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RADTRAN 5

Technical Manual

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ABSTRACT

This Technical Manual contains descriptions of the calculational models and mathematical and numerical methods used in the RADTRAN 5 Computer Code for transportation risk and consequence assessment. The RADTRAN 5 code combines user-supplied input data with values from an internal library of physical and radiological data to calculate the expected radiological consequences and risks associated with the transportation of radioactive material. Radiological consequences and risks are estimated with numerical models of exposure pathways, receptor populations, package behavior in accidents, and accident severity and probability.

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1 INTRODUCTION

RADTRAN 5 is an ANSI FORTRAN 77 computer code for analysis of the consequences and risks of radioactive-material (RAM) transportation. The first release of the RADTRAN code was developed by Sandia National Laboratories (SNL), under contract to the Nuclear Regulatory Commission (NRC), as an analytical tool during preparation of the "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes" (NRC, 1977). The code was subsequently modified to accept free-format data and issued as RADTRAN II (Taylor and Daniel, 1982). The Department of Energy (DOE) has sponsored development of the second release and of all subsequent releases. With each release, the code's capabilities have been updated and expanded (Taylor and Daniel, 1982; Madsen, Wilmot and Taylor, 1986; Neuhauser and Kanipe, 1992).

RADTRAN 5 is to be used for the estimation of risks associated with incident-free transportation of RAM and with accidents that might occur during transportation. The U.S. Department of Transportation (DOT) defines incident-free (or normal) transportation as "transportation during which no accident, packaging, or handling abnormality or malevolent attack occurs."[1] This Technical Manual describes the mathematical and numerical models used in RADTRAN 5. This manual is intended to be used with a companion document, the RADTRAN 5 User Guide (Neuhauser and Kanipe, 2000), which describes input data and RADTRAN 5 input and output files. Throughout this document, bold italics identify important points.

All major modes of commercial transport may be analyzed with RADTRAN 5: highway, rail, barge, ship, cargo air, and passenger air.[2] The NRC and the U.S. Department of Transportation (DOT) regulate carriage of RAM by all modes in the United States. Regulations promulgated by the NRC are primarily contained in the Code of Federal Regulations (CFR), specifically Title 10 CFR Parts 71-73; regulations promulgated by the DOT are primarily contained in Title 49 CFR Parts 171-178. These regulations establish maximum permissible package dose rates, maximum permissible dose rates to vehicle crew members, exclusive-use shipment criteria, packaging certification conditions and other features of radioactive materials transportation. Compliance with these regulations of the package variables input by the user may be assessed with RADTRAN 5.

1.1 Definition of Risk

A common "shorthand" definition of risk is the product of consequence and probability. However, ***transportation risks, like the risks associated with carrying out any complex process, must be decomposed into "what can happen . . ., how likely things are to happen . . ., and the consequences for each set" of things that can happen*** (Helton, 1991). As the terminology in this description implies, set theory provides an ideal framework for formal expressions of risk. "What can happen" may be defined as disjoint sets of similar occurrences (S_i, i = 1, ...nS) -- that is, each set contains events with outcomes (consequences) that are similar. The sets are often scaled from minimum to maximum consequence. "How likely things are to happen" can be defined as the probability that an occurrence in set S_i will take place; and "the consequences for each set" consist of one or more specified consequence results (e.g., population dose) (Helton, 1991). One of the first steps in a risk analysis is definition of the sets of occurrences. In RADTRAN 5, this process is carried out separately for incident-free transportation and accidents. ***Since consequences must be calculated in order to calculate risk, RADTRAN 5 may also be used as for consequence assessment.***

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[1] Minor incidents (e.g. citation for improper placarding) and accidents below the reporting threshold may be excluded from the statistical data. 49 CFR 225.5 and 49 CFR 390.5 both identify a fatality, an injury that requires medical treatment, and damage exceeding some calculated dollar amount as reasons an incident/accident must be reported. 49 CFR 171.15 identifies evacuation of the public and transportation artery closure as additional reporting criteria. The radiological consequence of a subthreshold event usually is limited to increased stop time.

[2] Excludes minor modes such as horse-drawn vehicles, bicycles, motorcycles, air-cushion vehicles, etc.

RADTRAN 5 also may be used in conjunction with a Latin Hypercube Sampling (LHS) code to perform probabilistic risk assessments (PRAs). LHS is a structured-sampling method rather than a random Monte Carlo method. In PRA applications, values of input variables are selected from distributions that represent the range of values that each variable may assume. The resulting outputs (usually more than 50 and less than 500) may be displayed graphically as a Cumulative Complementary Density Function or CCDF, which is the method of choice for displaying risk results. The subject of PRA is discussed further in Chapter 7.

1.2 Calculations Performed in RADTRAN 5

1.2.1 Incident-Free Dose Calculation

In calculations for incident-free transportation, the probability term is set equal to 1.0 even though it is actually equal to 1.0 minus the small probability of an accident. Thus, consequences rather than risks are calculated. In theory, the result could also be thought of as a dose-risk derived from a rounded-off estimate of probability. However, if the incident-free value were added to the results of the appropriate accident dose-risk calculation (see Section 1.2.2), the sum would seldom appear to be different from the incident-free value alone at the two- or even three-significant-digit level of resolution. Thus, the two values always should be reported separately. ***The radiological consequences of incident-free transportation are population doses of the various population groups that might be exposed to radioactivity from the package(s) being analyzed.*** Certain individual doses are also calculated. RADTRAN 5 allows analysis of all population groups potentially exposed during incident-free transportation (Table 1-1). The user selects only those populations that are potentially involved for the problem under analysis and enters the required problem-specific data. For example, population groups usually associated with incident-free movement of a truck along a highway route-segment are:

- persons beside the route (off-link population),
- persons sharing the route (on-link population),
- persons at stops, and
- truck crewmembers.

The magnitudes of the calculated doses depend on variables such as population density, distance traveled, vehicle speed, and crew size. These variables are among those for which the user must enter problem-specific values. The numerical models used to describe these sets of occurrences are described in Chapter 3. The calculated doses for each population group are printed in the output. The printed results can have up to six significant digits, but this is a common artifact of computational results in many codes and should not be interpreted to mean, for example, that small differences in two results are significant. The unavoidable uncertainties in many input values clearly preclude such an assumption. ***It is strongly recommended that no more than two significant digits be used when reporting the results of a RADTRAN analysis.***

1.2.2 Accident Dose-Risk Calculation

Dealing with Infinite Sets

In accident-risk analysis with RADTRAN 5, the analyst begins with the set of all accidents that might occur during the transportation event being analyzed and that might involve one or more of the RAM transportation conveyances being analyzed. This set and most of its subsets are infinitely large. In order to make the problem manageable (i.e., finite), the analyst must do several things. The first step is to remove highly improbable events (e.g., transportation vehicle struck by meteorite) from consideration. This is generally accomplished by establishing a *probability cut-off*, and all risk analyses employ either an explicit or an implicit probability cut-off.

There are at least three methods of establishing a cut-off value. The most common method involves the use of historical statistics. To illustrate this method, consider the set of all possible accidents in which only a fender is dented. This set, like the set of all possible accidents of which it is a subset, is infinitely large. To reduce it to finite

terms, five years of historical statistics on fender denting might be used to estimate the probability of such an accident. The historical data yield a set that can be defined as the set of all previous transportation accidents in which only a fender is dented and that are listed in the particular five years of historical data being used. When the number of such accidents is divided by the total vehicle-kilometers traveled in the same time period, the result is an estimate of the probability of occurrence of fender denting. This definition contains an implicit cut-off in that it excludes ways in which a fender could be dented that are so uncommon as to not have occurred in a five-year period. Events with probabilities of 10^{-12} to 10^{-13} per year or less usually would be excluded by this method.

Table 1-1- Potentially Exposed Population Groups by Mode

Truck	Rail	Ship & Barge	Air
Persons beside highway	Persons beside railroad	Persons beside waterway (inland waterways only)	N/A
Persons sharing highway	Passengers on passing trains	usually N/A	N/A
Public at stops	Workers at railyards; public at other stops	Workers at ports	Public and workers at airports
Truck crew	Crew (at railyards and pullovers)	Ship or Barge crew	Air crew; flight attendants
Handlers at intermodal transfer	Handlers at intermodal transfer	Handlers at intermodal transfer	Handlers at intermodal transfer
Interim storage workers & public	Interim storage workers & public	Interim storage workers & public	Interim storage workers & public
N/A	N/A	Passengers on vessel	Passengers on airplane
Inspectors at intermodal transfers, state borders, etc.	Inspectors at yards, intermodal transfers, state borders, etc.	Inspectors at ports, including intermodal transfer	Inspectors at airports, including intermodal transfer

A second means of establishing a cut-off value for RAM transportation accidents is the *one-in-a-million* criterion. For example, any scenario with an associated probability of inducing a latent cancer fatality less than one in a million per year (10^{-6} yr^{-1}) might be excluded. This criterion has been used in risk-based standards for benzene exposure, for example, promulgated by the Environmental Protection Agency (Cohrssen and Covello, 1989). The third method is to establish an *explicit* cut-off by excluding probabilities equal to or less than the probability of some rare but catastrophic natural event such as the meteorite strike mentioned above (e.g., about 2E-18 per year).[3]

An implicit cut-off established by historical statistics is the most commonly encountered type in accident-risk assessment. Probability estimates derived from historical accident data always contain an implicit cut-off in that they exclude types of accidents so rare as to never have appeared in the data set. Clearly, the larger the data set used to estimate accident probabilities, the fewer rare events are excluded.

However, including rare events (especially classes of events that are so improbable that none has yet occurred) has little effect on overall risk and consequence calculations. The reason for this is that the product of an extremely small probability and even a large consequence value is itself quite small. Transportation risk analyses performed by Sandia National Laboratories usually include one or two such categories in order to extend the accident consequence categories somewhat beyond those that can be predicted by historical data alone. This is routinely done for transportation risk analyses that are included in an Environmental Impact Statement (EIS) or Environmental Assessment (EA) prepared under the National Environmental Policy Act (NEPA) in order to ensure that a full range of outcomes has been covered.

[3] Chapman (1998) estimates chance of a destructive (but not Extinction Level) impact at as much as 10^{-5} yr^{-1} for the earth as a whole. The probability of striking any particular 100 m^2 area (i.e., the vicinity of a loaded cask) is 100 m^2 divided by the earth's surface area (5.1×10^{-14} m^2) multiplied by 10^{-5} yr^{-1}, which is approximately equal to 2×10^{-18} per year)

Accident-Severity Categories
The accidents remaining after application of a cut-off will still represent a wide range of consequences from little or none to quite severe. Therefore, they must be divided into new sets. To satisfy the "what can happen" criterion, each set must represent a logical grouping (*accident-severity category*) of accident outcomes.

Severity Fractions
To satisfy the "how likely is it" criterion, the overall probability of occurrence of an accident in a particular severity category must be estimated. A two-step process does this:

1. The *base probability* (accident rate) is derived, usually from the historical record for each mode being analyzed, although other methods are not excluded.
2. The base probability (accident rate) is multiplied in turn by the *conditional probabilities* (severity fractions) of the various accident-severity categories. Each product represents the total probability of occurrence of that accident-severity category. Severity fractions are usually derived by event-tree analysis although other methods are not excluded.

Radiological Consequences
There are two main types of radiological consequence: dispersion of contents and loss of shielding. Dispersion is analyzed in RADTRAN 5 with numerical models that represent:
- package response(s) to particular accident environments;
- form and nature of the direct radiation and/or the dispersed material that might escape a package following a particular accident;
- dispersion of any material released as airborne particulates or gases,
- distribution and density of downwind population; and
- exposure pathways via which released or dispersed material could cause human radiation doses.

Loss-of-shielding is analyzed in RADTRAN 5 with numerical models that represent:
- package contents as a source of radiation exposure;
- strength of the source as a function of contents and shielding damage;
- density of population in annular areas centered on the accident site.

Consequences and probabilities are printed in the output.

Number of Significant Digits in Output
As was noted in the discussion of incident-free results (Section 1.2.1), the number of significant digits in the printed output cannot be taken as an indication of calculational accuracy. ***It is strongly recommended that no more than two significant digits be used when reporting the results of a RADTRAN analysis.***

1.2.3 Other Calculations

In addition to the core capabilities discussed in the previous sections, RADTRAN has several additional features, some of which are automatically performed and some of which are optional. Among the former are the individual dose calculations. First, an individual dose for a person near a transportation route as shipments pass is calculated from user-defined input. Second, individual doses for persons located at various distances downwind from dispersion accidents are automatically calculated. One of the requested input values in the matrix of atmospheric dispersion data is maximum downwind distance of each concentration isopleth, and individual doses, summed over all exposure pathways, are calculated as part of the population dose calculation. These individual dose estimates are preserved, associated with the appropriate downwind distance, and reported in an output table. Finally, an importance analysis is automatically performed for incident-free dose calculations and printed in a table in the output. The total potentially exposed off-link population for multi-year shipping campaigns, in which migration is accounted for, also is automatically calculated. The values are printed in a separate table in the output. The final automatic calculation produces a table of nonradiological accident fatalities, which is printed in the output. This calculation combines user-provided fatality rates and distances traveled to generate total fatality estimates.

RADTRAN 5 also permits an optional calculation of dose to persons downwind from a dispersion event in which the user may enter separate population densities for each isopleth. Although the primary outputs of RADTRAN 5 are dose and dose-risk estimates, health-effects risks may also be calculated as an alternative output option. ***Two separate runs of RADTRAN 5 are required to obtain results in terms of both dose and health effects.***

1.3 Organization of Technical Manual

Chapter 2 of this Technical Manual describes the main component models in RADTRAN 5 and the processes and interactions represented by these component models. Chapters 3 through 5 describe in detail the RADTRAN 5 computations of dose-consequences and dose-risks under incident-free conditions and accident conditions. The equations used in RADTRAN 5 are given; each calculation and its contribution to the overall solution of the problem are discussed; and relationships with other operations in the RADTRAN 5 code are noted where necessary. Incident-free consequence models are discussed in Chapter 3; atmospheric dispersion is discussed in Chapter 4; and accident dose-consequence models for dispersion and loss of shielding in Chapter 5.

The primary output of RADTRAN 5 is dose risk, and dose risk may be converted into health-effects risk either by offline calculation or by a second run of the code. Calculation of health-effect risks is described in Chapter 6. Chapter 7 covers topics such as the user-friendly interface for generation of input files (RADDOG), the Latin Hypercube Sampling (LHS) method of performing probabilistic risk analyses, non-standard applications of the code, and verification/validation. Appendix A contains a list of all variables in the equations in this manual and indicates the equations in which each variable appears. Appendix B describes the b variables used in rail transportation analysis.

2 SCOPE OF RADTRAN 5

2.1 Overview of Radioactive Materials Transportation

Transportation of radioactive materials (RAM) involves a wide range of events and operations. ***Transportation is not a goal in itself.*** We move a material from one location to another to serve some other purpose; e.g., a radiopharmaceutical may be transported from its point of origin to a hospital so that it can be used in a life-saving diagnostic procedure.

RAM must be shipped in packages that meet regulatory standards, and the radiation dose rates outside these packages must be calculated or measured and demonstrated to comply with established limits. Compliance of the package data that is input by the user with these regulatory requirements is assessed by RADTRAN 5. However, the code also allows the user to assess the consequences of RAM transportation that fails to comply with regulations.

Seven modes of transportation are addressed in RADTRAN 5: two highway modes (tractor-trailer and light-duty vehicle), and rail, barge, ship, cargo air, and passenger air modes. There are a variety of conveyances in each mode (e.g. ship mode includes break-bulk freighters and container ships of a variety of tonnages) that may be used to transport RAM. Although not it is not entirely accurate usage in all cases, the term 'vehicle' is often used interchangeably with the term 'conveyance.' ***A shipment consists of one or more packages on a single conveyance.*** A single conveyance may take a package directly from its origination point to its ultimate destination, or a package may be transported to its destination by more than one conveyance and/or by one or more modes. RADTRAN 5 allows the user to analyze all mode combinations and associated conveyance changes (intermodal transfers). Crewmembers and inspectors may be exposed to the external radiation field around a package. If a package is shipped by more than one mode and/or conveyance, it will be handled during each transfer from one conveyance to another and from one mode to another. Thus, package handlers are exposed not only at route origins and destinations but also at transfer points. A package may be placed in interim storage en route, and if so, warehouse personnel will also be exposed. Low levels of public exposure will also occur.

A package may be picked up or delivered to a freight forwarder and then consolidated with other packages into a single shipment. This single shipment may consist of packages obtained from more than one shipper. The consolidated shipment may travel to a distribution point from which it may be separated into individual packages that are delivered to more than one consignee. Handling and warehouse storage can also occur during and between each of these transport phases as the packages change modes or carriers. Figure 2-1 shows the various paths that a shipment may undergo.

Since more than one mode may be used to transport a single package of radioactive material from its point of origin to its final destination, RADTRAN allows each mode to be considered separately in assessing radiological impact. Parameters that have mode-dependent values, such as conveyance velocity, package shielding, and population distribution, have different impacts on dose calculations. For further descriptions of general radioactive-materials transportation see Wolff (1984).

The characteristics of each segment (or link) of a transportation route may be considered with RADTRAN 5. These link characteristics include:

- mode of shipment,
- link length,
- vehicle speed,
- residential population density near the link.
- vehicle occupancy
- vehicle density,
- accident rate,

- road type (highway modes),
- fraction of land surrounding link under cultivation

Similarly, the characteristics of separate stops that can occur during a trip may be considered with RADTRAN 5. Stop characteristics include:

- mode of shipment
- population density within specified radial distances of stopped shipment
- shielding, if any, of population within the specified radial distances
- stop time (sometimes internally calculated).

Stop time may or may not be a route-specific value, depending on whether the length of a stop is determined by such factors as, for example, requirements to stop for inspection at certain state borders but not at others. Exclusive-use conveyances may experience more inspections (e.g., TRUPACT2 shipments to the Waste Isolation Pilot Plant) or fewer inspections (e.g., special trains) than ordinary commercial freight. Handlings and inspections are special types of stops at which small subpopulations may routinely come into proximity to the radioactive material (RAM) conveyance. Thus, the number of handlers and/or inspectors and their distances from the RAM shipment are additional required inputs for these calculations.

The potential radiological consequences of the transportation of radioactive material depend directly on the quantity and form of the radioactive material to be shipped (Eichholz, 1983). Characteristics of radioactive material packages that affect incident-free transportation are the package dose rate and the partition of the dose rate into gamma and neutron fractions. For certain classes of packages, the package dose rate is required by regulation to be expressed as a Transport Index (TI). ***The TI is a unitless quantity, the value of which is defined as the highest radiation dose rate in millirem per hour (mrem/hr) from all penetrating radiation at 1 meter (m) from any accessible external surface of the package, rounded up to the next highest tenth [49 CFR 173.389 (i) (1)]. The dose rate at 1 meter is an essential input to RADTRAN 5 for all package types, regardless of whether a TI is required by regulation to be calculated.*** Note also that radionuclide inventory data are **not** required for incident-free dose calculation.

Nine population subgroups are identified for incident-free consequence calculation. Five subgroups consist of *workers* who might be occupationally exposed; they are:

- conveyance crew members and escorts,
- cargo handlers and inspectors,
- railyard workers
- warehouse personnel,
- flight attendants (passenger-air mode only).

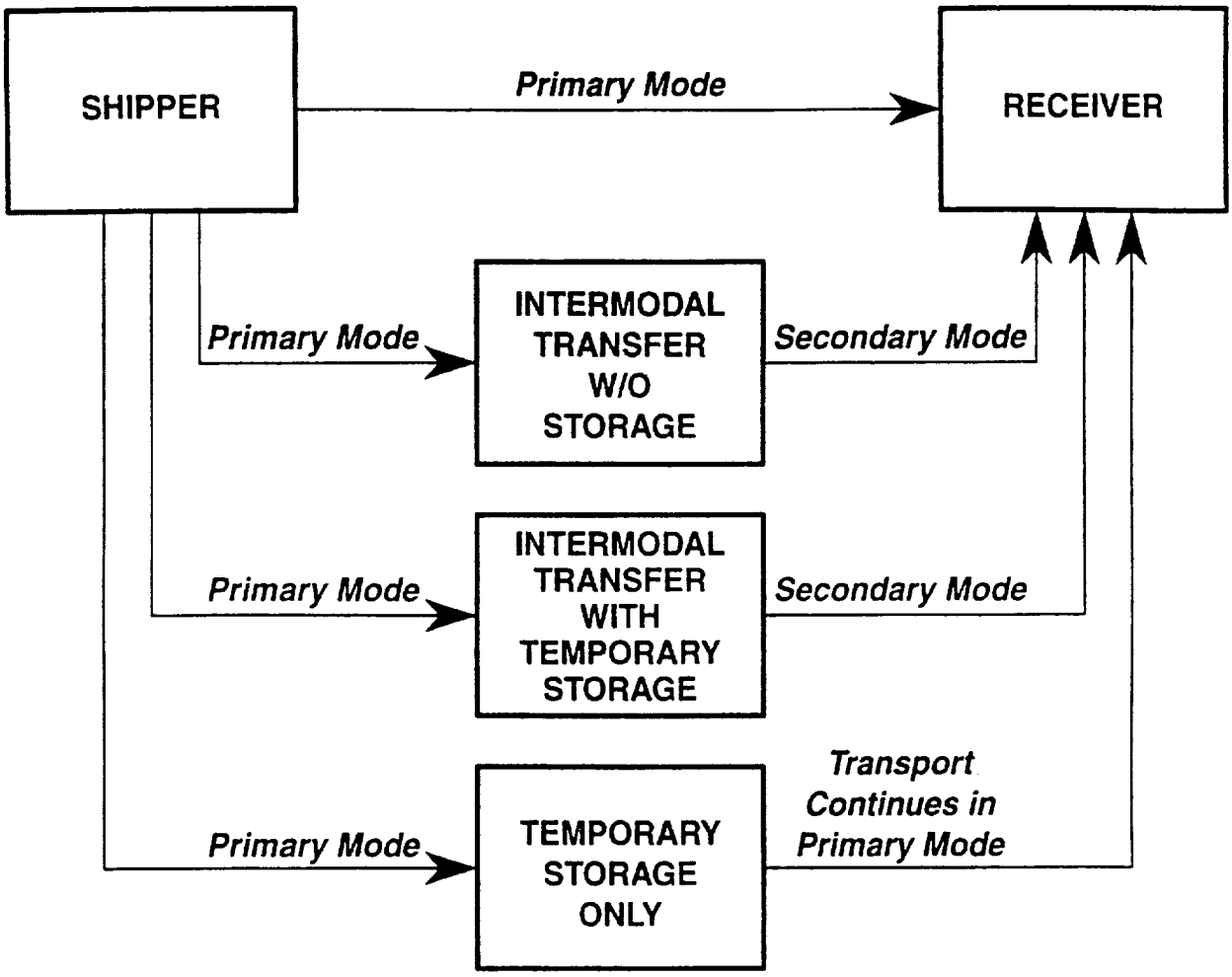
Four additional subgroups consist of members of the *public* who might be exposed; they are

- passengers [persons in the same conveyance as the package(s)],
- people in the vicinity of the transporting vehicle while it is stopped,
- people sharing a transport link with the vehicle, and
- people beside a transport link that the vehicle traverses.

The last group (people along the route) is modeled as being uniformly and symmetrically distributed around the link with a density and bandwidth that may be specified by the user. The last two subgroups are absent for most in-transit segments of travel by air and ship modes.

For dispersal and non-dispersal (loss-of-shielding) alike, accident consequences and risks are determined as much by the properties and physical forms of the radioactive material(s) being transported and the specific radionuclides they contain as by the overall activity level of the materials. Other factors that affect consequence and risk are accident probability, accident severity, package response, and dispersion environment. With RADTRAN 5, the user identifies a package in terms of both its external dose rate and its contents (radionuclide inventory).

Figure 2-1. Possible Transportation Paths



To calculate transportation accident risks, the consequences and probabilities of vehicular accidents must be calculated separately and then multiplied by each other. The radiological consequences of an accident are the potential doses (or health effects) that might occur as a result of:

- dispersion of a specified quantity of radioactive material released from a compromised package, and/or
- direct exposure of persons to ionizing radiation following damage to package shielding (loss of shielding).

The probability of occurrence of an accident in which radioactive material is released and/or shielding is damaged is determined from:

(1) the expected frequency of all accidents **and**
(2) the *conditional probabilities* of occurrence of accidents that are severe enough to result in one ore more specified levels of damage to package integrity and/or shielding.

A conditional probability is the probability, given that an accident occurs, that it will be of a specified severity. As noted in Chapter 1, the expected frequencies of accidents by mode and route segment are usually estimated from historical data and the conditional probabilities are usually derived from event trees. Up to 30 accident-severity categories may be defined for analysis with RADTRAN 5; each category must be assigned a conditional probability. Conditional probabilities do ***not*** depend on the properties of the package; instead they depend on the conveyance type and transportation mode. Package-response data (e.g., release fractions by accident-severity category) which ***are*** package-dependent are used to calculate consequences. The latter values are project-specific and must be provided by the user.

2.2 *Limitations of RADTRAN 5*

2.2.1 Fixed Facilities

RADTRAN 5 is not intended for the performance of detailed location-specific consequence or risk analyses such as are used for fixed facilities. In a location-specific analysis, the consequences and risks associated with events or operations at a single specified location are calculated with a population distribution, wind roses and other weather data, etc. that are known. Nuclear power reactors are examples of fixed facilities for which radiological risk assessments are performed. Computer codes such as MACCS2 (Chanin and Young, 1998a) are used to analyze fixed facilities. These codes require detailed weather and population data as input; such data are obtained in most cases during the impact-analysis phase of site development. ***Weather data of a high level of resolution are not available for most of the rest of the United States, including most segments of most highways, railroads, sea-lanes, etc.***

Many of the analytical methodologies in RADTRAN differ mathematically from those used with fixed locations. RADTRAN is intended to analyze a radiation source (e.g., a RAM package) moving through a constantly varying landscape (i.e., traversing a route) in which the exact location of any specific accident that might occur while the source is in transit cannot be known. Indeed, the number of possible locations of an accident is extremely large and cannot be predicted in advance. This uncertainty as to accident location sharply differentiates transportation risk analysis from fixed-facilities risk analysis, where the landscape is invariant.

2.2.2 Wind Direction

Each route segment may be assigned a distinct population density, as noted in Section 2.1. The assigned density is modeled in RADTRAN 5 as being ***uniformly distributed***. In codes for analysis of fixed locations, wind-direction data (wind roses) from weather stations are generally used; these codes permit the analyst to calculate population exposures for each population that might be downwind at the time of an accident at the fixed site. However, weather stations are absent on most transportation routes, and, thus, ***wind-direction probabilities are <u>unknown</u> for most links***. The basic RADTRAN 5 calculational strategy for dispersal intentionally precludes the need for such unobtainable data by modeling the population as uniformly distributed.

A new feature of RADTRAN 5 allows non-uniform population-density data to be entered under the keyword ISOPLETHP. The ISOPLETHP tool is useful for risk analysis only in special cases. However, it is highly useful as an analytical tool. For example, Mills and Neuhauser (1999b) used ISOPLETHP to compare the results of the approach to population modeling used in RADTRAN 5 (densities uniform along each route segment) to that used in

fixed-site codes (location-specific densities by isopleth area). They confirmed that the two methods yield comparable results for a cross-country route.

2.2.3 Atmospheric Stability

Atmospheric-stability is a term that is used to describe the degree of turbulence and, hence, of dilution during downwind transport in the atmosphere; it is discussed in Chapter 4. ***Like wind-rose data, atmospheric-stability data and associated wind speeds are only available from fixed locations with weather stations***. Collection of data at a few such locations and extrapolation of the results to other points in the surrounding region may be ultimately possible (so-called "mesoscale" weather), but consistently reliable methods of doing this are not yet available. National-average atmospheric-stability data may be used (Church and Luna, 1974). A limitation of this approach is that national-average data are not recommended for short routes. An alternative approach is the use of a single moderately conservative stability category and wind speed. See Chapter 4 for a detailed discussion of atmospheric dispersion.

2.2.4 Chronic Releases Cannot be Analyzed

Chronic releases are often modeled in computer codes for the analysis of operations at fixed facilities. Releases of this type cannot be analyzed with RADTRAN 5. ***Dispersal data entered into RADTRAN 5 must be for an instantaneous or "puff" release***. Releases that might occur over a period of a few seconds up to a few tens of minutes are considered to be "instantaneous" for purposes of this analysis; nearly all transportation-related releases would fall into this category. The so-called Briggs equations (see Wark and Warner, 1981, Chapters 4 and 5) which model releases as point releases, yield erroneously high values at short downwind distances when applied to "puff" releases. See Chapter 4 for a detailed discussion of atmospheric dispersion as modeled in RADTRAN 5.

2.2.5 Chemical Hazards Cannot be Analyzed

Chemical-hazards analyses necessary to an assessment of the nonradiological consequences and risks of shipping hazardous substances such as uranium hexafluoride are not included in RADTRAN 5.

2.3 Mathematical Solution Strategy

RADTRAN 5 uses FORTRAN intrinsic functions for simple math and algebra as well as FORTRAN functions EXP, ALOG, AMIN1, and SQRT to solve mathematical equations. The Sandia Math Library (SLATEC) routines used in RADTRAN 5 are SSORT, BSKIN, BESK0, BESK1, E1, and AVINT. Additional SLATEC routines are called in RADTRAN 5 because they, in turn, are called from the five routines listed above. The FORTRAN intrinsic functions are widely used and accepted as correct. The SLATEC routines are quality-assured solutions of various mathematical functions and are electronically available through the NetLib website maintained by AT&T Bell Laboratories and others (www.netlib.org/slatec)

The calculational sequence of the RADTRAN 5 Computer Code is shown in Figure 2.2. The outside box represents the first stage of RADTRAN 5 calculations; the second box represents the second stage, and so forth. The internal boxes represent the calculations RADTRAN 5 performs. They interact with the two outer boxes that supply input from the data file to produce the printed RADTRAN 5 output.

2.4 RADTRAN 5 Models

RADTRAN 5 contains nine sets of models that are used to estimate radiological consequences and risks of radioactive material transportation. Figure 2-2 shows which models are used in incident-free and accident calculations and their relationship to each other. Variable values for the component models come from user-supplied data and from internally calculated values. The incident-free calculational sequence produces expected values of population dose with the Package, Population Distribution, and Transportation models. Similar

models are used to calculate doses for accidents involving only loss of shielding. RADTRAN 5 produces expected values of population dose for accidents that result in dispersal by means of the Package, Transportation, Population Distribution, Accident-Severity, Package-behavior, and Meteorological models. The following sections briefly summarize these models.

2.4.1 Package Models

Point- and Line-Source Models for Incident-Free Transportation

The formulation for estimating incident-free population dose from external radiation emitted by package(s) of radioactive materials in most cases is based on an expression for dose rate as a function of distance from an isotropic point source of radiation (NRC, 1977). An isotropic point source is defined as a dimensionless source that emits radiation in all directions with equal magnitude. For such a source, dose rate is inversely proportional to the *square* of the radial distance from the source. A point-source model yields values of dose rates that agree well with actual dose rates measured at source-to-receptor distances greater than twice the characteristic package dimension (usually equivalent to twice the largest package dimension).

For larger packages, at exposure distances less than twice the largest package dimension, an isotropic line-source approximation is preferred. An isotropic line source is defined as a one-dimensional source that emits radiation uniformly in all radial directions along its entire length. For such a source, dose rate is inversely proportional to the distance from the source (rather than the square of the distance, as is the case for a point-source formulation).

Package Model: Isotopic Makeup and Properties of Package Contents

The Package Model also addresses the material(s) in the package(s) being analyzed and its (their) constituent radionuclides. These input data are used in the estimation of accident consequences. The variables for which input values must be supplied for each radionuclide in a package are:

- total number of curies per package (Ci);
- average total photon energy per disintegration (MeV);
- rate at which aerosol material is deposited on the ground (deposition velocity) (m/s);
- cloudshine dose factors (dose factor for immersion in a cloud of dispersed material) (rem-m^3/Ci-sec);
- physical characteristics (e.g., lung clearance time, which is dependent on particle size);
- half-life (days); and
- measures of the radiotoxicity of dispersed material (rem/Ci inhaled, etc.).

The internal radionuclide data library in RADTRAN 5 supplies all of the listed values except the first (number of curies) for all commonly shipped radionuclides. The user may use the DEFINE function of RADTRAN 5 to define additional radionuclides should that be necessary.

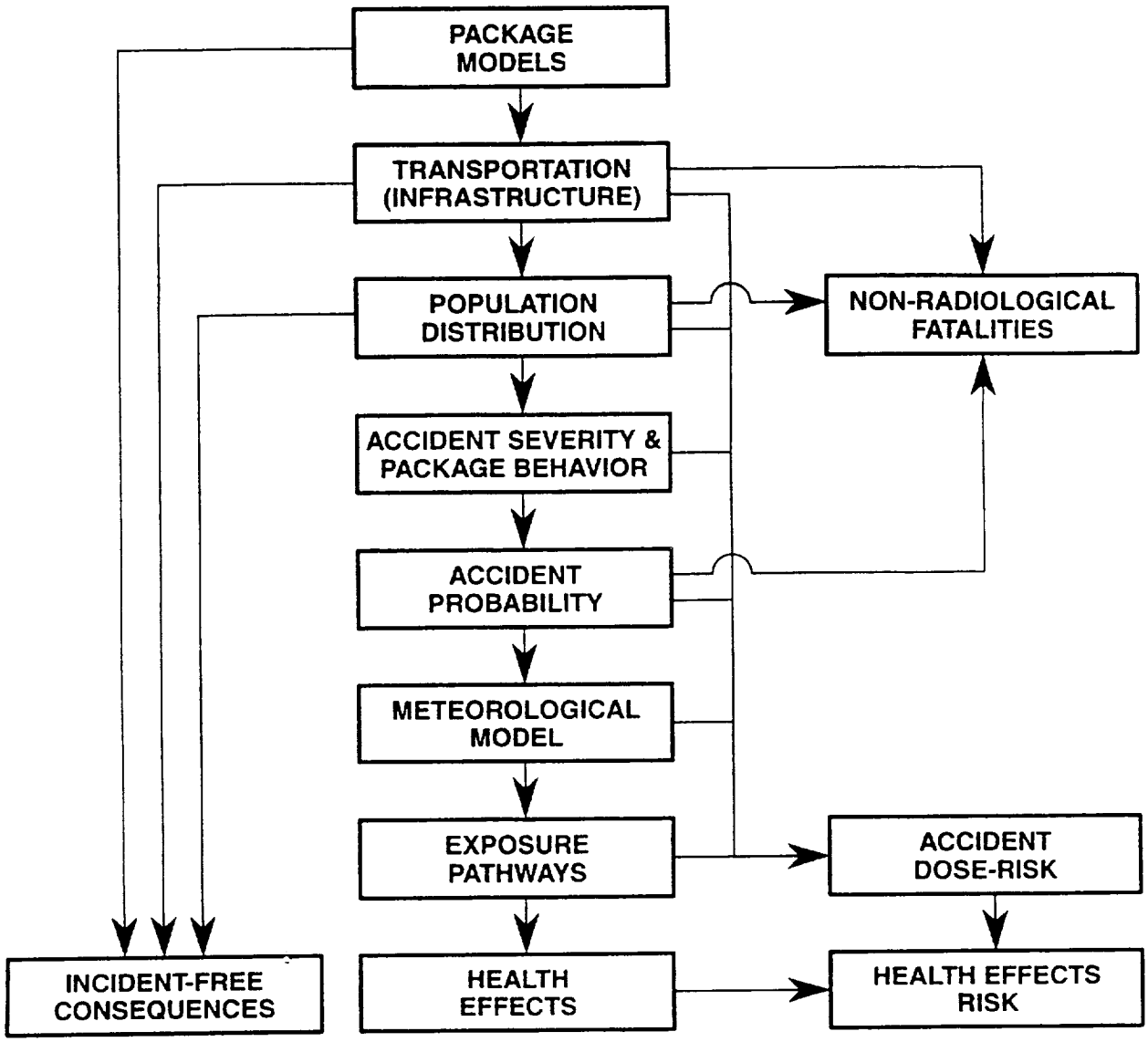
2.4.2 Transportation Models

The Transportation Models define those properties and characteristics of the transportation infrastructure that influence the calculation of incident-free dose, accident consequences, and accident probabilities. The two main divisions are route-segments and stops.

Route-Segment Model (LINK)

RADTRAN 5 allows separate treatment of each segment or link of a transportation route with the LINK subroutine. The LINK subroutine is a powerful analytical tool in RADTRAN 5 for analysis of route-related transportation risk factors. LINK allows the user to subdivide all or any part of a route into a maximum of 60 separate route segments (or segment aggregates). LINK also can be used to analyze the same route segment(s) in a variety of conditions

Figure 2-2. RADTRAN 5 Component Models and their Interrelationships



such as daytime and nighttime population densities (Mills and Neuhauser, 1999a), rush hour and non-rush-hour traffic conditions, and current and projected population densities.

The user must provide four types of input data:

- link length in kilometers;
- traffic-pattern data;
- shipment data;
- accident-rate data.

Traffic-pattern data include such factors as traffic density and vehicle occupancy. Shipment data include the number of shipments, the number of crew and passengers, if any, occupying the RAM transportation conveyance, the distance between the crew and the nearest package(s), etc. The first three categories of data are used for incident-free calculations as described in Chapter 3. The first and fourth categories (link length and accident rate (accidents/vehicle-km)) are multiplied by user-defined conditional probabilities of occurrence for accident-severity categories to generate a matrix of accident probabilities, as described in Chapter 5.

Stop Model (STOP LINK)

RADTRAN 5 contains a subroutine analogous to the LINK subroutine that combines user-provided data to calculate stop-related doses. ***The term "stop" is applied to instances in which a vehicle carrying RAM is stationary with respect to its surroundings.*** If known, information about each stop may be entered as individual stop-links. Multiple stops of like nature (e.g., refueling stops during highway-mode transportation) also may be ***aggregated***. When stops are aggregated, total stop time and average or typical properties of the aggregated stops should be used as input values. Since the exact location of refueling and rest stops usually cannot be predicted in advance, the aggregation method is often used for these types of stops. Other types of stops include inspections (e.g., at state or national borders), intermodal transfers, classification in railyards, and short-term storage while en-route. The potentially exposed populations associated with these various types of stops are discussed in Section 2.3.3. In all cases, however, the user defines one or more STOP LINKs and enters information on (1) the duration of each stop (or the aggregated stop time), (2) the number or density of potentially exposed persons, and (3) their location relative to the location of the stopped shipment. The latter options are discussed in Section 2.4.3.

2.4.3 Population Distribution Models

There are several distinct populations that may be exposed during incident-free transportation. ***People residing adjacent to a link are collectively referred to as the off-link population***, a term coined by the original developers of RADTRAN. This population is modeled as being uniformly distributed on an infinite flat plane at some user-defined density. Each route segment must be assigned a population density, even though it may be zero as in the case of maritime travel on the open seas.

For overland modes, up to three separate subpopulations may share the transport link. Collectively referred to by the original developers of RADTRAN as the ***on-link population***, they are separately modeled. The subgroups are:

- persons in vehicles traveling in the same direction as the transport vehicle,
- persons in vehicles traveling in the opposite direction, and
- persons in vehicles travelling in the same direction as the transport vehicle that pass that vehicle (highway modes only).

The first two subgroups are modeled as each occupying a single lane, which is treated as an infinite straight line along the length of which vehicles are uniformly spaced in both directions. The spacing is determined by user-supplied vehicle-density and velocity data. The third on-link subpopulation is addressed in the passing-vehicles model. In this model, persons in vehicles occupy the space in adjacent traffic lanes where vehicles reside while passing; a further condition of the passing-vehicles model is that the space is always filled by a vehicle for the duration of the trip, but not always by the same vehicle. The number of persons per vehicle is a user-defined variable. The calculated dose represents a conservative population-dose estimate rather than a dose to an individual. It is conservative because the passing space in the real world is ***not*** always occupied.

Members of the public who may be present at stops make up a separate population subgroup. Dose to this subgroup is modeled in one of two ways (1) as a specific number of persons located at a given distance from a stationary source for a specified amount of time or (2) as a population density located within an annular area for a specified amount of time.

Handlers and inspectors who may work in close proximity to a package are included in a separate population model. For large packages, these close-proximity doses are estimated with a line-source model. For the crewmember subgroup, the number of crewmembers, their distances from the package(s), and the nature of intervening shielding (if any) are user-definable, but the duration of exposure is calculated internally from speed and distance parameters. Finally, en-route storage, if any, is treated as an ordinary stop, and ***dose to warehouse personnel is calculated with the same model as public stop dose.***

2.4.4 Accident-Severity and Package-Behavior Models

The Accident-Severity Model allows the user to assign all accidents to a maximum of 30 user-definable severity categories. The category definitions should be based on quantitative estimates of the forces potentially applied to package(s) during accidents and on the loss of shielding and/or release of radioactive species that may occur in response to these forces. The latter are referred to as ***release fractions***. For loss-of-shielding situations, the analog to the "release fraction" is the fractional degradation of package shielding rather than actual release of contents. The categories should be clearly related to the set of fire, crush, impact, and puncture forces encountered in accidents and simulated in package-certification tests; however, unusual or specific abnormal environments associated with the problem being analyzed may be included as distinct categories. Several categorization schemes have been developed for spent fuel casks and other Type B packagings:

- 6 categories (Wilmot, 1981);
- 8 categories (NRC, 1977);
- 9 categories (Sprung et al., 1998)
- 20 categories (Fischer et al., 1987).

The preferred method of developing severity categories is event-tree analysis, which was used by three of the four authors cited above. The user is not required to use 30 categories, and categories may be aggregated or dis-aggregated as the needs of a problem dictate. However, the category definitions must cover the range of possible accidents (after taking any probability cut-off into account). In mathematical terms, ***the sum of the probabilities of occurrence (severity fractions) of all the categories defined by the analyst must be approximately 1.0.*** There is no necessary relationship between the number of categories and the range covered. All of the schemes cited above cover approximately the same range of accidents. However, the 9-category Sprung et al. scheme covers one scenario (severe fire without impact) that is not explicitly covered in the 20-category Fischer et al. scheme.

The Package-Behavior Model combines user-specified package-release fractions with other user-defined values representing, respectively, the fraction of each nuclide that becomes airborne and the fraction of an airborne radioactive material that is of respirable size as a consequence of involvement in an accident of a given severity. There must be a complete set of package-behavior data for each accident-severity category defined by the user. ***RADTRAN 5 contains no defaults nor are there any recommended values for these variables; their values must be assigned by the user.*** Other variables, such as the deposition velocity of airborne particles of each released material (an indicator of particle size), which also are used in the calculation, have defaults or recommended values, but they are subordinate to the main fractional release variables. The latter are combined with the accident probabilities for each severity category (see Section 2.4.5), the number of packages, and the number of trips to determine expected values of release of each material in each link. Sprung et al. (1998) gives values of all these variables in a 9-category scheme for a few specific materials (various types of research-reactor spent fuel).

2.4.5 Accident Probability Model

This section of the code is not so much a model as an array of input data that are combined by simple multiplication. The data consist of (1) the base accident probabilities for a given mode and link and (2) the conditional

probabilities, given that an accident occurs in a given transportation mode, that it will be of a particular severity. ***These conditional probabilities are called severity fractions.*** The base-rate values usually are derived from published historical data, but are not required to be. Severity-fraction values must reflect the severity-category scheme selected or developed by the user (see previous section). That is, a conditional probability must be associated with each severity category for each mode in the analysis. They should be developed concomitantly with the development of the severity categories themselves, preferably by generation of one or more event trees, as recommended in Section 2.4.4. Probabilities of fatalities from all causes are entered in a separate array; they also are developed from published sources and are used to generate estimates of non-radiological fatalities (see Section 2.4.8).

2.4.6 Meteorological Model

The dispersal of a cloud of aerosol debris potentially released at the site of a severe accident also must be described in order to estimate consequences. ***Basic dispersion calculations are not performed within RADTRAN 5.*** Instead, the user must provide either a table of time-integrated concentration (TIC) values, with corresponding downwind areas (isopleth areas) or fractional occurrences of Pasquill atmospheric stability categories A through F (Pasquill, 1961).

TIC and isopleth-area values may be generated by one of the puff models now available [e.g., AIRDOS (Moore et al. 1979), CAP88 (Beres, 1990); CAP88-PC (Parks, 1992), INPUFF (Petersen and Lavdas, 1986), etc.]. ***The initial "puff" must have dimension; that is, it should not be modeled as a point source.*** Doing the latter leads to false and excessively high concentration estimates in the innermost downwind isopleths. However, in the absence of specific information, it is acceptably conservative to model a "puff" as having a small diameter. ***"Smokestack" plume models for chronic releases should NOT be used to generate isopleth areas or TIC values.***

The user must enter the maximum downwind extent of each isopleth. RADTRAN 5 contains a tabulation of national-average values for these variables. The national averages may be used in the absence of other information and, in the United States, will generally yield acceptable results for routes longer than 500 km (310 mi.) (Mills and Neuhauser, 2000). As was noted in Chapter 2, it may not be desirable to employ these values for very short routes, especially routes of only a few kilometers.

Tabulated time-integrated concentration and area values for conservatively selected wind speeds also are included within the RADTRAN 5 code for each Pasquill category as a convenience to the user; the user is not required to employ them. The values are conservative because they represent a small-diameter (10 m) ground-level release and the lowest wind speed consistent with each stability category. Weighted averages of the individual atmospheric stability group results are calculated by RADTRAN 5 and printed in the output.

The Meteorological Model also calculates individual doses. The dose to an individual located on the centerline at the maximum downwind extent of each isopleth is calculated as a step in the population-dose calculation (see Figure 2-2), but the values were not saved in previous releases of RADTRAN. These calculations were originally preserved by a separate code (TICLD) that now has been incorporated into RADTRAN 5 (Weiner, Neuhauser and Kanipe, 1993). These individual-dose values are saved and printed in the output.

2.4.7 Exposure Pathways Models

In addition to the direct exposure that may be expected from loss-of-shielding scenarios, RADTRAN 5 models five exposure pathways associated with dispersal of material from damaged package(s). These pathways are:

- inhalation
- cloudshine
- resuspension
- groundshine

- ingestion.

Minor and/or uncommon pathways such as absorption through skin or through open wounds are not included. The impact on delayed doses from resuspension and groundshine of post-accident actions such as evacuation and clean-up activities may be accounted for with the Exposure Pathways Model.

2.4.8 Health Effects Model

Most doses calculated in RADTRAN 5 are either effective dose equivalents (E.D.E.s) or committed effective dose equivalents (C.E.D.E.s). Prompt doses (i.e., doses from short exposures to external radiation) are expressed as E.D.E.s. All incident-free doses are of this type, as are certain types of accident-related exposures. Doses that occur over long periods of time, such as doses from inhaled or ingested radionuclides that are retained in the lungs or gastrointestinal tract or are translocated to other organs are expressed as C.E.D.E.s. Dose commitments are calculated for periods of 1 year (for potential early effects) and 50 years (for latent effects). E.D.E.s and C.E.D.E.s for individuals are expressed in units of rem (see glossary). Population E.D.E.s and C.E.D.E.s are expressed in units of person-rem. Organ doses (in rem) also are computed for internal exposures via the inhalation and ingestion pathways. In the Health-Effects Model, organ doses associated with the various exposure pathways are compared to dose thresholds for early mortality and morbidity derived from Evans et al. (1985). Latent effects (cancers and genetic effects) are calculated by use of published conversion factors (NAS/NRC, 1990). The "whole-body" doses (E.D.E. and C.E.D.E.) are used to estimate cancer incidence; gonad dose is used to estimate genetic effects in future generations.

2.4.9 Non-Radiological Fatality Model

RADTRAN 5 contains a subroutine that calculates expected traffic fatalities from non-radiological causes. These expected values are the products of published accident fatality rates (from the Probability Model) and user-specified input on distance traveled (from the Transportation Model). Unlike radiological exposures, non-radiological fatalities may occur even when the conveyance is empty. ***Thus, the one-way trip distance must doubled in the calculation of non-radiological fatalities to account for the return trip of the conveyance.*** In view of the extreme uncertainties now known to be associated with particulate inhalation models, hypothetical fatalities from exposure to vehicle emissions are no longer estimated in RADTRAN.

2.5 Primary RADTRAN 5 Calculations

2.5.1 Incident-Free Transportation Dose Calculation

For analysis of incident-free conditions in RADTRAN 4, the package dose rate and packaging-specific characteristics are used to model a package (or shipment) of radioactive material as a modified point source and, for receptor distances less than two characteristic package dimensions from large packages, as a line source. Characteristics of the transportation system are then incorporated into mode-specific models, which use a set of input parameters to describe the population along the route and at stops, and other critical mode-dependent characteristics such as vehicle velocity and stop duration. Population densities for each route segment must be defined by the user, in addition to the characteristics of the various sub-populations that receive off-link, on-link, passenger, crew, stop, handling, and storage doses. The user-assigned values describing these potentially exposed subgroups may be varied by mode and by population-density zone (urban, suburban, and rural). The user is given wide latitude in adjusting parameters for analysis for a specific problem, but the quality and quantity of the available data will limit the accuracy of the results.

2.5.2 Importance Analysis

Each incident-free consequence analysis performed by RADTRAN 5 is accompanied by an ***importance analysis***, the results of which are printed in all forms of the output except the shortest (summary). This analysis uses partial derivatives as described in Chapter 6 to determine the effect on the overall result of a 1-% change in each input variable. The variables are listed in rank order from the largest positive change to the largest negative change.

2.5.3 Non-Radiological Fatalities

Fatalities from all causes, estimated as described in Section 2.4, are printed in the output in a separate table. These represent the deaths that would be expected to occur as a result of ordinary mechanical impacts. They include such categories as pedestrians struck by a vehicle, that result in one or more fatalities and exclude consequences associated with radiation exposure of any kind from hypothetical RAM package damage, which are calculated elsewhere in RADTRAN 5. ***Non-radiological fatalities are typically the largest fatality value calculated.***

2.5.4 In-Transit Individual Dose

In a separate calculation, the dose to an individual located at some user-specified distance from a shipment traveling at some user-specified velocity is calculated with dose-rate data from the Package Model. If the distance and velocity values are the smallest predicted for actual transportation conditions, then this subroutine will calculate a maximum or bounding value of individual dose.

2.5.5 Accident Risk Calculation

The accident module combines user-supplied data on packaging behavior (release fractions, etc.) and accident severity to assess radiological consequences (population doses) for accidents of varying severity. Separate calculations are performed for each accident-severity category in each population-density zone. The consequence value is multiplied by an appropriate probability of occurrence derived from historical accident data to give a risk value; the sum of these individual risk calculations weighted by segment length is the total radiological accident risk. To perform consequence calculations for release accidents, dispersal from the release point (hypothetical accident site) to downwind deposition areas is calculated either with Pasquill atmospheric-stability classes A through F or with user-defined values for time-integrated concentrations (TICs). Consequences associated with the six exposure-pathways models (i.e., direct exposure, inhalation, cloudshine, resuspension, groundshine, and ingestion) are calculated separately and summed.

3 RADTRAN 5 ANALYSES OF TRANSPORTATION UNDER INCIDENT-FREE CONDITIONS

3.1 Introduction to Incident-Free Transportation Calculations

RADTRAN 5 calculates the expected population doses or health effects, as the user chooses, for specific population groups and performs and importance analysis for each link of the route(s) under analysis. The population groups include the following:

- Off-link population
- On-link population
- Population in the vicinity of stops
- Conveyance passengers
- Transportation workers
- Package handlers.

Under keyword LINK, each route segment must be designated as rural, suburban, or urban in character. This character designation is usually based on population density, although it is not required to be. Doses are given on a link by link basis in the output along with rural, suburban, and urban subtotals. Total population doses as well as individual in-transit doses are calculated.

The importance analysis for incident-free transportation shows the increase or decrease that every variable causes in the outcome of RADTRAN 5 calculations if the input variable value is increased by one percent (see Chapter 6). Results are presented in tabular form in the output.

3.2 Population Dose Formulation

3.2.1 Gamma Radiation

The formulation used to assess population gamma dose during incident-free transportation is based on an expression for gamma dose rate as a function of distance from an isotropic point source (i.e., a source emitting gamma radiation in all directions with equal magnitude) (AEC, 1972). Reflection/absorption by the ground surface is neglected in this model. In RADTRAN 5, this type of point-source approximation is used to represent an individual package, shipment, or conveyance. In the absence of data allowing the specification of a neutron component of dose rate, the user should treat the entire dose rate as gamma radiation. Modifications that permit separation of the dose rate into gamma and neutron components are discussed in the next section. Because neutrons are rapidly attenuated in air, the all-gamma treatment gives a slightly conservative estimate of overall population dose.

The formulation given here treats the package or shipment dose-rates as if they were 100% gamma radiation. The gamma dose-rate formula for an isotropically radiating point-source (AEC, 1972) is given by

$$DR_g(r) = \frac{S_{photon}}{4\pi r^2} \cdot \exp(-\mu r) \cdot B(\mu r) \cdot C \qquad (1)$$

where

DR_g r)	=	gamma dose-rate at distance r (dose/time)
S_{photon}	=	particle or photon emission rate (photons/sec)
r	=	radial distance from point source (m)

$\frac{S_{photon}}{4\pi r^2}$	=	flux at distance r (photons/sec/cm^2)
μ	=	attenuation coefficient for surrounding medium (m)
$\exp(-\mu r)$	=	attenuation in medium at distance r (m^{-1})
$B(\mu r)$	=	dose-rate buildup factor for surrounding medium at distance r
C	=	flux-to-dose-rate conversion factor (see Equation 4).

For gamma radiation, the product $\exp(-\mu r)\cdot B(\mu r) \leq 1.0$ for most values of μ and r.[4] Thus, if the product is set equal to 1.0, then dose rate can be expressed in a generally conservative manner as

$$DR_g(r) = \frac{k}{r^2} \tag{2}$$

where

$$k = \frac{S_{photon} \cdot C}{4\pi} \tag{3}$$

The units of k are photons/sec, and the units of DR_g are photons/sec/m^2, which can in turn be converted to mrem/hr or any other dose-rate unit.

The metric of dose rate that is applied to a single package in RADTRAN 5 is equivalent to the Transport Index (TI). The TI is defined in U.S. regulations as the maximum measured or calculated dose rate, in mrem/hr, at a distance of 1 m from the package surface (49 CFR 173). In RADTRAN 5, this definition also is applied to a conveyance carrying a shipment of one or more packages of radioactive material. The first step to being able to use this regulation-defined value in the dose-rate formulation is to rewrite the factor k in Equation 2 as $k_0 \cdot DR_p$ (for a single package) or as $k_0 \cdot DR_v$ for a conveyance carrying a shipment. The term k_0 has units of m^2 and is referred to as the Package Shape Factor, because it directly relates to size of the package or conveyance being analyzed. A new expression for gamma dose rate ($DR_g(r)$) from a point source can then be developed as follows:

$$DR_g(r) = Q\frac{k_0 \cdot DR_{p\,or\,v}}{r^2} \tag{4}$$

where

Q	=	units conversion factor
k_0	=	package shape factor (m^2)
r	=	radial distance from point source (m)
p	=	index for package and
v	=	index for conveyance (vehicle).

When the dose rate is defined in mrem/hr, the conversion factor Q in Equation 4 takes on a value of 2.8E-10 rem-km-hr/mrem-m-sec and is designated Q_1. ***In RADTRAN 5, the dose-rate value measured at 1 m from the package surface is extrapolated back to the center of the package to achieve a true point-source configuration.*** In order to simplify this extrapolation, variations in the intensity of the radiation field around a package are ignored and ***the maximum measured or calculated dose-rate at 1 m is used to define the field strength at a radial distance measured from the center of the package to some specified package***

[4] At some values of r, the buildup [B(r)] in air from interaction of air molecules with incident gamma radiation may be large enough to make the product of buildup and attenuation product slightly exceed 1.0, but this phenomenon usually represents only a very small portion of the total distance range over which dose is assessed and can be ignored without affecting the result at the two significant-digit level of accuracy.

dimension plus 1 m. RADTRAN 5 then creates a point source that yields this field strength at the specified radial distance. In order to define what this radial distance should be, ***the actual package shape is converted into an equivalent spherical volume by means of an* effective package dimension *or d_e***. The effective package dimension is derived from an actual package dimension and is the diameter of the equivalent spherical volume that represents the package in the point-source formulation. The Package Shape Factor, k_0, is then set equivalent to the square of ½ of this diameter plus 1 m (i.e., the total radial distance from the center of the package to the point at which the regulatory dose rate was measured). Thus.

$$k_0 = (1 + 0.5d_e)^2 \tag{5}$$

where

k_0	=	point-source package shape factor (m^2)
d_e	=	effective package or conveyance dimension (m)

For single packages, the value of d_e is determined by selecting a ***characteristic package dimension, d_p***, from among the actual package dimensions such as length, width, diameter, etc. (This value is the RADTRAN input parameter CPD). It is generally recommended that d_p be the largest package dimension, since the resulting field strength estimate will be slightly conservative. For cylindrical packages, for example, d_p should be the cylinder length.

For vehicles and large packages where d_v or d_p might exceed 4 m, use of the largest dimension greatly overestimates the gamma dose rate, and a modified d_e must be calculated (Madsen, Wilmot and Taylor, 1986). Package dimensions greater than about 9 m should not be used. Thus, the possible expressions for d_e are

$$d_e = \begin{cases} d_p, \text{ if } d_p \le 4 \text{ meters, or} \\ d_v, \text{ if } d_v \le 4 \text{ meters, or} \\ 2(1+0.5d_p)^{3/4} - 0.55, \text{ if } d_p > 4 \text{ meters and} < 9 \text{ m, or} \\ 2(1+0.5d_v)^{3/4} - 0.55, \text{ if } d_v > 4 \text{ meters and} < 9 \text{ m} \end{cases} \tag{6}$$

Given the above conditions, it follows that for all values of $r > 2d_e$ the point-source equation is

$$DR_g(r) = Q \cdot \frac{DR_{p \text{ or } v} \cdot (1+0.5d_e)^2}{r^2} \tag{7}$$

where

Q	=	units conversion factor
DR	=	gamma dose rate at radial distance r (mrem/hr)
DR	=	maximum measured or calculated dose rate at 1 m from package or conveyance (mrem/hr)
r	=	radial distance from point source (m)
d_e	=	effective package dimension (m)

For large packages, at values of $r \leq 2d_e$, a* line source *approximation is applied for stops and handlings, where persons may closely approach the package or vehicle for relatively long periods of time. In a line-source approximation, the dose rate is proportional to 1/r rather than to $1/r^2$. The Package Shape Factor for use with line-source calculations is defined as follows:

$$k_0 = 1 + 0.5d_e \tag{8}$$

where

k_0	=	line-source package shape factor (m)
d_e	=	effective package dimension (m) [Equation 5].

3.2.2 Neutron Radiation

To assess population neutron dose during incident-free transportation an expression compatible with the gamma expression was developed that describes neutron dose rate as a function of distance from an external isotropic point source (i.e., a dimensionless source emitting neutron radiation in all directions with equal magnitude). Reflection/absorption by the ground surface is neglected as before. Neutron interactions with matter make transport through any medium, including air, more complex to model than gamma-radiation interactions. A model that is relatively simple and that parallels the treatment of gamma radiation was developed. Since package dose rate is required to be reported in mrem/hr (or sieverts (Sv)/hr), the RBE (relative biological effectiveness) difference between neutron and gamma radiations is already accounted for. The basic dose-rate equations are also equivalent, differing only in the values of the flux-to-dose-rate conversion factors. Thus, the first step is to restate the basic equation for dose rate at distance r from a point source as follows

$$DR_{total}(r) = \frac{(C_G \cdot E_G \cdot \exp(-\mu r) \cdot B(\mu r)) + (C_N \cdot E_N \cdot \exp(-\mu r) \cdot B(\mu r))}{r^2} \tag{9}$$

where

C_G	=	flux-to-dose-rate conversion factor for gamma radiation
C_N	=	flux-to-dose-rate conversion factor for neutron radiation
E_G	=	gamma emission rate (photons/sec)
E_N	=	neutron emission rate (neutrons/sec)
$\exp(-\mu r)$	=	attenuation by the medium through which the radiation is travelling (m^{-1})
$B(\mu r)$	=	buildup factor for the medium through which the radiation is travelling
r	=	radial distance from point source (m)

The products ($C_G \cdot E_G$) and ($C_N \cdot E_N$) both result in values with units of mrem/hr. Thus, the sum of the two terms equals the package or vehicle dose rate (DR_p or DR_v) when evaluated at the appropriate distance. Thus, each component of the sum can be represented as a fraction of the package or vehicle dose rate, and Equation 9 can be rewritten as follows

$$DR(r) = \frac{FG \cdot (\exp(-\mu r) \cdot B(\mu r)) + FN \cdot (\exp(-\mu r) \cdot B(\mu r))}{r^2} \tag{10}$$

Converting Equation 10 to an expression that depends on measured package or vehicle dose rate and characteristic dimension by the same method as for gamma radiation, yields

$$DR_N(r) = Q \frac{k_0 \cdot (FN \cdot DR_{p\,or\,v}) \cdot \exp(-\mu r) \cdot B(\mu r)}{r^2} \tag{11}$$

where

r	=	radial distance from point source (m)
Q	=	units conversion factor
k_0	=	package shape factor (m)
FG	=	fraction of dose rate at 1 m from package that is gamma radiation
FN	=	fraction of dose rate at 1 m from package that is neutron radiation
$DR_{p\,or\,v}$	=	maximum measured dose rate at 1 m from package or vehicle (mrem/hr)
p	=	index for package
v	=	index for conveyance (vehicle)

$\exp(-\mu r)$ =		attenuation by the medium through which the radiation is travelling (m^{-1})
$B(\mu r)$	=	buildup factor for the medium through which the radiation is travelling
r	=	radial distance from point source (m).

For any package with a neutron component of dose rate, the package shape factor will be equal to that used for gamma radiation, because the package dimension used to calculate k_0 is the same. This equation, however, cannot be further simplified in the way that the gamma expression was in Equation 2, because the product of attenuation and buildup for neutrons is often greater than 1.0 for a substantial part of the radial distance range, depending on the neutron energies. Instead, dimensionless coefficients are used in geometric progressions to express buildup, B(r), as follows:

$$DR_N(r) = Q \cdot k_0 \exp(-\mu r) \frac{(1 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4)}{r^2} \tag{12}$$

where all parameters are as defined in Equation 11 except for the coefficients a_1 through a_4, which are defined below.

Any neutron transport curve can be represented in Equation 12 by proper selection of values of a_1 through a_4. Since the linear attenuation coefficient for air (μ_{air}) describes attenuation by the primary medium through which neutrons would travel in the event of a loss-of-shielding event; μ_{air} is used as a default value (7.42E-03 m^{-1}) (Madsen, Wilmot and Taylor, 1986, p. 43). Values of the four coefficients were derived to fit the shape of the calculated dose-vs.-distance curve in air to the shape of the selected neutron transport curve (Figure 3-1). These values are

$$\begin{aligned} a_1 &= 2.02E\text{-}02; \\ a_2 &= 6.17E\text{-}05; \\ a_3 &= 3.17E\text{-}08; \\ a_4 &= 0. \end{aligned} \tag{13}$$

Significant levels of neutron radiation are seldom encountered in radioactive materials transportation. The coefficient values provided here are intended to facilitate neutron dose rate calculation in the main case for which such calculations might be appropriate – spent nuclear fuel transportation. The data are for fission neutrons; they were obtained with neutron cross section data from the ENDF/B-V cross section data library (Kinsey and Magurno, 1983) generated with the NJOY code (McFarlane et al., 1982). The source was assigned an energy spectrum obtained from Oak Ridge National Laboratory calculations of the neutron flux at the surface of a lead-shielded spent fuel shipping cask. Neutron transport calculations were performed with the ONEDANT code, which solves the one-dimensional (cylindrical) multigroup Bolttzmann transport equation by the discrete ordinates method (O'Dell et al., 1982). The ENDF library, NJOY, and ONEDANT are discussed and evaluated by Parks et al. (1988). A neutron transport curve through air at 50% humidity was calculated because air molecules and water vapor significantly attenuate neutrons (but not gamma radiation). These default data are generally acceptable for applications of RADTRAN 5 involving spent fuel. However, the user may carry out new neutron transport calculations and derive new coefficients that fit the resulting curve.

For a line source, the derivation is again similar to that for gamma radiation. It yields

$$DR_N(r) = Q \cdot k_0' \exp(-\mu r) \frac{(1 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4)}{r} \tag{14}$$

where

$DR_N(r)$	=	neutron dose rate at distance r (mrem/hr)
r	=	radial distance from source (m)
Q	=	units conversion factor
k_0'	=	line-source shape factor as defined above (m)

μ = linear attenuation coefficient (m^{-1}); default is value for air, 7.42E-03 m^{-1}
a_1, a_2, a_3, a_4 = dimensionless coefficients.

3.2.3 Summary of Final Expressions for Gamma and Neutron Radiation

Gamma and Neutron Fractions

The fractions of the dose rate that are gamma and neutron radiation are represented as f_G and f_N, respectively, throughout this technical manual, and the sum of the two must be unity ($f_G + f_N = 1.0$). ***Since the relative fractions of gamma and neutron change with distance from the package, values of f_G and f_N must be determined at the same 1-m distance from the package or vehicle surface as the dose-rate metrics DR_p and DR_v.***

Gamma Point Source – Final Form

The final form of the basic point-source expression used in RADTRAN5 for gamma radiation is

$$DR_G(r) = Q_1 \cdot DR_{p\,or\,v} \cdot FG \cdot k_0 \cdot \exp(-\mu r)\frac{(1 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4)}{r^2} = Q_1 \cdot \frac{k_0}{r^2} \cdot DR_{p\,or\,v} \cdot FG \qquad (15)$$

where
$DR_G(r)$ = gamma dose rate at distance r (mrem/hr)
r = radial distance from source (m)
Q_1 = units conversion factor = 2.8E-10 rem-km-hr/mrem-m-sec
$DR_{p\,or\,v}$ = package or vehicle dose rate at 1 m (mrem/hr)
FG = fraction of package or vehicle dose rate that is gamma radiation
k_0 = point-source shape factor (m^2)
μ = linear attenuation coefficient (m^{-1}) set equal to zero
a_1, a_2, a_3, a_4 = dimensionless coefficients set equal to zero.

As noted previously, attenuation and buildup are insignificant for gamma radiation; values for μ and the dimensionless coefficients are set to zero, which yields a value of 1.0 for the product of attenuation and buildup. Thus, the gamma expression reduces to the simple form above, which is also described in Equation 7.

Neutron Point Source – Final Form

The final form of the basic point-source expression for neutron radiation used in RADTRAN 5 is identical to Equation 12 and cannot be further simplified. It is:

$$DR_N(r) = Q_1 \cdot DR_{p\,or\,v} \cdot FN \cdot k_0 \exp(-\mu r)\frac{(1 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4)}{r^2} \qquad (16)$$

where
$DR_N(r)$ = neutron dose rate at distance r (mrem/hr)
r = radial distance from source (m)
Q_1 = units conversion factor = 2.8E-10 rem-km-hr/mrem-m-sec
$DR_{p\,or\,v}$ = package or vehicle dose rate (mrem/hr)
FN = fraction of package or conveyance dose rate that is neutron radiation
k_0 = point-source shape factor as defined above (m^2)
μ = linear attenuation coefficient (m^{-1}); default value is for air, 7.42E-03 m^{-1}
a_1, a_2, a_3, a_4 = dimensionless coefficients with default values given in Equation 14.

Gamma Line Source –Final Form

The final form of the basic line-source expression used in RADTRAN5 for gamma radiation is

$$DR_G(r) = Q_l \cdot DR_{p\,or\,v} \cdot FG \cdot k_0' \exp(-\mu r) \cdot \frac{(1 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4)}{r} \tag{17}$$

where all values are the same as in Equation 15 except that the point-source shape factor is replaced by the line-source shape factor.

Neutron Line Source – Final Form

The final form of the basic line-source expression used in RADTRAN 5 for neutron radiation is

$$DR_N(r) = Q_l \cdot DR_{p\,or\,v} \cdot FN \cdot k_0' \exp(-\mu r) \frac{(1 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4)}{r} \tag{18}$$

where all values are the same as for Equation 16 except that the point-source shape factor is replaced by the line-source shape factor.

3.3 Dose to Members of the Public

3.3.1 Dose to Persons Along the Transport Link While the Shipment is Moving – Highway, Rail and Barge Modes

This section describes computation of the total integrated gamma dose to an individual located at a specified perpendicular distance from the path of a radioactive material shipment passing at a specified velocity.

An expression for the total integrated dose to a stationary individual at a perpendicular distance, x, from the path of a moving source (i.e., a shipment in transit) with a dose-rate factor k, passing at a constant velocity V, has been derived from Equation (3) of AEC (1972) and is given by

$$D(x) = \frac{2 \cdot k_0 \cdot DR_v}{V} I(x) \tag{19}$$

and

$$I(x) = \int_x^{\infty} \frac{\exp(-\mu r) B(r)}{r\,(r^2 - x^2)^{1/2}} dr \tag{20}$$

where

$D(x)$	=	total integrated dose absorbed by an individual at distance x (rem)
k_0	=	point-source package shape factor (m^2)
DR_v	=	conveyance dose rate at 1 m from surface (mrem/hr)
V	=	conveyance speed (m/s)
x	=	perpendicular distance of individual from shipment path (m)
μ	=	attenuation coefficient (m^{-1})
$B(r)$	=	buildup factor expressed as a geometric progression

and

I(x) = integration function.

To obtain the integrated population dose along a unit length of travel, Equation 19 is multiplied by the population density and integrated over strips of width d on both sides of the transportation path:

$$D_{off} = 2 \cdot Q \cdot PD \int_{min}^{max} D(x)dx \tag{21}$$

where all variables are as defined in Equations 19 and 20 except for the following:

D_{off} = integrated population dose per km of strip (person-rem)
Q = units conversion factor
PD = population density (persons/km^2)
min = minimum distance from population to shipment centerline (m)
max = maximum distance perpendicular to shipment route over which exposure is evaluated (m).

The value of max is usually set to 800 m (~ 0.5 mi.) because that is the value historically used in AEC (1972), and in earlier releases of RADTRAN. The value is not tied to any analytical results indicating that it is appropriate; indeed, dose rates generally fall below detectable levels well before a distance of 800 m from the source. However, retaining the 800-m value is slightly conservative and does preserve parallelism and comparability with older analyses. It is recommended that this value be used to establish a baseline for comparison purposes even when the user selects another value of max for his or her analysis.

By inserting the expression for D(x) [Equation 19] into Equation 21, the latter can be rewritten as

$$D_{off} = Q_1 \cdot \frac{4 \cdot k_0 \cdot DR_v \cdot PD}{V} \cdot \int_{min}^{max} I(x)dx \tag{22}$$

where all variables are defined in Equations 20 and 21 and the units conversion factor, Q_1, is evaluated as 2.8E-10 rem-km-hr/mrem-m-sec.

For incident-free transportation, the total population dose for persons along a transport link is obtained in RADTRAN 5 by multiplying Equation 22 by the number of shipments of the type being analyzed.

The integration of Equation 22 is performed by use of a Gaussian quadrature, GAUS8, which is a Sandia National Laboratories' SLATEC math routine that integrates a real function of one variable over a finite interval (min to d, in this case).

The function integrated by GAUS8 is

$$I'(x) = \int_{x}^{\infty} \frac{\exp(-\mu r)B(r)}{r\,(r^2 - x^2)^{1/2}} dr \tag{23}$$

$$= \left\{ \left[\frac{BSKIN_{x \cdot \mu_s}}{x} + \left(a1_s - a3_s \cdot x^2\right) \cdot BESKO_{x \cdot \mu s} + \left[a2_s \cdot x + \frac{a3_s \cdot x}{\mu_s} \right] \cdot BESK1_{x \cdot \mu s} \right] \cdot e^{-x \cdot \mu_s} ; \text{if } \mu_s \neq 0 \right.$$

or

$$= \left\{ \frac{\pi}{2 \cdot x} ; \text{if } \mu_s = 0. \right.$$

where

x = value passed from function I′ from GAUS8; x ranges from min to d;

r	=	variable of integration (distance from source to receptor) (m)
μ_s	=	attenuation coefficient for gamma radiation if s = G or neutron radiation if s = N
$a1_s$, $a2_s$ $a3_s$	=	unitless coefficients for gamma radiation if s = G or neutron radiation if s = N;
BSKIN	=	Sandia National Laboratories' SLATEC math routine that computes repeated integrals of the modified K-zero Bessel function for argument $(x \cdot \mu_s)$;
BESK0	=	Sandia National Laboratories' SLATEC math routine that computes the modified Bessel function of the third kind of order zero for real argument $(x \cdot \mu_s)$:
BESK1	=	Sandia National Laboratories' SLATEC math routine that computes the modified Bessel function of the third kind of order one for real argument $(x \cdot \mu_s)$.

Up to this point the equations express only dose along a route of undefined length. In order to account for the distance traveled, Equation 23 must be multiplied by a route or segment length (DIST). However, any transportation of radioactive material package involves passage through varying population densities. In order to account for this, the RADTRAN 5 user should divide a route into *route segments* or *links* of length $DIST_L$ and assign a separate population density (PD_L) to each one. The total population dose (D_{off}) resulting from a trip then becomes the sum of the doses received in each route segment. The bandwidth (distance from min to max) may be subdivided into (1) a pedestrian strip immediately adjacent to the transportation link and (2) the remainder, where residences are located. The pedestrian population density is estimated in urban and suburban areas by the product ($PD_L \cdot RPD_{s\,or\,u}$), where PD_L is the residential population density and $RPD_{s\,or\,u}$ is the ratio of pedestrian density to residential density. The use of the integrated dose expression in Equation 22 results in the following expression per link.

$$D_{off} = 4 \cdot Q_1 \cdot k_{0_v} \cdot DR_v \cdot \frac{PD_L}{V_L} \cdot NSH_L \cdot DIST_L \cdot \left[\begin{array}{l} FG_v \left[\int_{min}^{SW} I_G(x)dx \cdot RPD_{s\,or\,u} + \int_{SW}^{max} I_G(x)dx \cdot SF \right] \\ + FN_v \left[\int_{min}^{SW} I_N(x)dx \cdot RPD_{s\,or\,u} + \int_{SW}^{max} I_N(x)dx \cdot SF \right] \end{array} \right] \quad (24)$$

where all variables are as defined for Equations 21 and 23 except for the following:

NSH_L	=	number of shipments that travel on link L
SW	=	sidewalk width (m); used as a limit of integration to define width of pedestrian walkway beside route and minimum value for distance over which dose to residents is integrated.
$RPD_{s\,or\,u}$	=	ratio of pedestrian density to residential population density in suburban (s) or urban (u) route segments.
SF	=	shielding factor

Values of min, sw, and max taken from Madsen, Wilmot and Taylor (1986) are given in Table 3-1. These may be used in the absence of route-specific information in most of the United States.

Each link is analyzed separately in RADTRAN 5. Most of the variables in Equation 24 are user-defined. That means the user must enter values for each variable for each link in the input file. Velocities must be entered in units of km/hr; they are converted internally to units of meters per second.

Each population-density zone (urban, suburban, and rural) may be assigned a different, user-definable nominal shielding factor. This factor is derived in Equation 25 and is the ratio (R) of the unshielded and the fully shielded case, which represents the reduction in integrated exposure caused by shielding effects:

TABLE 3-1 TYPICAL U.S. VALUES FOR min, SW, AND max

Population Zone	Highway Type	Value of min (m)	Value of SW (m)	Value of max (m)
Rural	Freeway	30	(none)[1]	800
Rural	Non-Freeway	30	(none)	800
Suburban	Freeway	30	(none)	800
Suburban	Non-Freeway	27	30	800
Urban	Freeway	30	(none)	800
Urban	City Street	5	8	800

1. Where "none" is shown for SW, no pedestrian walkway is modeled as being present beside the route.
2. "Non-freeway" in rural and suburban areas refers to non-divided, non-access-limited roads (e.g., state highways).

$$R = \frac{\int_{min}^{d} \left[\int_{x}^{\infty} \frac{\exp(-\mu_m r) B_m(\mu_m r)}{r(r^2 - x^2)^{1/2}} dr \right] dx}{\int_{min}^{d} \left[\int_{x}^{\infty} \frac{\exp(-\mu_{air} r) B_{air}(\mu_{air} r)}{r(r^2 - x^2)^{1/2}} dr \right] dx} \tag{25}$$

where μ_m and B_m are the attenuation and buildup factors, respectively, for the shielding medium, and μ_{air} and B_{air} are the attenuation and buildup factors, respectively, for air. This ratio for urban, suburban, and rural zones (RU, RS, and RR) may be defined in terms of construction methods and housing density characteristic of each zone. Values that are applicable for many parts of the United States are given in Table 3-2 although the user may enter other values. Care must be taken in the application of the nominal shielding factors. In rural Italy, for example, most houses are built of stone, and the value of RR suggested in Table 3-2 would be inappropriate; construction in many densely populated equatorial cities, on the other hand, is less substantial than indicated in Table 3-2.

TABLE 3-2 NOMINAL SHIELDING FACTORS

Population Zone	Variable Name	Construction Type	Suggested Value of R*
Rural	RR	No Shielding	1.0
Suburban	RS	Wood frame construction 45-ft square buildings; 100 ft between buildings; 6-in thick walls	0.87
Urban	RR	Concrete block walls 1-ft thick; 1 central wall/building. Buildings are contiguous in blocks 200 ft long; 60-ft wide streets	0.018

**Values are from Madsen, Wilmot and Taylor, 1986.*

Three shielding options are available, which are invoked by varying the IUOPT parameter.

- Option 1 - If Option 1 is selected, R is set to zero for all population zones. This is equivalent to assuming that all construction in all zones is heavy masonry, reinforced concrete, or some other extremely effective shielding material. Finley et al. (1980) supports this approach ***only*** for highly urban areas (e.g., New York City). For example, for travel on city streets in Manhattan, Finley et al. showed that pedestrians on sidewalks would accumulate virtually all dose. Finley et al. (1980) also gives values of 5 m for min and 8 m for SW to represent sidewalks along city streets. For rural and suburban non-freeway streets (e.g., most state highways) suggested values are 27 and 30 m. The

potential presence of unshielded nonresident persons is accounted for by introducing the factor RPD. The RPD (Ratio of Pedestrian Density) is the ratio of the density of pedestrians (per square kilometer of sidewalk) area to the baseline residential population in the same general area. Data from Finley et al. (1980) suggest a value of 6 for RPD in highly urbanized areas such as New York City. Values of RPD for many other urban areas are undoubtedly lower, but few quantitative data exist to support selection of a generally applicable value and none is recommended in this manual. The conservative New York value is often used in the absence of route-specific information, however.

- Option 2 – Option 2 allows building shielding to be accounted for in a relatively realistic manner. In this case, the result has two parts – one for the unshielded pedestrians on sidewalks or pedestrian walkways immediately adjacent to the route and another one for the population beyond the sidewalk out to the user-defined maximum distance. RR, RS, and RU may be taken from Table 3-1, or user-defined values may be employed. Suggested values of min and sw for highway mode are from 5 to 8 m for city streets and from 27 to 30 m for rural and suburban non-freeway routes. Values of 30 m for min and 800 m for max are suggested for limited-access divided highways (e.g., interstate highways). A pedestrian zone is omitted for the latter because pedestrian traffic is generally limited and may even be prohibited on such highways.
- Option 3 – In Option 3, shielding is neglected entirely and RR, RS and RU are set to 1.0. The calculation simply uses a uniform distribution of unshielded persons from the user-defined value of m out to the user-defined value of max. Suggested values are min = 30 m and max = 800 m for freeways in all population densities; min = 5 and max = 800 m for city streets; and min = 27 and max = 800 m for rural and suburban non-freeway links.

When a Highway-Route-Controlled Quantity (HRCQ) of radioactive material is shipped by truck, the truck is required by USDOT regulations to travel on interstate highways or state-designated alternative routes. HRCQ and routing regulations for highway shipments are defined and described in 49 CFR 171-177. ***In RADTRAN 5, interstate highways and similarly engineered highways are referred to as freeways.*** As already noted, freeways are modeled as having no pedestrians. It is also recommended that the same average velocity be used for all freeway segments, regardless of population density.

"Virtual route segments" can be constructed to account for time spent in rush-hour traffic in urban or suburban areas. That is, route segments on which rush hour traffic is expected can be entered twice, once with a "normal" velocity and traffic density and once with a rush-hour velocity and traffic density. The fractional representation of the rush-hour segment (i.e., the fraction of time rush-hour conditions are encountered on the route segment) is then accounted for by properly apportioning the total actual segment length between the two virtual segments. For example, if rush-hour traffic occurs for 4 hours per day on route segment x, then the fractional occurrence of rush-hour conditions is 4/24 or ~0.17. If segment x is 40 km in length, then 40 x 0.17 = 6.8 km is the length of the virtual segment to which the higher traffic density and lower average speed of rush-hour traffic should be assigned, and the remainder (33.2 km) is the length of the "non-rush-hour" segment. In the absence of specific data, it is recommended that the traffic density be doubled and the average velocity halved to represent rush-hour conditions. Route-specific data are usually only available from state or local authorities (e.g., Brogan, Cashwell, and Neuhauser, 1989). State or local regulations such a time-of-day restrictions on RAM shipments through certain cities, may affect the choice of values for these parameters.

Rail, Ship and Barge Modes

The population doses received by persons along a rail transport link or waterway are computed in a manner identical to that used for highway modes. The limits of integration (values of min, SW, and max) vary by mode. For rail mode, value of 30 and 800 for min and max, respectively, are often used in the absence of route-specific information. The value of sw is always zero for rail and water modes.

The 30-m value of min generally is a conservative representation of railroad right-of-way width, although larger and smaller values may be indicated by route-specific information. The 800-m value of max provides consistency and comparability with truck mode analyses and with earlier RADTRAN analyses. The user

may select any value, but modal alternatives (e.g., truck mode versus rail mode) can only be meaningfully compared if the limits of integration are the same or if differences (e.g., differences between modes) have logical explanations and are accounted for in the analysis.

All open ocean travel and travel on certain inland waterways (e.g., the Great Lakes) take place in uninhabited areas. Portions of a route passing through these areas may be either removed from the analysis or (preferably) assigned an off-link population density of zero. Passage on rivers, canals, congested port waters, etc. where a populated shoreline is within 800 m of the vessel should be represented as segments with non-zero population densities. The value of min in such areas would be dictated by the minimum distance from the navigable channel to the shoreline. A suitable value for min in congested waterways in the absence of location-specific data is 200 m. The maximum limit of integration should remain the same as that used for other modes if more than one mode is being analyzed; the standard value for all modes is 800 m.

Air Modes

For air transport, the entire in-transit incident-free dose calculation is set to zero because the average distance from an airplane in flight to persons on the ground is so large that the dose contribution is negligible. Calculation of dose to airline passengers and crew is discussed later in this Technical Manual.

3.3.2 Dose to Persons in Conveyances Sharing the Transport Link – Highway Modes

A schematic of this sub-model is shown in Figure 3-2. All conveyances traveling on highways are assumed to be motorized vehicles. Figure 3-3 shows that the dose consists of three separate components:

- dose to persons in vehicles travelling in the opposite direction to the shipment
- dose to persons in vehicles travelling in the same direction as the shipment, and
- dose to persons in passing vehicles.

The sum of these doses is referred to as the ***on-link dose***.

Dose to Persons Traveling in the Opposite Direction – Highway and Rail Modes

Both the shipment and the oncoming traffic are modeled as moving at a constant average speed V_v. This is exactly equivalent to the oncoming vehicles being at rest and being passed by the RAM transport vehicle traveling at a constant average speed of $2V_v$. The latter formulation is used to develop the on-link dose calculation in RADTRAN 5 because it permits the expression for a moving source from Equation 19 to be used with little modification. The integrated dose received by an individual in an oncoming vehicle located at a minimum perpendicular distance x from the centerline of the RAM transport shipment is:

$$D_{opp} = \frac{2 \cdot k_0 \cdot DR_v}{2V_v} \cdot I'(x) \tag{26}$$

where

D_{opp}	=	integrated dose to persons traveling in opposite direction (person-rem)
k_0	=	point-source package shape factor (m^2)
DR_v	=	package dose rate at 1 m from surface (mrem/hr)
$I'(x)$	=	integration function describing vehicle passing at minimum perpendicular distance x

The factor of 2 in Equation 26 accounts for dose accumulation while the RAM transport vehicle travels both toward and away from vehicles traveling in the opposite direction. To develop an expression for population dose for this exposure group, the population density must be determined. In this case it is modeled as a linear population density (persons/km) and is a function of vehicle density and vehicle occupancy. The

linear density of oncoming vehicles per km is given by N′, where N′ is the one-way traffic count (average number of vehicles per unit of time in all lanes). If PPV (number of persons per vehicle) defines vehicle occupancy, then the total number of persons traveling in the opposite direction to the shipment is $N' \cdot PPV$. The linear density of persons traveling in the opposite direction is then given by $\frac{N' \cdot PPV}{V_v}$. When combined with Equation 26 this expression yields:

$$D_{opp} = \frac{2 \cdot k_0 \cdot DR_v}{V_v} \cdot I'(x) \cdot \frac{N'}{V_v} \cdot PPV \cdot DIST_L \cdot NSH_v . \tag{27a}$$

This expression simplifies to:

$$D_{opp} = \frac{2 \cdot k_0 \cdot DR_v \cdot N'}{V_v^2} \cdot I'(x) \cdot PPV \cdot DIST_L \cdot NSH_v \tag{27b}$$

where

D_{opp}	=	integrated dose to persons in vehicles traveling in opposite direction (person-rem)
k_0	=	point-source package shape factor (m^2)
DR_v	=	dose rate at 1 m from surface of vehicle (mrem/hr)
N'	=	one-way traffic count (average number of vehicles per hour in all lanes)
V_v	=	average velocity of all traffic (m/s)
$I'(x)$	=	dose integration function from Equation 26
PPV	=	vehicle occupancy (average number of persons per vehicle)
$DIST_L$	=	distance traveled on link L
NSH_v	=	number shipments of vehicle v.

The values of x in Table 3-3 are suggested values for common types of highway and rail links. The values are user-definable, however, and may be changed as necessary to appropriately model the user's problem. The primary distinction between freeways and the other two road classes is that interstates are built to engineering standards that prescribe minimum lane widths, etc., which translates into a somewhat larger value of x.

Table 3-3 Minimum Perpendicular Lane-Separation Distances by Link Type

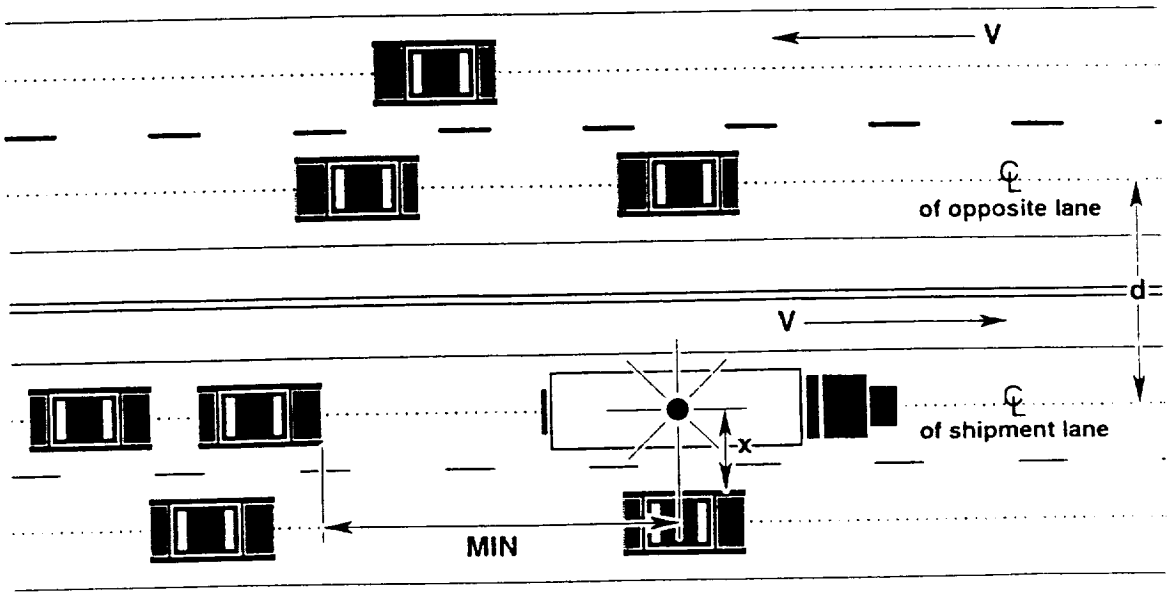
Type of Link	Value of x (meters)
Freeway (Interstate Highway)	15
Two-Lane Highway (e.g. State Hwy.)	3
City Street	3
Rail (double track)	3

By reference to Equation 24, a final expression for D_{opp} may be given as:

$$D = Q_2 \cdot k_0 \cdot DR_v \cdot NSH \cdot DIST_L \cdot PPV_L \cdot \frac{N'}{V_L^2} \cdot \left[\left(FG_v \cdot I'_G(x)\right) + \left(FN \cdot I'_N(x)\right)\right] \tag{28}$$

where all variables are as given in Equations (24) and (27) excepting the following:

Q_2	=	units conversion factor = 7.7E-08 rem-hr^2-m/mrem-sec^2-km.
I'_G	=	dose integration function for gamma radiation
I'_N	=	dose integration function for neutron radiation.



Legend

V - Traffic velocity
d - Distance fromRAM vehicle to traffic in opposite direction
x - Distance from RAM vehicle to passing vehicle
MIN - Minimum following distance

Figure 3-2 Illustration of Highway Traffic for Calculation of On-Link Dose

Dose to Persons Traveling in the Same Direction – Highway Mode Only

Trucks carrying radioactive material are modeled as moving at the same average velocity as the rest of the traffic. Thus, vehicles traveling in the same direction as the RAM shipment can be considered to be stationary with respect to the RAM vehicle and can be modeled as a linear continuum of vehicles beginning at some minimum distance beyond the RAM vehicle. The dose received by a person located at distance r from the shipment vehicle is computed by multiplying the dose rate from Equation 4 by the duration of exposure t (hr):

$$D_{sdir} = \frac{k_0 \cdot DR_v \cdot t}{r^2} \tag{29}$$

where all values are the same as in Equation 4 except for t, which is exposure time (hr).

For a given mode and link, the total exposure time t is given by the quotient of total distance and average velocity (V); total distance traveled is, in turn, the product of distance per shipment and number of shipments. Thus,

$$t = \frac{DIST_L \cdot NSH_L}{V_L} \tag{30}$$

People are modeled as being distributed uniformly among the vehicles with a linear population density given by (N'·PPV)/V. The dose to persons traveling in the same direction as the shipment is, therefore, the

product of the dose expression in Equation 29 and the linear population density (Equation 30) integrated from some minimum distance (min-sdir) to infinity:

$$D_{sdir} = 2 \cdot k_0 \cdot DR_v \cdot \left(\frac{N' \cdot PPV}{V}\right) \cdot \left(\frac{DIST \cdot NSH}{V}\right) \cdot \int_{min\text{-}sdir}^{\infty} \frac{\exp(-\mu r) B(\mu r)}{r^2} dr \tag{31}$$

where all values are the same as in Equations 29 and 30 except for the integral, which is the basic dose integration function for the RAM shipment. The factor of 2 in Equation 31 accounts for the fact that traffic is modeled as extended in two directions – both in front of and behind the RAM shipment.

In addition to persons in vehicles both in front of and behind the RAM shipment, the case of a passing vehicle is considered. The full value of the traffic count N′ is used in Equation 31 to estimate dose to the former. This in effect counts all vehicles in all lanes but treats them as though they were all in the same lane as the RAM shipment. The minimum exposure distance (min-sdir) depends on the average velocity, V, and therefore on the on-link population density, because the closest vehicle is modeled a being within 2 sec of travel of the RAM shipment. Thus, min-sdir (in meters) is given by the absolute value of 2V, where V is in units of m/sec. The average velocity is a user-defined input value and is entered in units of km/hr. RADTRAN 5 internally converts this value to m/sec. The integration in Equation 31 is performed with a Gaussian quadrature. Let the integral from Equation 31 be represented as Y_v. Then:

$$Y_v = \left[FG \cdot \int_{2V}^{\infty} \frac{e^{-\mu_G r} \cdot B_G(\mu r)}{r^2} dr\right] + \left[FN \cdot \int_{2V}^{\infty} \frac{e^{-\mu_N r} \cdot B_N(\mu r)}{r^2} dr\right] = \left[(FG \cdot P_{V,G}) + (FN \cdot P_{V,N})\right] \tag{32}$$

where

FG	=	fraction of DR_v that is gamma radiation
FN	=	fraction of DR_v that is neutron radiation
V	=	average velocity (m/s)
μ_G, μ_N	=	attenuation coefficients for gamma and neutron radiation (m^{-1})
$P_{V,G}$ or $P_{V,N}$	=	value of integral passed from Equation 31.

The value of P is determined as follows:

$$\text{If } \mu_S \neq 0;\ P_{v,S} = (a1 - \mu_S) \cdot E1_{(\mu_S \cdot 2V)} + e^{-\mu_S \cdot 2V} \cdot \left[\frac{1}{2V} + \left(\frac{a2_S}{\mu_S} + \frac{a3_S}{\mu_S^2} + \frac{2 \cdot a4_S}{\mu_S^3}\right) + 2V\left(\frac{a3_S}{\mu_S^2} + \frac{2 \cdot a4_S}{\mu_S^3}\right) + 2V^2\left[\frac{a4_S}{\mu_S}\right]\right]$$

or

$$\text{If } \mu_S = 0;\ P_{v,S} = \frac{1}{2V} \tag{33}$$

where

S	=	subscript for gamma (S = G) or neutron (S = N) radiation
E1	=	Sandia National Laboratories SLATEC math routine that computes the single-precision exponential integral for positive, single-precision argument ($\mu_S \cdot 2V$)
V	=	average velocity (m/sec)
2V	=	absolute value of minimum separation between vehicles (m)
μ_S	=	attenuation coefficient for gamma (S = G) or neutron (S = N) radiation (m^{-1})
$a1_S$,...$a4_S$	=	coefficients for gamma (S = G) or neutron (S =N) radiation.

By use of the same traffic characteristics as in the calculation of dose to persons traveling in the opposite direction and by incorporation of the results of this integration, the following expression is obtained for the dose received by persons traveling in the same direction as the shipment:

$$D_{sdir} = Q_2 \cdot k_0 \cdot DR_v \cdot \frac{N'_L}{V_L^2} \cdot PPV_L \cdot DIST_L \cdot NSH_v \cdot (F_1 + F_2) \tag{34}$$

where

Q_2	=	units conversion factor = 7.7E-08 rem-hr^2-m/mrem-sec^2-km
k_0	=	point-source shape factor (m^2)
DR	=	dose rate at 1 m for the surface of vehicle v (mrem/hr)
N'_L	=	one-way traffic count on link L (vehicles/hr)
V_L	=	average velocity on link L (m/sec)
PPV_L	=	vehicle occupancy on link L (persons/vehicle)
$DIST_L$	=	distance traveled on link L (km)
NSH_v	=	number of shipments of vehicle v
F_1, F_2	=	traffic factors defined below.

F_1 accounts for all vehicles except those passing the RAM shipment, while F_2 accounts for persons in vehicles in the passing lane immediately adjacent to the RAM shipment.

$$F_1 = 2Y_v V_L \tag{35a}$$

and

$$F_2 = \frac{1}{x} \cdot Y_v V_L \tag{35b}$$

where

x	=	minimum perpendicular distance to adjacent vehicle.

A dose is computed for each shipment and route segment (link) with Equation 34, and the results are summed over all shipments and links to obtain a total dose to persons traveling along the route in the same direction as the RAM shipment(s) being analyzed.

3.3.3 Dose to Airline Passengers – Passenger-Air Mode

The following equations are used to formulate dose to air passengers under normal conditions of transport. The formulation of the dose to air passengers is based in part on empirical data developed by Barker et al. (1974). In Barker's analysis, an empirical value of 3E-05 rem/hr/TI for air passengers was derived (where Barker's variable TI is the same as DR_p). Thus, the integrated dose formulation becomes

$$D_{airpass} = Q_3 \cdot k_p \cdot DR_v \cdot N_{pass} \cdot NSH \cdot \frac{DIST_L}{V_L} \tag{36}$$

where

$D_{airpass}$	=	integrated population dose to air passengers (person-rem)
Q_3	=	units conversion factor = 0.28 m-hr/km-sec
k_p	=	empirical dose-rate conversion factor (3E-05 rem/hr/TI)
DR_v	=	dose rate at 1 m from surface of shipment on aircraft v (mrem/hr)
N_{pass}	=	number of air passengers on board
NSH_v	=	number of shipments by aircraft v
$DIST_L$	=	distance traveled on link L (km)
V_L	=	average velocity on link L (m/sec).

3.4 *Dose to Population at Shipment Stops – All Modes*

If a transport conveyance stops for a crew change, passenger transfer, crew meals, refueling, storage, inspection, or any other cause, then persons at or near the stop point can be exposed to radiation from the shipment. RADTRAN 5 presents the user with a choice of two distinct ways to represent persons at stops.

3.4.1 Option 1 – Average-Distance Method

The first option is a simple model based on the number of nearby persons and a specified average distance. This method has been used to model truck stops (Madsen and Wilmot, 1983) and intermodal transfers at maritime ports (Neuhauser and Weiner, 1992). The equation for integrated population dose (D) for Option 1 is:

$$D = Q_4 \cdot DR_v \cdot NSH_v \cdot T_{st} \cdot P_{st} \cdot SF_{st} \cdot \left[\left(FG_v \cdot TR_{G,r_{st}}\right) + \left(FN_v \cdot TR_{N,r_{st}}\right)\right] \cdot \left\{ \begin{array}{l} \dfrac{k_{0_v}}{r_{st}^2}\text{(point source)} \\ or\ \dfrac{k'_{0_v}}{r_{st}}\text{(line source)} \end{array} \right\} \tag{37}$$

where

Q_4	=	units conversion factor = 1.0E+03 rem/mrem
k_{0_v}	=	point-source conveyance shape factor (m^2)
k'_{0_v}	=	line-source conveyance shape factor (m)
DR_v	=	conveyance dose rate at 1 m from surface (mrem/hr)
NSH_v	=	number of shipments
T_{st}	=	average stop time (hr)
P_{st}	=	average number of exposed persons
SF_{st}	=	shielding factor for stop population
FG_v	=	fraction of vehicle dose rate from gamma radiation at origin point
FN_v	=	fraction of neutron dose rate from neutron radiation at origin point
TR_G	=	term for gamma radiation source strength at distance r
TR_N	=	term for neutron radiation source strength at distance r
r_{st}	=	average radial source-to-receptor distance at stops (m).

Ostmeyer (1986a) derived a shielding factor of 0.1 for rail stops, which reflects gamma attenuation by other railcars and structures in classification yards. The source-strength terms, TR_G and TR_N, used in Equation 37 were derived from Equations 17 and 18. Their expanded form can be written as follows:

$$TR_G = \left[e^{-(\mu_G \cdot r)} \cdot \left[1 + a1_G \cdot r + a2_G \cdot r^2 + a3_G \cdot r^3 + a4_G \cdot r^4\right]\right] \tag{38a}$$

and

$$TR_N = \left[e^{-(\mu_N \cdot r)} \cdot \left[1 + a1_N \cdot r + a2_N \cdot r^2 + a3_N \cdot r^3 + a4_N \cdot r^4\right]\right] \tag{38b}$$

where

μ	=	attenuation coefficient for gamma (μ_G) or neutron (μ_N) radiation (m^{-1})
r	=	radial distance from source (m)
a1...a4	=	coefficients for gamma or neutron radiation.

Option 1 may be used for all transportation modes, although Option 2 is preferred for rail-mode calculations (see below).

3.4.2 Option 2. Annular-Area Method

In this option, dose is calculated for a population density within an annular area. This alternative is preferred for railyards and similar situations (Ostmeyer, 1986a). Many rail stops occur in railyards, and the vast majority of total train stop time occurs in railyards. In Option 2, the population in and near a railyard is modeled as a uniformly distributed population around the rail shipment; dose is then integrated over this population. Doses to railyard personnel who are involved in the inspection and maintenance of railcars (i.e., persons who are exposed at short distances from the shipment) are dealt with separately. Data developed by Griego, Smith and Neuhauser (1996) also allow Option 2 to be applied to truck stops.

The first step in calculation of stop dose with Option 2 involves integration over an annular area from radial distance x_{min} to some radial distance x_{max} while accounting for buildup and attenuation. These values will be used to modify the initial source strength (DR_v). This term (IR_S) is evaluated for gamma (S = G) and neutron (S = N) radiation as follows:

$$IR_S(x) = \left[\left(\frac{a_{1_S}}{\mu_S} + \frac{a_{2_S}}{\mu_S}(\mu_S x + 1) + a_{3_S}\left(\frac{x}{\mu_S} + \frac{2x}{\mu_S^2} + \frac{2}{\mu_S^3} \right) + a_{4_S}\left(\frac{x^3}{\mu_S} + \frac{3x^2}{\mu_S^2} + \frac{6x}{\mu_S^3} + \frac{6}{\mu_S^4} \right) \right) e^{-(\mu_S \cdot x)} \right] + E1(\mu_S \cdot x) \tag{39}$$

where

μ_S	=	attenuation coefficients for gamma (S = G) or neutron (S = N) radiation in air (m^{-1})
$a_1 \ldots a_4$	=	curve-fitting coefficients (see Equations 17 and 18) for gamma (S = G) or neutron (S = N)
x	=	radial distance from source to receptor (m)
E1	=	SLATEC routine that computes the single precision exponential integral for positive, single precision argument ($\mu_S \cdot x$).

The second step is to subtract the evaluation of the integral at x_{max} from the evaluation of the integral at x_{min}, where max and min are the maximum and minimum radii, respectively, of the annular area. This is accomplished as follows:

$$C_S = \{\mu_S \neq 0; [IR_S(\min) - IR_S(\max)] \text{ or } \mu_S = 0; \ln\left(\frac{\max}{\min}\right) = \ln(\max) - \ln(\min) \tag{40}$$

where

C_S	=	source-strength modifier over defined interval
μ_S	=	attenuation coefficient for gamma (μ_G) or neutron (μ_N) radiation (m^{-1})
IR_S	=	value from Equation 39
min	=	x_{min} = minimum value of radial distance from source (inner radius of annulus) (m)
max	=	x_{max} = maximum value of radial distance from source (outer radius of annulus) (m)

When the values C_G and C_n are used in place of TR_G and TR_N from Equation 38, the Option 2 stop-dose equation results, as is shown:

$$D_{stop} = 2\pi \cdot Q_4 \cdot k_{0_v} \cdot DR_v \cdot PD_{st} \cdot T_{st} \cdot NSH_v \cdot SF_{st} \cdot [FG(C_G) + FN(C_N)] \tag{41}$$

where

Q_4	=	units conversion factor = 1.0E-03 rem/mrem
k_{0_v}	=	point-source shape factor for vehicle v (m^2)
DR_v	=	vehicle dose rate at 1 m from surface (mrem/hr)
PD_{st}	=	population density of annular area at stop (persons/km^2)
T_{st}	=	duration of stop (hr)
NSH_v	=	number of shipments by vehicle v
SF_{st}	=	shielding factor at stop
FG	=	fraction of DR_v that is gamma radiation
FN	=	fraction of DR_v that is neutron radiation.

Evaluation for a line source is identical to that shown in Equation 41 except that the line-source shape factor k'_{0_v} is substituted for the point-source shape factor.

3.4.3 Use of Stop Model to Estimate Storage-Related Dose

Unlike its predecessors, RADTRAN 5 does not contain a separate mathematical model for storage dose. A period of storage that may occur during the course of transportation is in fact simply a prolonged stop. Either of the two stop-dose models described above (Sections 3.4.1 and 3.4.2) may be used to estimate dose to storage warehouse personnel. With each option, a shielding factor may be entered to account for shielding by other packages in storage in the same warehouse, and by other barriers, if any. No value can be recommended for the shielding factor. The user may estimate a value from location and shipment specific data, if available; otherwise, the shielding factor may be set to 1.0 (no shielding).

3.5 Dose to Workers

3.5.1 Dose to Crew Members – Highway and Air Modes

This section considers only crew members on conveyances while the shipment is en route. Other transportation workers, such as handlers and inspectors, are considered in the following sections. Since crewmembers remain stationary with respect to the package(s) on a vehicle during all or most of a trip, the dose calculation is similar to that for a stop. However, the position of crewmembers with respect to a package may dictate that a different characteristic package dimension should be used. This is the case, for example, with truck transportation of spent fuel; the package dimension most appropriate for calculation of crew dose is cask diameter rather than cask length.

The calculation of dose to crewmembers is analogous to that given in Section 3.4. The surface of the package or "vehicle" (e.g., end of semi-trailer) nearest to the crew area is modeled as a point source with the following situation-specific attributes:

- $k_{0,end}$, calculated for characteristic dimension, $d_{e,end}$;
- source-to-worker distance, r_{end}.
- shielding factor to account for shielded crew compartments.

Thus,

$$D_{crew} = Q_1 \cdot \frac{k_{0,end}}{r_{end}^2} \cdot DR_v \cdot NSH_v \cdot N_{crew} \cdot \frac{1}{V_L} \cdot DIST_L \cdot CSF_v \cdot \left[\left(FG_v \cdot TR_{G,r}\right) + \left(FN_v \cdot TR_{N,r}\right)\right] \tag{42}$$

where

D_{crew}	=	integrated dose to crew (person-rem)
Q_1	=	units conversion factor (2.8E+10 rem-m-hr/mrem-km-sec)

$k_{o,end}$	=	"crew-view" point-source package shape factor for $d_{c,end}$, where $d_{c,end}$ is the characteristic dimension of the package surface nearest to the crew (m^2)
r_{end}		source-to-worker distance (m)
DR_v	=	vehicle dose rate at 1 m from surface (mrem/hr)
NSH	=	number of shipments
N_{crew}	=	number of crew members
V_L	=	average velocity on link L
$DIST_L$	=	distance traveled on link L
CSF_v	=	crew shielding factor for vehicle v
FG_v	=	fraction of vehicle dose rate from gamma radiation
FN_v	=	fraction of vehicle dose rate from neutron radiation
$TR_{G,r}$	=	dose-distance relationship factor for gamma radiation
$TR_{N,r}$	=	dose-distance relationship factor for neutron radiation.

3.5.2 Dose to Workers – Rail Mode

In-Transit Doses that are not Explicitly Modeled

RADTRAN 5 does not contain an explicit model for calculating dose to the operating crew of a train while in transit because of:

1. The massive amount of shielding provided by engines,
2. The shielding provided by the intervening buffer cars required by regulation, and
3. The relatively large separation distances between a RAM-carrying railcar and the engine crew.

Analysts with a need to examine such doses may treat the crew as persons at a stop with the stop time set equal to the time in transit of the train and the distance set equal to the crew-to-railcar distance. Accounting for shielding, perhaps by hand calculation, is necessary, however, to generate a realistic dose estimate.

Doses to Workers in Rail Yards

Doses are estimated for rail workers who are in close proximity to the casks during inspection and classification of cars at rail yards (Ostmeyer, 1986a). Two cases are discussed: general freight and dedicated train shipment of radioactive material.

Because this dose is estimated for an inspector, classifier or other worker who is close to the railcars, which are large with respect to the worker, line-source geometry applies. The dose received by a worker for each classification and/or inspection operation is given by

$$D_{rail\ worker} = Q_1 \cdot k_0' \cdot DR_v \cdot NSH_v \cdot [(FG_v \cdot R_G) + (FN_v \cdot R_N)] \tag{43}$$

where

$D_{railworker}$	=	rail worker dose (person-rem)
Q_1	=	units conversion factor (2.8E+10 rem-m-hr/mrem-km-sec)
k_o'	=	line-source rail-car shape factor (m)
DR_v	=	dose rate at 1 m of rail car v (mrem/hr)
NSH_v	=	number of shipments by rail car v
FG	=	fraction of rail-car dose rate from gamma radiation
FN	=	fraction of rail-car dose rate from neutron radiation

and

$$R_S = \begin{cases} TR_{S,3.0} \cdot b_1 + TR_{S,4.0} \cdot b_2 + TR_{S,5.0} \cdot b_3 + TR_{S,7.0} \cdot b_4 + TR_{S,8.0} \cdot b_5 + TR_{S,9.0} \cdot b_6 + TR_{S,20.0} \cdot b_7 : \text{if general freight} \\ TR_{S,3.0} \cdot b_8 + TR_{S,4.0} \cdot b_9 + TR_{S,8.0} \cdot b_{10} + TR_{S,9.0} \cdot b_{11} : \text{if dedicated train} \end{cases}$$

where S is G (gamma) or N (neutron) and b_n is an exposure factor (person-hr/m).

Values of b_n are calculated from data given in Wooden (1986) (see Appendix B). The total dose to workers during classification and inspection in rail yards (D_{CL}) is given by

$$D_{CL} = D_{\text{rail worker}} \cdot NCL \tag{44}$$

where

$D_{\text{rail worker}}$ = dose to rail worker per classification or inspection from Equation 43

NCL = number of classifications or inspections per trip

The total number of classifications per trip (NCL) is determined as follows

$$NCL = DIC + \sum^{\text{all links}} (DDC \cdot DIST_L) \tag{45}$$

where

DIC = the number of distance-independent classifications per trip

DDC = the number of distance-dependent classifications per km

$DIST_L$ = length of link (km)

DIC represents the inspections that occur regardless of total trip distance. That number is determined by railroad company practices and is usually equal to two – one at the beginning and one at the end of each trip (Wooden, 1986). Federal regulations (49 CFR) require that railcars carrying hazardous material, including radioactive material, be inspected at interchanges. The number of interchanges per link is dependent on the length of the link ($DIST_L$). The recommended value for DIC is 2; the recommended value for DDC is derived from Ostmeyer (1986) and is 0.018 inspections per km.

3.5.3 Dose to Cargo Inspectors on Waterborne Vessels

As in the rail case, crewmembers aboard waterborne vessels are shielded by ship structures and generally are separated from the source locations (usually ship holds) by large distances. Therefore, no general crew dose is calculated in RADTRAN 5 for these modes of transport. However, periodic inspections of the packages are required. Since radioactive material must be physically separated from other types of cargo, the vehicle subscript (v) applies to a cargo hold of a ship or a deck stowage area of a barge rather than to the entire vessel. The inspector is modeled as being an average of 2 m away from the package or package array during the inspection, which requires the package or package array to be treated as a line source for all but very small packages. Since the latter are seldom, if ever, shipped by waterborne modes, the following relationship applies to all cases.

$$\frac{1\,\text{person}}{\text{day}} \cdot 1\,\text{min} \cdot \frac{1}{2\,\text{m}} = 0.5\,\frac{\text{person - min}}{\text{m - day}} \tag{46}$$

The integrated dose to cargo inspectors aboard waterborne vessels is given on a per-cargo-hold basis by

$$D_{\text{cargo inspector}} = 0.5 \cdot Q_5 \cdot k'_{0,\text{end}} \cdot \frac{DR_v \cdot DIST_L \cdot NSH_v}{V_L} \cdot CSF_v \cdot [(FG_v \cdot TR_G) + (FN_v \cdot TR_N)] \tag{47}$$

where

0.5	=	value from Equation 46 (person-min/m-day)
Q_5	=	units conversion factor = 2.0E-07 m-hr-day/km-sec-min
$k'_{0,end}$	=	"crew-view" line-source shape factor (m)
DR_v	=	cargo-hold dose rate at 1 m from surface (mrem/hr)
$DIST_L$	=	distance traveled on link L (km)
NSH_v	=	number of shipments by conveyance v (cargo-hold)
V_L	=	average velocity on link L (m/sec)
CSF_v	=	crew shielding factor for cargo hold v
FG_v	=	fraction of cargo-hold dose rate from gamma radiation
FN_v	=	fraction of cargo-hold dose rate from neutron radiation
$TR_{G,2}$	=	dose-distance relationship factor at 2 m for gamma radiation
$TR_{N,2}$	=	dose-distance relationship factor at 2 m for neutron radiation.

The choice of shape factor deserves discussion. Equation 47 uses $k'_{0,end}$, a line-source package shape factor, which is calculated with a characteristic package dimension appropriate to the "view" of a worker. The latter can vary from being equal to that for persons farther from the shipment (for a cubical or spherical package) to being less than one-half of the dimension used to develop a k_0 for the general public (for a long cylindrical package such as a spent-fuel cask). The actual view(s) presented to a ship-hold inspector depends on package shape, ship size, and stowage practices. The user is cautioned to carefully select an "inspector-view" package dimension when entering data for a RADTRAN analysis of transportation by water mode. In most cases the crew-shielding factor (CSF) will be 1.0, but the user has the option of altering the parameter in cases where inspectors are partially shielded by intervening structures (e.g., a cask inside a steel transportainer).

3.5.4 Dose to Flight Attendants – Passenger Air Mode

The following equations are used to formulate dose to flight attendants under normal conditions of transport. The flight-attendant dose should be added to the crew dose (pilot, co-pilot and/or navigator) to give total occupational dose for passenger-air mode. The formulation of the dose to flight attendants is based in part on empirical data developed by Barker et al. (1974). In Barker's analysis, an empirical value of 3E-05 rem/hr/TI for flight attendants was derived (where Barker's term, TI, is synonymous with DR_v as used here). Thus, the integrated dose formulation becomes

$$D_{air} = Q_3 \cdot k_p \cdot DR_v \cdot N_{flatt} \cdot NSH_v \cdot \frac{DIST_L}{V_L} \tag{48}$$

where

D_{air}	=	integrated population dose to flight attendants (person-rem)
Q_3	=	units conversion factor = 0.28 m-hr/km-sec
k_p	=	empirical dose-rate conversion factor (3E-05 rem/hr/DR_p)
DR_v	=	dose rate at 1 m from shipment surface in cargo hold of aircraft (mrem/hr)
N_{flatt}	=	number flight attendants on board
NSH_v	=	number of shipments by aircraft v
$DIST_L$	=	distance traveled on link L (km)
V_L	=	average velocity on link L (m/sec)

3.5.5 Dose to Handlers

Packages are handled during transportation primarily at intermodal transfers and during trips involving multiple deliveries (e.g., a van carrying many small packages of radiopharmaceuticals from a central

distribution point to several hospitals in a city). Handling is defined to include all operations concerned with the following:

- transfer from one mode to another;
- transfer from the originator's shipping dock or other facility to the first conveyance;
- transfer from the final conveyance to the destination shipping dock or other facility.

To evaluate dose to package handlers, packages are divided into two groups according to their size and the equipment necessary to move them. The two basic types are:

- small packages that are readily manipulated by a single person;
- all other packages (intermediate to large sizes).

To discern which type should be indicated, the input value for package size, d_p, is compared with a package-threshold value (SMALLPKG). If SMALLPKG is not exceeded, then the package is of the first type; if SMALLPKG is exceeded, then the package is of the second type. The recommended value for SMALLPKG is 0.5 m. Although it is unlikely that this value will need to be altered, the user may do so.

Small Packages ($d_p \leq$ SMALLPKG)

Shapiro (1977) concludes that the average dose received by workers handling small packages of radioactive material is 2.5E-04 rem/handling/TI (where Shapiro's TI is the same as DR_p). The absorbed dose per handling to handlers of small packages is given by:

$$D_{Hsmall} = k_H \cdot DR_p \cdot PPS \cdot NSH_v \cdot \left[\left(FG_p \cdot TR_{G,d_H}\right) + \left(FN_p \cdot TR_{N,d_H}\right)\right] \tag{49}$$

where

D_{Hsmall}	=	integrated dose to handlers of small packages (person-rem)
k_H	=	handling-to-dose conversion factor for small packages = 2.5E-04 rem/handling/DR_p
DR_p	=	package dose rate at 1 m from surface (mrem/hr)
PPS	=	number of packages per shipment
NSH_v	=	number of shipments by vehicle v
FG_v	=	fraction of cargo-hold dose rate from gamma radiation
FN_v	=	fraction of cargo-hold dose rate from neutron radiation
$TR_{G,d}$	=	dose-distance relationship factor at distance d for gamma radiation
$TR_{N,d}$	=	dose-distance relationship factor at distance d for neutron radiation
d_H	=	average package-to-handler distance (m).

Point-Source for Intermediate- and Large-Sized Packages ($d_p >$ SMALLPKG)

This calculation is used when the package-to-handler distance is greater than 2 times the characteristic package dimension. Handling of intermediate-sized packages such as 55-gal drums or large crates may require heavy equipment such as fork lifts or power assists and several people working simultaneously. The package is modeled as being stationary with respect to the handler(s). This situation is similar to the stop-dose calculation in that a certain number of persons are modeled as being at a fixed distance from the package for a certain period of time:

$$D_H = \frac{Q_4 \cdot k_0 \cdot DR_p \cdot PPS}{d_H^2} \cdot T_H \cdot PPH \cdot NSH_v \cdot \left[\left(FG_v \cdot TR_{G,d_H}\right) + \left(FN_v \cdot TR_{N,d_H}\right)\right] \tag{50}$$

where

D_H	=	integrated dose to handlers of medium and large packages (person-rem)

Q_4	=	units conversion factor = 1.0E-03 rem/mrem
k_0	=	point-source shape factor (m^2)
DR_p	=	package dose rate at 1 m from package surface (mrem/hr)
T_H	=	average exposure time of handlers (hr)
PPS	-	number of packages per shipment
d_H	=	average package-to-handler distance (m)
NSH_v	=	number of shipments of vehicle v
FG_v	=	fraction of cargo-hold dose rate from gamma radiation
FN_v	=	fraction of cargo-hold dose rate from neutron radiation
$TR_{G,dH}$	=	dose-distance relationship factor at distance d_H for gamma radiation
$TR_{N,dH}$	=	dose-distance relationship factor at distance d_H for neutron radiation.

Line-Source Calculation for Intermediate- and Large-Sized Packages (d_p > SMALLPKG)

This calculation is used when the package-to-handler distance is less than twice the characteristic package dimension. When radiological inspection, the attachment/detachment of rigging equipment, etc. require inspectors and/or handlers to closely approach the package, a point-source geometry is inappropriate. Line-source geometry is used instead (Weiner and Neuhauser, 1992). Thus,

$$D_{Hline} = Q_4 \cdot \frac{k_0' \cdot DR_p \cdot PPS_v}{d_H} \cdot T_H \cdot PPH \cdot NSH_v \cdot \left[\left(FG_v \cdot TR_{G,d_H}\right) + \left(FN_v \cdot TR_{N,d_H}\right)\right] \tag{51}$$

where all parameters are the same as in Equation 50 except that k_0 is replaced by k_0' and the denominator is d_H rather than d_H^2.

4 ATMOSPHERIC DISPERSION

An accident involving a shipment of radioactive material does not pose a hazard beyond the immediate vicinity of the accident unless material is released from the package(s) in a dispersible form. Atmospheric dispersion of aerosols and gases (dispersible forms) is modeled in RADTRAN 5. Principles of atmospheric dispersion are summarized in this chapter. Consequences of dispersal are evaluated in Chapter 5.

4.1 Basic Principles of Atmospheric Dispersion

Materials released into the air in particulate or gaseous form at the scene of an accident are dispersed as they are transported downwind, and diffuse vertically and laterally (crosswind) according to the degree of turbulence in the atmosphere. Although other representations are possible, most commonly used mathematical representations of atmospheric dispersion are based on a Gaussian plume model, developed by Pasquill (1961), in which gases or particles released into the atmosphere and dispersed exhibit ideal gas behavior. The principles on which the model is based are:

- The predominant force in plume transport is the wind; i.e., gases, aerosols, and particles dispersed in the air move predominantly downwind.
- The greatest concentration of material in a plume is along the plume centerline.
- Aerosols, gases, and other materials in a plume diffuse spontaneously from regions of higher concentration to regions of lower concentration.

In Gaussian models for a "puff" release (i.e., for an idealized instantaneous, perfectly spherical release), the concentration of the material in the puff has a normal distribution along the two axes perpendicular to wind direction (Figure 4-1). With few exceptions, source clouds for releases associated with transportation accidents should be modeled as puff releases. Unless a fire or other heat source lofts released material more than 10 meters, releases from transportation accidents occur at ground level and should be modeled accordingly. Source clouds for severe fires that might loft material above an accident site are sometimes modeled as cylinders (e.g., as done in the DIFOUT dispersion code; Luna and Church, 1969). The Gaussian models for continuous releases such as those from smokestacks (elevated releases) or pipeline leaks (ground-level releases) are inappropriate for use in transportation risk analysis.

Persons in the path of such an aerosol plume inhale material as the plume passes, and inhaled particles are deposited in their lungs in proportion to the time-integrated concentration [denoted by X (Greek letter *chi*) and having units of Ci-sec/m^3 or Sv-sec/m^3] of the aerosol. For radioactive materials, the value of X at any point downwind of the release location is directly proportional to the total activity of the released aerosol species [Q, with units of activity; curies (Ci) in RADTRAN 5] and is inversely proportional to the wind speed (u with units of m/sec). One way of describing the behavior of X as one moves away from a release location is to tabulate values of the dilution factor X/Q (referred to as "chi over Q") for a given wind speed versus downwind distance or versus isopleth area. Isopleths, or curves representing constant concentrations, are areas bounded by lines of equal X/Q. Graphical display of isopleths is essentially a "plan view" of downwind dispersion.

A puff release becomes increasingly diluted as it travels downwind. Therefore, isopleths with larger values of X/Q are nested within isopleths with smaller X/Q values (Figure 4-2). In the case of an elevated release, the area of highest X/Q may be displaced some distance downwind. The shapes of the isopleths vary with atmospheric stability and other factors but are usually elliptical (see Section 4.2.1). Atmospheric stability,

as classified by Pasquill, ranges from Highly Stratified (Class A) and Extremely Unstable (Class B) to Moderately Stable (Class F) (Pasquill, 1961).

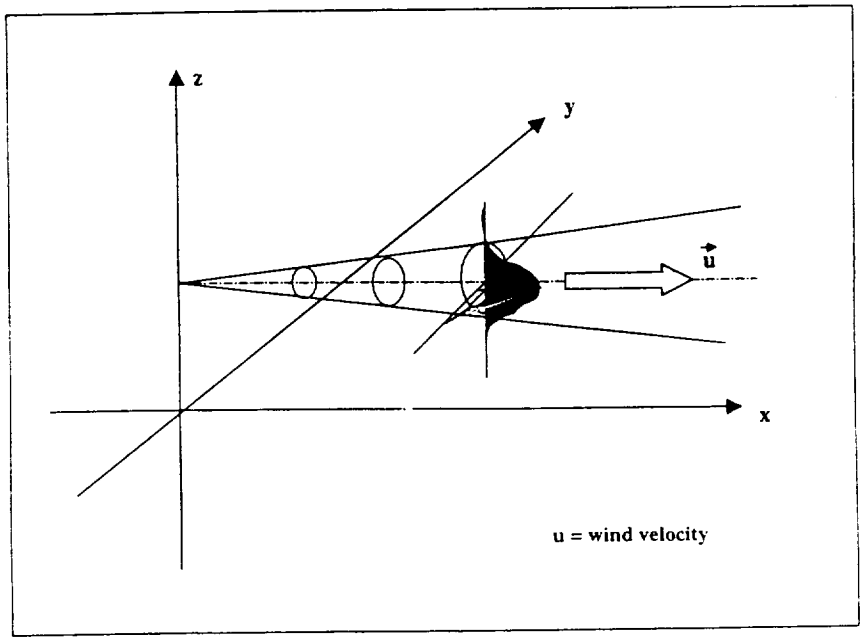


Figure 4-1 Diagram of Gaussian dispersion

Table 4-1 Pasquill Stability Classes as related to solar radiation and wind speed.

Surface wind speed at 10 m (m/sec)	DAY			NIGHT	
	Incoming Solar Radiation			Cloud Cover	
	Strong	Moderate	Slight	Overcast	Clear
<2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Each atmospheric stability class is characterized by two meteorological constants (σ_y and σ_z) which are the standard deviations of the Gaussian distributions that describe the lateral and vertical dispersions, respectively, of the plume under these atmospheric conditions. For a "puff" release, $\sigma_y = \sigma_z$. The shape of the Gaussian distribution describing the concentration of material as the cloud travels downwind also changes with atmospheric stability, becoming more circular as conditions become more stable. In general, Classes A, E, and F are compatible with very light winds, and classes B, C, and D, with moderate to high

wind speeds. This subject is reviewed by Turner (1977) and Till and Meyer (1983). The relationship between stability class and wind speed may be described by Table 4-1 (from Turner, 1960).

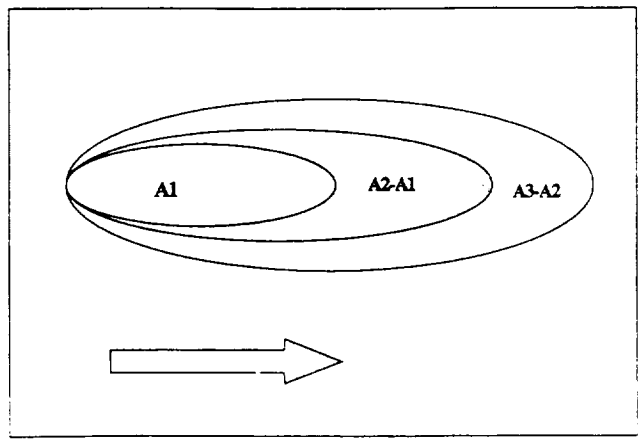


Figure 4-2 Typical Plume Footprint. The arrow represents wind direction. The shaded areas are, respectively, the area of the smallest isopleth (ellipse A_1), the area of the second isopleth (ellipse A_2 – ellipse A_1), and the area of the third isopleth (ellipse A_3 – ellipse A_2).

4.1.1 Atmospheric Dispersion Inputs to RADTRAN 5

The user may enter isopleth-related data for atmospheric dispersion into RADTRAN 5 by two methods: the single-table method and the stability-category method.

Method 1 - Single-Table Method

This method uses a single table of average or typical data (isopleth areas and X/Q values). In RADTRAN 5, a table of average or typical dispersion data for the U.S. is made available to users as a courtesy for their use in the absence of other data (Table 4-2). The X/Q values in this table are for a unit source (Q = 1 Ci). Alternatively, the user may opt to fill this table with data generated by any Gaussian dispersion model or code. Any number of isopleth areas, from a minimum of 2 up to a maximum of 30, may be used.

Several conditions must be taken into account when obtaining data to replace the national average data provided. ***Releases should be modeled as being instantaneous.*** Releases associated with impact accidents generally occur over a very short period of time. Historical highway accidents involving severe fires (**not** smoldering tires or other trivial fires) have seldom lasted more than one hour. For example, peak flame temperatures were experienced in the Caldecott Tunnel fire for less than 40 minutes (Fischer et al., 1987, p. 9-16). A fire this long would have had no effect on a Type B cask; atmospheric dispersion from Type A packages exposed to a similar fire generally would not continue after the fire was put out or was allowed to burn itself out.

Releases also are generally modeled as occurring at ground level. ***A ground-level release yields higher overall downwind concentrations and ground depositions than an otherwise comparable elevated release.*** Extremely severe fires are almost always accompanied by "thermal loft," which causes the initial radionuclide concentration in the source cloud to be *more* dilute than it would be if the same amount of material were released and dispersed without thermal loft (i.e., in a smaller source cloud at ground level). On the other hand, where there is lofting, the maximum ground-level aerosol concentration, while lower than the maximum for the same release at ground level, will occur at some distance downwind from the accident site.

Using a point source (i.e., an infinitely small source cloud) to model real releases gives erroneous and excessively high downwind concentrations for the innermost isopleths in particular. ***If the user generates new X/Q values with a dispersion code, the source cloud (a "puff" or sphere) must have some finite initial dimension***, but for conservatism is usually assigned a small diameter. The pre-calculated data included in the single-table option in RADTRAN 5 are for a "puff" that is 10-m in diameter (Table 4-2).

Finally, if X/Q values generated by another code are entered by the user, they should not have been depleted. That is, deposition of material out of the plume onto the ground should not already have been calculated. Deposition is calculated in RADTRAN 5 as described in Section 4.3.

Table 4-2 Dilution factors in Ci-sec/m^3 for national average weather- may be used with Method 1

Area (m^2)	Dilution Factor (Ci-sec/m^3)
4.59E+02	3.42E-03
1.53E+03	1.72E-03
3.94E+03	8.58E-04
1.25E+04	3.42E-04
3.04E+04	1.72E-04
6.85E+04	8.58E-05
1.76E+05	3.42E-05
4.45E+05	1.72E-05
8.59E+05	8.58E-06
2.55E+06	3.42E-06
4.45E+06	1.72E-06
1.03E+07	8.58E-07
2.16E+07	3.42E-07
5.52E+07	1.72E-07
1.77E+08	8.58E-08
4.89E+08	5.42E-08
8.12E+08	4.30E-08
1.35E+09	3.42E-08

Method 2 - Stability-Category Method

The stability category method involves use of default data. RADTRAN 5 contains tables of values for X/Q and isopleth areas for the six Pasquill stability classes (Table 4-3). The values, as in the single-table option, are for an instantaneous ground-level release and a small-diameter (10 m) source cloud. Furthermore, the values were determined from calculations for a single constant wind speed in each class.

Lower wind speeds result in less dispersion and are therefore conservative, in that, they yield larger values for downwind concentration than would higher wind speeds. The wind speeds in Table 4-3, suggested by Luna and Church (1972), are used to pre-calculated the values in the data tables available to RADTRAN users because they correspond to the lowest wind speed that is typical or representative of each class.

Table 4-3. Minimum Wind Speed by Stability Class for Method 2

Stability Class	Wind Speed (m/sec)
A	1
B	2
C	3
D	4
E	2.5
F	1

The only user input required by this option is the frequency of occurrence of each stability class. These data are recorded by most weather stations in the United States. A limitation of this option is that frequencies of occurrence of the stability classes vary considerably from one location to another. Furthermore, frequency data from two nearby locations can not be used to interpolate reliable values for an intervening highway segment or other link. Data from a weather station in a valley and from another weather station on a nearby elevation (e.g., mesa or mountainous location) *cannot* be averaged, for example, to give acceptable data for a route running part way up the slope from the valley. Thus, stability class frequency data of acceptable quality are often unavailable for particular highway and railway segments.

A limitation that applies to both methods is that the atmospheric dispersion models on which they are based contain idealized representations of topography and wind behavior. A strength of both options is that the idealizations are generally conservative for dose calculations. An additional contributor to the overall conservatism of the calculation is that simple Gaussian plume dispersion calculation neglects factors such as surface roughness and shifting wind directions that promote rapid dilution of material entrained in a plume.

The data in Tables 4-4 and 4-5 represent dilution factors, isopleth or "footprint" areas, and centerline downwind distances for the six Pasquill meteorological stability classes.

4.1.2 Other Types of Dispersion

Dispersion associated with release into oceans or other bodies of water is not modeled in RADTRAN 5. In cases where the aquatic dispersion might play a significant role in post-accident consequences, the user should supplement his or her analysis with an analysis of aquatic dispersion. A compartment model such as MARINRAD (Ensminger, Koplik and Nalbandian, 1987) is most often used for this type of analysis.

Table 4-4. Dilution factors in Ci-sec/m³ for the six Pasquill meteorological categories used in Method 2

AREA	PASQUILL CATEGORY					
(m^2)	A	B	C	D	E	F
4.59E+02	6.00E-03	4.00E-03	4.00E-03	4.30E-03	9.60E-03	6.20E-02
1.53E+03	1.70E-03	1.30E-03	1.10E-03	1.30E-03	3.20E-03	1.80E-02
3.94E+03	8.40E-04	5.50E-04	5.70E-04	6.50E-04	1.60E-03	8.40E-03
1.25E+04	1.70E-04	1.30E-04	1.30E-04	1.80E-04	4.00E-04	2.00E-03
3.04E+04	7.80E-05	6.00E-05	6.70E-05	9.50E-05	2.10E-04	9.20E-04
6.85E+04	2.80E-05	2.70E-05	3.00E-05	4.30E-05	1.40E-04	4.40E-04
1.76E+05	8.00E-06	1.00E-05	1.00E-05	1.80E-05	4.40E-05	2.00E-04
4.45E+05	2.20E-06	3.50E-06	5.00E-06	8.50E-06	2.10E-05	1.00E-04
8.59E+05	9.00E-07	1.60E-06	2.80E-06	5.00E-06	1.20E-05	6.20E-05
2.55E+06	1.40E-07	4.10E-07	1.00E-06	1.90E-06	4.80E-06	2.60E-05
4.45E+06	7.00E-08	2.20E-07	6.00E-07	1.30E-06	3.60E-06	1.90E-05
1.03E+07	1.10E-08	5.00E-08	1.70E-07	4.00E-07	1.40E-06	8.40E-06
2.16E+07	7.76E-09	3.20E-08	1.30E-07	3.00E-07	1.20E-06	7.00E-06
5.52E+07	2.24E-09	1.10E-08	5.70E-08	1.50E-07	6.00E-07	4.00E-06
1.77E+08	4.50E-10	2.50E-09	1.70E-08	5.50E-08	2.80E-07	2.00E-06
4.89E+08	1.13E-10	7.24E-10	6.32E-09	2.41E-08	1.38E-07	1.09E-06
8.12E+08	5.96E-11	4.09E-10	4.01E-09	1.65E-08	9.97E-08	8.22E-07
1.35E+09	2.76E-11	2.08E-10	2.33E-09	1.05E-08	6.77E-08	5.89E-07

Table 4-5. Areas and centerline distances for the six Pasquill meteorological classes used in Method 2

AREA	CENTERLINE DISTANCES (m)					
(m^2)	A	B	C	D	E	F
4.59E+02	2.36E+01	2.99E+01	3.34E+01	3.65E+01	4.19E+01	2.47E+01
1.53E+03	4.52E+01	5.41E+01	6.83E+01	7.66E+01	8.38E+01	6.00E+01
3.94E+03	6.49E+01	8.51E+01	9.84E+01	1.18E+02	1.30E+02	1.04E+02
1.25E+04	1.48E+02	1.82E+02	2.23E+02	2.61E+02	3.12E+02	2.90E+02
3.04E+04	2.21E+02	2.74E+02	3.22E+02	3.87E+02	4.68E+02	5.05E+02
6.85E+04	3.74E+02	4.17E+02	5.03E+02	6.33E+02	6.05E+02	8.57E+02
1.76E+05	5.89E+02	7.04E+02	9.25E+02	1.09E+03	1.26E+03	1.51E+03
4.45E+05	8.99E+02	1.23E+03	1.36E+03	1.73E+03	2.00E+03	2.48E+03
8.59E+05	1.21E+03	1.85E+03	1.87E+03	2.40E+03	2.85E+03	3.49E+03
2.55E+06	2.22E+03	3.80E+03	3.31E+03	4.37E+03	5.09E+03	6.51E+03
4.45E+06	2.78E+03	5.27E+03	4.40E+03	5.53E+03	6.11E+03	8.15E+03
1.03E+07	5.11E+03	1.15E+04	8.85E+03	1.15E+04	1.19E+04	1.46E+04
2.16E+07	5.71E+03	1.46E+04	1.03E+04	1.37E+04	1.35E+04	1.67E+04
5.52E+07	8.65E+03	2.56E+04	1.62E+04	2.11E+04	2.37E+04	2.49E+04
1.77E+08	1.46E+04	5.59E+04	3.17E+04	3.92E+04	4.39E+04	4.09E+04
4.89E+08	2.31E+04	1.08E+05	5.50E+04	6.56E+04	7.70E+04	6.29E+04
8.12E+08	2.82E+04	1.45E+05	7.07E+04	8.12E+04	1.01E+05	7.76E+04
1.35E+09	3.62E+04	2.06E+05	9.61E+04	1.06E+05	1.38E+05	9.71E+04

4.2 *Atmospheric Dispersion Calculations*

4.2.1 General theory

This section describes the basic calculations of a Gaussian plume dispersion model. The basic equation for Gaussian dispersion of radioactive materials in air, in terms of the dilution factor X/Q, is:

$$\frac{X}{Q} = \frac{1}{2\pi\pi u_y\ \sigma_z}\left[\exp\left\{-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right\}\right]\left[\exp\left\{\frac{-(z-H)^2}{2\sigma_z^2}\right\} + \alpha\exp\left\{\frac{-(z+H)^2}{2\sigma_z^2}\right\}\right] \tag{52}$$

where

X	=	concentration of dispersed substance (Ci/m^3)
Q	=	rate of release of dispersed substance (Ci/sec)
u	=	wind speed (m/sec)
σ_y	=	crosswind meteorological constant (m) [y-axis Gaussian half-width (see Figure 4-1)]
σ_z	=	vertical meteorological constant (m) [z-axis Gaussian half-width (see Figure 4-1)]
H	=	release height (m)
α	=	reflection term; set equal to 1 for all materials [N.B. more commonly $\alpha = 0$ for a completely depositing substance and $\alpha = 1$ for a fully dispersed, non-depositing substance (e.g., a gas)]

The source term Q can be in any convenient units of quantity. In RADTRAN 5, activity units (Ci) are used; other models that deal with non-radioactive materials usually express Q in grams or a similar mass unit. In RADTRAN 5, the dilution factor X/Q has units of Ci-sec/m^3-Ci released. RADTRAN 5 includes an additional conservatism by setting α, the reflection term, to 1 for both depositing and non-depositing substances. Equation 52 is an idealization frequently encountered in the literature; it does not contain a term for deposition of material from the air onto the ground. Deposition is accounted for by a modification of Equation 52, as described later in this section. Equation 52 is from an elevated tilting plume model for transport and diffusion of an instantaneous release from a point source (Luna and Church, 1969). This formulation was used because the initial equations for a spherical puff are more complex, but downwind behavior is identical and the principles involved are the same.

If the release is at ground level and there is no lofting of the cloud as a result of buoyancy effects, then H=0. This generally would be the case for a transportation accident in which there is no fire. Since the ground-level value of X/Q is the quantity of interest, z is set to 0. Equation 52 then becomes[5]

$$\frac{X}{Q} = \frac{1}{\pi u \sigma_y \sigma_z}\left[\exp\left\{-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right\}\right] \tag{53}$$

Figures 4-3a and 4-3b (from Turner, 1969) show the relationship between σ_y and σ_z and downwind distance. From the figures, it is evident that X/Q decreases rapidly as one moves laterally away from the plume centerline. The "footprint" of the plume, shown schematically in Figure 4-2 is thus an ellipse with the semi-major axis in the direction of the wind and a relatively small semi-minor axis. As meteorological stability increases from Class A to Class F, σ_y decreases and the semi-minor axis lengthens relative to the semi-major axis, yielding a shorter, "fatter" footprint. The ellipses of Figure 4-2 are isopleths – curves of

[5] When α =1 in Equation 52, the factor of 2 in the denominator is cancelled.

constant X/Q that may be obtained by solving Equation 53 for each Pasquill stability class for different values of downwind and crosswind distance. Both σ_y and σ_z are functions of the downwind distance. The areas in Tables 4-3 and 4-4 are the areas inside the isopleths.

At ground level along the plume centerline (y=0), Equation 53 reduces to

$$\frac{X}{Q} = \frac{1}{\pi u \sigma_y \sigma_z} \tag{54}$$

Deposition of particles from an airborne plume is calculated by incorporating the deposition velocity of the particle, V_d (m/sec), into Equation 54, which yields:

$$\frac{X}{Q} = \frac{V_d}{\pi u \sigma_y \ \sigma_z} \tag{55}$$

In Equations 54 and 55, X/Q is expressed in units of Ci/m^2-Ci released. The RADTRAN user can substitute X/Q values and footprint areas for an elevated release, if desired, by off-line calculation with Equation 53.

$$\frac{X}{Q} = \frac{1}{\pi u \sigma_y \sigma_z} \exp\left\{-\frac{y^2}{2\sigma_y^2}\right\} \exp\left\{-\frac{H^2}{2\sigma_z^2}\right\} \tag{56}$$

where all variables are previously defined.

If user-generated isopleths for the case of deposition only are substituted, then $\alpha = 0$ and Equation 56 becomes

$$\frac{X}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z} \exp\left\{-\frac{y^2}{2\sigma_y^2}\right\} \exp\left\{-\frac{H^2}{2\sigma_z^2}\right\} \tag{57}$$

where all variables are previously defined.

Calculation of deposition requires incorporation of the settling velocity into Equation 57,[6] which yields:

$$\frac{X}{Q} = \frac{V_d}{2\pi u \sigma_y \sigma_z} \exp\left\{-\frac{y^2}{2\sigma_y^2}\right\} \exp\left\{-\frac{\left[H - \frac{xV_d}{u}\right]}{2\sigma_z^{\ 2}}\right\} \tag{58}$$

where x is the downwind distance along the plume centerline (m) and all other variables are as previously defined.

[6] For a derivation of this equation see Chapter 5, Sections 5.5 and 5.6 of Wark and Warner (1981).

Figure 4-3a. Crosswind Gaussian half-width (σ_y) as a function of downwind distance and meteorological stability. A, B, C, D, E, and F are the six Pasquill meteorological stability classes. From Turner (1969) as cited in Wark and Warner, (1981).

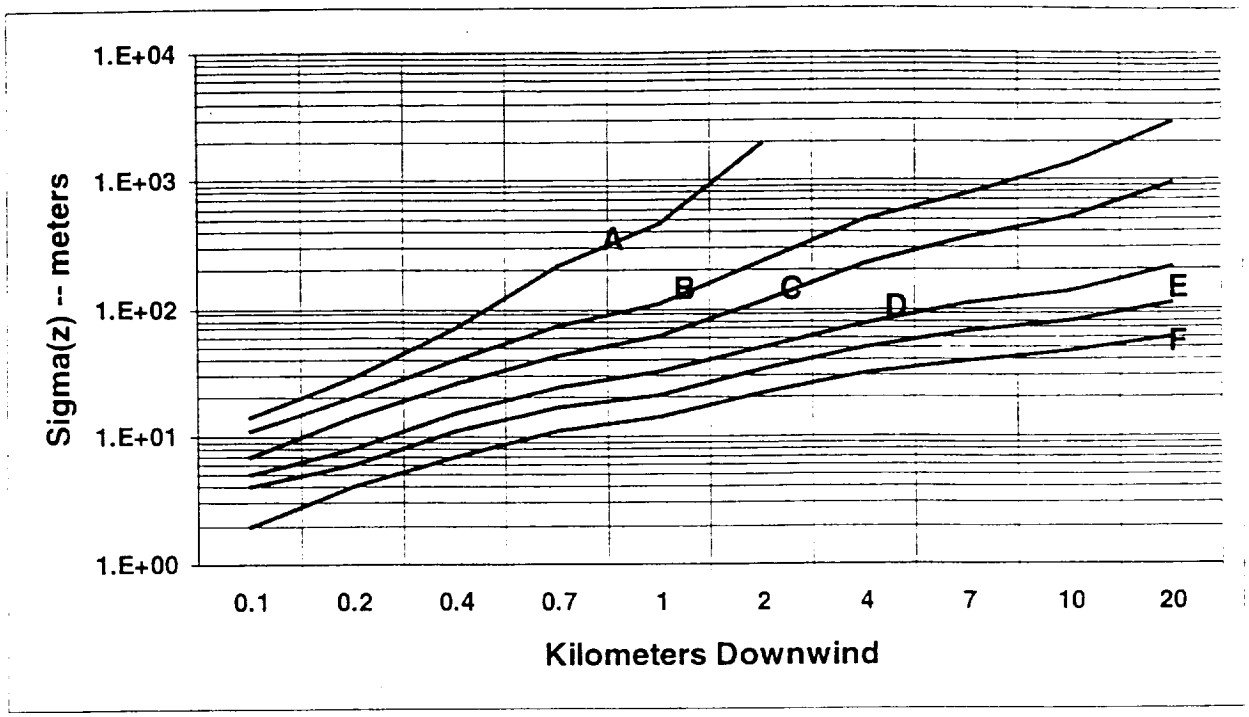
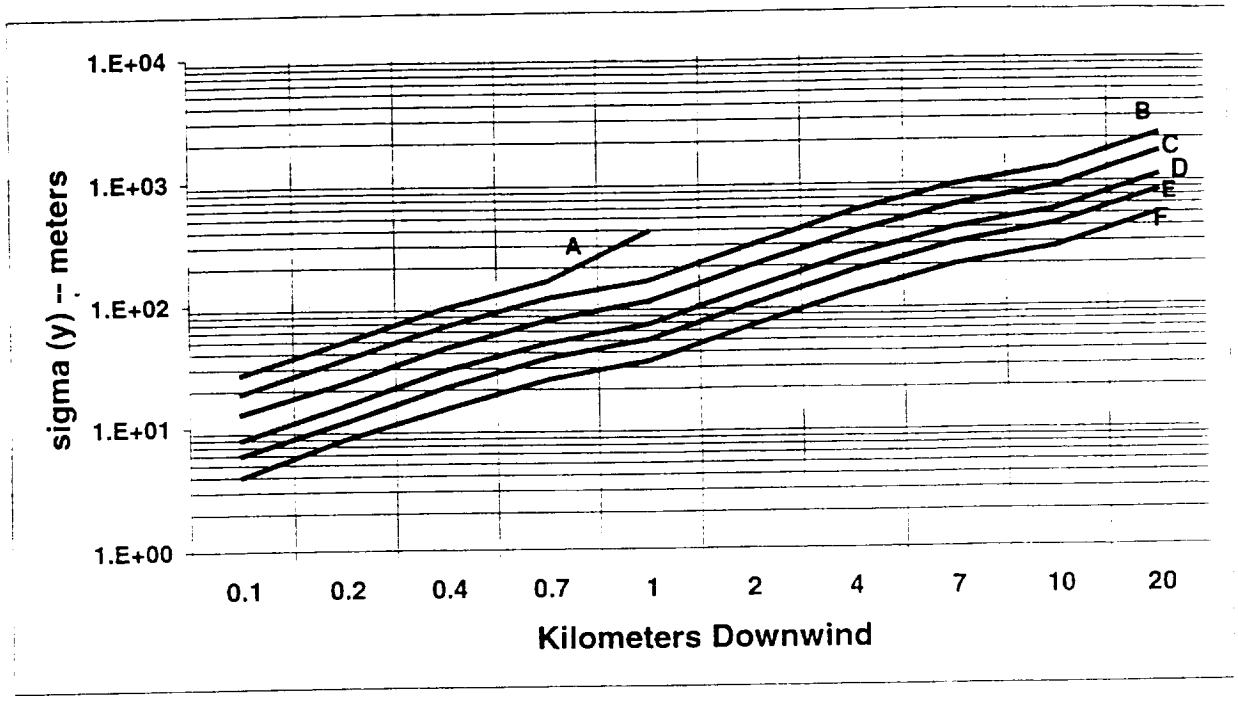


Figure 4-3b. Vertical Gaussian half-width (σ_z) as a function of downwind distance and meteorological stability. A, B, C, D, E, and F are the six Pasquill meteorological stability classes. From Turner (1969) as cited in Wark and Warner, 1981).



4.3 *RADTRAN Calculations*

4.3.1 Input Data

In RADTRAN 5, either Table 4-2 or Table 4-4 or an appropriate user-generated substitution, is used as input data. Advantage is taken of the fact that for a unit release (Q = 1 Ci), X/Q is equal to X. The remaining discussion applies to a unit release. For each meteorological stability class, the value of X at the downwind edge of A_1 is initially taken to be $\overline{X}$ (from the top line of Table 4-2 or Table 4-4) and set equal to $\overline{X}_1$. The area of the first isopleth A_1 must be small, so that the resulting underestimate of $\overline{X}_1$ will not be significant. The initial value of $\overline{X}$ for other isopleth areas is also taken to be the value X at the downwind end of the area.

The dilution factor for the area A_2-A_1 (see Figure 4-2) is the geometric mean of the largest and smallest dilution factors for that area:

$$\overline{X}_2^0 = \sqrt{X_2 - X_1} \tag{59}$$

The nth dilution factor is thus

$$\overline{X}_n^0 = \sqrt{X_n - X_{n-1}} \tag{60}$$

Equations 59 and 60 are used in RADTRAN 5 for non-depositing materials (e.g., gases). Deposition velocity is introduced into the calculation in two places, as described below.

4.3.2 First introduction of V_d

The amount deposited (Ci/m^2) in the first isopleth area DEP_1^0 is:

$$DEP_1^0 = \overline{X}_1 \cdot V_d \cdot A_1 \tag{61}$$

where

X	=	concentration of dispersed material (Ci/m^3)
V_d	=	deposition velocity (m/s)
A_1	=	isopleth area (m^2).

The amount of material deposited in the nth area, n≥2, is

$$DEP_n^0 = \overline{X}_n \cdot V_d \cdot [A_n - A_{n-1}] \tag{62}$$

where all variables are previously defined.

The total amount of material deposited out to A_n is then

$$DEP_n^0 = DEP_1^0 + \sum_{i=2}^{n} DEP_i^0 \tag{63}$$

where all variables are previously defined.

4.3.3 Second introduction of V_d

Deposition of material results in depletion of the airborne puff or plume, as indicated by Equations 61 - 63. None of these equations is used directly in RADTRAN 5. Instead, depletion of the plume as the material moves downwind is calculated iteratively.

When deposition occurs, the value of $\overline{X}_n^0$ changes because the puff has been depleted by the amount deposited. A revised value, $\overline{X}_n^1$, is calculated:

$$\overline{X}_n^1 = \sqrt{\left(\overline{X}_n \cdot \left(1 - DEP_n^N\right) \cdot \overline{X}_{n-1}^0 \cdot \left(1 - DEP_{n-1}^N\right)\right)} \tag{64}$$

where all variables are previously defined.

Because the puff is depleted, the amount deposited will also change as one moves downwind. A revised estimate of the material deposited, DEP_n^1, is given by

$$DEP_n^1 = \overline{X}_n^0 \cdot V_d \cdot \left[A_n - A_{n-1}\right] \tag{65}$$

where all variables are previously defined.

Revised values of DEP are computed in an iterative fashion until the relative error of DEP_n^0 and DEP_n is less than 0.001. Replacing X_n by the average $\overline{X}_n$ at each stage of the iteration accelerates convergence. The iterative method is applied repetitively for each value of n in ascending order starting with n=2.

4.3.4 Amount of Material Deposited

Total deposition (Ci/m^2 per Ci released) is denoted DC (deposited contamination). For the nth area interval, this is given by:

$$DC_n = V_d \cdot \overline{X}_n \tag{66}$$

4.3.5 Calculation of IF

The IF (integration factor) is an integration of the dilution factor over all downwind isopleths. The IF is used in the calculation of dose by the inhalation pathway (see Equation 77). This integration is performed by the AVINT subroutine of RADTRAN 5, which uses a numerical technique of overlapping parabolas intended specifically for use with tabulated data in the form f(x), where values of x may be arbitrarily spaced (Jefferson, 1982). AVINT allows RADTRAN to accept isopleth-area and X/Q values from any air dispersion calculation or code.

Data points should be closest together in regions where the function is changing most rapidly. For atmospheric dispersion, this means that isopleths nearest the release point should be selected at smaller intervals than isopleths at greater distance from the release point.[7] Thus, when isopleths are selected so that A_1 of Figure 4-3 is relatively small, underestimation of $\overline{X}_1$ will be minimal. The only constraints on isopleth selection are those imposed by the AVINT subroutine:

- Each isopleth area should be at least 6% larger than the preceding area;
- Each isopleth area should be no more than 4 times larger than the preceding area; and

[7] If data points are spaced too far apart, the AVINT routine will produce incorrect results. The user intending to generate problem-specific dispersion data is directed to Jefferson (1982) for more information.

- Since AVINT requires at least two data pairs, input data for at least two isopleth areas must be entered (if only a single pair of dispersion parameters is entered, then an error message appears and the calculation does not proceed).

5 CALCULATION OF ACCIDENT DOSES AND DOSE-RISKS

5.1 Introduction to Accident Consequence Calculations

Radiation dose is the primary consequence calculated with RADTRAN 5. Dose values are multiplied by probabilities to yield **dose-risk** values. Varying types of accident have varying consequences. The following sections describe how accidents are categorized by dose level and how doses are calculated for the various exposure pathways. Shielding damage and actual releases may be modeled separately.

5.1.1 Exposure Pathways

Six potential radiation exposure pathways may be modeled in RADTRAN 5:

- Direct Radiation (Loss of Shielding)
- Cloudshine
- Inhalation
- Groundshine
- Resuspension
- Ingestion.

5.1.2 Accident Severity and Package Response

In RADTRAN 5, the spectrum of accidents is described in terms of *package response*. The user may define up to 30 accident-severity categories. Accident categorization is somewhat flexible. ***Most commonly, each category represents all transportation accident outcomes that result in a specified package response, regardless of how that response is elicited***. However, differing means of arriving at the same outcome may also be treated separately. Severity-categories are best derived by means of event-tree analysis, and the RADTRAN approach allows several branches of an event tree that lead to a similar package response to be grouped together and their probabilities summed.

For a given level of package response, actual releases, if any, are determined in part by the physical-chemical properties of the contents. Technically, the term "release" is distinguished from the term "loss of shielding" (LOS) by the fact that in the former some part of the contents is expelled from the packaging. However, any scenario in which some or all of the contents of a package merely end up outside the packaging, without downwind dispersal of particulates, should be treated as a LOS event because it involves an unshielded source. ***Only when material is dispersed away from the immediate vicinity of the accident are dispersion models and pathways appropriate***. When material is released in gaseous or aerosol form, then the atmospheric-dispersion calculations discussed in Chapter 4 are used to estimate downwind concentrations and depositions of the material onto the ground.

5.1.3 Dose Calculation Outline

Consequences are calculated in a step-wise fashion. The first step is to develop an expression for an individual dose or dose rate for a particular exposure pathway. For example, a general expression for inhalation dose to an individual in the nth downwind isopleth for an accident of severity j is developed. This expression is then multiplied by the total number of persons in the same dose group [i.e., the product of the area ($A_n - A_{n-1}$ in m^2) and the population density in that area (persons/m^2)] to yield a population-dose value. The letter indices used with RADTRAN accident variables are given in Table 6-1. For groundshine, and resuspension, the initial expression is for a dose rate rather than a dose. Dose-rate expressions must be

multiplied by both the duration of exposure and the numbers of persons exposed to yield population doses. In each case, modifying factors such as radioactive decay also are accounted for.

For the inhalation and direct-exposure pathways, individual doses are calculated and examined to determine whether they exceed predetermined thresholds for early fatalities. Individual doses that may result in early fatalities are retained in the total population doses calculated by RADTRAN 5. This means a few doses, at most, are double-counted, because the total population doses are used to estimate latent fatalities (LCFs). This yields slightly conservative LCF estimates in the rare instances in which early-fatality thresholds are exceeded.

Table 5-1. Indices of RADTRAN Variables

Index Letter	Variable
i	Radionuclide
j	Severity category
k	Radius from LOS accident
l	Link (route segment)
m	Material
n	Isopleth area
o	Organ (whole body, lung, gonads, etc.)
p	Population density (rural, suburban, or urban)

5.2 *Mathematical Model for Dose in Loss-of-Shielding Accidents*

The building shielding options in Chapter 3 are also applied to loss-of-shielding (LOS) accident modeling. The three options and their characteristics are summarized briefly here.

- IUOPT1 – all residents of buildings are assumed to be fully shielded and all persons in rural and suburban areas are assumed to be in buildings (i.e., there are no pedestrians in the vicinity of an accident).
- IUOPT2 – all residents of buildings in all population zones are assumed to be exposed at a lower rate, based on a user-defined shielding factor (SF); all pedestrians are modeled as being unshielded; and in city streets, pedestrians are confined to sidewalk areas. Sidewalk width is a user-definable variable.
- IUOPT3 – all residents of all population zones within user-specified radii of exposure are assumed to be unshielded.

In many cases, the vast majority of the radionuclide inventory of a package will not contribute to the LOS source strength because of self-shielding, regardless of how much shielding is degraded. Modeling of such materials is discussed in Section 5.2.3.

5.2.1 LOS Gamma Dose for Small Packages

The following dose-rate formula, which is adapted from Equation (1) for a uniformly radiating source may be used to calculate gamma dose for LOS accidents involving small packages.

$$DR_g(r) = \frac{Q \cdot Ci \cdot PPS \cdot EF \cdot \varepsilon \cdot e^{-\mu r} \cdot B(\mu r)}{r^2} \tag{67}$$

where

$DR_g(r)$	=	gamma dose rate at distance r (mrem/hr)
Q	=	units conversion constant
Ci	=	number of curies per package
PPS	=	number of packages per shipment
EF	=	exposure fraction (see Section)
ε	=	photon energy (Mev)
μ	=	linear absorption coefficient (m^{-1})
$B(\mu r)$	=	dose-rate buildup factor
r	=	distance from source (m)

For gamma radiation, the simplifying assumption that $[e^{-\mu r} \cdot B(r)] = 1.0$ reduces the expression to

$$DR_g(r)_{i,j,k,l,m} = \frac{Q_6 \cdot Ci_i \cdot PPS_{l,m} \cdot EF_{i,j} \cdot \varepsilon_i}{r_k^2} \tag{68}$$

where

$DR_g(r)$	=	gamma dose rate at distance r (mrem/hr)
Q_6	=	0.5 rem-m/hr-Ci-Mev
Ci_i	=	number of curies of isotope i
$PPS_{l,m}$	=	number of packages of material m traveling on link l
$EF_{i,j}$	=	exposure fraction of isotope i in severity category j (see next section)
ε_i	=	photon energy of isotope i (Mev)
r_k	=	radial distance from source to annular area k (meters); $r_k = RADIST_k - RADIST_{k-1}$ for k = 2...NRAD; r_1 defines the innermost circle (exclusion area)

Drivers of cars potentially caught in a traffic jam near a LOS accident in highway mode are not modeled separately. The pedestrian (unshielded) population in the innermost annulus (first term in brackets in Equation 69 below) is adjusted with the RPD (ratio of pedestrian density to baseline population density) because it is assumed the first annulus encompasses pedestrian walkways or sidewalks adjacent to the roadway. Persons at greater distances are represented as enjoying some degree of shielding from intervening buildings, automobiles, etc., which is accounted for by assigning appropriate values to the SF (shielding fraction) coefficient in the second term.

Integration over the annuli produces the following formulation for dose from LOS (D_{LOS}) accidents:

$$D_{LOS} = Q_7 \cdot Q_6 \cdot Ci_i \cdot PPS \cdot \varepsilon_i \cdot EF_j \cdot T \cdot PD \cdot \left[RPD \cdot \int_{r_1}^{r_2} \frac{2\pi}{r^2} dr + SF_p \int_{r_2}^{r_{NRAD}} \frac{2\pi}{r^2} dr \right] \tag{69}$$

where

Q_7	=	10^{-6} km^2/m^2
Q_6	=	$0.5 \frac{rem - m^2}{hr - Ci - Mev}$
Ci_i	=	Curies per package of isotope i
PPS	=	Number of packages per shipment
ε_i	=	photon energy of isotope i (Mev)

EF_j	=	exposure fraction of package j
T	=	exposure time (hours)
PD	=	population density (persons/km^2)
RPD	=	ratio of pedestrian density
SF_p	=	shielding fraction for non-pedestrians in population zone p
r_1	=	innermost radius (m).
r_2	=	(r_1 + SWALK) (m), where SWALK = sidewalk width
r_{NRAD}	=	outermost radius (m)

Since

$$\int_{r_1}^{r_2} \frac{2\pi r}{r^2} dr = 2\pi \ln \frac{r_2}{r_1}$$

Equation 69 reduces to

$$D_{LOS} = 2\pi \cdot Q_7 \cdot Q_6 \cdot Ci_i \cdot PPS \cdot \varepsilon_i \cdot EF_j \cdot T \cdot PD \cdot \left[RPD \ln \frac{r_2}{r_1} + SF_p \ln \frac{r_{NRAD}}{r_2} \right] \quad (70)$$

where all parameters are the same as those listed in Equation 69.

If IUOPT is 1, then SF_p is equal to zero and the second term drops out of the equation. For IUOPT 2 or 3, SF_p is a fractional value between zero and 1.0. If there are no sidewalks, then $r_1 = r_2$ and the first term drops out. Normally, no pedestrian strip is modeled for freeways, but users may include population in this innermost area if it is appropriate for their analyses (e.g., a bicycle trail that parallels the highway for some distance).

5.2.2 LOS Neutron Dose for Small Packages

For those few isotopes with non-zero neutron emission values, the product of ε_i and Q_6 in Equation 70 is replaced with

$$\frac{NE_i}{30{,}000\pi} \cdot 10^{-6} \frac{m^2}{cm^2}$$

where

NE_i	=	neutron emission value for isotope i (neutrons/sec-Ci)

This substitution can be made because:

$$\frac{\text{neutron}}{\text{sec - Ci}} \cdot \frac{m^2}{30{,}000\pi \cdot cm^2} \cong \frac{\text{rem - m}^2}{\text{hr - Ci}} \quad \text{and, therefore, } \varepsilon_i \cdot Q_6 = \frac{\text{rem - m}^2}{\text{hr - Ci}} \text{ (Shleien, 1992, p.54).}$$

Neutron emission values are included in the RADTRAN radionuclide data library for nuclides that emit neutrons by spontaneous fission. The NE expression is automatically substituted in Equation 70 as outlined above for these isotopes.

5.2.3 Exposure Fraction (EF)

The exposure fraction is a measure of shielding degradation and should vary according to accident severity category (j index). In many cases, damage would be localized and radiation levels would not increase uniformly around the entire package. However, in RADTRAN 5, external radiation from shielding damage is modeled as radiating equally in all directions around the package and any shielding damage is modeled as causing a uniform increase in the surrounding radiation field strength (NRC, 1977). This simplification is slightly conservative, and it removes the need to account for differences in dose rates caused by various possible package orientations and damage locations. The primary criterion then becomes what fraction of the contents is exposed.

Values of exposure fraction (EF) for a LOS scenario are entered in the same array in RADTRAN 5 into which release-fraction (RF) values are entered for dispersal calculations. The user controls the calculations that are performed. ***This means that two separate runs of the code are required to obtain both LOS and dispersal-related doses.***

5.2.4 LOS Model Options for Type B Packages and Special Form Materials

The LOS portion of the Package Model is intended for common packaging types used for radiopharmaceuticals and low-level waste, which will lose all integrity in severe accidents and spill much of their contents on the ground in the vicinity of the package. Except when all of the spilled material disperses (e.g., a gas), the undispersed portion should be treated as a loss-of-shielding situation. ***Robust packagings such as spent-fuel casks, and any package containing "special-form" radioactive materials, must be treated differently from smaller packages***. Special-form materials (1) are made of steel or other rugged, high-melting-point materials and (2) contain radionuclides as an integral, inseparable component (e.g., activated hardware in a spent-fuel assembly). They are, by definition, nondispersable when subjected to the range of forces that characterize transportation accidents. Exposure fractions are indexed to the radionuclide (i index) to maintain parallelism with the dispersal calculations, but the EF for a LOS event is really a material-level rather than an isotope-level parameter. Therefore, ***LOS incidents involving special form materials should be analyzed with Option 2 for analysis of stops (annular area method)(see Section 3.4.2)***.

With Option 2, persons who might be in the vicinity of a LOS accident are represented as being uniformly distributed within a set of annular areas surrounding the accident location. ***The inner radius of the innermost annular area (r_1) must define a circular exclusion area around the accident location within which there are no people.*** Beyond this radius, the incremental dose area is given by $(2\pi r)dr$. Dose is the product of integration of this incremental dose area, integrated dose rate, time of exposure, and population density within the dose area. The dose rate normally should be the surface dose rate of the special form material or spent fuel that is exposed and may be treated as 100% gamma or entered as gamma and neutron fractions, as desired. If the shielding is only partially compromised or reduced (e.g., lead slump in a steel-lead-steel spent-fuel cask), then the shielding factor (SF_{sl}) in the Option 2 stop equation (Equation 41) can be made equivalent to the EF.

5.2.5 Exposure Times

In rural and suburban areas, the recommended exposure time (T or ΔT) is 0.67 hours; in urban areas, it is 0.42 hour. Exposure time is the sum of the time required for first responders to (a) arrive at the accident site, (b) decide on a course of action and (c) move persons away from the immediate area (Mills, Neuhauser and Smith, 1995).

5.2.6 Early-Effects Calculation

Gamma Radiation

A variation of the IUOPT1 model is also used to assess early effects, since only unshielded persons (i.e., persons out of doors) located at relatively short distances from a LOS accident location could potentially receive doses above the early-effects thresholds. Exposure time (T_{exp}) is defined as the time elapsed before first responders arrive and establish a cordon around the accident site.[8] ***If the Option 2 Stop Model is being used to analyze LOS scenarios for large packages, then early effects will not be calculated by RADTRAN 5.***

The modifying parameter, RPD (see Chapter 3), is used to estimate the number of persons out of doors for accidents that occur on city streets. The expected number of exposed persons ($EXP_{k,u}$) in each annular area on a city street is given by

$$EXP_{k,u} = Q_7 \cdot r_k \cdot SEG \cdot SWALK \cdot [RPD \cdot PD_u] \tag{71}$$

where

Q_7	=	units conversion factor = 1.0E-6 km^2/m^2
r_k	=	annular radius for nondispersal accidents defined by input variable RADIST; $r_k = RADIST_k - RADIST_{k-1}$ for k =2...NRAD, where r_1 defines the innermost circle (the radius of the exclusion area).
SWALK	=	width of segment where pedestrians are located (e.g., sidewalks) (m)
SEG	=	number of segments per annulus = 8
RPD	=	multiplier of PD_u that accounts for non-residents (acronym of ratio of pedestrian density)
PD_u	=	urban population density (persons/km^2).

For urban areas without sidewalks (e.g., interstate passing through an urban area),

$$EXP_{k,u} = Q_7 \cdot \pi \cdot PD_u \cdot UBF \cdot RU \cdot r_k^2 \tag{72}$$

where all variables are the same as in Equation 71 except for

UBF	=	fraction of persons indoors (acronym of urban building fraction)
RU	=	building shielding factor for urban areas
r_k	=	annular radius for nondispersal accidents defined by input variable RADIST; $r_k^2 = (RADIST_k)^2 - (RADIST_{k-1})^2$

In suburban and rural areas, EXP_s and EXP_r, are given by

$$EXP_{r\,or\,s} = Q_7 \cdot \pi \cdot PD_{r\,or\,s} \cdot r_k^2 \tag{73}$$

where all variables are the same as in Equations 71 and 72.

The LOS-related dose (D_{LOS}) to the population in the kth annular area is

$$D_{LOS} = \frac{Q_6 \cdot Ci_i \cdot PPS \cdot \varepsilon_i \cdot EF_j \cdot T}{r_k^2} \tag{74}$$

---

[8] The recommended value of T_{exp} in urban areas is ~25 min. Rush hour situations could involve greater response times, for example, while the presence of an imminent hazard reduces decision time. Thus, T_{exp} is eminently suitable for uncertainty analysis by means of Latin Hypercube Sampling (LHS). Mills, Neuhauser and Smith (1995) discuss this topic.

where

Q_6	=	units conversion factor = 0.5E-06 rem-m^2/hr-Ci-Mev
Ci_i	=	number of curies of ith isotope (Ci)
PPS	=	number of packages per shipment
ε_i	=	photon energy of ith isotope (Mev)
T	=	exposure time (hr)
EF_j	=	exposure fraction for accident of severity j
r_k	=	annulus radius k for non-dispersal accidents (m)

Neutron Radiation

If one or more neutron emitters are among the isotopes in a package, then Equation 74 is modified as follows.[9]

$$D_{LOS} = \frac{Q_8 \cdot NE_i \cdot Ci_i \cdot PPS \cdot T \cdot EF_j}{30{,}000\pi \cdot r_k^{\,2}} \tag{75}$$

where

Q_8	=	units conversion factor = 1.0E-06 m^2/cm^2
NE_i	=	neutron emission factor for radionuclide i (neutrons/sec-Ci)
Ci_i	=	number of curies of ith radionuclide (Ci)
PPS	=	number of packages per shipment
EF_j	=	exposure fraction for accident of severity j
T	=	exposure time (hr)
r_k	=	annulus radius k for non-dispersal accidents (m)

5.3 *Mathematical Models for Dose in Dispersion Accidents*

5.3.1 Mathematical Model for Dose to an Individual from Inhalation of Dispersed Materials

In RADTRAN 5, the average individual inhalation dose attributed to a released amount of respirable aerosol of isotope i in material m within each downwind isopleth area, (A_n-A_{n-1}), is computed as follows:

$$D_{inh} = \sum_{m}^{\text{all materials}} \sum_{i}^{\text{all radionuclides}} \sum_{o}^{\text{all organs}} \left(Ci_i \cdot PPS_L \cdot RF_{i,j} \cdot AER_{i,j} \cdot RESP_{i,j} \cdot RPC_{i,o} \cdot \overline{X}_n \cdot BR\right) \tag{76}$$

where

D_{inh}	=	individual inhalation dose (rem)
Ci_i	=	number of curies of isotope i in package (Ci)
PPS_L	=	number of packages on link L
$RF_{i,j}$	=	fraction of package contents released in accident of severity j
$AER_{i,j}$	=	fraction of released material that is in aerosol form in accident of severity j
$RESP_{i,j}$	=	fraction of aerosol material that is respirable in accident of severity j
$RPC_{i,o}$	=	dose conversion factor (rem per Ci) for ith isotope and oth organ (lung, marrow, and thyroid)
$\overline{X}_n$	=	dilution factor (chi) in nth isopleth area (Ci-sec/m^3 per Ci released; see Chapter 4)

[9] Note on units: $\frac{\text{neutron}}{\text{cm}^2 \cdot \text{sec}} \equiv \frac{\text{rem}}{\text{hr}}$

BR = breathing rate (m^3/sec)

5.3.2 Derivation of Mathematical Model for Integrated Population Dose from Direct Inhalation of Dispersed Material

The integrated population dose (D_{inh}^{pop}) from direct inhalation following a release of material in aerosol form is given by

$$D_{inh}^{pop} = Q_7 \cdot Ci_i \cdot PPS_L \cdot RF_{i,j} \cdot AER_{i,j} \cdot RESP_{i,j} \cdot RPC_i \cdot IF \cdot BR \cdot PD_L \cdot A_n \tag{77}$$

where,

Q_7	=	units conversion factor = 10^{-6} km^2/m^2
Ci_i	=	number of curies of radionuclide i per package (Ci)
PPS_L	=	number of packages per shipment on link L
$RF_{i,j}$	=	release fraction of radionuclide i in accident of severity j
$AER_{i,j}$	=	fraction of released radionuclide i that is aerosol in accident of severity j
$RESP_{i,j}$	=	fraction of aerosolized radionuclide i that is respirable in accident of severity j
RPC_i	=	dose conversion factor for radionuclide i (rem per curie inhaled)[10]
IF	=	integral of time-integrated atmospheric dilution factors, X, over all downwind areas
BR	=	breathing rate (m^3/min)
PD_L	=	population density on link L (persons/km^2)
A_n	=	area of nth isopleth (m^2)

The calculation of IF is described in Chapter 4. In urban areas, persons inside and persons outside of buildings may accumulate inhalation dose. To account for this, the population density term in Equation 77 is multiplied by the following term:

[(UBF · BDF) + (USWF · RPD)]

where

UBF	=	fraction of persons indoors (or urban building fraction)
BDF	=	building dose factor
USWF	=	fraction of persons out of doors (or urban sidewalk fraction)
RPD	=	ratio of pedestrian density to residential density.

The reasons this term is used are:

(1) For persons in buildings, an additional measure of protection is provided by the structure itself (Engelmann, 1990). This effect is accounted for by a Building Dose Factor (BDF).

(2) The total number of persons located in buildings in an urban area is modeled as the product of the potentially exposed population and the Urban Building Fraction (UBF), which is the fraction of the population in buildings.[11] Thus, the first term in the expression (UBF·BDF), acts as a modifier of the product of population density (PD_u) and area (A_n) and yields number of persons in buildings, who are exposed a lower rate according to the value of BDF.

(3) Persons out of doors (USWF) are modeled as being completely unshielded. While this is a user-supplied input value, it should equal 1 – UBF.

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[10] May be reset to zero for special-form materials with the DEFINE function of RADTRAN 5.

[11] In previous releases of RADTRAN, this variable was defined as the fraction of the urban area occupied by buildings, but new GIS-based methods of determining population density already account for the unequal distribution of population within the urban area, and UBF + USWF should equal 1.

(4) The Pedestrian Density Ratio (RPD) is the ratio of pedestrian density to residential density. It is used to account for persons out of doors who are not residents (e.g., shoppers). It is used as a multiplier of the basic urban population density. The RPD is a user-supplied value, but city-specific data are difficult to obtain. The default value of 6 is from New York City (Finley et al., 1980) and is likely to be conservative for many other urban areas.

The basic inhalation dose calculation can also be manipulated to yield dose to persons in enclosed spaces. This specialized technique was developed to examine potential doses to persons onboard an aircraft from a hypothetical leaking radioactive materials container (Neuhauser, 1992).

5.3.3 Derivation of Mathematical Models for Integrated Population Dose from Resuspension

Population dose via the inhalation pathway may also result from deposited materials because particulates can be resuspended by various mechanisms, such as wind, and subsequently be inhaled. The additional dose from this exposure pathway is accounted for by using a Resuspension Dose Factor (RDF). The RDF is a nondimensional factor that is applied to the direct inhalation dose. Resuspension dose (D_{res}) can thus be expressed as

$$D_{res} = D_{inh} \cdot (RDF - 1), \tag{78}$$

where

D_{inh}	=	direct inhalation dose (from Equation 77)
RDF	=	resuspension dose factor

The resuspension dose factor is a nondimensional value that is applied to the inhalation dose, following NRC, 1975.

$$RDF = 1 + V_d\left(8.64 \times 10^4\right) \cdot \left[\frac{10^{-5}}{\lambda_1}\left(1 - e^{-18250\lambda_1}\right) + \frac{10^{-9}}{\lambda_2}\left(1 - e^{-18250\lambda_2}\right)\right] \tag{79}$$

where

V_d	=	deposition velocity (m/sec)
λ_1	=	$0.693[1/RT_{1/2} + 1/t_{1/2}]$
λ_2	=	$0.693/t_{1/2}$
$RT_{1/2}$	=	resuspension half-life (days)
$t_{1/2}$	=	radioactive half-life (days).

For consistency with other RADTRAN dose models, a value of 50 years (18250 days) is used for the period of dose integration. The resuspension half-life is set to 365 days (NRC, 1975) and the radioactive half-life is radionuclide-specific.

5.3.4 Mathematical Model for Integrated Population Dose from Cloudshine

Cloudshine is defined as radiation emitted directly by airborne particulates. As a general rule, cloudshine dose is not large and seldom contributes significantly to total transportation-accident dose (Finley et al., 1980). However, dose from an aerosol release of certain radionuclides could be significant, particularly those that emit high-photon-energy gamma radiation such as ^{24}Na and ^{60}Co, which are used in radiomedicine. Cloudshine Dose Factors (CDFs) are calculated for both photon- and neutron-emitting

radioisotopes (DOE, 1988; Eckerman & Ryman, 1993).[12] The CDF gives dose from immersion in a semi-infinite hemispherical cloud of unit concentration of a radionuclide, which can be used to calculate total dose when actual concentration, time of cloud passage, and involved radionuclides are considered.

The basic equation for individual dose from cloudshine from gamma-emitters is

$$D_{cld}^{ind} = \sum^{materials} \sum^{isotopes} \sum^{organs} \left(Ci_i \cdot PPS \cdot CDF \cdot \overline{X}_n \cdot RF_{i,j} \cdot AER_{i,j} \right) \tag{80}$$

where

Ci_i	=	number of curies of radionuclide i (Ci)
PPS	=	number of packages per shipment
CDF_i	=	cloudshine dose factor for radionuclide i (rem-m^3/Ci-sec)
$\overline{X}_n$	=	time-integrated concentration of radionuclide i in nth isopleth (Ci-sec/m^3)
$RF_{i,j}$	=	release fraction of radionuclide i in accident severity j
AER	=	fraction of released radionuclide i that is in aerosol form in accident severity j.

The equation for integrated population dose from cloudshine (D_{cld}^{pop}) is

$$D_{cld_{i,j,L,m}}^{pop} = Q_7 \cdot Ci_i \cdot PPS_{L,m} \cdot RF_{i,j} \cdot AER_{i,j} \cdot CDF_i \cdot IF \cdot PD_L \tag{81}$$

where

Q_7	=	units conversion factor = 10^{-6} km^2/m^2
Ci_i	=	number of curies of radionuclide i per package (Ci)
$PPS_{L,m}$	=	number of packages of material m per shipment on link L
$RF_{i,j}$	=	fraction of radionuclide i released from package in accident severity j
$AER_{i,j}$	=	fraction of released radionuclide i that is in aerosol form in accident severity j
CDF_i	=	cloudshine dose factor (rem-m^3/Ci-sec)
IF	=	integral of time-integrated atmospheric dilution factors over all downwind areas
PD_L	=	population density on link L (persons/km^2).

Equation 81 is used without modification in rural and suburban areas. In urban areas, the factor (UBF·BDF + USWF·RPD) is applied to account for air filtration in buildings and exposure of pedestrians. This yields the following equation:

$$D_{cld_{i,j,L,m,u}} = Q_7 \cdot Ci_i \cdot PPS_{L,m} \cdot RF_{i,j} \cdot AER_{i,j} \cdot CDF_i \cdot IF \cdot PD_L \cdot (UBF \cdot BDF + USWF \cdot RPD) \tag{82}$$

where all variables are as defined in Equation 81 except for the last term, which is defined in Section 5.3.2. The index L must define an urban link.

5.3.5 Mathematical Model for Integrated Population Dose from Groundshine

Groundshine is defined as radiation emitted from particulate material that has been deposited on surfaces. As an aerosol cloud disperses downwind, some the particulates in the cloud deposit on the ground. The amount of deposition is calculated as described in Chapter 4. Persons living or working in the plume "footprint" will receive a dose from this deposited material. This section describes the derivation of

[12] CDFs can be reset to zero for constituents of special-form materials with the DEFINE function of RADTRAN 5.

equations that relate gamma flux to dose rate and then expresses gamma flux in terms of deposited radionuclide concentrations calculated in Chapter 4.

The basic equation for uncollided (unscattered) gamma flux at some distance, r, above a uniformly contaminated infinite-plane source is taken from Glasstone and Sesonske (1991; Equation 10:17)

$$\phi_g = \frac{S}{2} E_1(\mu r) \tag{83}$$

where

ϕ_g	=	uncollided photon flux from uniformly contaminated, infinite plane source at some distance r above the plane (photons/cm^2/sec)
S	=	source strength (photons/cm^2/sec)
E_1	=	first-order exponential integral
μ	=	linear attenuation coefficient (m^{-1})
r	=	distance above plane source (m)

At distances within a few meters of a planar gamma source, the rate of energy deposition per unit mass (i.e., the dose rate) is mainly a function of photon flux, photon energy, and attenuation by the medium through which the radiation is traveling. In order to derive an expression for dose rate of gamma emitters from Equation (83), each decay event is assumed to behave as a single photon decay with an energy equal to ε, the average photon energy per disintegration, regardless of whether the actual decay is a single photon or a cascade (Glasstone and Sesonske, 1991). The source-strength term, S, in Equation (83) can then be converted from photons/cm/sec to microcuries per m^2 (1 disintegration/sec = 2.703E-5 microcuries). If $E_1(\mu r)$ is evaluated at 1 m above the ground (i.e., at r = 1) for μ_{air} and for ε_i (the photon energy in Mev of radionuclide i), then the following expression relating dose rate (DR) to deposited concentration follows from NRC (1975; Equation VI-C-1).

$$DR_i = CL_i \cdot GDF_i \tag{84}$$

where

CL	=	contamination level of radionuclide i (μCi/m^2)
GDF	=	groundshine dose factor for radionuclide i (rem-m^2/day-μCi)

Groundshine dose factor values are taken from Federal Guidance Report 12 and are included in the RADTRAN radionuclide library for all radionuclides listed.[13][14] Equation 83 describes the dose rate from a uniformly contaminated, infinite plane source with no surface roughness. The dose rate from radionuclides deposited on irregular or rough surfaces such as asphalt and soil will generally be lower. In addition, the source strength will decrease with time as a result of factors such as downward mixing into the soil, radioactive decay, and the effects of rain and wind. The NRC (1975, Appendix V) suggests a model for the time-dependence of groundshine dose rate. The values are empirical and are based on studies of cesium-137 and other radionuclides in fallout on various types of soil. The resulting equation for groundshine dose rate at time T [DR(T) in rem/day] is:

[13] This formulation neglects neutron emissions from spontaneous fission; they are not included in the dose factors from Federal Guidance Report 12. Underestimation of groundshine dose might occur if large amounts of one or more neutron emitters (e.g., Cm-242, Cm-244, Cf-252) are present. The neutron contribution may be calculated external to RADTRAN with a slab geometry code (e.g., NITRAN2; Takahashi and Rusch, 1979).

[14] Groundshine dose factors should be reset to zero by the user (with the DEFINE function) for constituents of special-form materials.

$$DR(T) = CL_i \cdot GDF\left[0.63e^{-0.0031t_{1/2}} + 0.37e^{-0.00002 1t_{1/2}}\right] \cdot e^{\frac{-0.693ET}{t_{1/2}}} \quad (85)$$

where

CL_i	=	contamination level of radionuclide i ($\mu Ci/m^2$)
GDF_i	=	groundshine dose factor for radionuclide i (rem-m^2/day-μCi)
$t_{1/2}$	=	half-life of radionuclide i (days)
ET	=	elapsed time (days)

The term CL is derived from the deposited concentration ($DC_{i,j}$: see Equation 66), which has units of Ci/m^2 per Ci released, as follows:

$$CL_{i,j} = Q_9 \cdot PPS \cdot DC_{i,j} \cdot Ci_{i,j} \quad (86)$$

where

Q_9	=	units conversion factor = 1.0E+6 μCi/Ci
PPS	=	number of packages per shipment
DC_i	=	deposited concentration of radionuclide i from a single package in an accident of severity j (Ci/m^2 per Ci released)
CR_i	=	number of curies of radionuclide i released from package in an accident of severity j (Ci) = $Ci_i \cdot RF_{i,j}$ (inventory and release fraction of radionuclide i in an accident of severity j)

The first two exponential terms in Equation 85 describe physical removal processes such as weathering and suspension; and the third exponential term describes loss from radioactive decay.

The groundshine dose model allows the user to account for post-accident clean up. The ratio between the initial contamination level (CL) and the level after clean-up (CU) is used to describe the level of action taken. The Total Decontamination Factor (TDF) is calculated over all radionuclides as follows:

$$TDF = \frac{\sum^{\text{all materials}} \sum^{\text{all radionuclides}} CL_i}{CU} \quad (87)$$

The basic groundshine dose model outlined above is modified to account for additional influential factors:

- An initial period of exposure to full level of deposition, which occurs regardless of the action chosen.
- Decisions regarding interdiction level after clean up (CU), or no-action alternatives.
- Duration of clean-up, if any;
- Exposure of returned population to residual levels; if clean-up was selected, or to initial deposited level, if no action was selected; or
- Interdiction (population is evacuated and does not return).

5.4 Action Levels

Action levels or thresholds represent the decision-making step in RADTRAN 5. The variable INTERDICT sets one threshold; CU sets the other. Action levels are used to determine the post-deposition response on the basis of TDF as follows:

- If TDF $\leq$ 1.0, then no action will be taken (this result indicates that CL $\leq$ CU)

- Otherwise, if TDF > 1.0 ≤ INTERDICT, then the area will be evacuated and cleaned-up.
- If TDF > INTERDICT, then the area will be evacuated and interdicted.

No regulatory body has yet set a threshold for clean up (Chanin and Murfin, 1996). Thus, the only recommended value for CU remains the proposed EPA guideline of 0.2 $\mu Ci/m^2$ for total deposited activity (EPA, 1977). The recommended value for INTERDICT is 40, indicating that the numerator of Equation 87 is 40 times greater than CU (= 8 $\mu Ci/m^2$ for the 0.2 $\mu Ci/m^2$ threshold).

5.5 *Calculation of Dose for No-Action Decision*

When TDF ≤ 1.0, dose is calculated as follows:

$$D_{gnd} = Q_7 \cdot GDF_i \cdot t_{1/2_i} \cdot A_n \cdot PD_L \cdot CL_{n,j,i}[TRM1 + TRM2] \tag{88}$$

where

Q_7	=	units conversion factor = 1.0E-6 km^2/m^2
GDF_i	=	groundshine dose factor (rem-m^2/day-μCi)
$t_{1/2i}$	=	half-life of radionuclide i (day)
A_n	=	area of nth isopleth (km^2)
PD_L	=	population density of link L (person/km^2)
$CL_{n,j,i}$	=	contamination level of isotope i in nth area for accident of severity j (Ci/m^2)
TRM1	=	$\left[\lambda_1(1-e^{-\lambda_2 T_E}) + \lambda_3(1-e^{-\lambda_4 T_E})\right]$
TRM2	=	$\left[\lambda_1 e^{-(\lambda_2 T_S)} + \lambda_3(e^{-\lambda_4 T_S} - e^{-\lambda_4 \cdot 1.83E+4})\right]$

$$\lambda_1 = \frac{0.63}{0.0031 t_{1/2_i} + 0.693}$$

$$\lambda_2 = \frac{0.0031 t_{1/2_i} + 0.693}{t_{1/2_i}}$$

$$\lambda_3 = \frac{0.37}{0.000021 t_{1/2_i} + 0.693}$$

$$\lambda_4 = \frac{0.000021 t_{1/2_i} + 0.693}{t_{1/2_i}}$$

TRM 1 in Equation 88 represents the pre-evacuation time period and the exponent T_E represents the elapsed time (days) before evacuation, which the user specifies under keyword EVACUATION. The second term (TRM2) represents the doses incurred during the time in which the area is surveyed (T_S exponent) and for a subsequent 50-year period (1.83E+4 days = 50 years) after the evacuated population returns. Doses calculated with Equation 88 are summed over all radionuclides to yield total dose per isopleth area. In the no-action case, there is no difference in the level of deposited concentration because no clean up is performed, and both terms are multiplied by CL_i.

5.6 *Calculation of Dose for Evacuation and Clean-Up*

When 1.0 <TDF≤INTERDICT, the period of time between deposition and the decision to evacuate would precede clean-up efforts and would be the only time inhabitants of the contaminated area would be exposed to the total amount of radionuclides deposited on the ground. The pre-evacuation dose is calculated in the same way as the no-action dose except that TRM2 is multiplied by CU instead of CL, to reflect the lower level of residual radioactivity.

$$D_{gnd} = Q_7 \cdot GDF_i \cdot (A_n - A_{n-1}) \cdot PPS_L \cdot PD_L \cdot t_{1/2_i} \left[TRM1 \cdot CL_i + TRM2 \cdot CU\right] \quad (89)$$

where

Q_7	=	units conversion factor = 1.0E-06 km^2/m^2
GDF_i	=	groundshine dose factor for isotope i (rem-m^2/day-μCi)
A_n	=	area of nth isopleth (km^2)
PD_L	=	population density (persons/km^2)
PPS_L	=	number of packages per shipment on link L
$t_{1/2i}$	=	half-life of isotope i (days)
TRM1	=	see Equation 88
TRM2	=	see Equation 88

The period of time actually required to carry out a clean-up operation would most likely be prolonged because of regulatory issues, but a relatively short clean-up time may be used for conservatism. The reason a short clean-up period is conservative for public-dose estimation is that a realistic clean-up time (e.g., months or years) permits additional radioactive decay to occur. As a result, short and moderate half-life radionuclides would decay to quite low levels before clean up was completed. This class of radionuclides includes important gamma producers (e.g., cobalt-60; 1.3 Mev gamma; $t_{1/2}$ = 5.27 y). The residual radioactivity after clean up would be depleted in these radionuclides if realistic clean-up times were used. Short clean-up times (e.g., days), on the other hand, would give a proportional representation of the remaining radionuclide mix, similar to that of the originally deposited material, and would include the short and medium half-life radionuclides. The radionuclide mix will always be depleted in very short half-life isotopes such as I-131 ($t_{1/2}$ = 8.034 days), regardless of how optimistically the clean-up time is estimated.

Calculation of Dose for Interdiction Decision

When TDF > INTERDICT, the deposited concentration of radioactivity in an isopleth area exceeds the interdiction threshold. The dose is determined by the following.

$$D_{gnd} = Q_7 \cdot GDF_i \cdot t_{1/2_i} \cdot PPS \cdot (A_n - A_{n-1}) \cdot PD_L \cdot TRM1 \cdot CL_{n,j,i} \quad (90)$$

where

Q_7	=	units conversion factor = 1.0E-06 km^2/m^2
GDF_i	=	groundshine dose factor for radionuclide i (rem-m^2/day-μCi)
A_n	=	area of nth isopleth (km^2)
PPS	=	number of packages per shipment
PD_L	=	population density on link L (persons/km^2)
$t_{1/2i}$	=	half-life of radionuclide i (days)
TRM1	=	see Equation (88)
$CL_{n,j,i}$	=	contamination level of radionuclide i in nth area for accident of severity j

In this case, TRM2 is omitted, thereby removing a post-clean-up component of groundshine dose.

Calculation of Total Dose

The decision process for selecting among the triad of options discussed in this section is repeated for each downwind isopleth. The total dose from groundshine (per accident) is calculated by summing the results for all isotopes in each isopleth.

$$D_{gnd\text{-}Total} = \sum_{n=1}^{NAREAS} D_{gnd} \tag{91}$$

where

$D_{gnd\text{-}Total}$ = Total groundshine dose

D_{gnd} = Groundshine dose (person-rem) for the ith radionuclide in the nth isopleth in accident of severity j on link l

5.6.1 Ingestion Dose [optional]

Food supplies may become contaminated by radionuclide deposited in the environment. This pathway is limited to accidents that result in the contamination of agricultural (i.e., rural) areas. Because the marketing and distribution systems for agricultural products result in widespread dissemination of contaminated foodstuffs, potentially exposed persons are distributed throughout the population as a whole and are not restricted to persons living in the plume deposition "footprint." The COMIDA computer code (Abbot and Rood, 1993, 1994), specifically the second release, COMIDA2, which was developed for use with MACCS2 (Chanin and Young, 1998b) has been used to develop estimates of ingestion dose for most isotopes in the internal data library.

5.7 Accident Probability and Dose-Risk

The following section describes how input variables for accident rate and accident-severity probability are summed to develop a probability term for accident risk calculations. Also described is the combination of these probabilities with the dose calculations from Section 5.1 to generate dose-risks for transportation accident conditions.

5.7.1 Probabilities of Accidents

Radiological consequences are calculated on a per accident basis, which makes the calculations independent of the way the analysis is structured. Probabilities, however, are not. An essential step in calculating dose-risk, therefore, is to define accident-severity categories and then estimate the probability of occurrence of accidents of each severity for each route segment identified in the analysis. As noted in Chapter 2, the user must define accident-severity categories. The probabilities associated with them are ***conditional probabilities***. As such, they must be multiplied by the base accident probability, which is usually estimated from historical accident-rate data. The base accident rate and the population density vary by route segment. Thus, the equation describing accident probability on a route segment is:

$$\gamma_{j,L} = AR_L \cdot SV_{j,L} \cdot NSH_L \cdot DIST_L \tag{92}$$

where

$\gamma_{j,L}$ = probability of an accident of severity j on link L

AR_L = accident rate on link L (accidents/vehicle-km)

$SV_{j,L}$ = conditional probability of occurrence of an accident of severity j on link L

NSH_L = number of shipments on link L

$DIST_L$ = length of link L (km).

5.7.2 Dose-Risk for Loss-of-Shielding (LOS) Accidents

Loss of shielding occurs when some or all of the packaging components that act as radiation shields during transport are degraded in some way in the course of an accident. The package contents are modeled as a static source of some calculated source strength (see Section 5.2). The dose-risk per link for LOS is expressed as

$$RISK_L^{LOS} = \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{LOS} \tag{93}$$

where

$\gamma_{j,L}$ = probability of an accident of severity j on link L for shipment
D_{LOS} = dose per LOS accident of severity j on link L for shipment (person-rem)

5.7.3 Dose-Risk for Accidents with Dispersal

Inhalation Dose-Risk

The inhalation dose-risk calculation for each material m in dispersal accidents on a single link L is

$$RISK_L^{INH} = \sum_{i=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{inh} \tag{94}$$

where

$\gamma_{j,L}$ = probability of an accident of severity j on link L
D_{inh} = dose from inhalation of isotope i in material m in an accident of severity j on link L (person-rem)
NSEV = number of accident-severity categories.

Resuspension Dose-Risk

The resuspension dose-risk ($RISK^{RES}$) calculation for each material m in dispersal accidents on a single link L is

$$RISK_L^{RES} = \sum_{i=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{res} \tag{95}$$

where

$\gamma_{j,L}$ = probability of an accident of severity j on link L
D_{res} = dose from inhalation of isotope i in an accident of severity j on link L (person-rem)
n = number of radionuclides in package
NSEV = number of accident-severity categories

Cloudshine Dose-Risk

The cloudshine dose-risk ($RISK^{CLD}$) calculation for each material m in dispersal accidents on a single link L is

$$RISK_L^{CLD} = \sum_{i=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{cld} \tag{96}$$

where

$\gamma_{j,L}$	=	probability of an accident of severity j on link L
D^{CLD}	=	dose from cloudshine of isotope i in an accident of severity j on link L (person-rem)
n	=	number of radionuclides in package
NSEV	=	number of accident-severity categories

Groundshine Dose-Risk

The groundshine dose-risk ($RISK^{GND}$) calculation for dispersal accidents on a single link l is

$$RISK_L^{GND} = \sum_{i=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{gnd} \tag{97}$$

where

$\gamma_{j,L}$	=	probability of an accident of severity j on link L
D_{gnd}	=	dose from groundshine of isotope i in an accident of severity j on link L (person-rem)
n	=	number of radionuclides in package
NSEV	=	number of accident-severity categories

Ingestion Dose-Risk

The ingestion dose-risk calculation for dispersal accidents on a single link L is

$$RISK_L^{ING} = \sum_{i=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{ing} \tag{98}$$

where

$\gamma_{j,L}$	=	probability of an accident of severity j on link L
D_{ing}	=	dose from ingestion of isotope i an accident of severity j on link L (person-rem)
n	=	number of radionuclides in package
NSEV	=	number of accident-severity categories

5.7.4 Overall Dose-Risk from Dispersion

The total dose-risk for the population residing near link L is the sum of dose-risks over all exposure pathways that affect the persons in the plume "footprint" (inhalation, resuspension, cloudshine, and groundshine). ***Ingestion dose is listed separately in the output and should not be added to the other pathways because an entirely different population is exposed via this pathway.***

$$RISK_L^{TOTAL} = \sum^{inh,\, res,\, cld,\, gnd} RISK^{n} \tag{99}$$

where

$RISK^{INH}$ =	inhalation dose risk
$RISK^{RES}$ =	resuspension dose risk
$RISK^{CLD}$ =	cloudshine dose risk

$RISK^{GND}$ = groundshine dose risk
n = index for risk class.

Link-level risks may be summed or grouped in various ways (e.g., rural, suburban and urban links may be summed separately) as the needs of the users analysis require. The ingestion dose, if calculated, should be reported separately.

6 Health Effects

6.1 Acute Health Effects

The nature of health effects that may result from exposure to radiation depends on both the total dose and the dose rate. Acute health effects are those that occur when individual dose exceeds some threshold value. Acute effects are also referred to as *deterministic effects*. Another term that is used is *prompt effects* since the symptoms appear shortly after exposure rather than after a long latent period as for most cancers.

A dose sufficient to cause acute health effects must be delivered in a short period of time; varying from a few seconds to a few days depending on the source strength. Such a dose may be delivered by external radiation and/or by inhalation or ingestion of large amounts of radioactive material. In the latter case, the lung or intestinal tract, respectively, is the organ most directly irradiated.

Variability in radiation response within a population and variability in the type of medical care available mean there is not a single dose threshold for mortality. This has led to the use of LD (lethal dose) metrics. The LD_{50}, which represents the dose that yields 50% mortality of an exposed population, is an example. For a single short whole-body exposure to external low-LET[15] radiation and minimal post-exposure medical treatment, the Reactor Safety Study gave an LD_{50} of 345 rem (NRC, 1975). More recent data have confirmed this value. The National Council on Radiation Protection (NCRP) gives an $LD_{50/30}$[16] as a range of doses with a median of 340 rem whole-body dose for minimal medical care (NCRP, 1989). Above this dose, the chance of early mortality increases until it reaches 99% above 400 rem with minimal care. The survival rate at this dose level can be almost doubled with intensive medical treatment (e.g., bone marrow transplants), but death is virtually certain above 1000 rem even with intensive medical care (NRC, 1975; Evans et al., 1985; NCRP, 1989). Most thresholds for non-fatal effects, which are referred to as *early morbidities*, are organ-based. Some organs, such as the lung, are considerably more radiation resistant than others , such as bone marrow. One-year bone marrow doses are calculated and used to model the effects of external whole body radiation.

Doses large enough to result in acute effects are so rare in RAM transportation that none has yet occurred. In RADTRAN 5 the potential occurrence of early effects is estimated for (a) exposure to external penetrating radiation in LOS scenarios and (b) internal exposure from inhaled particulates. The ongoing reassessment of dosimetry for Hiroshima and Nagasaki survivors and data from other smaller groups of individuals exposed to high doses of radiation have resulted in the publication of new models (Evans et al., 1985; NRC, 1990; ICRP, 1991) that have replaced the Reactor Safety Study (NRC, 1975). Early effects values in previous releases of RADTRAN were taken from the Reactor Safety Study for minimal care. The early-effects values used in RADTRAN 5 for acute effects are taken from Evans et al. (1985) for an intermediate level of care since no values were calculated for minimal care.

Thresholds for acute effects must be applied at the level of individual dose. In RADTRAN, individual dose estimates by isopleth area or by annular area (for LOS accidents) are examined to determine whether a threshold has been exceeded. Estimation of acute effects potentially associated with LOS accidents is discussed in Section 6.1.1. Estimation of acute effects potentially associated with inhalation of particulates is discussed in Section 6.1.2. If the RADTRAN stop model was used to calculate LOS dose, then the calculations in Sections 6.1.1 and 6.1.2 are not performed automatically and must be performed externally by the user.

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[15] LET refers to Linear Energy Transfer; low-LET radiations include beta, gamma, and X-rays. Neutrons are the only types of high-LET external radiation assessed in RADTRAN.

[16] $LD_{50/30}$ is a dose that causes 50% lethality within 30 days.

6.1.1 Mathematical Model for Number of Expected Early Fatalities and Early Morbidities for Loss-of-Shielding (LOS) Accidents

Early Fatalities

Once organ doses have been computed as described in Chapter 5 (Equations 74 and 75), the probability of an early fatality (P^{EF}) is determined. It is the product of a computed dose and the probability of death as a result of receiving such a dose when receiving an intermediate level of medical care (Table 6-1). The expected number of people in each annular area (EXP_k), as calculated in Equations 71 through 73, is also a variable. Bone is used to represent external radiation effects because of the low threshold dose for the organ. Lung dose is used to assess acute mortality from inhalation of particulates following dispersion. The values derived from Evans et al. (1985). The "old values" from the Reactor Safety Study are given in Table 6-2 strictly for comparison purposes.

The expected number of early fatalities (N^{EF}) for each population-density class (rural, suburban, or urban) is then given by:

$$N_{j,L}^{EF} = \sum_{k=2}^{NRAD} \left(EXP_k \cdot P_{j,k,L}^{EF} \right) \qquad (100)$$

where

EXP_k	=	expected number of people in kth annular area (from Equations 71 through 73)
$P_{j,k,L}^{EF}$	=	probability of early fatality for accident of severity j in kth annular area on link L (computed dose x probability from Table 6-1)
NRAD	=	number of annular areas (k index).

The summation in Equation 100 starts with k=2 because the innermost annular area is modeled as an exclusion area, as described in Chapter 5. A severe fire is part of many high-severity accident scenarios. Such a fire usually would force people to leave the 2 or 3 innermost annular areas because of the extreme heat. Since it is only within relatively short radial distances of a shipment that large prompt doses can be incurred as a result of LOS, treating these annuli as being populated in all accident severities leads to early-effects estimates for LOS that are somewhat conservative. A certain amount of conservatism is derived from the intermediate-care assumption; the number of fatalities can be reduced by intensive medical treatment.

Early Morbidities

The approach to estimation of early morbidities is to use a step probability function, P^{EM}, which assumes a value of unity for doses above the threshold and a value of zero for doses below the threshold. The thresholds listed in Table 6-3 represent acute doses above which some type of debilitating physiological response is likely (Evans et al., 1985). In RADTRAN 5, the probability of an early morbidity in a LOS accident is determined by comparison of the calculated individual dose from Equations 74 and 75 in each annular area with the threshold for external whole-body exposure (bone marrow). The expected number of early morbidities ($N^{EM\text{-}LOS}$) per accident is then given by:

$$N_{j,L}^{EM\text{-}LOS} = \sum_{k=2}^{NRAD} \left(EXP_k \cdot P_{j,k,L}^{EM} \right) \qquad (101)$$

Table 6-1. Probabilities of Early Fatality – Marrow and Lung Doses
(derived from Evans et al. 1985)

Marrow Dose (rem)	Fatality Incidence	Marrow Dose (rem)	Fatality Incidence	Lung Dose (rem)	Fatality Incidence
<160	0.00000	570	0.99482	<500	0.00000
160	0.00913	580	0.99679	525	0.00759
170	0.01234	590	0.99808	550	0.01050
180	0.01639	600	0.99889	575	0.01430
190	0.02143	610	0.99938	600	0.01922
200	0.02761	620	0.99967	625	0.02549
210	0.03510	630	0.99983	650	0.03341
220	0.04408	640	0.99992	675	0.04329
230	0.05475	650	0.99996	700	0.05548
240	0.06729	660	0.99998	725	0.07038
250	0.08188	6700	0.99999	750	0.08837
260	0.09872	>670	1.00000	775	0.10988
270	0.11797			800	0.13529
280	0.13977			825	0.16498
290	0.16425			850	0.19925
300	0.19150			875	0.23830
310	0.22155			900	0.28218
320	0.25438			925	0.33077
330	0.28990			950	0.38372
340	0.32798			975	0.44042
350	0.36838			1000	0.50000
360	0.41078			1025	0.56130
370	0.45481			1050	0.62293
380	0.50000			1075	0.68335
390	0.54583			1100	0.74095
400	0.59172			1125	0.79420
410	0.63706			1150	0.84178
420	0.68123			1175	0.88274
430	0.72363			1200	0.91656
440	0.76371			1225	0.94326
450	0.80096			1250	0.96331
460	0.83499			1275	0.97755
470	0.86552			1300	0.98709
480	0.89237			1325	0.99306
490	0.91551			1350	0.99653
500	0.93502			1375	0.99840
510	0.95111			1400	0.99933
520	0.96406			1425	0.99974
530	0.97423			1450	0.99991
540	0.98199			1475	0.99997
550	0.98776			1500	0.99999
560	0.99192			>1500	1.00000

Table 6-2 Comparison of RADTRAN 5 Values with Previous Fatality Values (abbreviated listing)

Dose (rem)	*Bone Marrow old values*	*Bone Marrow new values*	*Lung old values*[a]	*Lung new values*
100,000	1.0	1.0	1.0	1.0
80,000	1.0	1.0	1.0	1.0
70,000	1.0	1.0	1.0	1.0
40,000	1.0	1.0	1.0	1.0
30,000	1.0	1.0	1.0	1.0
25,000	1.0	1.0	1.0	1.0
20,000	1.0	1.0	1.0	1.0
10,000	1.0	1.0	0.60	1.0
8,000	1.0	1.0	0.10	1.0
6,000	1.0	1.0	0.06	1.0
4,000	1.0	1.0	0.03	1.0
3,000	1.0	1.0	0	1.0
2,000	1.0	1.0	0	1.0
1,000	1.0	1.0	0	0.50000
800	0.996	1.0	0	0.13529
700	0.900	1.0	0	0.05548
600	0.400	1.0	0	0.01922
500	0.05	0.999	0	0
		1.0 if > 680		
400	0	0.978	0	0
300		0.770	0	
200		0.356	0	
150	0	0.083	0	0
100	0	0.012	0	0
<100	0	0	0	0

a. For Lung Type 1 with minimal care; all other values for intermediate level of care.

where

EXP = number of people in kth annular area

P^{EM} = probability of early morbidity in accident of severity j in kth annular area on link L, where
P = 1 if individual dose is greater than or equal to the threshold, and
P = 0 if individual dose is less than the threshold

NRAD = number of annular areas.

Early fatalities are subtracted from early morbidities to prevent double counting of acute health effects.

Table 6-2 Early Morbidity Threshold Values (derived from Evans et al., 1985, except where noted)

Organ Index (o)	Organ	Organ-Dose Morbidity Threshold (rem)	Physiological Effect
1	Lung (internal)[a]	500	Radiation Pneumonitis
2	Bone Marrow[b]	50	Depression of Hematopoesis[c]
3	Gastrointestinal Tract (stomach)	50	Prodromal Vomiting
4	Thyroid (radioiodines)	200	Hypothyroidism

[a] For external dose, 50% incidence of pneumonitis occurs at approximately 1000 rem to the thorax (Shleien, 1992, p. 602). Large external doses to the thorax occur only at whole-body doses well above the mortality threshold.
[b] ICRP 60 (ICRP, 1991, Table B-1).

The effects at or just above the threshold dose for marrow or GI tract can be indistinguishable from a mild viral infection and may go undiagnosed. At higher doses, the effects are pronounced and onset more rapid. Weakness, diarrhea, skin erythema, epilation, and other symptoms appear. This suite of symptoms, also referred to as the Acute Radiation Syndrome, involves effects on numerous organs following whole-body external radiation.

Additional possible morbidities such as lens opacities and temporary sterility are not estimated separately. The threshold for opacities of the lens that are detectable but do not cause visual impairment has been estimated at 60 rem (0.6 Sv) whole-body dose or higher, depending on dose rate and radiation type, on the basis of atomic bomb survivor data (NAS, 1990, p. 363). Neutrons appear to be more effective than gamma radiation. Actual cataracts do not occur until doses are much higher (around 200 rad ***to the eye***); doses of 200 rad to the eye usually only occur in the course of medical treatment. External radiation exposure from transportation accident scenarios, unlike medical-treatment scenarios, do not include situations in which a single organ (e.g., lens of the eye) could receive such a large dose without the rest of the body also receiving very high doses. Such an individual would already have been counted as an early morbidity or mortality. Thus, lens opacities are not treated separately, since doing so would amount to double counting. Temporary sterility may occur in males at gonad doses above 15 rem (0.15 Sv) (NAS, 1990, p. 365); no hospitalization or other treatment is required and the condition is not permanent. As was the case with cataracts, doses of this magnitude to the gonads normally would not occur unless the dose to the whole body is above at least one of the thresholds in Table 6-2. Thus, this organ dose is not considered separately. Fetal effects (mental retardation) also are not considered. In atom bomb survivor data, fetal effects were not observed before 8 weeks or after 26 weeks of gestation (NAS, 1990, p. 359). If the user wishes to estimate the number of fetal effects by an external calculation, various approaches are possible. For example, the ICRP sets 200 mrem (0.2 rem or 2 mSv) as a maximum recommended occupational dose to the abdomen for pregnant women (ICRP, 1990, p. 42). The user could multiply the number of exposed individuals in annuli with total individual doses >200 mrem, if any, (value taken directly from RADTRAN 5 output) by an appropriate factor[17] to generate an estimate.

The primary mechanism for exposure of the thyroid to above-threshold doses is inhalation or ingestion of radioiodine. Hypothyroidism is a non-fatal consequence of radioiodine inhalation or ingestion that results following the death of hormone-producing cells in the thyroid.

[17] E.g., for a pregnancy rate of 3%, the factor would be equal to: chance of being female (~0.5) x chance of female being pregnant (0.03) x chance of being in week 8 – 26 (~0.53) = 0.008 ≅ 0.01.

6.1.2 Mathematical Model for Number of Acute Health Effects from Inhalation of Dispersed Material

Early Fatalities

The probability of early fatalities from inhaled radionuclides is calculated in a manner analogous to the nondispersal case. For each downwind isopleth, A_n, the lung and bone marrow organ doses from Equation 76 are compared to the P^{EF}, the probability of early fatality (see Table 6-1). The P^{EF} for the lung accounts for dose to the lung itself. The P^{EF} for bone-marrow accounts for irradiation of the rest of the body by radiation emitted by the inhaled particulates lodged in the lung and for translocation of particles out of the lung and into other, more radiation-sensitive organs. The expected number of early fatalities is given by

$$N_{j,L}^{EF\text{-}INH} = \sum_{o=1}^{2} \sum_{n=1}^{NAREAS} \left(EXP_n \cdot P_{j,L,n,o,i}^{EF} \right) \tag{102}$$

where

$N_{j,L}^{EF\text{-}INH}$	=	number of early fatalities per dispersal accident of severity j on link L
NAREAS	=	nth isopleth area
EXP	=	expected number of persons in nth isopleth area
PD_n	=	population density of nth isopleth area (persons/km^2)
A_n	=	area of nth isopleth (km^2)
EXP_n	=	expected number of people in nth isopleth $[PD_n \cdot (A_n - A_{n-1})]$
P^{EF}	=	probability of early fatality in accident of severity j in nth isopleth for organ o on link L for radionuclide i

Early Morbidities

Early morbidity doses are estimated by reference to Equation 76 and by comparison of the organ doses with the thresholds in Table 6-3. The organs included are the lung, bone marrow, gastrointestinal tract, and thyroid (radioiodines only). Table 6-3 gives threshold dose values for manifestation of physiological effects. The number of early morbidities is estimated by summing over these organs.

$$N_{j,L}^{EM\text{-}INH} = \sum_{o=1}^{4} \sum_{n=1}^{NAREAS} \left(EXP_n \cdot P_{j,L,n,o}^{EM} \right) \tag{103}$$

where

$N_{j,L}^{EM\text{-}INH}$	=	number of early morbidities per dispersal accident in accident of severity j
NAREAS	=	nth isopleth area
EXP	=	expected number of people in nth isopleth area $[PD_n \cdot (A_n - A_{n-1})]$
$P_{j,L,n,o,i}^{EM}$	=	probability of early morbidity in accident of severity j in nth isopleth area on link L for organ o and radionuclide i, where P = 1 if individual dose is greater than or equal to the threshold, and P = 0 if individual dose is less than the threshold
PD_n	=	population density in nth isopleth area (persons/km^2)
A_n	=	area of nth isopleth (km^2)

6.2 *Latent Health Effects*

➡***The occurrence of radiogenic cancers and genetic effects is* stochastic*; that is, the* probability *of occurrence increases as dose increases, but the* severity *of the cancer or genetic effect does not.*** RADTRAN 5 uses the linear, no-threshold (LNT) model of the stochastic dose-effect relationship. In the LNT model, the probability of a latent effect is assumed to be a linear function of dose for all doses no matter how small the dose may be. The LNT model is widely regarded as being highly conservative for doses equal to or less than background (approximately 300 mrem/year in the United States) (Muckerheide, 1995). The vast majority of doses for incident-free transportation and for most accidents lie in this range.

The dose-effect conversions factors used in RADTRAN 5 are taken from BEIR V (NAS, 1990) for low doses and low dose-rates; they are consistent with ICRP 60 (ICRP, 1991). They are:

1. 5.0E-04 LCF/person-rem for the public
2. 4.0E-04 LCF/person-rem for workers.
3. 1.0E-04 Genetic Effects/person-rem.

6.2.1 Calculation of Latent Cancer Fatalities and Genetic Effects for Nondispersal Accidents

Once integrated population dose is determined, dose-effect conversion factors can be applied. The expected total dose equivalent and the gonad dose are used to estimate incidence of latent cancers and genetic effects, respectively, giving

$$N_{i,j,L}^{LCF\text{-}LOS} = LCFC \cdot D_{LOS} \tag{104}$$

and

$$N_{i,j,L}^{GE\text{-}LOS} = GEC \cdot D_{LOS}^{gonad} \tag{105}$$

where

$N_{i,j,L}^{LCF\text{-}LOS}$ = expected number of latent cancer fatalities per accident of severity j

$N_{i,j,L}^{GE\text{-}LOS}$ = expected number of genetic effects per accident of severity j

D_{LOS} = total dose equivalent (person-rem) for accident of severity j

D_{LOS}^{gonad} = organ dose (person-rem) for accident of severity j

LCFC = latent cancer fatalities conversion factor (LCF/person-rem)

GEC = genetic effects conversion factor (GE/person-rem).

6.2.2 Calculation of Latent Cancer Fatalities and Genetic Effects for Dispersal Accidents

Inhalation

Latent effects from inhalation are considered for the inhalation dose equivalent and for the gonad dose. The former is given by

$$N_{i,j,l,m}^{LCF\text{-}INH} = LCFC \cdot D_{inh} \tag{106}$$

where

$N^{LCF\text{-}INH}$ = expected number of latent cancer fatalities from inhalation per dispersal accident

LCFC = dose-effect conversion factor (LCF/person-rem)
D_{inh} = dose equivalent from inhalation (person-rem)

Expected numbers of genetic effects are obtained with the dose-conversion factor for genetic effects.

$$N_{i,j,l,m}^{GE\text{-}INH} = GEC \cdot D_{LOS}^{gonad} \tag{107}$$

where
$N^{GE\text{-}INH}$ = expected number of genetic effects from inhalation per dispersal accident
GEC = dose-effect conversion factor for genetic effects (LCF/person-rem)
D_{LOS}^{gonad} = gonad organ dose from inhalation (person-rem)

Resuspension
Latent effects from inhalation of resuspended particulates are considered for the inhalation dose equivalent and for the gonad dose. The former is given by

$$N_{i,j,l,m}^{LCF\text{-}RES} = LCFC \cdot D_{res} \tag{108}$$

where
$N^{LCF\text{-}RES}$ = expected number of latent cancer fatalities from resuspension per dispersal accident
LCFC = dose-effect conversion factor (LCF/person-rem)
D_{res} = dose equivalent from resuspension (person-rem).

Expected numbers of genetic effects are obtained with the dose-conversion factor for genetic effects.

$$N_{i,j,l,m}^{GE\text{-}RES} = GEC \cdot D_{res}^{gonad} \tag{109}$$

where
$N^{GE\text{-}RES}$ = expected number of genetic effects from resuspension per dispersal accident
GEC = dose-effect conversion factor for genetic effects (LCF/person-rem)
D_{res}^{gonad} = gonad dose from resuspension (person-rem).

Cloudshine
Latent effects from exposure to external penetrating radiation during passage of a cloud of dispersed radioactive material are calculated as follows.

$$N_{i,j,l,m}^{LCF\text{-}CLD} = LCFC \cdot D_{cld} \tag{110}$$

and

$$N_{i,j,l,m}^{GE\text{-}CLD} = GEC \cdot D_{cld}^{gonad} \tag{111}$$

where
$N^{LCF\text{-}CLD}$ = expected number of latent cancer fatalities per accident of severity j
$N^{GE\text{-}CLD}$ = expected number of genetic effects per accident of severity j
D_{cld} = total dose equivalent (person-rem) for accident of severity j from cloudshine pathway
D_{cld}^{gonad} = gonad organ dose (person-rem) for accident of severity j from cloudshine pathway
LCFC = latent cancer fatalities conversion factor (LCF/person-rem)

GEC = genetic effects conversion factor (GE/person-rem).

Groundshine
Latent effects from exposure to external penetrating radiation from deposited radioactive material are calculated as follows.

$$N_{i,j,l,m}^{LCF\text{-}GND} = LCFC \cdot D_{gnd} \tag{112}$$

and

$$N_{i,j,l,m}^{GE\text{-}GND} = GEC \cdot D_{gnd}^{gonad} \tag{113}$$

where

$N^{LCF\text{-}GND}$ = expected number of latent cancer fatalities per accident of severity j
$N^{GE\text{-}GND}$ = expected number of genetic effects per accident of severity j
D_{gnd} = total dose equivalent (person-rem) for accident of severity j from groundshine pathway
D_{gnd}^{gonad} = gonad organ dose (person-rem) for accident of severity j from groundshine pathway
LCFC = latent cancer fatalities conversion factor (LCF/person-rem)
GEC = genetic effects conversion factor (GE/person-rem).

Ingestion
Latent effects from exposure to internal radiation following ingestion of radioactive material are calculated as follows.

$$N_{i,j,l,m}^{LCF\text{-}ING} = LCFC \cdot D_{ing} \tag{114}$$

and

$$N_{i,j,l,m}^{GE\text{-}ING} = GEC \cdot D_{ing}^{gonad} \tag{115}$$

where

$N^{LCF\text{-}ING}$ = expected number of latent cancer fatalities per accident of severity j
$N^{GE\text{-}ING}$ = expected number of genetic effects per accident of severity j
D_{ing} = total dose equivalent (person-rem) for accident of severity j from ingestion pathway
D_{ing}^{gonad} = gonad organ dose (person-rem) for accident of severity j from ingestion pathway
LCFC = latent cancer fatalities conversion factor (LCF/person-rem)
GEC = genetic effects conversion factor (GE/person-rem).

6.3 Total Health Risk from Accidents

Calculation of the expected number of health effects per accident was discussed in Section 6.2. For non-dispersal and dispersal accidents alike, the effects are combined with accident probabilities to give a total health-effect risk ($RISK^{HE}$).

$$RISK^{HE}_{i,l,m} = \sum_{j=1}^{NSEV} \gamma_{j,l} \cdot N_{i,j,l,m} \qquad (116)$$

where

NSEV	=	jth accident-severity category
γ	=	probability of occurrence of an accident of severity j on route segment l
N	=	expected number of morbidities, or mortalities, or latent cancer fatalities (LCFs) from all pathways per accident of severity j on route segment l involving material m

For each route segment, the LCF values calculated by Equation (116) are summed for all materials (m index) in the shipment and printed in the RADTRAN 5 output as the health-effects risk for each route segment identified by the analyst. Morbidities and mortalities, if any, are reported in separate tables.

6.4 Expected Number of Accidents

The formulation for the expected number of accidents is discussed in this section. The computed values are given in a separate table in the RADTRAN 5 output. Calculation of accident probability (γ) was described in Chapter 5. The values of γ that are associated with each specific number of health effects can be combined to give the total expected number of accidents for each discrete number of health effects. Because health-effect-inducing accidents are very infrequent, a Poisson probability density function may be used with the expected number of accidents as the parameter of the distribution:

$$P(B) = \frac{B \cdot e^{-\gamma}}{B!} \qquad (117)$$

where

P(B)	=	probability of exactly B accidents
γ	=	expected number of accidents
B!	=	B factorial [$=1 \cdot 2 \cdot 3 \cdot \ldots \cdot (B-1)(B)$]. 0! is defined as being equal to 1.

Accidents with zero health effects per accident can be investigated by examining the case of B=0. To account for the possibility of one accident with exactly zero health effects, the probability that accidents with zero health effects will occur is computed by use of Equation (117) where B=0 and γ = the probability of accidents with no health effects. The appropriate value of γ can be obtained by subtracting the expected number of accident with one or more health effects from the total expected number of accidents.

By subtracting the probability of an accident with zero health effects from one (1.0), the probability of one or more accidents with zero health effects is obtained:

$$P(\text{1 or more accidents with 0 health effects}) = 1 - P(\text{0 health effects}) = 1 - e^{\gamma} \qquad (118)$$

where γ = [probability of no health effects].

In addition, zero health effects can be obtained by having zero accidents. The probability associated with this outcome of transportation is obtained by computing the total expected number of accidents of all severities for shipment of material m:

$$\gamma = \sum_{p=1}^{NPOP} AR_L \cdot NSH_{Lm} \cdot DIST_L \tag{119}$$

where

AR_L	=	accident rate on link L (accident/vehicle-km)
NSH_L	=	number of shipments on link L of material m
$DIST_L$	=	length of link L (km)

By applying the Poisson distribution to this value of γ with B=0, the probability of zero accidents can be calculated. The results are printed in the output.

6.5 *Importance Analysis*

RADTRAN 5 performs an importance analysis summary for incident-free transportation for each link of the route. The importance analysis summary shows the increase or decrease that every parameter value causes in the outcome of RADTRAN calculations if the value is increased by one percent (1%). It measures the relative importance of all the parameters used in a particular input file.

Consider the total incident-free dose, D, given by

$$D = \sum_a \sum_b d_b(x_1, x_2, \ldots, x_c) \tag{120}$$

Here, the first summation represents all shipments and the second summation represents all dose subgroups. The importance measure, I_c, is defined as the person-rem change in D, given a one-percent (1%) change in the value of parameter x_c. The value of ΔD is approximated by the product of one percent of each parameter and the first partial derivative of the dose expression with respect to that parameter. The Importance (I) of the cth parameter is calculated according to

$$I_c = x_c \frac{\partial D}{\partial x_c} = \sum_a \sum_b x_c \frac{\partial d_b}{\partial x_c} \tag{121}$$

This can be rewritten as,

$$I_c = x_c \frac{\partial D}{\partial x_c} = \sum_a \sum_b \frac{\partial d_b}{\partial x_c} \frac{x_c}{d_b} d_b \tag{122}$$

or as

$$I_c = x_c \frac{\partial D}{\partial x_c} = \sum_a \sum_b \left(\frac{d \ln d_b}{d \ln x_c} \right) d_b \tag{123}$$

Values of Equation 123 calculated for each input variable are printed in each RADTRAN 5 output. Figure 6-1 is an example of the importance analysis summary for incident-free dose, which is printed with the output for each run of RADTRAN 5.

Figure 6-1. Example of Importance Analysis in RADTRAN 5 Output for a Single Route-Segment

```
INCIDENT-FREE IMPORTANCE ANALYSIS SUMMARY
ESTIMATES THE PERSON-REM INFLUENCE OF A ONE PERCENT INCREASE IN THE
PARAMETER

LINK     PARAMETER                          IMPORTANCE     CHANGE
SEG1-----------------------------------------------------------------
         DOSE RATE FOR VEHICLE (TI)          8.693E-01    10.0000 %
         NUMBER OF SHIPMENTS                 8.693E-01    10.0000 %
         DISTANCE TRAVELED                   8.693E-01    10.0000 %
         NUMBER OF CREW MEMBERS              6.837E-01     7.8657 %
         K ZERO FOR CREW DOSE                6.837E-01     7.8657 %
         CREW DOSE ADJUSTMENT FACTOR         6.837E-01     7.8657 %
         K ZERO FOR VEHICLE                  1.855E-01     2.1343 %
         NUMBER OF PEOPLE PER VEHICLE        1.815E-01     2.0881 %
         TRAFFIC COUNT                       1.815E-01     2.0881 %
         SHIELDING FACTOR (RR,RS,RU)         4.020E-03     0.0462 %
         POPULATION DENSITY                  4.020E-03     0.0462 %
         NUMBER OF FLIGHT ATTENDANTS         0.000E+00     0.0000 %
         RATIO OF PEDESTRIAN DENSITY (RPD)0.000E+00        0.0000 %
         DIST DEP RAIL WORKR EXPOSR FACTR 0.000E+00        0.0000 %
         VELOCITY                           -1.051E+00    -12.0881 %
         DISTANCE FROM SOURCE TO CREW       -1.367E+00    -15.7314 %
```

6.6 Regulatory Checks

A check sequence is included in RADTRAN 5 to assess compliance with exclusive-use shipment criteria and regulatory compliance of the user's input values that describe the shipment with the maximum permissible dose rates to which the general public, and transportation and other workers may be exposed.

Title 49 of the Code of Federal Regulations (Sections 173 through 177) specifies criteria that must be applied to determine whether a package or shipment is to be designated as exclusive-use. The criteria are the following:

1. The package dose rate is greater than 10 mrem/hr (49 CFR 173.441(b))
2. The surface dose rate of the package is greater than 200 mrem/hr (49 CFR 173.441(b));
3. The sum of all dose rates for the packages in a shipment would exceed 200 mrem/hr (49 CFR 174.7(b), 176.704, 177.842)
4. The sum of all dose rates of a package that is not handled during in a closed vehicle cannot exceed 1000 mrem/hr (49 CFR 173.441(b)(1));
5. The dose rate at any surface of the vehicle cannot exceed 200 mrem/hr (49 CFR 173.441(b)(2));
6. The dose rate at a distance of 2 m (6.6 ft) from any edge of the transporting vehicle cannot exceed 10 mrem/hr (49 CFR 393.441(b)(3)); or
7. The dose rate in the crew compartment must be less than 2 mrem/hr (49 CFR 173.441(b)(2))

The regulatory checks that RADTRAN 5 performs tell the user whether the variables for a shipment of radioactive material that he or she has entered in a RADTRAN 5 input file comply with Federal regulations for maximum permissible dose rates to population or crew, and with exclusive-use criteria. RADTRAN 5 does not allow the user to perform a computer run for a shipment that fails to meet these regulations without a printed message being inserted in the output file. Should the user choose to ignore the regulatory checks, a message stating that the regulatory checks have been disabled will be printed in the output.

6.6.1 Exclusive-Use Designation

An exclusive-use package is one that must be transported in a vehicle exclusively assigned to that shipment (i.e., shipped without other freight or cargo present in the same vehicle or ship hold). There are three criteria, and if any one of them is exceeded, then the package must be designated as exclusive-use.

1. Any package with a DR_p greater than 10 (mrem/hr);
2. Any package with a surface dose rate greater than 200 mrem/hr;
3. Any shipment (vehicle) consisting of more than one package in which the summed dose rate of all packages is greater than 50 (mrem/hr).

A shipment not originally designated exclusive-use by the RADTRAN 5 user will be re-designated as exclusive-sue (i.e., the exclusive-use flag in the input file may be reset to *true*), if any of the test results are true. That is, if

- $DR_p > 10$
- $DR_p \dfrac{1+0.5d_{e_p}}{0.5d_{e_p}} > 200$, where d_{e_p} is the characteristic package dimension
- $\sum_{i=1}^{i=n} DR_{p_i} \cdot PPS_i > 50$, where PPS is the number of packages of type i in the shipment.

The second formula extrapolates the package dose rate to the surface on the basis of the radial distance from the line-source representation of the package by use of the characteristic package dimension and the line-source model.

If one of these regulatory criteria is exceeded, execution of RADTRAN 5 is not stopped, but an informational message describing the exceedance is printed in the output. This allows the user to analyze shipments that may exceed the criteria. Some radiopharmaceutical shipments, for example, may take place under a waiver of the third rule. If all three tests are satisfied, then the shipment meets the nonexclusive-use requirements, the calculation proceeds, and no informational message is printed in the output.

Satisfying these tests does not mean that the shipment cannot be exclusive-use, only that it is not required to be. However, if a particular shipment is designated exclusive-use by the analyst, then it must comply with exclusive-use regulations, which involve additional regulatory checks described below.

By regulation, the dose rate at any point on the outer surface of the exclusive-use vehicle cannot exceed 200 mrem/hr [10 CFR 71.47 and 49 CFR 173.441(b)]. In addition to the package-surface check described above, RADTRAN 5 performs a check of the dose rate at the outer surface of the vehicle (under the assumption that there is no intervening space between the vehicle surface and package surfaces). The vehicle is treated as a line source at distances closer than 1 m. The surface dose rate is given by

$$DR_{surface} = DR_v \frac{1+0.5d_{e_v}}{0.5d_{e_v}} \tag{124}$$

where

$DR_{surface}$ = dose rate a vehicle surface (mrem/hr)
DR_v = vehicle dose rate at 1 m from surface (mrem/hr)
d_{e_v} = effective dimension of shipment vehicle (m)

In this case, if the regulatory limit of 200 mrem/hr for vehicle surface dose rate is exceeded, then DR_v is reset to the result of the following expression for all subsequent calculations

$$DR_v = 200\left[\frac{0.5d_{e_v}}{1+0.5d_{e_v}}\right] \tag{125}$$

The following message is printed in the output to inform the user:
FOR [vehicle label] THE SURFACE DOSE RATE COULD EXCEED 200 MREM/HR.
THE VEHICLE DOSE RATE HAS BEEN RESET TO EQUAL [y]
where y = result of Equation 125.

Once the surface dose rate check is satisfied, then the dose rate in the crew compartment (DR) is examined to determine whether the calculated value is less than or equal to the regulatory limit of 2 mrem/hr by evaluating the following expression.

$$DR_{crew} = k_{0,end} \cdot DR_v \cdot CSF_v \left[\left[\frac{FG_v \cdot TR_{G,r}}{r_{end}^2} \right] + \left[\frac{FN_v \cdot TR_{N,r}}{r_{end}^2} \right] \right] \tag{126}$$

where

DR_{crew}	=	dose rate in the crew compartment (mrem/hr)
$k_{0,end}$	=	point-source crew-view shape factor (m)
DR_v	=	vehicle dose rate (mrem/hr)
CSF_v	=	crew shielding factor for vehicle v
FGv	=	fraction of vehicle dose rate from gamma radiation
FN_v	=	fraction of vehicle dose rate from neutron radiation
$TR_{G,r}$	=	gamma dose-distance relationship at distance r
$TR_{N,r}$	=	neutron dose-distance relationship at distance r
r_{end}	=	distance from source to crew (m)

The crew-view shape factor ($k_{0,end}$) is determined by use of Equation to a d_e derived from the characteristic dimension of the package surface closest to the crew compartment. For spent-fuel truck shipments, for example, this dimension would usually be the cask diameter. If the dose rate is acceptable, then the actual value is used for calculating dose to crewmembers. If the dose rate is calculated to be greater than 2 mrem/hr, then the value is reset to 2 mrem/hr for the calculation of crew dose because measures (e.g., added shielding) must have been taken to ensure regulatory compliance before transportation is permitted. The following message is printed in the output to inform the user.
FOR THE SHIPMENT OF [vehicle label] THE DOSE RATE IN THE CREW COMPARTMENT COULD EXCEED 2 MREM/HR. THE DOSE RATE HAS BEEN RESET FROM [x] TO 2 FOR CREW DOSE CALCULATIONS
where x = result of Equation 21.

If this test is satisfied, then RADTRAN 5 examines the dose rate at 2 m from the edge of the vehicle. Packages are modeled as being located at the edge of the vehicle, and the loaded vehicle is assigned a line source configuration. The expression for this dose rate is

$$DR_v(2\,m) = DR_v \cdot \left[\frac{1 + 0.5 d_{e_v}}{2 + 0.5 d_{e_v}} \right], \tag{127}$$

where

$DR_v(2\,m)$	=	total dose rate at 2 m from the vehicle surface (mrem/hr)
DR_v	=	total dose rate at 1 m from the vehicle surface (mrem/hr)
d_{e_v}	=	effective dimension of shipment vehicle (m)

If the vehicle dose rate at 2 meters exceeds 10 mrem/hr, then DR is set equal to $10\left[\frac{2+0.5d_{e_v}}{1=0.5d_{e_v}}\right]$ for the calculation of dose to persons along the transport link, dose to persons sharing the transport link, and dose while stopped. This is done in anticipation of regulatory compliance, and the following informational message is printed:

FOR THE SHIPMENT OF [vehicle label], THE DOSE RATE A 2 METERS COULD EXCEED 10 MREM/HR. THE VEHICLE DOSE RATE HAS BEEN RESET TO EQUAL [z].

where $z = 10\left[\frac{2+0.5d_{e_v}}{1=0.5d_{e_v}}\right]$

Otherwise, DR_v is used directly. In addition, several quantitative criteria must be satisfied. These criteria are:

A. For all modes except air, if a shipment is designated as exclusive-use but is not required to be, then the following message is printed:

THE SHIPMENT BY [vehicle label] IS DESIGNATED AS EXCLUSIVE USE BUT IS NOT REQUIRED TO BE SO DESIGNATED BY REGULATIONS.

B. If a shipment is designated as exclusive-use and is by air mode, then the following message is printed:

!!!! WARNING !!!! 49 CFR 173 DOES NOT PERMIT EXCLUSIVE USE AIR SHIPMENTS, COMPUTATIONS PROCEED...

C. Conversely, if a shipment has not been designated as exclusive-use, but is required to be, then the following message is printed in the output:

[vehicle label] HAS BEEN DESIGNATED AS EXCLUSIVE USE.

7 Special Topics

7.1 RADTRAN 5 Validation

➨Validation is the process of ensuring that a model embodied in a code is an acceptable representation of the process it is intended to replicate.

7.1.1 Source Representation in Incident-Free Dose Calculations

The incident-free dose calculations in RADTRAN 5 are based on idealized models of RAM packages and conveyances. The models do not directly account for secondary factors such as reflection and shielding by the conveyance itself and, in some cases, intervening objects. The models conservatively estimate the influence of build-up and attenuation. Thus, they are somewhat conservative in all situations. The degree of conservatism has not been fully quantified, but preliminary empirical results indicate that RADTRAN yields values for off-link dose that are a factor of eight to ten higher than measured values (McFadden, Boles, and Steinman, 1999). This is consistent with earlier studies with the INTERTRAN code (based on RADTRAN II) (Permattei et al., 1985; DeMarco et al., 1983). The latter authors found that the INTERTRAN/RADTRAN II predictions were larger than measured doses for several classes of incident-free dose. In fact, Permattei et al. had difficulty detecting a measurable dose at locations immediately adjacent to the transport route for actual spent fuel shipments in Italy.

7.1.2 Health Effects Conversion Factors

The validity of the calculations that RADTRAN performs also depends on the health-physics community's understanding of radiological health effects causation and on the accuracy and completeness of user-supplied data. The health-effects model from the "Reactor Safety Study" (NRC, 1975), which is obsolete, was formerly hard-coded into RADTRAN. It is absent from RADTRAN 5; and the equations have been modified to permit currently accepted dose-effect conversion factors to be used as direct multipliers of the dose-consequence calculations. The factors now used calculate LCFs for a linear, no-threshold (LNT) model, modified for low-dose, low-dose-rate situations. The factors are 5E-04 LCFs per person-rem for the general public and 4E-10 LCFs per person-rem for workers (ICRP 60, 1990; NRC, 1989)). A recently empanelled BEIR (Biological Effects of Ionizing Radiation) committee of the National Research Council will be critically reexamining the LNT model. RADTRAN 5 may require modification following the publication of their report.

7.1.3 Package Behavior and Accident Probabilities

RADTRAN 5 does not contain a specific model of package behavior for any given package type. The user must define these values for the problem at hand, but recommended input values, based on package test data, event trees, DOT data, etc. are available for many problems and are included in the sample files at the TRANSNET Internet site. All such values are subject to ongoing re-evaluation. For example, a recent major reassessment of maritime transportation (Sprung et al., 1998) supercedes earlier analyses (e.g., DOE, 1986); the newer values yield somewhat lower risk estimates than the older work.

7.2 Verification and Software Quality Assurance

➨Verification is the process of ensuring that the equations formulated by a code's developers are faithfully executed in the program. The method of verification used is described in Kanipe and Neuhauser (1995) and in the RADTRAN 5 Software Quality Assurance Plan (SQAP) (Kanipe and Neuhauser, 2000). The RADTRAN 5 SQAP follows ANSI guidance and standard reporting outlines. As part of the QA plan, all code revisions are logged; this log is made available on the Internet at the TRANSNET site.

7.3 Non-Radiological Risk - Fatality Risk

Risk of fatality associated with transportation accidents but having non-radiological causes (e.g., physical trauma, fire) is calculated by RADTRAN 5 and printed in the output for each route-segment in the analysis. The expected number of non-radiological fatalities (FATAL) is calculated by

$$FATAL_L = 2 \cdot NONRAD_{r,\ s,\ or\ u} \cdot DIST_L \cdot NSH_L \tag{124}$$

where

NONRAD	=	rural, suburban, or urban nonradiological fatality rate (fatalities/km)
DIST	=	length of Lth route segment (km)
NSH	=	number of shipments on Lth route segment

The factor of two is included to account for return trips when the vehicle is traveling without radioactive material cargo. The appropriate value of NONRAD is determined by the user's designation of each route segment as being rural, suburban, or urban in nature.

7.4 RADDOG Input File Generator

RADDOG is a PC-compatible code written in C+ and developed for use with RADTRAN. It allows the user to build a RADTRAN input file 'from scratch' or by editing a previous file. RADDOG applications are discussed extensively in the RADTRAN 5 User Guide (Neuhauser and Kanipe, 2000)

7.5 Geographical Information System (GIS) Data

A Geographical Information System or GIS can be an important source of data for a RADTRAN input file (Ganter and Neuhauser, 1995). A GIS is particularly well suited to route-segment definition and to development of data on population density and population subgroups (e.g., environmental justice). The underlying data generated by a GIS can be converted into one or more spreadsheets (e.g., with Microsoft Excel®). The relevant data can then be extracted and placed in a RADTRAN input file. A GIS has been developed at Sandia National Laboratories that currently uses 1990 census-block data (with updates) to estimate population densities within specified population bandwidths around a transportation link and under a plume footprint anywhere in the United States. The development of data with the Sandia GIS has been automated (Mills and Neuhauser, 1999c).

It is anticipated that data and graphics developed from the Sandia GIS will be made available on the TRANSNET site along with the input files routinely published on the site for all analyses performed by Sandia National Laboratories. The actual GIS cannot be made interactive, of course, because the very large graphics files make transmission over phone lines virtually impossible. Many states, counties and cities have developed similar GISs for their own areas. These are powerful sources of high-resolution data and users are encouraged to seek them out. Recent applications of the Sandia GIS include:

- examination of urban-area avoidance in truck routing (Mills and Neuhauser, 1998);
- diurnal variation in off-link population density (Mills and Neuhauser, 1999a);
- comparison of methods of estimating population under a dispersion plume (Mills and Neuhauser, 1999b); and

- development of environmental-justice methods for transportation (Mills and Neuhauser, 2000).

7.6 Latin Hypercube Sampling (LHS) Interface

Latin Hypercube Sampling (LHS) is a method of Monte Carlo analysis that relies on structured sampling from one or more parameter probability distributions (e.g., emergency-response-time distribution). With LHS, a relatively small number of samples (usually 50 to 100) can be used to generate a meaningful CCDF (Complementary Cumulative Density Function). CCDFs are used to graphically illustrate the results of a probabilistic risk analysis. LHS is also ideally suited to sensitivity analysis applications, as was demonstrated with RADTRAN 4 (Mills, Neuhauser, and Kanipe, 1995). A semi-automated interface with the Sandia National Laboratories' LHS code (Wyss and Jorgensen, 1998) has been developed for RADTRAN 5. Its use is discussed in detail in the RADTRAN 5 User Guide (Neuhauser and Kanipe, 1999).

7.7 Population Residence Time

Demographic data from the U.S. Bureau of the Census indicate that approximately 80% of the U.S. population relocate every three years (Israeli and Nelson, 1992). One ramification of this phenomenon is that for multi-year shipping campaigns (e.g., shipments to a spent-fuel repository) potentially exposed populations living near the transportation route would not consist in subsequent years entirely of the same people as those who resided there in the first year. The Census Bureau data were used to develop an algorithm to account for this (Smith, Neuhauser, and Kanipe, 1996). The RADTRAN 5 output contains a section that gives the estimated total number of persons residing within a designated bandwidth during the user-specified number of years over which the shipments will occur (specified by keyword CAMPAIGN). One limitation of the calculation is that it does not explicitly account for situations in which occupancy is less than 100%, although a "background" level of vacancies is part of the original demographic data. Persons who move in and out of an area are modeled as replacing each other, so the same size of population is modeled as being exposed for each trip. Thus, this calculation has no effect on the off-link population dose calculated by RADTRAN 5, only on the size of the affected population.

➨***Although it is tempting to divide the cumulative off-link population dose by the total population to obtain an average individual incident-free dose, the resulting value is meaningless.*** The decrease in radiation intensity with the square of distance from the source and the wide variation in residence time at the individual level (for long shipping campaigns) jointly dictate that such an "average dose" would tell one little about the radiological status of the potentially exposed population. The individual dose subroutine is recommended instead for calculation of doses to receptors at various distances from and/or with varied frequencies of exposure to multiple shipments.

Another aspect of demographic change is increases/decreases in population density over time (most commonly seen as an increase in areas of suburban density). This phenomenon is not explicitly modeled in RADTRAN 5. However, projections of growth may be used to compare hypothetical future route-related risk predictions with present (baseline) values in exactly the same manner as that used to compare two distinct routes.

7.8 *Environmental Justice*

Environmental justice in transportation must be addressed in environmental impact statements (EISs) and environmental assessments (EAs). Bullard and Johnson (1997) discuss examples of environmental justice issues in transportation. RADTRAN 5 may used in conjunction with a GIS (see Section 7.4) to objectively and quantitatively analyze potential differences in impacts on population subgroups that may occur as a result of a routing decision. Two types of analysis may be performed. The first type involves comparisons of two or more routes. Either the relative frequency of occurrence or the actual resident population sizes of racial, economic, or other minority groups may be compared. For these comparisons to be meaningful, the routes should be broken up into segments that reflect the socio-economic zones through which the route passes, and the results for each segment should be calculated separately. The second type of analysis involves comparisons of the minority make-up of populations residing within various distances (bandwidths) of a single transportation link. This can be used, for example, to determine whether minority representation near a transportation corridor is higher than in other areas of the same city, county, etc. Examples of both types of analyses are examined in Mills and Neuhauser (2000).

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APPENDIX A

Index of Variables in RADTRAN 5

VARIABLE LIST

Variable	Description	Equations
α	reflection term (set equal to 1 for all materials)	52
a_1	dimensionless coefficient = 2.02E-02	12, 13, 14, 15, 16 17, 18
a_2	dimensionless coefficient = 6.17E-05	12, 13, 14, 15, 16 17, 18
a_3	dimensionless coefficient = 3.17E-08	12, 13, 14, 15, 16 17, 18
a_4	dimensionless coefficient = 0	12, 13, 14, 15, 16 17, 18
$a1_s$, $a2_s$ $a3_s$	unitless coefficients for gamma radiation if s = G or neutron radiation if s = N;	23, 33, 38a, 38b, 39
A	isopleth area (m^2)	61, 62, 65, 88, 89, 90
AER	aerosol fraction	76, 77, 80, 81, 82
AR	accident rate (accidents/vehicle-km)	92, 119
$b_1, \ldots, b_{11}$	railyard worker exposure factors	43
B	number of accidents	117
$B(\mu r)$	dose-rate buildup factor for surrounding medium at distance r	1, 9, 10, 11, 20, 23, 25, 31, 32, 67,
BDF	building dose factor	82
BESK0 =	Sandia National Laboratories' SLATEC math routine that computes the modified Bessel function of the third kind of order zero for real argument $(x \cdot \mu_s)$;	23
BESK1 =	Sandia National Laboratories' SLATEC math routine that computes the modified Bessel function of the third kind of order one for real argument $(x \cdot \mu_s)$.	23
BR	breathing rate (m^3/sec)	76, 77,
BSKIN =	Sandia National Laboratories' SLATEC math routine that computes repeated integrals of the modified K-zero Bessel function for argument $(x \cdot \mu_s)$;	23
X =	greek letter 'chi;' concentration of a dispersed substance(Ci/m^3)	52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 64, 65, 66, 76, 80
C	flux-to-dose-rate conversion factor	1, 3
C_G	flux-to-dose-rate conversion factor for gamma radiation	9
C_N	flux-to-dose-rate conversion factor for neutron radiation	9
C_S	source-strength modifier over defined interval where S = G for gamma and S = N for neutron radiation	40
CDF	cloudshine dose factor (rem-m^3/Ci-sec)	80, 81, 82
Ci	curies (Ci)	67, 68, 69, 70, 74, 75, 76, 77, 80, 81, 82
CL	contamination level (μCi/m^2)	84, 85, 86, 87,

		88, 89, 90
CSF_v	crew shielding factor for vehicle v	42, 47, 126
CTLVL	deposition level (Ci/m^2 per Curie released)	66
CU	contamination level after clean-up ($\mu Ci/m^2$)	87, 89
d_e	effective package or conveyance dimension (m)	5, 7, 8, 124, 125, 127
d_H	average package-to-handler distance (m)	49, 50, 51
d_p	characteristic package dimension (m)	6
d_v	characteristic conveyance (vehicle) dimension (m)	6
D	incident-free dose	120, 121, 122, 123
D_{off}	integrated off-link population dose per km (person-rem)	21, 22, 24
D_{air} =	integrated population dose to flight attendants (person-rem)	48
$D_{airpass}$	integrated dose to air passengers (person-rem)	36
$D_{cargoinspector}$	dose to cargo inspector	
D_{CL}	total integrated dose from classification and inspection (person-rem)	44
D_{cld}	integrated dose from cloudshine pathway (person-rem)	80, 81, 82, 96, 110
D_{cld}^{gonad}	integrated dose to gonads from cloudshine pathway (rem)	111
D_{crew}	integrated dose to crew members (person-rem)	42
D_{gnd}	integrated dose from groundshine pathway (person-rem)	88, 89, 90, 91, 97, 112
D_{gnd}^{gonad}	integrated dose to gonads from groundshine pathway (rem)	113
D_H =	integrated dose to handlers of medium & large packages (person-rem)	50
D_{Hline}	integrated dose to handlers for line-source geometry (person-rem)	51
D_{Hsmall}	integrated dose to handlers of small packages (person-rem)	49
D_{inh}	integrated dose from inhalation pathway (person-rem)	76, 77, 78, 94, 106
D_{inh}^{gonad}	integrated dose to gonads from inhalation pathway (rem)	107
D_{ing}	integrated dose from ingestion pathway (person-rem)	98, 114
D_{ing}^{gonad}	integrated dose to gonads from ingestion pathway (rem)	115
D_{LOS}	integrated dose to public from loss of shielding (person-rem)	69, 70, 74, 75, 93, 104
D_{LOS}^{gonad}	integrated dose to gonads from loss of shielding (rem)	105
D_{opp}	integrated on-link population dose to persons in vehicles traveling in the opposite direction (person-rem)	26, 27a, 27b
$D_{railworker}$	integrated rail worker dose (person-rem)	43, 44
D_{res}	integrated dose from resuspension pathway (person-rem)	78, 95, 108
D_{res}^{gonad}	integrated dose to gonads from resuspension pathway (rem)	109
D_{sdir}	integrated on-link population dose to persons in vehicles traveling in the same direction (person-rem)	29, 31
D_{stop}	integrated population dose at a stop (person-rem)	41
D(x)	total integrated dose absorbed by an individual at distance x (rem)	19, 21
DC	deposited concentration (Ci/m^2)	86
DDC =	the number of distance-dependent classifications per km	45
DEP	amount deposited in an isopleth area (Ci)	61, 62, 63, 64, 65,
DIC	the number of distance-independent classifications per trip	45
DIST	length of link (km)	24, 31

$DIST_L$	length of link L (km)	27a, 27b, 28, 30, 34, 36, 45, 47, 48, 92, 119
DR	dose rate (mrem/hr)	84
DR_{crew}	dose rate in crew compartment (mrem/hr)	126
DR(r)	dose-rate at distance r (dose/time); may have subscripts (e.g., $DR_g(r)$)	1, 2, 4, 7, 10, 11, 12, 14, 15, 16, 17, 18, 67, 68,
DR(T)	dose rate at time T following deposition (rem/day)	85
DR_p	dose rate of package at 1 m from surface (mrem/hr)	4, 7, 11, 15, 16, 17, 18, 49, 50, 51
$DR_{surface}$	surface dose rate (mrem/hr)	124
DR_v	dose rate of conveyance at 1 m from surface (mrem/hr)	4, 7, 11, 15, 16, 29, 31, 34 17, 18, 19, 22, 24, 26, 27a, 27b, 28, 36, 37, 40, 42, 43, 47, 48, 124, 125, 126, 127
DR_v(2 m)	total dose rate at 2 m from the vehicle surface (mrem/hr)	127
ε	Greek letter 'eta,' photon energy (Mev)	67, 68, 69, 70, 74
$e^{-\mu r}$	[see exp(-μr)]	
exp(-μr)	attenuation in a medium at distance r (m^{-1})	1, 9, 10, 11, 12, 14, 15, 16, 17, 18, 20, 23, 25, 31, 32, 33, 38a, 38b, 67
E_1	first-order exponential integral	83
E_G	gamma emission rate (photons/sec)	9
E_N	neutron emission rate (neutrons/sec)	9
E1	Sandia National Laboratories SLATEC math routine that computes the single-precision exponential integral for positive, single-precision argument ($\mu_S \cdot x$)	33, 39
EF	exposure fraction for loss of shielding	67, 68, 69, 70,
ET	elapsed time (days)	85
EXP	number of exposed persons in an annular area	71, 72, 73, 100, 101, 102, 103
F_1 =	traffic factor	34, 35a
F_2	traffic factor	34, 35b
FG	fraction of dose rate at 1 m from package or conveyance that is gamma radiation	10, 15, 17, 24, 28, 32, 37, 41, 42, 43, 47, 49, 50, 51, 126
FN	fraction of dose rate at 1 m from package or conveyance that is neutron radiation	10, 11, 16, 18, 24, 28, 32, 37, 41, 42, 43, 47, 49, 50, 51, 126
γ	Greek letter "gamma," expected number of accidents	117, 118, 119
$\gamma_{j,L}$	Greek letter "gamma," probability an accident	92, 93, 94, 95,

		96, 97, 98, 116.
GDF	groundshine dose factor (rem-m^2/day-μCi)	84, 85, 88, 89, 90
GEC	genetic effects conversion factor	105, 107, 109, 111, 113, 115
H	release height (m)	52, 56, 57, 58
I_c	importance of cth parameter	121, 122, 123
I(x)	integration function	20, 22, 24
I′(x)	function integrated by GAUS8; describes vehicle passing at minimum perpendicular distance x	23, 26, 27a, 27b, 28
IF	integrated factor over all downwind areas (***)	77, 81, 82
IR_S	integration over an annular area from radial distance x_{min} to radial distance x_{max}	39, 40
k	symbol for flux (photons/sec)	2, 3,
k_0	package shape factor (for point source) (m^2)	4, 5, 11, 12, 15, 16, 19, 22, 26, 27a, 27b, 28, 29, 31, 34, 37, 41, 50
$k_{o,end}$	"crew-view" point-source package shape factor (m^2)	42, 47, 126
k_0	package shape factor (for line source) (m)	8, 14, 17, 18, 24, 37, 43, 51
k_H =	handling-to-dose conversion factor for small packages (2.5E-04 rem/handling/DR_p)	49
k_p	empirical dose-rate conversion factor (3E-05 rem/hr/TI)	36, 48
(1) λ_1	decay factor $= 0.693(1/365 + 1/t_{1/2})$	79
(2) λ_1	$\frac{0.63}{0.0031t_{1/2_1} + 0.693}$ (see TRM1)	88
(1) λ_2	decay factor $= 0.693/t_{1/2}$	79
(2) λ_2	$\frac{0.0031t_{1/2_1} + 0.693}{t_{1/2_1}}$ (see TRM1)	88
λ_3	$\frac{0.37}{0.000021t_{1/2_1} + 0.693}$ (see TRM2)	88
λ_4	$\frac{0.000021t_{1/2_1} + 0.693}{t_{1/2_1}}$ (see TRM2)	88
LCFC	latent cancer fatality conversion factor for general public	104, 106, 108, 110, 112, 114
μ	attenuation coefficient for surrounding medium (m^{-1})	1, 9, 10, 11, 12, 23, 67, 83
μ_{air}	attenuation coefficient for air (m^{-1})	25
μ_S =	attenuation coefficient for gamma (S = G) or neutron (S = N)) radiation (m^{-1})	33, 39, 40

max	maximum distance perpendicular to shipment route over which exposure is evaluated (m) used as limit of integration	21, 22, 24
max	outer radius of annulus (m)	40
min	minimum distance from population to shipment centerline (m) used as limit of integration	21, 22, 24, 25
min	inner radius of annulus (m)	40
min-sdir	minimum distance = $\lvert 2V \rvert$	31
N =	expected number of morbidities, or mortalities, or latent cancer fatalities (LCFs) from all pathways	116
N_{crew}	number of crew members	42
N_{flatt} =	number flight attendants on board	48
N_{pass} =	number of air passengers on board	36
N^{EF}	number of early fatalities	100
$N^{EF\text{-}INH}$	number of early fatalities from inhalation	102
$N^{EM\text{-}LOS}$	number of early morbidities from loss of shielding accident	101
$N^{EM\text{-}INH}$	number of early morbidities from inhalation	103
$N^{GE\text{-}CLD}$	number of genetic effects from cloudshine	111
$N^{GE\text{-}GND}$	number of genetic effects from groundshine	113
$N^{GE\text{-}LOS}$	number of genetic effects from loss of shielding accident	105
$N^{GE\text{-}ING}$	number of genetic effects from ingestion	115
$N^{GE\text{-}INH}$	number of genetic effects from inhalation	107
$N^{GE\text{-}RES}$	number of genetic effects from resuspension	109
$N^{LCF\text{-}CLD}$	number of latent cancer fatalities from cloudshine	110
$N^{LCF\text{-}GND}$	number of latent cancer fatalities from groundshine	112
$N^{LCF\text{-}ING}$	number of latent cancer fatalities from ingestion	114
$N^{LCF\text{-}INH}$	number of latent cancer fatalities from inhalation	106
$N^{LCF\text{-}LOS}$	number of latent cancer fatalities from loss of shielding accident	104
$N^{LCF\text{-}RES}$	number of latent cancer fatalities from resuspension	108
N'	one-way traffic count (average number of vehicles per hour in all lanes)	27a, 27b, 28, 31
N_L'	traffic count on link L	34
NCL	number of rail classifications per trip	44, 45
NE	neutron emission factor (neutrons/sec-Ci)	75
NRAD	number of annular areas	74, 75
NSH	number of shipments	24, 27a, 27b, 28, 44
NSH_L	number of shipments on link L	30, 34, 92, 119
NSH_v	number of shipments by conveyance v	36, 37, 41, 42, 43, 47, 48, 49, 50, 51
π	Greek letter 'pi;' = 3.1415	1, 3, 41, 52, 53, 54, 55, 56, 57, 58, 69, 70, 72, 73, 75
ϕ	Greek letter 'phi,' uncollided flux (photons/cm^2/sec)	83
P_{st}	average number of exposed persons at stop	37
P^{EF}	probability of early fatality	100, 102
P^{EM}	probability of early morbidity	101, 103
$P_{V,G}$ or $P_{V,N}$	form of integral from Equation 31	
PD	population density (persons/km^2)	21, 22, 69, 70,

PD_L	population density on link L (persons/km^2)	71, 72, 73, 24, 77, 81, 82, 88, 89, 90
PD_{st}	population density at a stop (persons/km^2)	41
PPS	number of packages per shipment	49, 50, 51, 67, 68, 69, 70, 74, 75, 76, 77, 80, 81, 82, 86, 89, 90,
PPV	vehicle occupancy (ave. number of persons per vehicle)	27a, 27b, 31
PPV_L	vehicle occupancy on link L	28, 34
(1) Q	units conversions factor	4, 7, 11, 12, 14, 21, 67
(2) Q	rate of release of dispersed substance (Ci/sec)	52, 53, 54, 55, 56, 57, 58
Q_1	units conversion factor = 2.8E-10 rem-km-hr/mrem-m-sec	15, 16, 17, 18, 22, 24, 42, 43
Q_2	units conversion factor = 7.7E-08 rem-hr^2-m/mrem-sec^2-km.	28, 34
Q_3	units conversion factor = 0.28 m-hr/km-sec	36, 48
Q_4	units conversion factor = 1.0E-03 rem/mrem	37, 41, 50, 51
Q_5	units conversion factor = 2.0E-07 m-hr-day/km-sec-min	47
Q_6	units conversion factor = 0.5 rem-m/hr-Ci-Mev	68, 69, 70, 74
Q_7	units conversion factor = 1.0E-06 km^2/m^2	69, 70, 71, 72, 73, 77, 81, 82, 88, 89, 90
Q_8	units conversion factor 1.0E-06 m^2/cm^2	75
Q_9	units conversion factor = 1.0E+6 μCi/Ci	86
r	radial distance from point source (m)	1, 2, 4, 7, 9, 10, 11, 12, 14, 15, 16 17, 18, 20, 23, 25, 28, 29, 32, 43, 67, 69, 70, 83
r_{end}	source-to-worker distance for truck crew members (m)	42, 126
r_k	radial distance from source for annular area determination (m)	68, 71, 72, 73, 74, 75
r_{st} =	average radial source-to-receptor distance at stops (m)	37
r_{stow}	source-to-worker distance at railyards	43
R	ratio of unshielded and shielded cases for calculation of off-link dose	25
R_S	railyard worker dose factor for gamma (S = G) and neutron (S = N)	43
RDF	resuspension dose factor	78, 79
RESP	respirable fraction	76, 77,
RF	release fraction	76, 77, 80, 81, 82
$RISK^{HE}$	health-effects risk	116
$RISK^{CLD}$	cloudshine dose-risk	96, 99
$RISK^{GND}$	groundshine dose-risk	97, 99
$RISK^{ING}$	ingestion dose-risk	98
$RISK^{INH}$	inhalation dose-risk	94, 99
$RISK^{LOS}$	dose-risk for loss of shielding	93
$RISK^{RES}$	resuspension dose-risk	95, 99

$RISK^{TOTAL}$	total dose-risk from dispersion	99
RPC	dose conversion factor (rem/Ci)	76, 77,
$RPD_{s\ or\ u}$	ratio of pedestrian density to residential population density in suburban (s) or urban (u) route segments.	24, 69, 70, 71, 82
RU	building shielding factor for urban areas	72
σ_y	crosswind meteorological constant (m)	52, 53, 54, 55, 56, 57, 58
σ_z	vertical meteorological constant (m)	52, 53, 54, 55, 56, 57, 58
S	source strength (photons/cm^2/sec)	83
S_{photon}	particle or photon emission rate (photons/sec)	1, 3
$\frac{S_{photon}}{4\pi r^2}$	flux at distance r (photons/sec/cm^2)	1
SEG	number of segments per annulus = 8	71
SF	shielding factor	24
SF_p	shielding factor in population zone p	69, 70,
SF_{st}	shielding factor for stop population	37, 41
$SV_{j,L}$	fraction of accidents of severity j on link L	92
sw	sidewalk width (m); used as a limit of integration	24
SWALK	width of sidewalk (m)	71
t	exposure time for on-link dose calculation	29, 30
$t_{1/2}$	half-life (days)	85, 88, 89, 90
T	exposure time (hr)	69, 70, 74, 75
T_E	time before evacuation begins (days) (see TRM1)	88
T_H	average exposure time of handlers (hr)	50, 51
T_S	survey time (days) (see TRM2)	88
T_{st}	average stop time (hr)	37, 41
TDF	total decontamination factor	87
TR_G	term for gamma radiation source strength at distance r	37, 38a, 42, 43, 49, 50, 51
$TR_{G,2}$	dose-distance relationship factor at 2 m for gamma radiation	47
$TR_{G,r}$	dose-distance relationship factor at r m for gamma radiation	126
TR_N	term for neutron radiation source strength at distance r	37, 38b, 42, 43, 49, 50, 51
$TR_{N,2}$	dose-distance relationship factor at 2 m for neutron radiation	47
$TR_{N,r}$	dose-distance relationship factor at r m for neutron radiation	126
TRM1	$\left[\lambda_1(1-e^{-\lambda_2 T_E})+\lambda_3(1-e^{-\lambda_4 T_E})\right]$	88, 89, 90
TRM2 =	$\left[\lambda_1 e^{-(\lambda_2 T_S)}+\lambda_3(e^{-\lambda_4 \cdot T_S}-e^{-\lambda_4 \cdot 1.83E+4})\right]$	88, 89
u	wind speed (m/sec)	52, 53, 54, 55, 56, 57, 58
UBF	urban fraction of persons indoors	72, 82,
USWF	urban sidewalk fraction	82

V		conveyance velocity (m/s)	24
V_d		particle deposition velocity (m/s)	55, 58, 61, 62, 65, 66, 79
V_L		conveyance speed on link L (m/s)	28, 30, 34, 35a, 35b, 36, 42, 47, 48
V_v		conveyance speed (m/s)	19, 22, 26, 27a, 27b, 31,
x	=	minimum perpendicular distance of individual from shipment path or radial distance from stopped shipment (m)	19, 20, 22, 23, 25, 26, 35b, 39
x_{min}		see min (m)	40
x_{max}		see max (m)	40
Y_v		integral from Equation 31	32, 35a

APPENDIX B

Derivation of b Factor for Rail Transportation

B.1 Introduction

This appendix documents the derivation of the factors b_1 through b_{11} that are used in calculating incident-free dose to rail workers (Section 3.5.2, Equation 43).

The b factors were developed from time and motion data reported in Wooden (1986). Wooden conducted "a detailed analysis of rail operations that are important for assessing the risk of transporting high-level nuclear waste." Wooden identified three categories of activities that take place in rail operations, mainly in railyards, during which rail workers routinely would come into proximity to a spent-fuel shipment or similar large-quantity Type B shipment. These activity categories are:

- Classification
- Repair
- Inspection.

The emphasis of the Wooden report was on "general freight" shipments, which includes all three categories. Only Inspection is routinely practiced for dedicated rail shipments. For each operation in a category, Wooden estimated the average number of person-hours necessary to perform a task and the average distance from a hypothetical RAM car. Wooden derived these values from actual observations of worker numbers and elapsed times. In some cases, elapsed time was determined by velocity of the railcar(s). The resulting values, given below, give person-hours for each task and average worker distance. At all distances except 20 m, a line-source formulation is applied; at 20 m a point-source formulation is required. The units of b are person-hr/m in all cases, however, so the k_0 in the usual point-source formulation was set equal to $3.5\,k_0'$ and the 20-m case was treated mathematically in the same manner as a line-source (Wooden, 1986, Appendix A).

Section B.2 contains tables that list the person-hours and distances for each step in each of four possible classification operations. The type of classification operation actually used depends on the layout of the railyard. Section B.3 describes similar steps for performing a railcar inspection; and Section B.4 addresses the four types of railcar-repair facilities. Finally, in Section B.5, b factors are derived from the foregoing data.

B.2 Classification Procedures

B.2.1 Shove-to-Rest FLAT

Operation	person-hr	distance (m)
Rider – RAM car cut	.0204	3
Rider – cover car cut	.0055	3
RAM car-locom.	.0056	4
trim engine	2.7E-04	3
trim engine	4.9E-04	3
trim engine	7.0E-06	20^2
trim engine	7.5E-04	4
trim engine	1.5E-03	4
trim engine	1.2E-05	20^2

B.2.2 Shove-to-Rest Low Hump

Operation	person-hr	distance (m)
Rider – RAM car cut	.0204	3
Rider – cover car cut	.0055	3
Rider – rehump	.0207	3
Rider – rehump	.0018	4
trim engine	2.7E-04	3
trim engine	4.9E-04	3
trim engine	2.0E-06	20^2
trim engine	2.5E-04	4
trim engine	5.0E-04	4
trim engine	4.0E-06	20^2

B.2.3 Shove over Hump

1. From Hump Crest end-to-end

Operation	person-hr	distance (m)
hump engine crew	.0425	3
tower occupants	.00193	5
tower occupants	.00136	9
trim engine crew	7.6E-04	3
trim engine crew	7.0E-06	20^2
trim engine crew	7.5E-04	4
trim engine crew	3.7E-06	20^2

2. From Hump Crest push-pull

Operation	person-hr	distance (m)
hump engine crew	.0425	3
tower occupants	.0028	9
trim engine crew	7.6E-04	3
trim engine crew	.0015	4
trim engine crew	7.0E-06	20^2
trim engine crew	7.5E-04	4
trim engine crew	1.2E-05	20^2

3. From HazMat track[1] end-to-end

Operation	person-hr	distance (m)
hump engine – rider	.0305	3
hump engine – crew	.0012	20[2]
hump engine - pin puller	6.7E-04	3
hump engine - pin puller	.015	3
hump engine – rider	.005	3
hump engine – rider	.0067	3
tower occupants	.00193	5
tower occupants	.00136	9
trim engine crew	7.6E-04	3
trim engine crew	7.0E-06	20[2]
trim engine crew	7.5E-04	4
trim engine crew	3.7E-05	20[2]

4. From HazMat track[1] push-pull

Operation	person-hr	distance (m)
hump engine crew	.0305	3
hump engine crew	.0012	20[2]
hump engine crew	.02737	3
tower occupants	.0028	9
trim engine crew	7.6E-04	3
trim engine crew	7.0E-06	20[2]
trim engine crew	7.5E-04	4
trimengine crew	.0015	4
trim engine crew	1.2E-05	20[2]

B.2.4 Shove from Trim End

1. Shove from trim end; from hump crest; end-to-end

Operation	person-hr	distance (m)
hump personnel	.0186 (p. 65)	5
hump personnel	.0131 (p. 65)	9
hump personnel	5.9E-04 (p. 49)	3
hump personnel	4.4E-04 (p. 49)	4
hump personnel	9.5E-04 (p. 51)	4
tower occupants	.00193	5
tower occupants	.00136	9
trim engine - classifying (rider)	.0383 (p.65)	3
trim engine – classifying (crew)	.1189	4
trim engine – assembly	.00954	3
trim engine – assembly	.00938	4
trim engine – assembly	.00102 (p. 54)	20[2]

[1] Also called "dynamite track" where hazardous material cars are placed in yard while drafts of cars are being coupled to form a consist (train of cars); usually remote from other areas of yard.

2. Shove from trim end; from hump crest push-pull

Operation	person-hr	distance (m)
hump personnel	.0334 (p. 65)	9
hump personnel -pin puller	.0012 (p. 49)	3
hump personnel - pin puller	9.0E-04 (p.55)	4
hump personnel	.0019 (p. 51 & 55)	4
hump personnel	.0028 (p. 55)	9
trim engine – classifying (rider)	.0383 (p. 65)	3
trim engine – classifying (crew)	.1189	4
trim engine – assembly	.00954	3
trim engine – assembly	.00039	20^2
trim engine – assembly	.0469	4

3. Shove from trim end; from HazMat track; end-to-end

Operation	person-hr	distance (m)
hump personnel – shoving –cab	.0500 (p.66)	3
hump personnel – shoving – cab	.0750 (p.66)	4
hump personnel – cut	.00067 (p. 67)	3
hump personnel – placement	.015 (p. 67)	3
hump personnel – pickup	.0075 (p. 67)	3
hump personnel – cab	.01125 (p. 67)	4
tower occupants	.00193	5
tower occupants	.00136	9
trim engine – classifying (rider)	.0383 (p. 65)	3
trim engine – classifying (crew)	.0439 (p. 66)	4
trim engine – assembly	.00954	3
trim engine – assembly	.00938	4
trim engine – assembly	.00102	20^2

4. Shove from trim end; from HazMat track; push-pull

Operation	person-hr	distance (m)
hump personnel – shoving –cab	.0500 (p.66)	3
hump personnel – shoving – cab	.0750 (p.66)	4
hump personnel – cut	.6.7E-04 (p. 67)	3
hump personnel – placement	.015 (p. 67)	3
hump personnel – pickup	.0075 (p. 67)	3
hump personnel – cab	.01125 (p. 67)	4
tower occupants	.0028 (p.55)	9
trim engine – classifying (rider)	.0383 (p. 65)	3
trim engine – classifying (crew)	.0439 (p. 66)	4
trim engine – assembly	.00954	3
trim engine – assembly	.0469	4
trim engine – assembly	3.9E-04	20^2

B.3 Inspection

Operation	person-hr	distance (m)
RAM train inspection	.0220	3
Adjacent track inspection –near side	.0078	4
Adjacent track inspection – far side	.0025	8
Inspection 2 tracks away	.0030	9

B.4 Repairs

1. Large Intermediate Terminal - One Spot Repair Facility (Wooden, p. 73-75)

Operation	person-hr	distance (m)
Repair in covered facility	.0077	3
Repair in covered facility	.0046	5
Repair in covered facility	.0029	5
Repair on cleaning tracks	.0012	3
Repair on cleaning tracks	.0008	5
Repair in arrival yard	.0083	3
Repair in arrival yard	.0058	5
Repair in arrival yard	.0017	3
Repair in arrival yard	.0012	5

2. Very Large Intermediate Terminal - One Spot Repair Facility (Wooden, p. 73, 75, & 77)

Operation	person-hr	distance (m)
Repair in covered facility	.0111	3
Repair in covered facility	.0067	5
Repair in covered facility	.0042	5
Mini rip track	.0037	3
Mini rip track	.0026	5

3. Interchange Terminal – One Spot Repair Facility (p. 73 & 77)

Operation	person-hr	distance (m)
Repair in covered facility	.0233	3
Repair in covered facility	.014	5
Repair on adjacent track	.0089	5

4. Small Terminal – Rip Track Repair Facility (3 parallel tracks) p. 77 & 78)

Operation	person-hr	distance (m)
Repair on RAM car	.0132	3
Repair on adjacent car	.0091	5
Repair on adjacent track (near)	.0050	7
Repair on adjacent track (far)	.0043	9

B.5 Calculation of b Factors

The following tables show the summations over all operations of all person-hr/m values for a fixed distance value. The distance values are: 3 m; 4 m; 5 m; 7 m; 8 m; 9 m; and 20 m. The summation for the 3-m distance for general freight is denoted b_1, the summation for the 4-m distance is denoted b_2, and so forth.

The person-hr values are taken from the tables in Sections B.1 through B.4. In the case of classification operations, the values also are modified by:

(a) the probability of a classification being performed by one of the four possible methods outlined (= 0.25 per method); and

(b) the probability that a RAM car will be in the 1st trim-end quarter of the train (= 0.25).

Modifier (b) affects values only for Shove-over-Hump and Shove-Trim-End operations. In the case of repairs, the values are modified by the probability of a repair being performed in each of the four types of repair facilities (= 0.25 per type).

B.5.1 General Freight ($b_1 - b_7$)

a. Exposure at 3 m from all operations = b_1 = 0.092009

Category	Operation	person-hr	Frequency/ classification or repair	Probability of trim-end location	Total
Classification	Shove to Rest	0.02040			
		0.00550			
		0.00076			
		0.02040			
		0.00550			
		0.02070			
		0.00076			
	Total	***0.07402***	***0.25***	***N/A***	***0.018505***
Classification	Shove over Hump	0.04250			
		0.00076			
		0.04250			
		0.00076			
		0.03050			
		0.02737			
		0.00076			
		0.03050			
		0.02737			
		0.00076			
	Total	***0.20378***	***0.25***	***0.25***	***0.012736***
Classification	Shove Trim End	0.00059			
		0.03830			
		0.00954			
		0.00120			
		0.03830			
		0.00954			
		0.05000			
		0.02317			
		0.03830			
		0.00954			
		0.05000			
		0.02317			
		0.03830			
		0.00954			
	Total	***0.33949***	***0.25***	***0.25***	***0.021218***
Inspection	Inspection	0.0220			0.022
	Total	***0.0220***	***1***	***N/A***	***0.022***
Repairs	Repairs	0.0077			
		0.0012			
		0.0083			
		0.0017			
		0.0111			
		0.0037			
		0.0233			
		0.0132			
	Total	***.0702***	***0.25***	***N/A***	***0.01755***
TOTAL					.092009

b. Exposure at 4 m from all operations = b_2 = 0.049201

Category	Operation	person-hr	Frequency/ classification or repair	Probability of trim-end location	Total
Classification	Shove-to-Rest	0.00560			
		0.00075			
		0.00150			
		0.00180			
		0.00075			
	Total	***0.01040***	***0.25***	***N/A***	***0.0026***
Classification	Shove over Hump	0.00075			
		0.00075			
		0.00150			
		0.00075			
		0.00075			
		0.00150			
	Total	***0.0060***	***0.25***	***0.25***	***0.000375***
Classification	Shove Trim End	0.00044			
		0.00095			
		0.11890			
		0.00938			
		0.00090			
		0.00190			
		0.11890			
		0.04690			
		0.07500			
		0.01125			
		0.04390			
		0.00936			
		0.07500			
		0.01125			
		0.04390			
		0.04690			
	Total	***0.61483***	***0.25***	***0.25***	***0.038426***
Inspection	Inspection	0.0078			
	Total	***0.0078***	***N/A***	***N/A***	***0.007800***
TOTAL					0.049201

c. Exposure at 5 m from all operations = b_3 = 0.016845

Category	Operation	person-hr	Frequency/ classification or repair	Probability of trim-end location	Total
Classification	Shove over Hump	0.00193			
		0.00193			
	Total	***0.00386***	***0.25***	***0.25***	***0.000241***
Classification	Shover Trim End	0.01860			
		0.00193			
		0.00193			
	Total	***0.02246***	***0.25***	***0.25***	***0.001403***
Repairs	Repairs	0.0046			
		0.0029			
		0.0008			
		0.0058			
		0.0012			
		0.0067			
		0.0042			
		0.0026			
		0.0140			
		0.0089			
		0.0091			
	Total	***0.0608***	***0.25***	***N/A***	***0.0152***
TOTAL					0.016845

d. Exposure at 7 m from all operations = b_4 = 0.00125

Category	Operation	person-hr	Frequency/ classification or repair	Probability of Trim End Location	Total
Repairs	Repair	0.0050			
	Total	***0.0050***	***0.25***	***N/A***	***0.00125***
TOTAL					0.00125

e. Exposure at 8 m from all operations = b_5 = 0.0025

Category	Operation	person-hr	Frequency/ classification or repair	Probability of Trim End Location	Total
Inspection	Inspection	0.0025			
	Total	***0.0025***	***N/A***	***N/A***	***0.0025***
TOTAL					0.0025

f. Exposure at 9 m from all operations = b_6 = .008023

Category	Operation	person-hr	Frequency/ classification or repair	Probability of Trim End Location	Total
Classification	Shove over Hump	0.00136			
		0.00280			
		0.00136			
		0.00280			
	Total	***0.00832***	***0.25***	***0.25***	***0.00052***
Classification	Shove Trim End	0.01313			
		0.00136			
		0.03340			
		0.00280			
		0.00136			
		0.00280			
	Total	***0.05485***	***0.25***	***0.25***	***0.003428***
Inspection	Inspection 2 tracks away	0.0030			
	Total	***0.0030***	***N/A***	***N/A***	***0.0030***
Repairs	Repair	0.0043			
	Total	***0.0043***	***0.25***	***N/A***	***0.001075***
TOTAL					0.008023

g. Exposure at 20 m from all operations = b_7 = 0.000340

Category	Operation	person-hr	Frequency/ classification or repair	Probability of Trim End Location	Total
Classification	Shove to Rest	0.000007			
		0.000012			
		0.000002			
		0.000004			
	Total	***0.000025***	***0.25***	***N/A***	***0.000006***
Classification	Shove over Hump	0.000007			
		0.000037			
		0.000007			
		0.000012			
		0.001200			
		0.000007			
		0.000037			
		0.001200			
		0.000007			
		0.000012			
	Total	***0.002526***	***0.25***	***0.25***	***0.000157***
Classification	Shove Trim End	0.001020			
		0.000390			
		0.001020			
		0.000390			
	Total	***0.002820***	***0.25***	***0.25***	***0.000176***
TOTAL					0.000340

B.5.2 Dedicated Rail ($b_8 - b_{11}$)

For dedicated rail, only exposures from inspections are included because the consist (train of cars) is not broken down and reassembled at each railyard as it is for ordinary freight. Thus, there are no proximate worker exposures associated with classification operations in railyards. Further, only emergency repairs are performed in the course of dedicated rail transportation.

a. Exposure at 3 m from inspections = b_8 = 0.022

Category	Operation	person-hr	Frequency/ classification or repair	Probability of trim-end location	Total
Inspection	Inspection	0.0220			0.022
	Total	***0.0220***	***N/A***	***N/A***	***0.022***
TOTAL					0.022

b. Exposure at 4 m from inspections = b_9 = 0.0078

Category	Operation	person-hr	Frequency/ classification or repair	Probability of trim-end location	Total
Inspection	Inspection	0.0078			
	Total	***0.0078***	***N/A***	***N/A***	***0.0078***
TOTAL					0.0078

c. Exposure at 8 m from inspections = b_{10} = 0.0025

Category	Operation	person-hr	Frequency/ classification or repair	Probability of Trim End Location	Total
Inspection	Inspection	0.0025			
	Total	***0.0025***	***N/A***	***N/A***	***0.0025***
TOTAL					0.0025

d. Exposure at 9 m from inspections = b_{11} = 0.0030

Category	Operation	person-hr	Frequency/ classification or repair	Probability of Trim End Location	Total
Inspection	Inspection 2 tracks away	0.0030			
	Total	***0.0030***	***N/A***	***N/A***	***0.0030***
TOTAL					0.0030

B.6 Literature Cited

Wooden, D.G., 1986, "Railroad Transportation of Spent Nuclear Fuel," SAND86-7083, Sandia National Laboratories, Albuquerque, NM.

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