equation: 2.6.
EFF_SURF_DEN	Effective surface density of the soil. Location: Ingestion Pathway Details window. Valid Input: ≧ 0. Default: 240 [kg/m^2] (assumes a 15-cm plow layer [NRC 1977a]). Equation: 3.59, 3.60.
F_EDBL_COW	Fraction of plant contamination reaching edible portion of animal-consumed vegetation. Location: Ingestion Pathway Details window. Valid Input: 0 to 1. Default: 1 (NRC 1977a). Equation: 3.58 to 3.60.
F_EDBL_HUM	Fraction of plant contamination reaching edible portion of human-consumed vegetation. Location: Ingestion Pathway Details window. Valid Input: 0 to 1. Default: 1 (NRC 1977a). Equation: 3.58 to 3.60.
F_RETAIN	Fraction of air-deposited contamination retained on vegetation. Location: Ingestion Pathway Details window. Valid Input: 0 to 1. Default: 0.2 (NRC 1977a). Equation: 3.58 to 3.60.
FAILS(i)	Fraction of failed rods in spent fuel cask *i* can be used for fraction of failed packages in a multiple package shipment for other radioactive materials; *i* is the accident response region (accident severity category) index, maximum of 20. Location: Accident window. Valid Input: 0 to 1. Default: 0.03, 0.1, 2*1, 0.03, 0.1, 2*1, 0.03, 0.1, 10*1 (NRC modal study [LLNL 1987]). Equation: 3.1.

TABLE G.10 (Cont.)

Input Parameter	Description
FARM	Fraction of land that is farmland within the zone bounded by the nearest [XPZ(1)] and farthest [XPZ(2)] distances from an accident. Location: Population Ingestion Parameters window. Data-Dependent Default: Dependent on the currently selected state (ISTATE) if the default checkbox is checked (FARM is set to −1). The values used for calculations are from Saricks et al. (1989). Valid Input: > 0 and ≦ 1, −1 for data-dependent default. Default: 0.44 (U.S. average, Saricks et al. [1989]). Equation: 3.109.
FDISP(i,j)	Fraction of released inventory dispersed to the atmosphere as a respirable aerosol for accident response region *i* (maximum of 20) for radionuclide type *j* (1 to 5). Location: Accident window. Valid Input: 0 to 1. Default: 0, 19*1, 0, 19*1, 0, 19*1, 0, 19*1, 0, 19*1 (NRC modal study [LLNL 1987]). Equation: 3.1.
FLOCA	Fire location for user-defined accident scenario. The distance of the cask from the fire. Location: Defined Accident Scenario window. Valid Input: 0 to 10 (modal study [LLNL 1987]). Default: 0 [m] (engulfing fire). Equation: É.3, E.4.
FRAD(i)	Fraction of dose rate at user-defined distance from the waste package contributed by gamma (1) and neutron (2) radiation. Location: Shipment Parameters window. Valid Input: 0 to 1 for FRAD(1); FRAD(2) = 1 − FRAD(1). Default: 0.60, 0.40 (intermediate values for existing PWR and BWR casks, see Table G.4). Equation: 2.4.
FRCRUD(i)	Fraction of spalled crud released in each accident response region (accident severity category) (*i*) for SNF inventory. Location: Accident window. Valid Input: 0 to 1. Default: 20*1 (all spalled crud [the crud that has flaked or broken off the fuel rods] is assumed to be released if a leak path is available; a number of mechanisms could be operable that would mitigate some or all of the release; these mechanisms include deposition and gravitational settling of the crud within the cask, as well as the possibility of the crud blocking the leak path itself.). Equation: Multiplied by CAREA, CACTD, FSPAL, and crud inventory to get cobalt-60 source term to add to SNF inventory releases.

TABLE G.10 (Cont.)

Input Parameter	Description
FRELS(i,j)	Fraction of inventory released from failed rods to the cask cavity in accident response region *i* for each of the five radionuclide types (*j*); can be used for the fraction released from the shipping package for shipments other than SNF. Location: Accident window. Valid Input: 0 to 1. Default: NRC modal study (LLNL 1987). Equation: 3.1.
FSEV(i,j)	Conditional probability of each accident response region *i* (accident severity category) for the two transportation modes (*j*) (1 - truck, 2 - rail). Location: Accident window. Valid Input: 0 to 1. Default: NRC modal study (LLNL 1987). Equation: Multiplied by ACTA and by impact estimated using accident region *i* parameters to estimate the risk for that accident severity under a given set of weather conditions.
FSPAL(i)	Crud spallation fraction in each accident response region *i*. Location: Accident window. Valid Input: 0 to 1. Default: 0.0, 3*1., 0.15, 3 *1., 0.15, 3*1., 0.15, 3*1., 0.15, 3*1 (based on Sandoval et al. [1991] and the NRC modal study [LLNL 1987]). Equation: Multiplied by CAREA, CACTD, FRCRUD, and crud inventory to get cobalt-60 source term to add to SNF inventory releases.
GMEAT	Farmland meat productivity. Location: Population Ingestion Parameters window. Data-Dependent Default: dependent on the currently selected state (ISTATE) if the default checkbox is checked (GMEAT set to −1). The values used for calculations are from Saricks et al. (1989). Valid Input: 0 to 50,000 (the maximum for 1982 was 17,000 in Iowa [Saricks et al. 1989]); −1 for the data-dependent default. Default: 3,070 [kg/km^2-yr] (U.S. average). Equation: 3.109.
GMILK	Farmland milk productivity. Location: Population Ingestion Parameters window. Data-Dependent Default: dependent on the currently selected state (ISTATE) if the default checkbox is checked (GMILK is set to −1). The values used for calculations are from Saricks et al. (1989). Valid Input: 0 to 100,000 (the maximum for 1982 was 75,000 in Wisconsin [Saricks et al. 1989]); −1 for the data-dependent default. Default: 6,710 [kg/km^2-yr] (U.S. average). Equation: 3.109.

TABLE G.10 (Cont.)

Input Parameter	Description
GVEGE	Farmland vegetation productivity. Location: Population Ingestion Parameters window. Data-Dependent Default: Dependent on the currently selected state (ISTATE) if the default checkbox is checked (GVEGE is set to −1). The values used for calculations are from Saricks et al. (1989). Valid Input: 0 to 400,000 (the maximum for 1982 was 330,000 in Illinois [Saricks et al. 1989]); −1 for the data-dependent default. Default: 55,800 [kg/km^2-yr] (U.S. average). Equation: 3.109.
HEATF(i)	Heat flux generated for each accident response region *i* (accident severity category). Used to determine the effective release height from buoyant plume rise. Location: Accident window. Valid Input: ≥ 0. Default: 4*500, 16*2.0E6 [cal/s] (based on a heat content of 1.07E-4 cal/g and a density of 11.3 kg/gal [CRC 1970] for diesel fuel; a 2.0E6 cal/s heat flux corresponds to a burn rate of approximately 1 gal/min). Equation: 3.3 to 3.9.
HS	Physical release height of escaped material. This value could be the cask height or road height unless other information is available. Location: Accident window. Valid Input: 0 to 200 (> 200 m is approximately where the wind speed power law, used in the effective wind speed and release height calculations, starts to break down [Hanna et al. 1982]). Default: 1.0 [m] (approximate height above ground of cask on a tractor-truck trailer or railcar). Equation: 3.2 to 3.4.
HSIZE	Cask length. Used for shape factor corrections of external dose from cask and initial dispersion of plume. Location: Shipment Parameters window. Data-Dependent Default: Dependent on the transportation mode selected if the default box is checked (IMOD). Valid Input: > 0 and ≤ 25 (a limiting value would be a railcar loaded with waste packages being treated as a single source for routine risk calculations; the useful length of some railcars exceeds 20 m [AAR 1974]). Default: 5.46 [m] (cask size used for developing the routine dose rate curves [Chen and Yuan 1988]; if the default box is checked, the NRC modal study [LLNL 1987] value for a truck or rail cask will be used). Equation: 3.37, B.9, B.15.

TABLE G.10 (Cont.)

Input Parameter	Description
HSTP(i)	Exposure duration for each population stop type *i* for routine population calculations. A maximum of 10 independent stop types may be defined (NSTY = 10 maximum; each type is defined with an independent stop time. Location: Routine On-Link/Stops Parameters window. Valid Input: 0 to 100 (Commercial shipments rarely remain in one place for more than a few hours; allowance is given for severe weather or mechanical problems.). Default: 10*1 [h] (Unit time duration). Equation: 2.6.
HTEXP	Short-term exposure duration immediately after an accident; used in population calculations. Location: Population Parameters window. Valid Input: > 0 to 100; based on EPA protective action guidelines' (EPA 1991) loose definition of the early phase of an accident, which is defined to extend up to a few days after the initiation of a release when all airborne material is assumed to have deposited; however, emergency response procedures in most cases would limit such exposure to hours, if not minutes. In addition, most of the short-term dose is dominated by inhalation of the passing plume, which generally passes by within minutes of an accident but can take longer due to a prolonged release, slower wind speeds, and/or farther distances from the release point. External exposure from ground contamination can be accounted for with the long-term exposure option for any prolonged exposure period. Default: 2.0 [h] (evacuation could be expected to be completed in most cases within this time frame in the aftermath of an accidental release, see e.g., Sprung et al. [1990]). Equation: 3.92, 3.98.
HZLM	Radionuclide selection criterion applied to three pathways to reduce the number of radionuclides being considered. Setting to 0 selects all radionuclides. The radionuclides that are estimated to cause approximately 99% of the potential risk are selected when HZLM = 0.01. The estimated risk in the screening process using HZLM is only a rough estimate, and HZLM should be set to a smaller value than required. Location: SNF Inventory or User-Defined Inventory window. Valid Input: 0 to 1. Default: 0.01 (1%) (generally selects less than 10 out of possibly hundreds of radionuclides from a SNF shipment). Equation: C.15.
IACDT	Determines whether accident calculations are performed. Accident calculations include short-term effects: external dose from the cask with possible loss of shielding, external dose from material deposited on the ground from the plume passage, inhalation of material as the plume passes, and external cloudshine from the material as it passes. The long-term doses may also be calculated: long-term groundshine, inhalation and cloudshine from resuspended material, and ingestion through food and water pathways. Location: Main Options window. Valid Input: 0 - do not perform accident calculations; 1 - perform accident calculations. Default: 1 (perform accident calculations). Equation: Controls program option.

TABLE G.10 (Cont.)

Input Parameter	Description
IACFOD	Determines whether the food being grown at the time of the accident is discarded or distributed for ingestion. This food is contaminated by the direct deposition of radionuclides during the plume passage. Location: Ingestion Parameters or Population Ingestion Parameters window. Valid Input: 0 - discard initially contaminated food; 1 - do not discard initially contaminated food. Default: 0 (discard initially contaminated food). Equation: Controls program option.
IACOEF	Determines whether the default or user external cask dose coefficients are to be used. Location: Shipment Parameters window. Valid Input: 0 - default dose coefficients, 1 - user-defined dose coefficients. Default: 0 (use default gamma and neutron dose curves). Equation: Controls program option.
IADD	Number of individual receptor locations. Location: Individual/Population option selected in the Main Options window; increased or decreased with the Save and Delete Individual buttons in the Individual Parameters window. Valid Input: 1 to 20, 0 for population calculations. Default: 1 (individual problem with one receptor). Equation: Controls program option.
IBOUND	Determines level of conservatism in the acute health risk calculations. Location: Individual Parameters or Population Parameters window. Valid Input: 1 = lower bounds, 2 = central estimates, 3 = upper bounds. Default: 2 (central estimates). Equation: Controls program option.
ICONSQ	Determines whether a risk or consequence problem is being specified. If consequence is chosen, the accident rate (ACTA) is not used, the relative probability of the accident severity category (FSEV) is set to 1, and the probability of the user-defined weather condition (METFREQ), one wind speed for one stability class, is 1. Location: Main Options window. Valid Input: 0 = risk problem, 1 = consequence problem. Default: 0 (risk problem). Equation: Controls program option.
IDFOOD(i)	Determines whether or not the food pathway (ingestion) is calculated for individual receptor *i* (maximum of 20 receptors, number of receptors set by IADD). Location: Individual Parameters window. Valid input: 0 = do not calculate food pathway, 1 = calculate food pathway. Default: 20*1 (calculate food pathway). Equation: Controls program option.

TABLE G.10 (Cont.)

Input Parameter	Description
IDISPMOD	Controls which dispersion coefficients are used for the plume dispersion calculations. A 0 specifies Pasquill-Gifford coefficients to be used for effective release heights <30 m and Briggs coefficients to be used for higher releases. Alternately, Pasquill-Gifford coefficients (1) or Briggs coefficients (2) may be specifically selected. Pasquill-Gifford coefficients should be used for releases at or near ground level. Briggs coefficients were derived from elevated release studies but are not recommended for elevated releases much greater than 100 m. Location: Accident window. Valid Input: 0 = dependent on effective release height, 1 = Pasquill-Gifford coefficients, 2 = Briggs coefficients. Default: 0 (dependent on effective release height). Equation: Controls program option.

IDPG(100)	Radionuclide type for each element:
	(1: particulate; 2: ruthenium; 3: cesium; 4: iodine; 5: inert gas).
	Location: User-Defined Inventory window.
	Valid Input: 1 to 5.
	Default:
	`1,1,1,5,5,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,5,5,1,1,1,1,1,1,2,2,2,`
	`1,1,1,1,1,1,1,1,4,5,3,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,`
	`1,1,1,1,1,1,1,1,1,5,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,`
	respectively, for
	`H, HE, LI, BE, B, C, N, O, F, NE, NA, MG, AL,`
	`SI, P, S, CL, R, K, CA, SC, TI, V, CR, MN, FE',`
	`CO, NI, CU, ZN, GA, GE, AS, SE, BR, KR, RB, SR, Y',`
	`ZR, NB, MO, TC, RU, RH, PD, AG, CD, IN, SN, SB, TE',`
	`I, XE, CS, BA, LA, CE, PR, ND, PM, SM, EU, GD, TB',`
	`DY, HO, ER, TM, YB, LU, HF, TA, W, RE, OS, IR, PT',`
	`AU, HG, TL, PB, BI, PO, AT, RN, FR, RA, AC, TH, PA',`
	`U, NP, PU, AM, CM, BK, CF, ES, FM`

IHARD	Impact object hardness index for a user-defined accident scenario. Location: Defined Accident Scenario window. Valid Input: 1 = unyielding, 2 = medium, 3 = soft, 4 = very soft. Default: 1 (Unyielding). Equation: Determines impact velocity using lookup Table E.1.
IMOD	Transportation mode option flag. Used for determining some data-dependent defaults [ACTA, CAREA, UMT, HSIZE, RSIZE, SPEED, RDWTH, PPVH, XPZ(1)]. Location: Main Options window. Valid Input: 1 = truck, 2 = rail. Default: 1 (truck) Equation: Controls program option.

TABLE G.10 (Cont.)

Input Parameter	Description
INDTYPE(i)	Selects the individual type (member of the general public or an occupational worker) of receptor *i*. Selection determines the health risk factors for potential cancer incidence, cancer fatality, and genetic effects to be used for routine and long-term health risk calculations. Location: Individual Parameters window. Valid Input: 0 - occupational worker, 1 - member of the general public. Default: 20*1 (member of the general public). Equation: Controls program option.
IPFOD	Population food pathway option flag. The ingestion dose to the population is a societal dose. That is, the dose is independent of the number of people in the affected area and is based on the assumption that all of the food grown in the affected area will be consumed, either locally or in other areas. Location: Population Parameters window. Valid Input: 0 = population food pathway off, 1 = population food pathway on. Default: 1 (include population food pathway). Equation: Controls program option.
IPWATR	Number of water body locations for population drinking water dose calculations. The user sets XRECEP (1) and XRECEP (2) to input the coordinates of each location. Location: Set by enabling water ingestion in the Population Parameters window and incremented or decremented by the New and Delete Water Bodies buttons, respectively, in the Water Pathway for Population window. Valid Input: 1 to 20, 0 if drinking water not considered. Default: 0 (drinking water not considered). Equation: Controls program option.
IRDTY	Road type option flag. Used in determining some data-dependent defaults [ACTA, NUMLANES, RDWTH, WDTHMED, XPZ(1)]. Location: Shipment Parameters window. Valid Input: Truck:1 = interstate highway, 2 = primary road, 3 = secondary road; Rail: 1 = total, 2 = mainline only. Default: 1 (interstate highway/total rail). Equation: Controls program option.
IRTP(i)	Long-term pathway option flag for individual receptor *i* (maximum of 20 receptors, number of receptors set by IADD). IRTP(1) is used for population calculations. Location: Main Options window. Valid Input: 1 = calculate short- and long-term exposures; 0 = calculate short-term exposures only. Default: 20*1 (short-term and long-term pathways). Equation: Controls program option.

TABLE G.10 (Cont.)

Input Parameter	Description
IRUTIN	Routine dose calculation option flag. Location: Main Options window. Valid Input: 0 = no routine calculations, 1 = do routine calculations. Default: 1 (do routine calculations). Equation: Controls program option.
ISHLT(i)	Shelter type for individual receptor *i* for routine and short-term accident calculations (maximum of 20 receptors, number of receptors set by IADD). See Table 3.5 in the RISKIND manual or the Individual Parameters input window for the shielding values used for each selection. The shielding values are taken from NRC (1975). Location: Individual Parameters window. Valid Input: 0 = outdoors (no shielding), 1 = frame house, 2 = brick house, 3 = office building, 4 = automobiles on road, 5 = user-specified shielding factor (defined in SHLDVAL). Default: 20*0 (outdoors, no shielding). Equations: 2.5, 2.7, 2.8, 3.47 to 3.50.
ISHPF	Shape factor correction option when user-defined Dose Rate Curve coefficients are specified. Location: Checkbox in Shape Factor box in Dose Rate Curve Parameters window. Valid Input: 0 = shape factor correction active, 1 = shape factor correction not used. Default: 0 (include shape factor). Equation: Controls program option.
ISPENT	Option flag for selecting the type of radioactive inventory. Location: Main Options window. Valid Input: 1 = spent fuel, radionuclide inventory is estimated as defined by the RTYPE, BURNUP, and TFUEL variables as in the original code; 0 = user radionuclide inventory. Default: 1 (spent fuel inventory). Equation: Controls program option.
ISTATE	Index of state to use in determining data-dependent defaults (ACTA, FARM, GVEGE, GMEAT, GMILK, POPD). 1. AL 2. AZ 3. AR 4. CA 5. CO 6. CT 7. DE 8. FL 9. GA 10. ID 11. IL 12. IN 13. IA 14. KS 15. KY 16. LA 17. ME 18. MD 19. MA 20. MI 21. MN 22. MS 23. MO 24. MT 25. NE 26. NV 27. NH 28. NJ 29. NM 30. NY 31. NC 32. ND 33. OH 34. OK 35. OR 36. PA 37. RI 38. SC 39. SD 40. TN 41. TX 42. UT 43. VT 44. VA 45. WA 46. WV 47. WI 48. WY 49. U.S. Location: Main Options window. Valid Input: 1 to 49. Default: 49 (U.S.). Equation: Array index. Determines data-dependent defaults.

TABLE G.10 (Cont.)

Input Parameter	Description
ITREAT	Option flag for level of medical treatment for acute health risk effects. Location: Individual Parameters or Population Parameters window. Valid Input: 1 = minimal treatment, 2 = supportive treatment. Default: 1 (minimal treatment). Equation: Controls program option.
ITYPE	Pasquill atmospheric stability categories. Location: Defined Meteorology window. Valid Input: 1 to 6 corresponds to Pasquill stability categories A to F. Default: 4, Pasquill stability class D (neutral stability classes are prevalent about 50% of the time on average across the United States [Doty et al. 1976]). Equation: Array index. Determines the dispersion coefficients used in Equations 3.32 to 3.34.
IWATER(i)	Individual *i* water consumption pathway option flag (maximum of 20 receptors, number of receptors set by IADD). Location: Individual Parameters window. Valid Input: 0 = water consumption not included, 1 = water consumption included. Default: 20*0 (water ingestion exposure pathway not included). Equation: Controls program option.
IYOURS	Accident problem type option flag. Location: Radio buttons in Accident Scenarios box in Main Options window; if the third option is selected, *i* is determined by the Region Considered field in the Accident window. Valid Input: −1 = input your own accident scenario; 0 = risk over all accident severity categories; i = use *i*th accident response region, 1 to NSV (number of regions considered). Default: −1 (user-defined accident scenario). Equation: Controls program option.
IYOURW	Meteorological data input option flag. Location: Main Options window. Valid Input: 1 = input user-provided wind speed and stability, 0 = risk over all weather types (all combinations of wind speed and stability category). Default: 1 (user-defined single weather type). Equation: Controls program option.
IZONE	Population zone index used for determining some data-dependent defaults and dispersion coefficients (ACTA, SPEED, XPZ(1),TRAF_DEN). Location: Main Options window. Valid Input: 1 = rural, 2 = suburban, 3 = urban. Default: 1 (rural, the majority of most transportation routes are in rural population zones). Equation: Controls program option.

TABLE G.10 (Cont.)

Input Parameter	Description
LSHLT(i)	Shelter type for long-term accident calculations for individual receptor *i*. Fraction of time spent over the long-term in the specified shelter type is input with the OCUPF(i,j) parameter. See Table 3.5 in the RISKIND manual or the Individual Parameters input window for the shielding values used for each selection. The shielding values are taken from NRC (1975). Location: Individual Parameters window. Valid Input: 0 = outdoors (no shielding), 1 = frame house, 2 = brick house, 3 = office building, 4 = automobiles on road, 5 = user-defined (values in SHLDVAL). Default: 20*0 (outdoors, no shielding). Equation: 3.69, 3.71. 3.73.
METFREQ	Probability of a given weather condition (1 weather stability category and 1 wind speed). Used in risk calculations with user-defined weather selected (IYOURW = 1). Location: Defined Meteorology window. Valid Input: 0 to 1. Default: 1 (consequence calculation). Equation: Multiplied by the impacts from a defined set of weather conditions (single stability class and wind speed) to obtain the risk for that set of weather conditions.
NISOPL	Number of concentration isopleths used in a population accident problem. Starting at the area of highest radionuclide concentration, the average concentration in each surrounding isopleth is reduced by a factor of 3.162 (10^1/2). Location: Accident window. Valid Input: 4 to 20. Default: 10 (covers five orders of magnitude difference in contaminant concentrations between the innermost isopleth (the area of highest concentration) and the outermost isopleth (the area of lowest concentration considered). Equation: Controls program loop.
NSTP(10)	Number of stops occurring for each population problem stop type. A maximum of 10 independent stop types may be defined (NSTY = 10 maximum); each type is defined with an independent number of stops. Location: Routine On-Link/Stops Parameters window. Valid Input: 1 to 100. Default: 10*1 (1 stop for each stop type). Equation: 2.6.
NSTY	Number of population problem stop types for routine calculations. Location: Routine On-Link/Stops Parameters window. Valid Input: 0 to 10. Default: 0 (no special stops considered for routine calculations). Equation: Controls program option.
NSV	Number of accident response regions (accident severity categories) considered. Location: Accident window when risk over all regions is calculated. Valid Input: 1 to 20. Default: 20 (NRC modal study [LLNL 1987]). Equation: Controls program option.

TABLE G.10 (Cont.)

Input Parameter	Description
NUMLANES	Number of lanes going in each direction for the truck route of interest or the number of neighboring parallel tracks for the rail transport mode. Used for routine on-link population calculations. Data-Dependent Default: Dependent on the road type (IRDTY) and population zone (IZONE), if the default box is checked. Location: Shipment Parameters window when population calculations are to be performed (IADD = 0). Valid Input: 1 to 10. Default: 2 for truck, 1 for rail (over 90% of the U.S. interstate highway system consists of four-lane roads, two in each direction [FHWA 1991]). Equation: 2.15.
NUTYPE(i)	Label for radionuclide type *i*. Location: Accident window. Valid Input: Alphanumeric text, limited to 12 characters. Default: "Particulates," "Ru," "Cs," "I," "Gas" for i = 1 to 5, respectively (NRC modal study [LLNL 1977]). Equation: Program display option.
OCUPF(i,j)	Indoor and outdoor occupancy factors (j = 1 and 2, respectively) for calculating long-term doses. Remaining fraction assumed to be off-site. OCUPF(1,j) used for population calculation. Location: Individual Parameters or Population Parameters window. Valid Input: 0 to 1. Default: 20*0.62(indoors), 20*0.02(outdoors) (EPA [1989a]; average based on time spent at home). Equation: 3.69, 3.71, 3.73. 3.101, 3.104, 3.107.
PAG	Long-term dose value for determining cleanup levels for population problems. The EPA has published suggested PAGs dealing with exposure to accidental radioactive releases (EPA 1991). These guidelines deal with the early (short-term) and later phases (long-term) following an accidental release. Early phase considerations are discussed in the RISKIND manual but are not implemented in the program because forewarning (i.e., time to mitigate potential exposure) of an accidental transport-related release is not likely, and cleanup is not a short-term mitigative action. The most restrictive of the longer term guidelines suggests a limit of 5 rem to a single individual over a 50-year exposure period. If the exposure to a single individual in a given population isopleth exceeds the PAG value over the exposure time set (default for YEVD is 50 yr), RISKIND will perform an extra set of calculations for that isopleth to determine the approximate ground concentrations needed after cleanup to stay within the PAG limit. This determination "reduces" the dose from inhalation of resuspended material, groundshine, and ingestion. Short-term doses and water ingestion are not considered. Location: Soil and Resuspension Factors window when performing population calculations (IADD = 0). Valid Input: 0.1 to 27, less restrictive PAGs from the EPA suggest a limit of 2 rem in the first year following an accident and 0.5 rem/yr for each subsequent year, $2 + 0.5 \times 49 = 27$. Default: 5.0 [rem/YEVD yr] (see description of parameter above). Equation: Used to scale contaminant ground concentrations on an isopleth-by-isopleth basis if an average individual receptor were to receive a dose greater than the PAG value.

TABLE G.10 (Cont.)

Input Parameter	Description
PFIN(i)	Contaminated fractions of each food type *i* (*i* = 1 meat, 2 milk, 3 vegetation, 4 reserved for future use, 5 water) consumed by individuals. Location: Ingestion Parameters or Population Parameters window for meat, milk, and vegetation; Water Pathways Parameters window for water for individuals; if water intake is selected for population calculations, all water ingested by the persons at each water body location is assumed to be contaminated. Valid Input: 0 to 1. Default: 5 * 1.0 (all food ingested is contaminated). Equation: 3.74 to 3.77.
PHALF	Radionuclide removal half-life from soil. The rate constant for radionuclide removal from soil is 0.693/PHALF. Location: Soil and Resuspension Factors window. Valid Input: >0 to 135 (Sprung et al. 1990). Default: 50 [yr] (Parks 1992). Equation: 3.51, 3.52, 3.57.
PMIX	Annual afternoon mixing height. For calculations involving Pasquill stability class A (unstable) weather, the mixing height is taken to be 1.5*PMIX. The mixing height is set equal to PMIX for other unstable conditions (classes B and C), and the average of AMIX (annual morning mixing height) and PMIX is used to determine the mixing height for calculations involving Pasquill stability class D weather (neutral conditions). Location: All Weather window. Valid Input: > 0 and ≦ 5,000 (mixing heights can range from a few tens of meters to > 4,000 m [Holzworth 1972]). Default: 1,600 [m] (typical values for the annual average afternoon mixing height in the United States range from 1,200 to > 2,600 m, more than two-thirds of the country has mixing heights < 2,000 m [Holzworth 1972]). Equation: 3.15 to 3.18, 3.30, 3.31.
POPD	Average population density between distances, XPZ(1) and XPZ(2), for population calculations, accident and off-link routine. Location: Population Parameters window. Data-Dependent Default: Average population density for the selected state (ISTATE), if the default box is checked. Valid Input: > 0 to 1.0E6 (This is an arbitrary maximum density corresponding to 1 person/m^2. Densities such as this could be exceeded at public functions such as outdoor concerts or ball games. However, shielding from the surrounding persons would become a factor at higher densities for routine calculations and is not accounted for.). Default: 6.0 [persons/km^2] (average rural population density [NRC 1977b]). Equation: 2.12, 3.88, 3.98.

TABLE G.10 (Cont.)

Input Parameter	Description
POPTYPE	Selects the population type (members of the general public or occupational workers). Selection determines the health risk factors for potential cancer incidence, cancer fatality, and genetic effects to be used for routine and long-term health risk calculations. Location: Population Parameters window. Valid Input: 0 = occupational workers, 1 = members of the general public. Default: 1 (members of the general public). Equation: Controls program option.
POPW(i)	Number of persons consuming water from each water body *i* (maximum of 20) in a population accident calculation. Location: Water Pathway for Population window. Valid Input: 1 to 100 (the drinking water model in RISKIND is only intended for small, local water distribution systems). Default: 20*1, (1 person drinking from each water body). Equation: 3.113.
PPVH	Number of people per vehicle sharing the transport route. Location: Routine On-Link/Stops Parameters window. Valid Input: 0 to 1,000 (allowance is made for passenger trains). Default: 2 (for truck transportation; a value of 5 is often used for rail transportation [Neuhauser and Kanipe 1992]). Equation: 2.16.
PSTP(i)	Number of persons exposed at each stop type *i* for routine population calculations. A maximum of 10 independent stop types may be defined (NSTY = 10 maximum). Location: Routine On-Link/Stops Parameters window. Valid Input: 1 to 1,000. Default: 10*50 (Neuhauser and Kanipe 1992). Equation: 2.6.
QA	Feed (wet weight) ingestion rate for beef cattle and milk cows. Location: Ingestion Pathway Details window. Valid Input: $\geq$ 0 to 100. Default: 50 [kg/d] (NRC 1977a). Equation: 3.61, 3.62.
RAIN	Rainfall rate. The wet deposition model in RISKIND is only appropriate for rainfall rates on the order of a few mm/h. Higher rainfall rates lead to water runoff, which is not considered. Location: Defined Meteorology or All Weather window. Valid Input: 1 to 25 (Runoff occurs in urban areas during rainfall rates approximately greater than 3 mm/h; extremely heavy rains such as 25 mm/h may not produce runoff in agricultural areas not previously saturated with water to some extent [Ritchie et al. 1978]). Default: 0.0 [mm/h] (no rainfall). Equation: 3.24.

TABLE G.10 (Cont.)

Input Parameter	Description
RDWTH	Width of one lane for truck transportation. Used in routine on-link population calculations. Location: Shipment Parameters window when setting up routine population calculations. Data-Dependent Default: Dependent on the road type (IRDTY) and population zone (IZONE) if the default box is checked. Valid Input: 2 to 10. Default: 3.7 [m] (The majority of roads in the United States have a lane width of 12 ft [FHWA 1991].). Equation: 2.15, 2.16.
RFIE	Fraction of population indoor during routine transit and/or accident. Location: Population Parameters window. Valid Input: 0 to 1. Default: 0.0 (everyone outdoors, no credit for shielding). Equation: 2.12, 3.90, 3.93, 3.96.
RSALF	Resuspension factor decay half-life. The resuspension decay constant is given by 0.693/RSALF. Location: Soil and Resuspension Factors window. Valid Input: > 0 and $\leqq 100$ (based on Sprung et al. [1990]). Default: 0.137 [yr] (NRC 1974). Equation: 3.53 to 3.55, 3.57.
RSIZE	Radius of cask. Used for shape factor corrections of external dose from cask and initial dispersion of plume. Location: Shipment Parameters window. Data-Dependent Default: Dependent on the transportation mode selected if the default box is checked (IMOD). Valid Input: > 0 and $\leqq 5$ (a limiting value would be a railcar loaded with waste packages being treated as a single source for routine risk calculations; the useful height of some railcars exceeds 3 m [AAR 1974]). Default: 0.56 [m] (size of truck cask from Chen and Yuan [1988] used for developing the routine dose rate curves; if the default box is checked, the NRC Modal study [LLNL 1987] value for a truck or rail cask will be used.). Equation: 3.38, B.7, B.11, B.13, B.17 to B.19.
RTYPE	Reactor type for spent fuels. Location: SNF Inventory window. Valid Input: "BWR" or "PWR." Default: "PWR." Equation: Controls program option.

TABLE G.10 (Cont.)

Input Parameter	Description
SEXT(i,j)	External dose multiplication factor due to loss of shielding in an accident; expressed in multiples of TIDX (dose rate at 1 m) for each accident response region *i* (j = 1 gamma, 2 neutron). Location: Accident window. Valid Input: ≧ 1. Default: 40*1 (no loss of shielding in accident). Equation: 3.49.
SHIPDIST	Distance traveled next to off-link population of interest for routine transport calculations. Location: Population Parameters window. Valid Input: ≧ 0.1 and ≦ 5,000. Default: 1.0 [km] (unit distance). Equation: 2.12.
SHLDVAL	User input shielding factor for exposure pathway *i* (i = 1 inhalation, 2 cloudshine, 3 groundshine). Location: Individual Parameters or Population Parameters window. Valid Input: 0 to 1; 0 = full shielding, 1 = no shielding. Default: 1.0 (no shielding). Equation: User-specified value for ISHLT, LSHLT, and WSHLT arrays.
SPEED	Vehicle travel speed during routine transport. Location: Shipment Parameters window. Data-Dependent default: Dependent on the selected transportation mode, population zone, and route type if the default box is checked (IMOD, IZONE, IRDTY). Valid Input: > 0 and ≦ 240 (the maximum credible speed was determined to be 240 km/h in the NRC modal study [LLNL 1987]. Default: 88 or 64 [km/h] (truck on interstate in rural zone or rail in rural zone). Equation: 2.8, 2.10, 2.12, 2.15, 2.16.
STARNAME	Identifier of meteorological site chosen (filename of actual STAR file used). Location: All Weather window, selected indirectly in the Read Met File window when choosing STAR file by site location. Valid Input: Alphanumeric text (valid filename). Default: " " (No STAR file selected). Equation: Program display option.
SUFF	Final resuspension factor for determining resuspended air concentrations. Location: Soil and Resuspension Factors window. Valid Input: ≧ 1E-11 and ≦ 1E-4 (based on [Kennedy and Strenge 1992]). Default: 1E-9 [1/m] (NRC 1974; Anspaugh et al. 1974). Equation: 3.53 to 3.55, 3.57.

TABLE G.10 (Cont.)

Input Parameter	Description
SUFI	Initial resuspension factor for determining resuspended air concentrations. Location: Soil and Resuspension Factors window. Valid Input: ≧ 1E-11 and ≤ E-4 (based on [Kennedy and Strenge 1992]). Default: 1E-5 [1/m] (NRC 1974). Equation: 3.53 to 3.55, 3.57.
T_GROW_COW	Time of exposure to contamination for animal-consumed vegetation during the growing season. Location: Ingestion Pathway Details window. Valid Input: 0 to ≦ 180 (most crops have minimum growing periods of 90 days or less [Kennedy and Strenge 1992]). Default: 30 [days] (NRC 1977a). Equation: 3.59, 3.60.
T_GROW_HUM	Time of exposure to contamination for human-consumed vegetation during the growing season. Location: Ingestion Pathway Details window. Valid Input: 0 to ≦ 180 (most crops have minimum growing periods of 90 days or less [Kennedy and Strenge 1992]). Default: 60 [days] (NRC 1977a). Equation: 3.59, 3.60.
T_HARVEST_ COW	Time to first harvest of animal-consumed vegetation since an accidental release of radioactive material. Location: Ingestion Pathway Details window. Valid Input: 0 to ≦ 180 (most crops have minimum growing periods of 90 days or less [Kennedy and Strenge 1992]). Default: 15 [days] (The probability of the accident during a specific portion of the growing season is unknown; therefore, the time to first harvest is taken to be half the growing season.) Equation: 3.58, 3.60.
T_HARVEST_ HUM	Time to first harvest of human-consumed vegetation since an accidental release of radioactive material. Location: Ingestion Pathway Details window. Valid Input: 0 to ≦ 180 (most crops have minimum growing periods of 90 days or less [Kennedy and Strenge 1992]). Default: 30 [days] (The probability of the accident during a specific portion of the growing season is unknown; therefore, the time to first harvest is taken to be half the growing season.). Equation: 3.58, 3.60.
TABK	Ambient temperature. Used in the plume rise calculations for accidental releases. Location: Defined Meteorology or All Weather window. Valid Input: 211 to 330 (minimum and maximum recorded temperatures in the United States [National Climatic Data Center]). Default: 283 [K] (Parks 1992). Equation: 3.8.

TABLE G.10 (Cont.)

Input Parameter	Description
TD2M	External dose rate at 2 m from the cask. Location: Shipment Parameters window. Valid Input: > 0 and ≤ MAX (where MAX corresponds to a dose rate that would produce 10 mrem/h at 2 m from the lateral side of the transport vehicle, the maximum allowable rate [49 CFR 173 (DOT 1994) and 10 CFR 71 (NRC 1994b)]). Default: 10 [mrem/h] (maximum allowable external dose rate with cask at vehicle edge, TIOFF = 0). Equation: Converted to dose rate at 1 m for calculations as TIDX.
TEXT(i)	Individual receptor *i* short-term exposure duration immediately after accident. Location: Individual Parameters window. Valid Input: >0 to 100, based on EPA protective action guidelines' (EPA 1991) loose definition of the early phase of an accident, which is defined to extend up to a few days after the initiation of a release when all airborne material is assumed to have deposited. However, emergency response procedures in most cases would limit such exposure to hours if not minutes. In addition, most of the short-term dose is dominated by inhalation of the passing plume, which generally passes by within minutes of an accident but can take longer due to a prolonged release, slower wind speeds, and/or farther distances from the release point. External exposure from ground contamination can be accounted for with the long-term exposure option for any prolonged exposure period.). Default: 2.0 [h] (evacuation could be expected to be completed in most cases within this time frame in the aftermath of an accidental release, see e.g., Sprung et al. [1990]). Equation: 3.48, 3.49.
TFLAME	Flame temperature used for determining the accident response region (accident severity category) for a user-defined accident scenario. Location: Defined Accident Scenario window. Valid Input: ≧ 1,000 and ≦ 1,600 (NRC modal study [LLNL 1987]). Default: 1,350 [K] (approximately 70% of fires expected in transportation accidents will not achieve temperatures more than 1,350 K, NRC modal study [LLNL 1987]). Equation: Used to look up value in Table E.3 for Equation E.2.
TFUEL	Spent fuel cooling time. Location: SNF Inventory window. Valid Input: 1 to 100. Default: 10 [yr] (As of the end of 1993, approximately 40% of BWR spent fuel and 50% of PWR spent fuel in storage were discharged prior to 1986 [EIA 1995].) Equation: Used with lookup table of DOE SNF database described in Appendix A.

TABLE G.10 (Cont.)

Input Parameter	Description
TIDX	External dose rate at 1 m from cask surface. Location: Shipment Parameters window. Valid Input: > 0 and ≤ MAX (where MAX corresponds to a dose rate that would produce 10 mrem/h at 2 m from the lateral side of the transport vehicle, the maximum allowable rate [49 CFR 173 (DOT 1994) and 10 CFR 71 (NRC 1994b)]). Default: 21 [mrem/h] (maximum allowable external dose rate of 10 mrem/h at 2 m, using the default dose curve coefficients to obtain the dose rate at 1 m with cask at vehicle edge TIOFF = 0). Equation: 2.4.
TIOFF	Offset of cask surface from the lateral edge of the transport vehicle. Location: Shipment Parameters window. Valid Input: 0.0 to 5.0 (a limiting value would be the width of a railcar [AAR 1974]. Default: 0.0 [m] (outside edge of cask surface coincides with edge of the transport vehicle). Equation: 2.5 to 2.15.
TITLE	Case identifier to be printed in header of output file. User-defined label. Location: Main Options window. Valid Input: Alphanumeric text, limited to 48 characters. Default: "Default Case." Equation: Program display option.
TRAF_DEN	Traffic density (the one-way vehicle count per lane). Location: Routine On-Link/Stops Parameters window. Valid Input: 0 to 2,200 (2,200 passenger cars per hour per lane is about the maximum flow rate attainable under ideal conditions. Any more cars leads to congestion and stop-and-go traffic. [AASHTO 1994]. Default: 235 (based on 470 vehicles per hour in a rural zone (NRC 1977b), with the assumption that traffic was evenly distributed between two lanes). Equation: 2.16.
TREATM	Contaminated water treatment efficiency. A treatment efficiency of 0.7 would mean that 70% of the contamination was removed from the water consumed. Location: Water Pathway or Water Pathway for Population window. Valid Input: 0 to 1. Default: 0.0 (no treatment). Equation: 3.66, 3.67.
TSTP(i)	Stop duration by individual receptor *i* for routine calculations. Location: Individual Parameters window. Valid Input: 0 to 100 (commercial shipments rarely remain in one place for more than a few hours; allowance is given for severe weather or mechanical problems). Default: 20*1.0 [h] (unit time duration). Equation: 2.5.

TABLE G.10 (Cont.)

Input Parameter	Description
TYPCSK	User label for cask/shipping package description. Location: SNF Inventory or User-Defined Inventory window. Valid Input: Alphanumeric text, limited to 20 characters. Default: "Modal Truck" or "Modal Rail," depending on the transportation mode selected. Equation: Program display option.
UF(i)	Fraction of contaminated foodstuffs for each food type *i* (i = 1 meat, 2 milk, 3 vegetation) produced that is used for human consumption. For population accident calculations involving ingestion. Location: Population Ingestion Parameters window. Valid Input: 0 to 1. Default: 3*1 (All contaminated food produced is consumed by humans.). Equation: 3.109.
UMT	Total uranium in cask. A typical fuel assembly contains approximately 0.45 (PWR) or 0.20 (BWR) MTU (EIA 1995). The total amount of uranium in the shipping cask is the amount per assembly multiplied by the number of assemblies in the cask. Location: SNF Inventory window. Data-Dependent Default: The amount of uranium in PWR fuel in the cask studied in the NRC modal study (LLNL 1987) is used if the default box is checked. Depending on the transportation mode selected (IMOD), the amount in 1 assembly (truck) or 21 assemblies (rail) per cask will be used. Valid Input: > 0 and ≦ 30 (Most railcars have a weight limit near 70 tons, with higher values for specially designed cars [AAR 1974]). However, the largest certified railcar shipping cask, the NAC-STC, can only carry 26 PWR assemblies (about 12 MTU) and has a maximum gross weight of 114 metric tons [NRC 1994a]). Default: 0.46 (Truck) or 8.89 (Rail) [MTU] (LLNL 1987). Equation: Used with lookup table of DOE SNF database described in Appendix A.
VCASK	Accident cask velocity. Input is the speed of the cask at the time of impact for accident calculations. Location: Defined Accident Scenario. Valid Input: > 0 and ≦ 240 (the maximum credible speed was determined to be 240 km/h in the NRC modal study [LLNL 1987]). Default: 65 [km/h] (Approximately half of all truck accidents occur in the 51 to 84 km/h range, and 32% occur within approximately the same range for rail (NRC 1974). Equation: E.1.

TABLE G.10 (Cont.)

Input Parameter	Description
VDEP	Ground deposition velocity of radionuclides for population accident calculations. Typical deposition velocities are generally less than 0.01 m/s (Sehmel 1980; McMahon and Dennison 1979). However, the deposition velocity is dependent on such variables as particle size and type, surface roughness, and atmospheric stability. Values will tend to be higher over some areas of farmland with taller crops, wooded areas, and suburban/urban areas. Location: Defined Meteorology or All Weather window, depending on the selected weather option. Valid Input: 0 to 0.07 (based on references in Sehmel [1980] and McMahon and Dennison [1979]). Default: 0.01 [m/s] (see discussion above in the input parameter description). Equation: 3.81, 3.82. Used in place of VDEPNUC in Equations 3.19, 3.20, 3.27, 3.29, and 3.30 for population calculations.
VDEPNUC(5)	Deposition velocity of each nuclide type for individual receptor problems. Typical deposition velocities are generally less than 0.01 m/s (Sehmel 1980; McMahon and Dennison 1979). However, the deposition velocity is dependent on such variables as particle size and type, surface roughness, and atmospheric stability. Values will tend to be higher over some areas of farmland with taller crops, wooded areas, and suburban/urban areas. Location: Nuclide-Dependent Deposition Velocities window. Valid Input: 0 to 0.07 (based on references in Sehmel [1980] and McMahon and Dennison [1979]). Default: 0.01 , 0.01 , 0.01 , 0.01 , 0.00 [m/s] (See discussion above in the input parameter description.). Equation: 3.19, 3.20, 3.27, 3.29, 3.30.
VERSION	Version of RISKIND used to set up problem. Location: Not accessible from screen interface, not intended for modification by users. Valid Input: Not applicable. Default: Current version. Equation: Not applicable.
WBDYD(i)	Depth of water body at each receptor *i* (20 maximum) for individual accident calculations involving water consumption. For population calculations, depth of water body *i* (20 maximum) if water consumption is considered. Location: Water Pathways Parameters or Water Pathway for Population window. Valid Input: > 0 and ≤ 10 (the drinking water model in RISKIND is only intended for small local water distribution systems). Default: 20*2.0. [m]. Equation: 3.63, 3.66, 3.67.

TABLE G.10 (Cont.)

Input Parameter	Description
WBDYW(i)	Cross-wind width of water body at each receptor *i* (20 maximum) for individual accident calculations involving water consumption. For population calculations, cross-wind width of water body *i* (20 maximum) if water consumption is considered. Location: Water Pathways Parameters or Water Pathway for Population window. Valid Input: > 0 and ≦ 1,000 (the drinking water model in RISKIND is only intended for small local water distribution systems). Default: 20*50 [m]. Equation: 3.65.
WDTHMED	Width of median between opposing lanes of traffic for truck transport or distance between adjacent track centerlines for rail transport. Used in routine on-link population calculations. Location: Shipment Parameters window when routine population calculations are specified (IADD = 0, IRUTIN = 1). Data-Dependent Default: Dependent on the road type (IRDTY) and population zone (IZONE), if the default box is checked. Valid Input: 0 to 50. Default: 15 for truck, 6 for rail [m] (median widths of 15 to 30 m are common on rural freeways [AASHTO 1994]). Equation: 2.15.
WEXCG(i)	Exchange rate of water body at each receptor *i* (20 maximum) for individual accident calculations involving water consumption. For population calculations, exchange rate of water body *i* (20 maximum) if water consumption is considered. Location: Water Pathways Parameters or Water Pathway for Population window. Valid Input: 0 to 100. Default: 20*1. [/yr] (unit exchange rate). Equation: 3.66, 3.67.
WS(i)	Average wind speed *i* for one of the six wind-speed classes of the wind frequency data when using the all weather option. Location: All Weather window. Valid Input: 0.1 to 25 (The dispersion model in RISKIND was not developed for the higher wind speeds encountered in stormy weather such as hurricanes.). Default: 0.89, 2.46, 4.47, 6.93, 9.61, and 12.52 [m/s] (STAR file wind speed categories). Equation: Used in place of WSM in Equation 3.10 when calculating risks over all weather conditions.
WSHLT(i)	Fraction of population with each shielding type *i* for population calculations (1 = frame house, 2 = brick house, 3 = office building, 4 = cars on road, 5 = user-defined [SHLDVAL]). These values are heavily dependent on location and time of day. Location: Population Parameters window. Valid Input: 0 to 1, summation over *i* should = 1. Default: 0.36, 0.38, 0.21, 0.05, 0.0 (based on information in [NRC 1975]). Equation: 2.12, 3.91, 3.94, 3.97.

TABLE G.10 (Cont.)

Input Parameter	Description
WSM	Wind speed measured at anemometer height (ANH) with the user-specified weather option. Location: Defined Meteorology window. Valid Input: 0.1 to 25 (The dispersion model in RISKIND was not developed for the higher wind speeds encountered in stormy weather such as hurricanes.). Default: 4.0. [m/s] (Wind speeds in this range are the most common. The 4.47 m/s wind speed category in most STAR files has the highest frequency of occurrence.). Equation: 3.10.
XIN(i)	Individual food consumption rate of food type *i* for individual problems (*i* = 1 meat, 2 milk , 3 vegetation, 5 water). Location: Ingestion Parameters and Water Pathway Parameters. Valid Input: 0 to 5. Defaults: 1-meat: 0.30; 2-milk: 0.85; 3-vegetation: 1.6; 5-water: 2.0 [kg/d] (NRC 1977a). Equation: 3.74 to 3.77.
XING(i)	Average individual food consumption rate of food type *i* (i = 1 meat, 2 milk, 3 vegetation, 5 water) for population problems. Location: Population Ingestion Parameters window for meat, milk, and vegetation; Water Pathway for Population window for water. Valid Input: 0 to 5. Defaults: 1-meat: 0.26; 2-milk: 0.30; 3-vegetation: 0.52; 5-water: 1.0 [kg/d] (NRC 1977a). Equation: 3.113, used in place of XIN in Equations 3.74 to 3.77 for local individual calculations for PAG determination.
XNAME(i)	User label for individual receptor *i* (maximum of 20 individuals). Location: Individual Parameters window. Valid Input: Alphanumeric text, maximum of 20 characters. Default: "Individual 1." Equation: Program display option.
XPZ(i)	Population zone downwind distances (*i* = 1 minimum, 2 maximum) for accident calculations and nearest and farthest distances to shipment route for off-link population routine calculations. Location: Population Parameters window. Valid Input: 0.001 to 80.0 (NRC 1977c). Defaults: 0.05, 80.0 [km] (NRC 1977c). Equation: 2.12, 3.83, 3.98.

TABLE G.10 (Cont.)

Input Parameter	Description
XRECEP(i,j)	Individual Problem: Accident Problem: Individual receptor *j* location coordinates: *i* = 1, downwind distance (km); *i* = 2, crosswind distance (km); *i* = 3, elevation of receptor (m). Population Problem: Accident Problem: Water body *j* location coordinates: *i* = 1, downwind distance (km); *i* = 2, crosswind distance (km). Location: Individual Parameters window for individual calculations or Water Pathway for Population window for population calculations. Valid Input: 0.001 to 80.0, XRECEP(1) (NRC 1977c). 0 to 80.0, XRECEP(2) 0 to 1,000.0, XRECEP(3). Default: 20*(1.0, 0., 0.) (unit distance downwind on the plume centerline). Equation: 3.4 to 3.6, 3.11 to 3.15, 3.20, 3.25 to 3.30, 3.35, 3.36.
YEVD	Long-term exposure time following a potential accident. Location: Individual Parameters window for individual calculations or Population Parameters window for population calculations. Valid Input: 0 to 70. Default: 50.0 [yr] (EPA 1988). Equation: 3.52, 3.53, 3.57, 3.59, 3.60, 3.66, 3.67.
YIELD_COW	Yield density of animal-consumed vegetation on farmland. Location: Ingestion Pathway Details window. Valid Input: 0 to 5. Default: 0.7 [kg/m^2] (NRC 1977a). Equation: 3.58 to 3.60.
YIELD_HUM	Yield density of human-consumed vegetation on farmland. Location: Ingestion Pathway Details window. Valid Input: 0 to 5. Default: 2.0 [kg/m^2] (NRC 1977a). Equation: 3.58 to 3.60.

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APPENDIX H:

SAMPLE PROBLEMS

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APPENDIX H:

SAMPLE PROBLEMS

This appendix illustrates the use of RISKIND through two sample problems. A sample problem for incident-free dose calculations is presented in Sections H.1 through H.3. A sample problem for dose calculations under accident conditions is presented in Sections H.4 through H.6. In the first problem, the impacts to four receptors encountered along the shipment route are estimated. The second problem considers the consequence to a population subgroup located 200 to 400 m away from a potential accident. Descriptions of the input parameters used in RISKIND are provided in Appendix G.

H.1 SAMPLE PROBLEM ONE: INCIDENT-FREE CONDITIONS

The first sample problem considers incident-free transportation of spent nuclear fuel (SNF) along a local interstate highway. The four receptors are the nearest resident to the interstate (75 m), a customer at a gas station by the local interstate on-ramp (40 m), a child playing in a nearby school yard (200 m), and a motorist traveling behind the shipment for 15 min (20 m). The sample problem input file, as generated by the user interface and used by the FORTRAN calculational portion of the program, is given in Section H.2. The shipping cask is assumed to be a GA-4 truck cask, and the spent fuel is assumed to be 10 years old with a dose rate of 10 mrem/h at 2 m. The radiation field is 83% gamma and 17% neutron in dose. Two modes of exposure are evaluated: one is for a stop with an exposure time of one hour, and the other is for a passing truck. For the motorist, the stop time is set to 0.25 h to model the time spent following the shipment.

The sample problem output file is given in Section H.3. The output reflects the input parameters and represents the calculated doses for the four receptors for the two modes of exposure.

H.2 INPUT DATA FILE FOR SAMPLE PROBLEM ONE: INCIDENT-FREE CONDITIONS

```
&INDATA
 VERSION = '1.10R'
 TITLE = 'Sample Problem 1, Routine Transport',
 ACTA =          1              ,
 METFREQ =       1              ,
 PPVH =         -1              ,
 TRAF_DEN =     -1              ,
 PAG =           27             ,
 QA =            50             ,
 STATEN = '',
 HS =            1              ,
 HZLM =          .01            ,
 IACDT =         0              ,
 IACFOD =        0              ,
 IBOUND =        2              ,
 IMOD =          1              ,
 IRDTY =         1              ,
 IRUTIN =        1              ,
 ICONSQ =        0              ,
 NISOPL =        10             ,
 IACOEF =        0              ,
 ISPENT =        1              ,
 ITREAT =        1              ,
 ISTATE =        49             ,
 IZONE =         2              ,
 WDTHMED =      -1              ,
 NUMLANES =     -1              ,
 OUTFIL ='output\sample1.out',
 EFF_SURF_DEN =                 240          ,
 PHALF =         50             ,
 RSALF =         .137           ,
 UF =  3*1,
 SEXT =  40*1,
 IDISPMOD =      0              ,
 SPEED =        -1              ,
 SHIPDIST =      1              ,
 BRTPOP =        8000           ,
 SUFI =          .00001         ,
 SUFF =          .000000001     ,
 TD2M =          10             ,
 TIDX =          0              ,
 TIOFF =         0              ,
 VDEP =          .001           ,
 VDEPNUC =  3*.001, .01 , 0     ,
 YEVD =          50             ,
 BURNUP =        35000          ,
 CACTD =         1              ,
 CAREA =         39             ,
 FRAD =  .83 , .17 ,
 HSIZE =         4.77           ,
 RSIZE =         .5             ,
 RTYPE ='PWR',
 TFUEL =         10             ,
 TYPCSK ='Modal Truck',
 UMT =           .46            ,
 IADD =          4              ,
 POPTYPE =       1              ,
 DECAY_WEATHER =                .0495        ,
 F_RETAIN =      .2             ,
 F_EDBL_COW =    1              ,
 F_EDBL_HUM =    1              ,
 T_HARVEST_COW =                15           ,
```

```
 T_HARVEST_HUM =              30           ,
 YIELD_COW =    .7            ,
 YIELD_HUM =    2             ,
 T_GROW_COW =   30            ,
 T_GROW_HUM =   60            ,
 IDFOOD =   4*0, 16*1,
 IDPG =   1 , 5 , 3*1, 5*5, 6*1, 2*5, 16*1, 2*5, 6*1, 3*2, 7*1, 4 , 5 , 3 , 30*1, 5 ,
14*1, 10*0,
 IRTP =   20*1,
 ISHLT =   1 , 2*0, 4 , 16*1,
 LSHLT =   20*0,
 INDTYPE =   20*1,
 WSHLT =   1 , 4*0,
 SHLDVAL =   1 , 2*0,
 IWATER =   20*0,
 OCUPF =   20*.5, 20*.25,
 POPW =   20*1,
 TEXT =   20*2,
 TSTP =   3*1, .25 , 16*1,
 BRTIND =   20*8000,
 DISTSTOP =   .075 , .04 , .2 , .02 , 16*1,
 DISTPASS =   .075 , .04 , .2 , .02 , 16*1,
 WBDYD =   20*2,
 WBDYW =   20*50,
 WEXCG =   20*1,
 XRECEP =   .05 , 2*0, .03 , 2*0, .15 , 2*0, .1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 ,
2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0,
1 , 2*0, 1 , 2*0, 1 , 2*0,
 XNAME =     'Nearest Resident',
   'Gas Station Customer',
   'Child in School Yard',
   'Motorist',
    16*'',

 NUTYPE =     'Particulate',
   'Ru',
   'Cs',
   'I',
   'Gas',

 ANH =          10            ,
 TABK =         288           ,
 IYOURW =       1             ,
 DMIX =         800           ,
 ITYPE =        4             ,
 RAIN =         0             ,
 WSM =          4             ,
 AMIX =         300           ,
 PMIX =         2400          ,
 DFREQ =   36*.0278,
 WS =   .67 , 2.46 , 4.47 , 6.93 , 9.61 , 12.52 ,
 DFACT =        .5            ,
 PFIN =   5*1,
 TREATM =       0             ,
 XIN =   .3 , .85 , .77 , 2*1,
 IYOURS =      -1             ,
 VCASK =        65.57         ,
 ALPHA =        90            ,
 BETA =         90            ,
 IHARD =        1             ,
 TFLAME =       1199.67       ,
 DFIRE =        5             ,
 FLOCA =        0             ,
 DSTP =   2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 ,
50 , 2 , 50 ,
 FARM =        -1             ,
 GMEAT =       -1             ,
```

```
 GMILK =       -1              ,
 GVEGE =       -1              ,
 HSTP =  10*1,
 HTEXP =        2              ,
 IPFOD =        1              ,
 IPWATR =       0              ,
 NSTP =  10*1,
 NSTY =         0              ,
 POPD =         2              ,
 PSTP =  10*50,
 RDWTH =       -1              ,
 RFIE =          .583          ,
 XING =  .26 , .33 , .28 , 2*0,
 XPZ =  .05 , 80 ,
 NSV =          20              ,
 FRELS =  3*.000002, .00002 , 3*.000002, .00002 , 3*.000002, .00002 , 3*.000002,
5*.00002, 3*.000027, .00027 , 3*.000027, .00027 , 3*.000027, .00027 , 3*.000048,
5*.00048, 3*.0002, .002 , 3*.0002, .002 , 3*.0002, .002 , 3*.0002, 5*.002, 3*.0025,
.043 , 3*.0025, .043 , 3*.0025, .043 , 3*.0043, 5*.043, 3*.33, .63 , 3*.33, .63 ,
3*.33, .63 , 3*.39, 5*.63,
 FDISP =  0 , 19*1, 0 , 19*1, 0 , 19*1, 0 , 19*1, 0 , 19*1,
 FSEV =  .994316 , .0038192 , .0017984 , .0000001532 , .00001687 , .000000233 ,
.0000001574 , 3.926E-14 , .00002362 , .0000003008 , .0000002034 , 1.495E-14 ,
.00001525 , .0000001592 , .0000001076 , 7.681E-16 , .00000957 , .00000007201 ,
.00000004873 , 1E-16 , .993962 , .0027204 , .0005545 , .000000001786 , .0012275 ,
.0000005011 , .0000001021 , .000000000000329 , .00079511 , .0000003255 , .00000006634
, 2.137E-13 , .000614 , .0000002531 , .00000005162 , 1.644E-13 , .0001249 ,
.00000001075 , .00000005296 , 3.459E-14 , 20*.0000000001,
 FAILS =  .03 , .1 , 2*1, .03 , .1 , 2*1, .03 , .1 , 10*1,
 FSPAL =  0 , 3*1, .15 , 3*1, .15 , 3*1, .15 , 3*1, .15 , 3*1,
 FRCRUD =  20*1,
 HEATF =  4*500, 16*2000000,
&END
```

H.3 OUTPUT DATA FILE FOR SAMPLE PROBLEM ONE: INCIDENT-FREE CONDITIONS

```
================= RISKIND Program Output, Version 1.10      ========= Page:   1
 Title       : Sample Problem 1, Routine Transport
 Date/Time   : 10/30/95 13:13
 Input  File : c:\riskind\input\sample1.inp
 Output File : output\sample1.out
================================================================================




================================================================================
============================ RISKIND Computer Program ==========================
================================================================================



 Problem Description
 ---------------------------------------

               Individual Receptors

               Routine Calculations



     Note: * next to input description signifies
           a data dependent default value
```

```
================= RISKIND Program Output, Version 1.10     ========= Page:   2
 Title        : Sample Problem 1, Routine Transport
 Date/Time    : 10/30/95 13:13
 Input  File  : c:\riskind\input\sample1.inp
 Output File  : output\sample1.out
==============================   Routine Problem  ==============================

==============================================================================
=================== RISKIND Routine Individual Problem Input ===================
==============================================================================


 Shipment Parameters
_____________________________________________

                    Transport Mode [IMOD]: Truck
                  Population Zone [IZONE]: Suburban
                       Dose at 2 m [TD2M]:   10.00 mrem/hr
               Measurement Offset [TIOFF]:    0.00       m
                 Gamma Fraction [FRAD(1)]:    0.83
               Neutron Fraction [FRAD(2)]:    0.17
                      Cask Length [HSIZE]:    4.77       m
                      Cask Radius [RSIZE]:    0.50       m
                 Traveling speed [SPEED]*:   88.00   km/hr
                Individual type [INDTYPE]:  Public
            Risk Conversion Factors
                    Non-Fatal Cancers/rem: 1.0E-04
                        Fatal Cancers/rem: 5.0E-04
                      Genetic Effects/rem: 1.3E-04
```

#	Individual Name	Stop Distance [DISTSTOP] [km]	Stop Time [TSTP] [hr]	Passing Distance [DISTPASS] [km]
1	Nearest Resident	7.5E-02	1.00	7.5E-02
2	Gas Station Customer	4.0E-02	1.00	4.0E-02
3	Child in School Yard	2.0E-01	1.00	2.0E-01
4	Motorist	2.0E-02	0.25	2.0E-02

```
================= RISKIND Program Output, Version 1.10      ========= Page:   3
 Title       : Sample Problem 1, Routine Transport
 Date/Time   : 10/30/95 13:13
 Input  File : c:\riskind\input\sample1.inp
 Output File : output\sample1.out
==============================   Routine Problem  ==============================

================================================================================
================== RISKIND Routine Individual Problem Results ==================
================================================================================
```

#	Individual Name	Dose (rem)	Expected Non-Fatal Cancers	Expected Cancer Fatalities	Expected Genetic Effects
		========== Stop ==========			
1	Nearest Resident	4.3E-06	4.3E-10	2.1E-09	5.6E-10
2	Gas Station Customer	4.4E-05	4.4E-09	2.2E-08	5.7E-09
3	Child in School Yard	8.4E-07	8.4E-11	4.2E-10	1.1E-10
4	Motorist	4.7E-05	4.7E-09	2.3E-08	6.1E-09

#	Individual Name	Dose (rem)	Expected Non-Fatal Cancers	Expected Cancer Fatalities	Expected Genetic Effects
		========== Passing ==========			
1	Nearest Resident	8.3E-09	8.3E-13	4.2E-12	1.1E-12
2	Gas Station Customer	5.1E-08	5.1E-12	2.5E-11	6.6E-12
3	Child in School Yard	3.3E-09	3.3E-13	1.7E-12	4.4E-13
4	Motorist	1.2E-07	1.2E-11	5.9E-11	1.5E-11

H.4 SAMPLE PROBLEM TWO: ACCIDENT CONDITIONS

The second sample problem considers accident conditions during transport. The input file, as generated by the user interface and used by the FORTRAN calculational portion of the program, is given in Section H.5. In this problem, a collective population dose (consequence) to a specific population subgroup is estimated from accident conditions. This population subgroup extends from 200 to 400 m from the potential accident site and has an average population density of 600 persons/km^2. The spent fuel is assumed to be pressurized-water reactor fuel, with a burnup of 33,000 megawatt-days per metric ton of initial heavy metal (MWd/MTIHM) and a 10-year cooling period. Only short-term exposure from the plume passage is assumed. Weather conditions at the time of the potential accident are assumed to be stability category D and a wind of 4 m/s blowing toward the receptor group. The consequence from an accident in the second accident response region, R(2,1), as defined in the modal study (Lawrence Livermore National Laboratory [LLNL] 1987), is estimated.

The sample problem output file is given in Section H.6. The first page of the report gives a brief scenario summary. An input echo is then given starting on page 2; the input parameters are grouped into categories according to their function. Population data tables are followed by the meteorological input data and a table with the shipment parameters, including cask information. Two tables with radionuclide input data are next (pages 4-6), which include the radionuclide inventory retrieved from the SNF database. The inventory is determined on the basis of the cask information given in the preceding table. The radionuclide inventory is accompanied by the dose conversion factors for each radionuclide. This inventory is input to the screening routine described in Appendix C for determining the radionuclides that dominate the risk estimates for each accident response region of interest.

The input data conclude with a list of general accident parameters that include the release height and the type of dispersion coefficients used. These data are followed by input data, specific to the accident response region under consideration, that contains information such as the radionuclide release fractions and the screened list of radionuclides to be used for risk estimates.

For the population consequence scenario, intermediate calculations are given that present isopleth-specific data such as the number of persons affected, the contaminated area, radionuclide concentrations, and the estimated dose (page 9). Overall collective dose and health risk estimates for the response region are then given in conjunction with a breakdown by exposure pathway. A summary dose table concludes the report output.

Graphical presentation of the data for a better perspective on the results is available in two formats for population consequences. A breakdown of the population fatality risk is displayed in Figure H.1. Figure H.2 presents a plot of the radionuclide air concentration isopleths estimated for sample problem 2, which shows the extent of the contaminated area under consideration. Both plots are available at the conclusion of a calculation run for display on the user screen with an option to print.

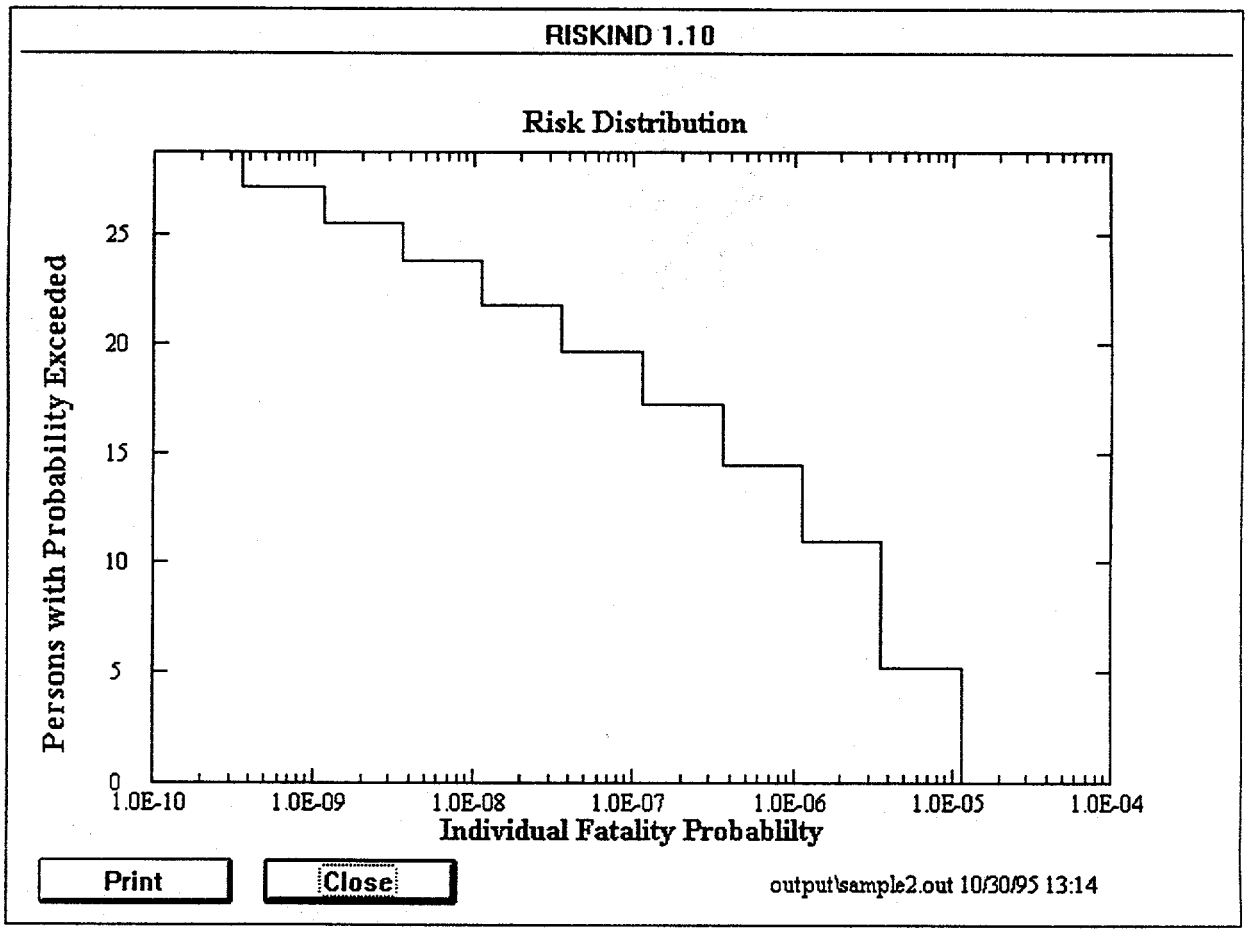

FIGURE H.1 Population Cancer Fatality Probability for Sample Problem 2

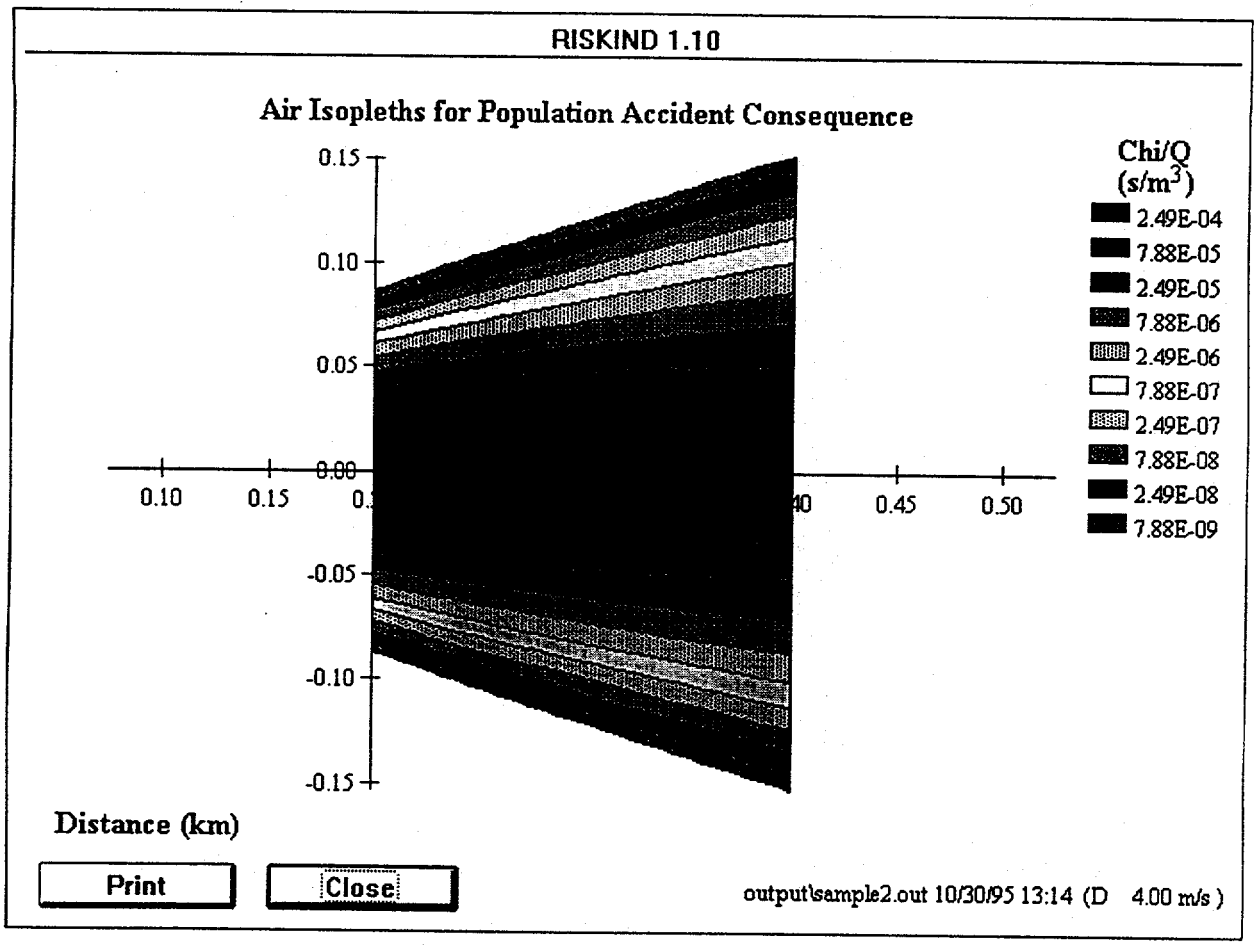

FIGURE H.2 Radionuclide Concentration Isopleths for Sample Problem 2

H.5 INPUT DATA FILE FOR SAMPLE PROBLEM TWO: ACCIDENT CONDITIONS

```
&INDATA
 VERSION = '1.10R'
 TITLE = 'Sample Problem 2, Accident Conditions',
 ACTA =          1              ,
 METFREQ =       1              ,
 PPVH =         -1              ,
 TRAF_DEN =     -1              ,
 PAG =           27             ,
 QA =            50             ,
 STATEN = '',
 HS =            1              ,
 HZLM =          .01            ,
 IACDT =         1              ,
 IACFOD =        0              ,
 IBOUND =        2              ,
 IMOD =          1              ,
 IRDTY =         1              ,
 IRUTIN =        0              ,
 ICONSQ =        1              ,
 NISOPL =        10             ,
 IACOEF =        0              ,
 ISPENT =        1              ,
 ITREAT =        1              ,
 ISTATE =        49             ,
 IZONE =         1              ,
 WDTHMED =      -1              ,
 NUMLANES =     -1              ,
 OUTFIL ='output\sample2.out',
 EFF_SURF_DEN =                  240          ,
 PHALF =         50             ,
 RSALF =         .137           ,
 UF =  3*1,
 SEXT =  40*1,
 IDISPMOD =      1              ,
 SPEED =        -1              ,
 SHIPDIST =      1              ,
 BRTPOP =        8000           ,
 SUFI =          .00001         ,
 SUFF =          .000000001     ,
 TD2M =          10             ,
 TIDX =          0              ,
 TIOFF =         0              ,
 VDEP =          .01            ,
 VDEPNUC =  3*.001, .01 , 0 ,
 YEVD =          50             ,
 BURNUP =        33000          ,
 CACTD =         1              ,
 CAREA =         39             ,
 FRAD =  .83 , .17 ,
 HSIZE =         4.77           ,
 RSIZE =         .5             ,
 RTYPE ='PWR',
 TFUEL =         10             ,
 TYPCSK ='Modal Truck',
 UMT =           .46            ,
 IADD =          0              ,
 POPTYPE =       1              ,
 DECAY_WEATHER =                 .0495        ,
 F_RETAIN =      .2             ,
 F_EDBL_COW =    1              ,
 F_EDBL_HUM =    1              ,
 T_HARVEST_COW =                 15           ,
 T_HARVEST_HUM =                 30           ,
```

```
 YIELD_COW =    .7            ,
 YIELD_HUM =    2             ,
 T_GROW_COW =   30            ,
 T_GROW_HUM =   60            ,
 IDFOOD =   20*1,
 IDPG =   1 , 5 , 3*1, 5*5, 6*1, 2*5, 16*1, 2*5, 6*1, 3*2, 7*1, 4 , 5 , 3 , 30*1, 5 ,
14*1, 10*0,
 IRTP =   0 , 19*1,
 ISHLT =   20*1,
 LSHLT =   20*0,
 INDTYPE =   20*1,
 WSHLT =   1 , 4*0,
 SHLDVAL =   1 , 2*0,
 IWATER =   20*0,
 OCUPF =   20*.5, 20*.25,
 POPW =   20*1,
 TEXT =   20*2,
 TSTP =   20*1,
 BRTIND =   20*8000,
 DISTSTOP =   20*1,
 DISTPASS =   20*1,
 WBDYD =   20*2,
 WBDYW =   20*50,
 WEXCG =   20*1,
 XRECEP =   1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 ,
2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0, 1 , 2*0,
1 , 2*0, 1 , 2*0,
 XNAME =     ' Individual 1 ',
    19*'',

 NUTYPE =     'Particulate',
   'Ru',
   'Cs',
   'I',
   'Gas',

 ANH =          10            ,
 TABK =         288           ,
 IYOURW =       1             ,
 DMIX =         800           ,
 ITYPE =        4             ,
 RAIN =         0             ,
 WSM =          4             ,
 AMIX =         300           ,
 PMIX =         2400          ,
 DFREQ =   36*.0278,
 WS =   .67 , 2.46 , 4.47 , 6.93 , 9.61 , 12.52 ,
 DFACT =        .5            ,
 PFIN =   5*1,
 TREATM =       0             ,
 XIN =   .3 , .85 , .77 , 2*1,
 IYOURS =       2             ,
 VCASK =        65.57         ,
 ALPHA =        90            ,
 BETA =         90            ,
 IHARD =        1             ,
 TFLAME =       1199.67       ,
 DFIRE =        5             ,
 FLOCA =        0             ,
 DSTP =   2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 , 50 , 2 ,
50 , 2 , 50 ,
 FARM =        -1             ,
 GMEAT =       -1             ,
 GMILK =       -1             ,
 GVEGE =       -1             ,
 HSTP =   10*1,
 HTEXP =        2             ,
```

```
 IPFOD =        1              ,
 IPWATR =       0              ,
 NSTP =  10*1,
 NSTY =         0              ,
 POPD =         600            ,
 PSTP =  10*50,
 RDWTH =       -1              ,
 RFIE =         0              ,
 XING =  .26 , .33 , .28 , 2*0,
 XPZ =  .2 , .4 ,
 NSV =          20             ,
 FRELS =  3*.000002, .00002 , 3*.000002, .00002 , 3*.000002, .00002 , 3*.000002,
5*.00002, 3*.000027, .00027 , 3*.000027, .00027 , 3*.000027, .00027 , 3*.000048,
5*.00048, 3*.0002, .002 , 3*.0002, .002 , 3*.0002, .002 , 3*.0002, 5*.002, 3*.0025,
.043 , 3*.0025, .043 , 3*.0025, .043 , 3*.0043, 5*.043, 3*.33, .63 , 3*.33, .63 ,
3*.33, .63 , 3*.39, 5*.63,
 FDISP =  0 , 19*1, 0 , 19*1, 0 , 19*1, 0 , 19*1, 0 , 19*1,
 FSEV =  .994316 , .00382 , .0017984 , .0000001532 , .00001687 , .000000233 ,
.0000001574 , 3.926E-14 , .00002362 , .0000003008 , .0000002034 , 1.495E-14 ,
.00001525 , .0000001592 , .0000001076 , 7.681E-16 , .00000957 , .00000007201 ,
.00000004873 , 1E-16 , .993962 , .0027204 , .0005545 , .000000001786 , .0012275 ,
.0000005011 , .0000001021 , .000000000000329 , .00079511 , .0000003255 , .00000006634
, 2.137E-13 , .000614 , .0000002531 , .00000005162 , 1.644E-13 , .0001249 ,
.00000001075 , .00000005296 , 3.459E-14 , 20*.0000000001,
 FAILS =  .03 , .1 , 2*1, .03 , .1 , 2*1, .03 , .1 , 10*1,
 FSPAL =  0 , 3*1, .15 , 3*1, .15 , 3*1, .15 , 3*1, .15 , 3*1,
 FRCRUD =  20*1,
 HEATF =  4*500, 16*2000000,
&END
```

H.6 OUPUT DATA FILE FOR SAMPLE PROBLEM TWO: ACCIDENT CONDITIONS

```
================= RISKIND Program Output, Version 1.10     ========= Page:   1
 Title        : Sample Problem 2, Accident Conditions
 Date/Time    : 10/30/95 13:14
 Input  File  : c:\riskind\input\sample2.inp
 Output File  : output\sample2.out
==============================================================================



==============================================================================
========================== RISKIND Computer Program ==========================
==============================================================================



 Problem Description
_____________________________________________

              Population Dose

              Accident Calculations
                 Single Accident Analysis
                 Single Weather Analysis

                 Acute Exposure
                    Plume Inhalation
                    Plume Immersion
                    Early Ground Exposure
                    Exposure to Cask



     Note: * next to input description signifies
           a data dependent default value
```

```
================= RISKIND Program Output, Version 1.10      ========= Page:   2
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
==============================  Input Parameters  ==============================


================================================================================
======================== RISKIND Accident Population Input =====================
================================================================================


 Population Accident Parameters
 ------------------------------

                  Minimum Distance [XPZ(1)]:    0.20          km
                  Maximum Distance [XPZ(2)]:    0.40          km
                  Population Density [POPD]:  600.00 person/km2
             Average Breathing Rate [BRTPOP]: 8000.00       m3/yr
          Accident Exposure Duration [HTEXP]:    2.00          hr
             Accident Indoor Fraction [RFIE]:    0.00
                   Population type [POPTYPE]:  Public
               Risk Conversion Factors
                Non-Fatal Cancers/person-rem: 1.0E-04
                    Fatal Cancers/person-rem: 5.0E-04
                 Genetic Effects/person-rem: 1.3E-04
          Fraction of Indoor Shelter [WSHLT]
                                Frame House:    1.00
                                Brick House:    0.00
                                Office Bldg:    0.00
                                Automobile :    0.00
                                Other      :    0.00

 Derived Shielding Factors
 -------------------------

                           Acute Inhalation:    1.00
                         Acute Cloud Shine:    1.00
                           Acute External:    1.00
```

```
================= RISKIND Program Output, Version 1.10     ========= Page:   3
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
============================  Input Parameters  ============================

 Meteorological Parameters
_____________________________________________

                Dry deposition rate [VDEP]: 1.00E-02      m/s
                     Rain fall rate [RAIN]: 0.00E+00     mm/h
                   Anemometer height [ANH]:    10.00        m
                Ambient Temperature [TABK]:   288.00        K
                      Mixing height [DMIX]:   800.00        m
                  Wind at anemometer [WSM]:     4.00      m/s
            Pasquill stability cat. [ITYPE]:       D



 Shipment Parameters
_____________________________________________

                Transportation Mode [IMOD]:    Truck
                        Dose at 2 m [TD2M]:    10.00  mrem/hr
                Measurement Offset [TIOFF]:     0.00        m
                  Gamma Fraction [FRAD(1)]:     0.83
                Neutron Fraction [FRAD(2)]:     0.17
                       Cask Length [HSIZE]:     4.77        m
                       Cask Radius [RSIZE]:     0.50        m
                   Amount of Uranium [UMT]:     0.46      MTU
                      Reactor Type [RTYPE]:      PWR
                   Reactor Burnup [BURNUP]: 3.30E+04     MWD
                 Fuel Cooling Time [TFUEL]:    10.00       yr
         Total Surface Area of Cask [CAREA]:    39.00       m2
      Crud Surface Activity Density [CACTD]:     1.00  uCi/cm2
```

```
================= RISKIND Program Output, Version 1.10     ========= Page:   4
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
==============================  Input Parameters  ==============================
```

Nuclide Parameters

Nuclide Inventory and DCFs

Nuclide Name	Inventory Amount [Ci]	Dose Conversion Factors: Inhalation [Sv/Bq]	Ingestion [Sv/Bq]	Cloud [Sv/s] [Bq/m3]	Ground [Sv/s] [Bq/m2]	Nucl. Class	Decay Const. [1/yr]
H 3	2.08E+02	1.73E-11	1.73E-11	0.00E+00	0.00E+00	Particul	5.60E-02
FE 55	1.06E+02	7.26E-10	1.64E-10	0.00E+00	0.00E+00	Particul	2.60E-01
CO 60	1.07E+03	5.91E-08	7.28E-09	1.26E-13	2.35E-15	Particul	1.30E-01
NI 63	1.84E+02	1.70E-09	1.56E-10	0.00E+00	0.00E+00	Particul	6.90E-03
KR 85	2.23E+03	1.03E-11	1.03E-11	1.19E-16	2.64E-18	Gas	6.50E-02
SR 90	2.64E+04	3.53E-07	4.14E-08	1.97E-16	5.61E-18	Particul	2.40E-02
Y 90	2.64E+04	2.28E-09	2.91E-09	1.90E-16	5.33E-18	Particul	9.50E+01
RU106	2.36E+02	1.30E-07	8.30E-09	1.04E-14	2.12E-16	Ru	6.90E-01
RH106	2.36E+02	8.95E-10	8.95E-10	1.04E-14	2.12E-16	Ru	7.30E+05
SB125	5.73E+02	3.75E-09	9.85E-10	2.02E-14	4.33E-16	Particul	2.50E-01
TE125M	1.40E+02	1.97E-09	9.92E-10	4.53E-16	3.61E-17	Particul	4.40E+00
CS134	2.50E+03	1.25E-08	1.98E-08	7.56E-14	1.52E-15	Cs	3.40E-01
CS137	3.76E+04	1.10E-08	1.59E-08	2.73E-14	5.54E-16	Cs	2.30E-02
BA137M	3.56E+04	2.49E-09	2.49E-09	2.88E-14	5.86E-16	Particul	1.40E+05
CE144	6.41E+01	1.01E-07	5.71E-09	2.80E-15	5.83E-17	Particul	8.90E-01
PR144	6.41E+01	1.17E-11	3.15E-11	1.94E-15	3.79E-17	Particul	2.10E+04
PM147	4.21E+03	1.06E-08	2.83E-10	6.92E-19	3.40E-20	Particul	2.60E-01
SM151	1.70E+02	8.10E-09	1.05E-10	3.61E-20	5.02E-21	Particul	7.70E-03
EU154	1.88E+03	7.73E-08	2.58E-09	6.14E-14	1.18E-15	Particul	7.90E-02
EU155	6.87E+02	1.12E-08	4.13E-10	2.49E-15	5.90E-17	Particul	1.40E-01
PU238	1.21E+03	1.06E-04	8.65E-07	4.87E-18	8.37E-19	Particul	7.90E-03
PU239	1.58E+02	1.16E-04	9.56E-07	4.24E-18	3.67E-19	Particul	2.90E-05
PU240	2.24E+02	1.16E-04	9.56E-07	4.75E-18	8.02E-19	Particul	1.10E-04
PU241	3.68E+04	2.23E-06	1.85E-08	2.19E-19	5.20E-21	Particul	4.80E-02
AM241	8.17E+02	1.20E-04	9.84E-07	8.18E-16	2.74E-17	Particul	1.60E-03
CM244	7.22E+02	6.70E-05	5.45E-07	4.91E-18	8.78E-19	Particul	3.80E-02

```
================= RISKIND Program Output, Version 1.10     ========= Page:   5
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
==============================  Input Parameters  ==============================
```

Nuclide Health Effects Parameters

Nuclide Name	Solubility Class	Acute Organ Dose Conversion Factors =========Inhalation========= [Sv/Bq] Marrow	Lung	Intestine	========Ground========== [Sv/s//Bq/m2] Marrow	Lung	Intestine
H 3	D	1.62E-11	1.62E-11	1.62E-11	0.00E+00	0.00E+00	0.00E+00
FE 55	W	1.65E-10	1.76E-10	1.92E-10	0.00E+00	0.00E+00	1.89E-19
CO 60	Y	6.22E-09	1.24E-07	5.95E-09	2.34E-15	2.27E-15	1.94E-15
NI 63	Y	1.05E-12	5.95E-12	4.59E-13	0.00E+00	0.00E+00	0.00E+00
KR 85	D	0.00E+00	0.00E+00	0.00E+00	2.43E-18	2.45E-18	1.97E-18
SR 90	Y	1.08E-09	7.03E-07	1.70E-08	4.77E-18	4.98E-18	0.00E+00
Y 90	Y	1.51E-11	9.19E-09	1.27E-08	4.57E-18	4.76E-18	0.00E+00
RU106	Y	1.05E-09	6.76E-07	3.51E-08	2.06E-16	2.03E-16	1.80E-16
RH106	Y	2.58E-10	2.58E-10	1.14E-09	2.06E-16	2.03E-16	1.80E-16
SB125	W	2.41E-14	7.30E-11	3.24E-12	4.05E-16	4.03E-16	3.79E-16
TE125M	W	5.14E-14	1.05E-11	2.38E-12	1.37E-17	1.77E-17	1.78E-17
CS134	D	1.08E-08	1.08E-08	1.27E-08	1.48E-15	1.46E-15	1.34E-15
CS137	D	7.57E-09	8.11E-09	8.11E-09	5.39E-16	5.30E-16	4.93E-16
BA137M	D	2.73E-11	2.73E-11	0.00E+00	5.70E-16	5.60E-16	5.22E-16
CE144	Y	1.08E-09	5.68E-07	3.24E-08	5.31E-17	5.43E-17	1.83E-17
PR144	Y	1.92E-14	9.46E-11	2.16E-14	3.66E-17	3.61E-17	2.54E-17
PM147	Y	1.41E-10	3.51E-08	1.62E-09	1.86E-20	2.20E-20	3.48E-21
SM151	Y	3.78E-12	1.19E-11	8.65E-13	1.39E-21	1.01E-21	4.45E-21
EU154	Y	2.46E-11	1.57E-10	9.19E-12	1.16E-15	1.14E-15	1.03E-15
EU155	Y	3.78E-12	2.54E-11	1.59E-12	4.71E-17	5.34E-17	6.05E-17
PU238	Y	2.97E-07	7.03E-05	2.97E-08	1.94E-19	7.87E-20	7.35E-19
PU239	Y	2.70E-07	6.76E-05	2.70E-08	1.19E-19	7.87E-20	3.24E-19
PU240	Y	2.70E-07	6.76E-05	2.70E-08	1.88E-19	7.81E-20	7.02E-19
PU241	Y	2.97E-10	5.68E-08	1.41E-10	4.18E-21	4.36E-21	0.00E+00
AM241	W	4.32E-06	1.81E-05	2.97E-08	1.68E-17	2.00E-17	2.52E-17
CM244	W	4.59E-06	1.92E-05	3.24E-08	2.04E-19	9.00E-20	7.10E-19

```
================= RISKIND Program Output, Version 1.10      ========= Page:   6
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
============================== Input Parameters ==============================
```

Nuclide Health Effects Parameters

Name	Acute Organ Dose Conversion Factors =========Cloudshine======== [Sv/s//Bq/m3] Marrow	Lung	Intestine
H 3	0.00E+00	0.00E+00	0.00E+00
FE 55	0.00E+00	0.00E+00	9.85E-19
CO 60	1.23E-13	1.24E-13	1.11E-13
NI 63	0.00E+00	0.00E+00	0.00E+00
KR 85	1.09E-16	1.14E-16	9.59E-17
SR 90	1.68E-16	1.84E-16	0.00E+00
Y 90	1.62E-16	1.77E-16	0.00E+00
RU106	9.76E-15	1.01E-14	8.99E-15
RH106	9.76E-15	1.01E-14	8.99E-15
SB125	1.88E-14	1.95E-14	1.82E-14
TE125M	1.86E-16	2.23E-16	4.10E-16
CS134	7.19E-14	7.37E-14	6.84E-14
CS137	2.59E-14	2.65E-14	2.48E-14
BA137M	2.73E-14	2.80E-14	2.61E-14
CE144	2.55E-15	2.68E-15	7.73E-16
PR144	1.88E-15	1.91E-15	1.52E-15
PM147	4.46E-19	5.45E-19	1.55E-19
SM151	1.13E-20	7.13E-21	3.91E-20
EU154	5.87E-14	5.99E-14	5.54E-14
EU155	1.85E-15	2.22E-15	2.42E-15
PU238	1.68E-18	1.06E-18	3.77E-18
PU239	2.67E-18	2.65E-18	3.50E-18
PU240	1.66E-18	1.09E-18	3.69E-18
PU241	1.75E-19	1.99E-19	0.00E+00
AM241	5.21E-16	6.74E-16	8.00E-16
CM244	1.46E-18	7.07E-19	3.57E-18

```
================= RISKIND Program Output, Version 1.10      ========= Page:   7
 Title        : Sample Problem 2, Accident Conditions
 Date/Time    : 10/30/95 13:14
 Input  File  : c:\riskind\input\sample2.inp
 Output File  : output\sample2.out
===============  Input Parameters  - Accident Response Region:  2===============

 Accident Parameters
```

Physical Release Height [HS]:	1.00	m
Dispersion Model Coefficients [IDISPMOD]:	Pasquill-Gifford	
Accident Analysis Type:	Consequence	

Accident Response Region Parameters

Response Region [IYOURS]:	2	
Region Conditional Probability [FSEV]:	3.82E-03	
Heat Flux [HEATF]:	5.00E+02	cal/s
Loss of Cask Shielding Factor [SEXT]		
Gamma:	1.00	
Neutron:	1.00	
Failure Rate [FAILS]:	1.00E-01	
Crud Spallation Rate [FSPAL]:	1.00E+00	
Crud Release Rate [FRCRUD]:	1.00E+00	

Nuclide Class [NUTYPE]	Conditional Release Fraction [FRELS]	Dispersion Fraction [FDISP]	Released and Dispersed Fraction (FRELS*FAILS*FDISP)
Particulate	2.00E-06	1.00E+00	2.00E-07
Ru	2.70E-05	1.00E+00	2.70E-06
Cs	2.00E-04	1.00E+00	2.00E-05
I	2.50E-03	1.00E+00	2.50E-04
Gas	3.30E-01	1.00E+00	3.30E-02

```
================= RISKIND Program Output, Version 1.10      ========= Page:    8
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
=============== Intermediate Calcs - Accident Response Region:  2===============

================================================================================
================================ Nuclide Release ===============================
================================================================================
```

Nuclide Name	Release Amount [Ci]	Hazard Index Inhalation	Hazard Index Ingestion	Hazard Index Ground
CO 60	1.07E-01	6.46E-02	1.16E-02	1.52E-01
SR 90	5.28E-03	1.89E-02	1.32E-02	5.79E-05
CS134	5.00E-02	6.50E-03	9.86E-03	1.87E-02
CS137	7.52E-01	8.49E-02	9.63E-01	8.29E-01
PU238	2.42E-04	2.61E-01	2.27E-04	5.38E-07
PU239	3.16E-05	3.73E-02	3.87E-05	3.64E-08
PU240	4.48E-05	5.29E-02	5.49E-05	1.13E-07
PU241	7.35E-03	1.67E-01	7.47E-05	5.14E-08
AM241	1.63E-04	1.99E-01	2.01E-04	1.36E-05
CM244	1.44E-04	9.85E-02	5.04E-04	1.97E-07
Total	9.22E-01	9.90E-01	9.99E-01	1.00E+00

```
================= RISKIND Program Output, Version 1.10      ========= Page:   9
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
=============== Intermediate Calcs - Accident Response Region:  2===============

================================================================================
======================== Population Intermediate Calcs =========================
================================================================================

                Integral of X/Q (air)    : 3.10E+00      s/m
                Integral of X/Q (ground): 3.10E-02 unitless
                Effective Release Height: 1.49E+00        m
```

Population Air Isopleth Areas and X/Qa Values

Area #	Distance Near [km]	Distance Far [km]	Contaminated Area [km2]	X/Q Range [s/m3]
1	2.00E-01	3.91E-01	8.59E-03	4.43E-04 - 1.40E-04
2	2.00E-01	4.00E-01	9.70E-03	1.40E-04 - 4.43E-05
3	2.00E-01	4.00E-01	5.84E-03	4.43E-05 - 1.40E-05
4	2.00E-01	4.00E-01	4.66E-03	1.40E-05 - 4.43E-06
5	2.00E-01	4.00E-01	4.00E-03	4.43E-06 - 1.40E-06
6	2.00E-01	4.00E-01	3.56E-03	1.40E-06 - 4.43E-07
7	2.00E-01	4.00E-01	3.24E-03	4.43E-07 - 1.40E-07
8	2.00E-01	4.00E-01	3.00E-03	1.40E-07 - 4.43E-08
9	2.00E-01	4.00E-01	2.80E-03	4.43E-08 - 1.40E-08
10	2.00E-01	4.00E-01	2.63E-03	1.40E-08 - 4.43E-09

```
================= RISKIND Program Output, Version 1.10     ========= Page:  10
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
=============== Intermediate Calcs - Accident Response Region:  2==============
```

Population Ground Isopleth Areas and X/Qg Values

Area #	Distance Near [km]	Distance Far [km]	Contaminated Area [km2]	X/Qg Range [1/m2]
1	2.00E-01	3.91E-01	8.59E-03	4.43E-06 - 1.40E-06
2	2.00E-01	4.00E-01	9.70E-03	1.40E-06 - 4.43E-07
3	2.00E-01	4.00E-01	5.84E-03	4.43E-07 - 1.40E-07
4	2.00E-01	4.00E-01	4.66E-03	1.40E-07 - 4.43E-08
5	2.00E-01	4.00E-01	4.00E-03	4.43E-08 - 1.40E-08
6	2.00E-01	4.00E-01	3.56E-03	1.40E-08 - 4.43E-09
7	2.00E-01	4.00E-01	3.24E-03	4.43E-09 - 1.40E-09
8	2.00E-01	4.00E-01	3.00E-03	1.40E-09 - 4.43E-10
9	2.00E-01	4.00E-01	2.80E-03	4.43E-10 - 1.40E-10
10	2.00E-01	4.00E-01	2.63E-03	1.40E-10 - 4.43E-11

```
================= RISKIND Program Output, Version 1.10      ========= Page:  11
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
=============== Intermediate Calcs - Accident Response Region:  2===============

================================================================================
========================= Population Intermediate Calcs ========================
================================================================================
```

Area #	People Affected [people]	Area Dose [person-rem]	=====Individual Dose===== Short-Term [rem]	Long-Term [rem]	Clean-up Factor
1	5.15E+00	1.17E-01	2.28E-02	0.00E+00	1.00E+00
2	5.82E+00	4.20E-02	7.21E-03	0.00E+00	1.00E+00
3	3.50E+00	7.98E-03	2.28E-03	0.00E+00	1.00E+00
4	2.80E+00	2.02E-03	7.21E-04	0.00E+00	1.00E+00
5	2.40E+00	5.47E-04	2.28E-04	0.00E+00	1.00E+00
6	2.14E+00	1.54E-04	7.21E-05	0.00E+00	1.00E+00
7	1.94E+00	4.43E-05	2.28E-05	0.00E+00	1.00E+00
8	1.80E+00	1.30E-05	7.21E-06	0.00E+00	1.00E+00
9	1.68E+00	3.83E-06	2.28E-06	0.00E+00	1.00E+00
10	1.58E+00	1.14E-06	7.21E-07	0.00E+00	1.00E+00
Totals	2.88E+01	1.70E-01			

```
================= RISKIND Program Output, Version 1.10     ========= Page:  12
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
===============      Results       - Accident Response Region:  2===============

================================================================================
========================== Accident Dose to Population =========================
================================================================================
```

Population Summary Results Per Accident	
Committed Effective Dose Equivalent	1.70E-01 person-rem
Expected Genetic Effects	2.21E-05
Expected Non-fatal Cancers	1.70E-05
Expected Cancer Fatalities	8.50E-05
Acute Risk (Expected Fatalities)	0.00E+00

Pathway	Dose per Accident (person-rem)			
Acute	1.70E-01			
Cask		1.16E-04		
Ground Shine		1.02E-07		
Inhalation		1.70E-01		
Cloud Shine		2.60E-04		
Long-Term	0.00E+00			
Ground Shine		0.00E+00		
Inhalation		0.00E+00		
Cloud Shine		0.00E+00		
Ingestion		0.00E+00		
Initial Year			0.00E+00	
Vegetable				0.00E+00
Meat				0.00E+00
Milk				0.00E+00
Long-Term			0.00E+00	
Vegetable				0.00E+00
Meat				0.00E+00
Milk				0.00E+00
Water				0.00E+00

Exposure Parameter	Organ Exposure Marrow	Lung	Intestine	Gonad
Population Exposure:				
Long-Term Dose [person-rem]	2.22E-01	1.27E-01	1.50E-02	2.41E-02
Maximum Individual:				
Brief Dose [Gy]	1.00E-06	1.66E-05	1.74E-05	
Brief Exposure Time [d]	1.00E+00	1.00E+00	1.00E+00	
Brief Dose Rate [Gy/hr]	4.18E-07	1.32E-06	1.07E-06	
Prolonged Dose [Gy]	5.23E-06	6.01E-05	1.82E-05	
Brief Exposure Time [d]	3.00E+01	3.65E+02	7.00E+00	
Prolong Dose Rate [Gy/hr]	7.26E-09	9.33E-07	7.00E-07	
Hazard	0.00E+00	0.00E+00	0.00E+00	
Risk [Expected Fatalities]	0.00E+00	0.00E+00	0.00E+00	

```
================= RISKIND Program Output, Version 1.10      ========= Page:  13
 Title       : Sample Problem 2, Accident Conditions
 Date/Time   : 10/30/95 13:14
 Input  File : c:\riskind\input\sample2.inp
 Output File : output\sample2.out
==============================       Results       ==============================

================================================================================
========================== Accident Risk to Population ==========================
================================================================================
```

Population Accident Dose Summary Results

Acute		Total	
Dose [person-rem]	Risk [Fatality]	Dose [person-rem]	Risk [Fatality]
1.70E-01	0.00E+00	1.70E-01	8.50E-05

APPENDIX H REFERENCE

Lawrence Livermore National Laboratory, 1987, *Shipping Container Response to Severe Highway and Railway Accident Conditions*, NUREG/CR-4829, UCID-20733, prepared by Lawrence Livermore National Laboratory, Livermore, Calif., for U.S. Nuclear Regulatory Commission, Washington, D.C., Feb.

APPENDIX I:

QUALITY ASSURANCE

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APPENDIX I: QUALITY ASSURANCE I-5

APPENDIX I REFERENCE I-5

FIGURE

I.1 RISKIND Change Request Form I-6

APPENDIX I:

QUALITY ASSURANCE

Every effort has been made to ensure that the RISKIND program is an acceptable and useful tool in radiological transportation risk assessment. The RISKIND project is governed by a quality assurance (QA) plan (Software Quality Assurance Plan for the RISKIND Computer Program) at Argonne National Laboratory (ANL). The QA plan governs all aspects of program maintenance and development in accordance with ANL requirements (Environmental Assessment Division Policy and Procedures Software Quality Assurance).

The previous version of the code underwent an independent validation procedure (Maheras and Pippen 1995). Version 1 of the program has undergone a comprehensive external peer review and beta-testing process. User testing, benchmarking against other established codes, and extensive comparisons against parallel spreadsheet calculations have served to validate and verify the models implemented in the program.

User feedback is an important factor in program development so that the program best serves the needs of the user. To assist the authors in providing the highest quality software, a change request form is provided for user feedback (Figure I.1). The completed form, along with any relevant support material such as input and output files, should be sent to the following address:

S.Y. Chen

Argonne National Laboratory

Environmental Assessment Division

Building 900

Argonne, Illinois 60439

APPENDIX I REFERENCE

S.J. Maheras, and H.K. Pippen, *Validation of the Transportation Computer Codes HIGHWAY, INTERLINE, RADTRAN 4, and RISKIND*, DOE/ID-10511, prepared by Science Applications International Corporation, Idaho Falls, Idaho, for U.S. Department of Energy, Washington, D.C.

RISKIND Change Request (Rev. 0)

1. Submitter's Name: _____ Date: _____

   Organization: _____ Phone: _____

   Address: _____ FAX: _____

   _____

   _____

2. RISKIND Version Number: _____

3. Request Type: ☐ Enhancement/New Feature
   ☐ Error Correction

4. Description of Request (include error messages, and/or annotated input and output files if applicable; append additional pages if needed):

5. ANL Use Only
   Received By: _____ Change Request #: _____-C-_____
   Date: _____ Project Leader: _____
   Date: _____

   Resolution:

   Project Leader: _____ Date: _____
   Modification Form #: _____-M-_____

Figure I.1 RISKIND Change Request Form

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