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RADTRAN 6 Technical Manual

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ABSTRACT

This Technical Manual contains descriptions of the calculation models and mathematical and numerical methods used in the RADTRAN 6 computer code for transportation risk and consequence assessment. The RADTRAN 6 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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The authors are indebted to the work of K. Sieglinde Neuhauser, the primary author of the RADTRAN 4 and 5 manuals. These works formed the basis of, and provided the organization and structure for, the present work. The senior author also wishes to acknowledge her personal debt to Dr. Neuhauser, who was her mentor in the field of radioactive materials transportation.

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ACRONYMS

AEC	[US] Atomic Energy Commission
Bq	becquerel
CFR	[US] Code of Federal Regulations
Ci	curie
EDE	effective dose equivalent
GIS	graphical information system
Gy	gray
HRCQ	highway route controlled quantity
IAEA	International Atomic Energy Agency
NRC	[US} Nuclear Regulatory Commission
RAM	radioactive materials
SF	shielding factor
Sv	sievert
SW	sidewalk
TEDE	total effective dose equivalent
TI	transport index
USDOT	US Department of Transportation

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1 INTRODUCTION

RADTRAN 6 is a program for analyzing the risks and consequences of transporting radioactive materials (RAM). The associated computer code is ANSI FORTRAN 95, developed by Sandia National Laboratories (SNL). RADTRAN was first released in 1977 (Taylor and Daniel, 1977) in conjunction with the preparation of NUREG-0170 (NRC, 1977a). The analytical capabilities of the code have been expanded and refined in subsequent releases. RADTRAN II was released in 1983 (Madsen et al., 1983); and RADTRAN III was released in 1986 (Madsen et al., 1986). RADTRAN 4 (Neuhauser and Kanipe, 1992) represented a new direction for RADTRAN development. The analyst now could carry out route-specific analyses by assigning route-segment-specific values for a number of parameters (population density, vehicle speed, traffic count, etc.). These route-specific capabilities were improved and expanded, and a number of features added, in RADTRAN 5 (Neuhauser, et al., 2000).

RADTRAN 6 was launched in 2009. In addition to the features in RADTRAN 5, version 6 includes a user-defined dispersion model, a model for accidents in which lead shielding is lost, an alternate ingestion dose model (INGEST), and an economic model. An uncertainty module has also been developed for RADTRAN. RADTRAN 6 bundled with the input file generator RadCat 6 is downloadable from https://radtran.sandia.gov /RadCat and can be run locally. The RADTRAN 6/ RadCat 6 User Guide (Weiner, et al., 2013) can also be downloaded from the website.

The present document does not duplicate the RADTRAN 6/ RadCat 6 User Guide (Weiner, et al., 2013) or the information which that document provides. The equations from Neuhauser, et al. (2000) have been retained verbatim.

1.1 Application of RADTRAN to Transportation Analyses

RADTRAN estimates consequences and risks associated with routine, incident-free transportation of radioactive materials (RAM) and with accidents that might occur during RAM transportation. The U.S. Department of Transportation (USDOT) defines incident-free (or normal) transportation as “transportation during which no accident, packaging, or handling abnormality or malevolent attack occurs.”[1] USDOT defines transportation “accidents” as incidents in which there is a death, injury, or enough damage to an involved vehicle that it cannot move under its own power; other events that interfere with routine transportation are called “incidents.” RADTRAN uses the term “accident” for both accidents and incidents.

Major modes of transport that may be analyzed with RADT have been retained verbatim.RAN are highway (on both primary and secondary roads), rail, and waterway.

---

[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 sub threshold event usually is limited to increased stop time.

Radiological risks from air transport can be calculated using parts of the highway calculation mode.

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 contained in the Code of Federal Regulations (CFR), specifically Volume 10 Part 71; regulations promulgated by the DOT are contained in Volume 49, Parts 173 to 178. These regulations establish maximum permissible package dose rates, maximum permissible dose rates to vehicle crew members, exclusive-use shipment criteria, packaging certification conditions, allowed releases of radioactive materials to the environment, protocols for preventing criticality, and other features of radioactive materials transportation. U.S. regulations are also consistent with those of the International Atomic Energy Agency (IAEA).

RADTRAN analyses are generally route-specific. A route may be subdivided into segments with independent, analyst-assigned values for population density and other route-specific parameters. Many parameters can be made segment-specific, and individual stops may be analyzed separately. Different vehicles may be included in a single RADTRAN analysis.

1.2 Definition of Risk

RADTRAN is a risk analysis code. Transportation risk analysis is based on the “risk triplet:” what can happen, how likely it is to happen, and the consequences, for each set of things that can happen (see, for example, Helton, 1991). "What can happen" is the transportation scenario: routine transportation, a minor accident, an accident with a fire, etc. "How likely things are to happen" is the probability of the particular scenario; and "the consequences" are the results or outcomes of the scenario (e.g., population dose) (Helton, 1991). Since consequences are calculated in order to calculate risk, RADTRAN can also be used as for consequence assessment. The RADTRAN algorithm multiplies the probabilities and consequences for each scenario considered.

RADTRAN also may be used in conjunction with distributed inputs and a random sampling code to estimate uncertainty and perform probabilistic risk assessments. Values of input variables are selected by random sampling from distributions that represent the range of values that each variable may assume. This is discussed further in Chapter 5.

1.3 Overview of Radioactive Materials Transportation

The modes of transportation addressed in RADTRAN include highway, rail, and waterway. Vehicles associated with these modes include tractor-trailer and light-duty vehicle for highway, railcars, and barges and varieties of ships for waterway transport. There are a variety of vehicles 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. A shipment consists of one or more packages on a single vehicle. A single vehicle 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 vehicle or by one or more modes. RADTRAN allows the user to analyze all mode combinations and associated vehicle changes (intermodal transfers).

Crew members 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 vehicle, it will be handled during each transfer from one vehicle 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. Some public exposure may also occur.

1.4 How RADTRAN works

RADTRAN is programmed in FORTRAN (currently FORTRAN 95) and uses FORTRAN intrinsic functions for simple mathematics and algebra, as well as FORTRAN functions EXP, ALOG, AMIN1, and SQRT to solve mathematical equations. Sandia Math Library routines used in RADTRAN are freestanding versions of Sandia Math Library (SLATEC) routines, which are quality-assured solutions of various mathematical functions. A validation and verification document for RADTRAN (Dennis, et al., 2008) is available on request from Sandia National Laboratories.

RADTRAN makes use of the following text files:

- RT6_Standard.INFILE and RT6_Defaults.INFILE, text files which contain default values for a number of parameters that are common to many analyses, including isopleth areas and dilution factors for national average meteorology. average breathing rate, and residential building shielding factors.
- RT6_Isotope.INFILE, a text file which contains the dose conversion factors and other radionuclide specific parameters for the RADTRAN radionuclide library of 149 radionuclides. The ingestion and inhalation dose conversion factors are based on ICRP 72; the others, on Federal Guidance reports (FRG) 11 and 12..
- RT6_Ingestion.BIN, a binary file which contains ingestion output for one curie of each of the radionuclides in the RADTRAN radionuclide library.

The input file generated using RadCat is copied into the RADTRAN input text file RADTRAN.INPUT. If distributed inputs are created and sampled on, a separate input file is generated for each sample.

RADTRAN input and output parameter values may use either standard international (SI) units (e.g., curies, rem) or historic units (e.g., sieverts, becquerels). RADTRAN internally performs calculations in historic units. In some cases, RADTRAN adjusts parameter units internally.

1.5 Organization of the Technical Manual

This manual includes a description of the models and computations in RADTRAN. Chapters 2 through 5 describe the main components of RADTRAN, the processes and interactions represented by these component models, how doses are calculated and the input parameters needed and used to exercise these models.

Incident-free (routine) transportation is discussed in Chapter 2, accident analysis (including atmospheric dispersion and near-filed effects, is discussed in Chapter 3, ingestion doses are discussed min Chapter 4, health effects are discussed in Chapter 5, and uncertainty is discussed in Chapter 6. This Technical Manual does not provide instructions for downloading and using RADTRAN 6 and the associated input file generator RadCat 6. Instructions may be found in the RADRAN 6/RadCat 6User Guide Weiner, et al, 2013)

The output of the incident-free calculations in RADTRAN, and of consequence calculations, are in units of dose or collective dose. In keeping with current (21st century) usage, the units used in this document are Standard International (SI) units: sieverts (Sv) for dose, person-Sv for collective dose, gray (Gy) for absorbed energy, and becquerel (Bq) for radioactivity. RADTRAN itself, because of its history, is programmed in historical units -- rem, person-rem, rad, curie (Ci) – but allows input and output in SI units. Conversions from one unit system to the other are

- 1 Sv = 100 rem; 1 rem = 0.01 Sv
- 1 Gy = 100 rad; 1 rad = 0.01 Gy
- 1 Bq = 2.7 x 10^{-11} Ci; 1 Ci = 3.7 x 10^{10} Bq = 0.037 TBq
- 1 TBq = 10^{12} Bq = 27 Ci
- Sv/Bq = 3.7 x 10^{12} rem/Ci; rem/Ci = 2.7 x 10^{-13} Sv/Bq

Output from accident risk calculations is also expressed in units of dose and collective dose, but is called “dose risk” when the probability term is incorporated.

Appendix A contains tables used with the INGEST ingestion dose model.

2 MODELING INCIDENT-FREE TRANSPORTATION

Transported radioactive materials (RAM) can emit ionizing radiation externally. The external radiation dose rates from transportation packages may be calculated or measured, and are the radiation source for any exposure, public or occupational, that occurs during routine, incident-free transportation and during accidents when there is no breach of containment. For incident-free transportation and any other condition not involving a breach of containment, the contents of the radioactive materials package does not matter; only the external dose rate matters.

In RADTRAN parlance, a "package" is the container and its radioactive contents that is being transported, "packaging" is the container, "vehicle" usually refers to the part of the vehicle that holds the package, like a railcar or semi-detached trailer, and "mode" refers to the transportation medium (highway, secondary road, rail, water). 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.

The characteristics of each segment (or link) of a transportation route may be modeled with the RADTRAN incident-free model The link characteristics which define the incident-free model input parameters include:

- mode of shipment,
- route segment (link) length,
- vehicle speed,
- residential population density along the route.
- residential shielding from external radiation,
- occupancy of other vehicles sharing the link with the RAM shipment,
- density of other vehicles sharing the link with the RAM shipment,
- vehicle external dose rate,
- road type (interstate highway, secondary road, rail, etc.).

Similarly, the characteristics of separate stops that can occur during a trip include:

- mode of shipment
- vehicle external dose rate
- population densities within specified radial distances of stopped shipment
- shielding, if any, of population within the specified radial distances
- stop time.

Handlings and inspections are special types of stops at which small subpopulations may routinely come into proximity to the radioactive material (RAM) vehicle. Thus, the number of handlers and/or inspectors and their distances from the RAM shipment are additional required inputs for these calculations.

Characteristics of radioactive material packages that affect doses from incident-free transportation are the package external dose rate and the partition of the dose rate into gamma and neutron fractions. For certain classes of packages, the package dose rate can 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 millisieverts (mSv) per hour[2] (millirem per hour) from all penetrating radiation at one 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 one meter is an essential input to RADTRAN for all package types. The radionuclide inventory data are not required for incident-free dose calculation.

Radiation doses from incident-free transportation may be calculated for any desired groups of workers, such as:

- vehicle crew members and escorts,
- cargo handlers and inspectors,
- rail yard workers
- warehouse personnel,
- flight attendants (passenger-air only).
- escorts

Radiation doses from incident-free transportation may be calculated for members of the public, including

- passengers [persons in the same vehicle as the package(s)],
- people in the vicinity of the transporting vehicle while it is stopped,
- people who live in the vicinity of a stop,
- 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 or stop 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.

2.1 Point- and Line-Source Models and Related Parameters

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 a dimensionless source that emits radiation in all directions with equal magnitude. A diagram of the point source formulation for various packages, and the critical package dimension, is shown in Figure 2.1. In Figure 2.1a, a

---

[2] In order to conform with international practice, the units of dose used are siverts, or fractions thereof (with rem, of fractions thereof, in parentheses.

cylindrical package, the critical dimension would be either the axis of the cylinder or the cross-sectional diameter, whichever is larger. In Figure 2.1b, the critical dimension would be the longer of the two diagonals. In the sphere of Figure 2.1c, the critical dimension is indicated.

For such a source, dose rate is inversely proportional to the square of the radial distance from the source at distances large compared to the package dimensions. A point-source model yields values of dose rates that are slightly larger than actual dose rates measured at source-to-receptor distances greater than twice the characteristic package dimension (usually equivalent to twice the largest package dimension) (Steinman, et al, 2002). Collective doses to a population, like the resident population along a route, are calculated by integrating over the area occupied by the population, so that the dose rate – the integrand – is slightly more complex than a simple inverse square dependence.

For larger packages, at exposure distances less than twice the largest package dimension, a line-source approximation is preferred. For such a source, dose rate is inversely proportional to the distance from the source, along the entire length of the source. (rather than the square of the distance, as is the case for a point-source formulation).

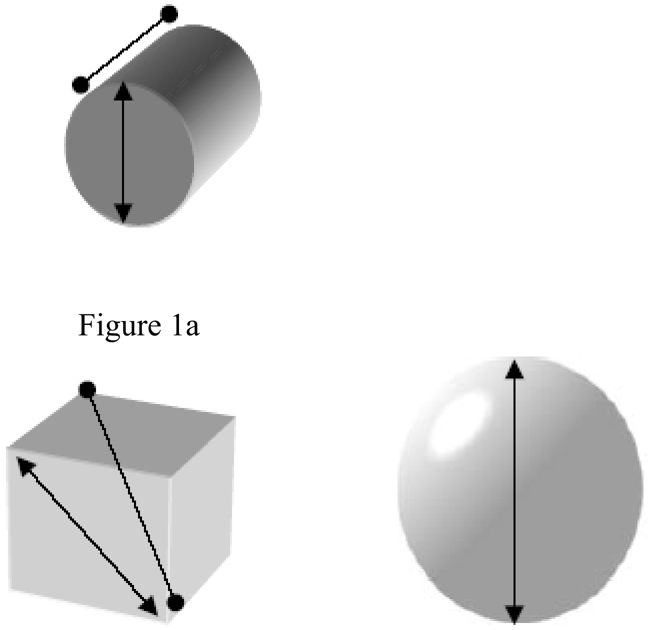

Figure 1a

Figure 1b

Figure 1c

Figure 2.1 Critical dimension of the transportation package.

Figure 2.2 shows the radioactive materials package, the relevant external dimensions, and a sample receptor.

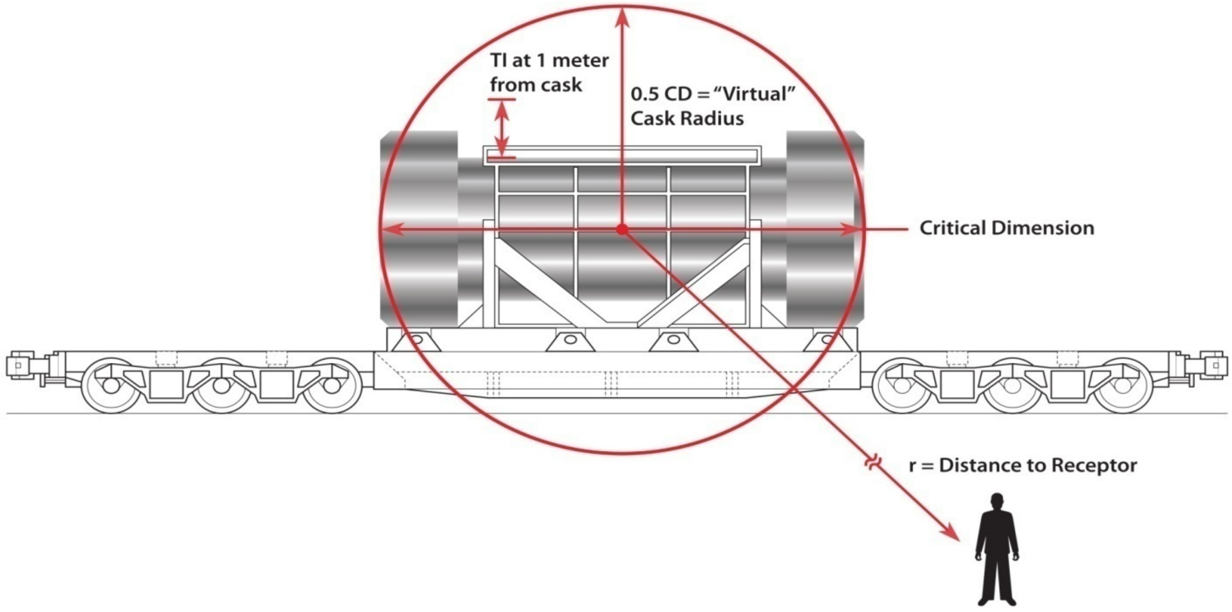

Figure 2.2. RADTRAN model of the vehicle in routine, incident-free transportation. The cask in this diagram is positioned horizontally and the critical dimension is the cask length (NRC, 2013, Figure 2-2).

2.2 Gamma Radiation

A gamma radiation dose during incident-free transportation is calculated using an expression for gamma dose rate as a function of distance from an isotropic point source (AEC, 1972). In the model, the source is a virtual point source located at the center of the package. Reflection and absorption by the ground surface are neglected in this model. Because neutrons are rapidly attenuated in air, an all-gamma treatment gives a slightly conservative estimate of population dose for populations 10 meters or more from the vehicle.

The gamma dose-rate for an isotropically radiating point-source (AEC, 1972) is given by equation 1.

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

$DR_g(r)$ = gamma dose-rate at distance r (Sv/hour)
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

$B(\mu r)$ = dose-rate buildup factor for surrounding medium at distance r

C^3 = 3.6×10^7

For gamma radiation in air, the product $\exp(-\mu r)\cdot B(\mu r) \leq 1.0$ so that, if the product is set equal to 1.0, the dose rate can be expressed in a generally conservative manner as

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

where

$$k = \frac{S_{photon} \cdot C}{4\pi} \quad . \qquad (3)$$

The U.S. regulation of 10 CFR 71.47(b)(3) limits the external radiation dose rate from a package to 0.1 mSv per hour (10 mrem per hour) at two meters from the outer surfaces of the vehicle[4]. The Transport Index (TI) is defined in 10 CFR 71.4 as 100 times the e maximum radiation in mSv at a distance of 1 m from the package surface (equivalent to the maximum radiation in mrem per hour at 1 meter from the surface (Figure 2.2). In RADTRAN, this definition also is applied to a vehicle carrying a shipment of more than one package of radioactive material, and the factor k in equation (3) is applied appropriately.

A package shape factor $k_{0,}$ defined by equation 4, relates to the size of the package or vehicle being analyzed. The gamma dose rate, $DR_g(r)$, from a point source can then be written as follows:

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

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 vehicle (vehicle).

When the dose rate is defined in mSv/hr, the conversion factor Q in Equation 4 takes on a value of 2.8E-10 Sv-km-hr/mSv-m-sec and is designated Q_1. In RADTRAN, the dose-rate value measured at 1 m from the package surface is extrapolated back to the center of the package as a virtual point source. In order to define what the radial distance to a

---

[3] DR = Sv/hr = joule/kg-hr = m^2kg/(sec-hr); 1 hour = 3600 sec; 1 m = 100 cm

[4] The regulation is presented here as it was originally written using historic units (rem, mrem). Throughout the rest of the test Standard International (SI) units are used. The conversion is 1 Sv = 100 rem.

receptor 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 (see Figure 2.2; the virtual source is at the center of the sphere in the figure). The package shape factor, k_0, is then,

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

where

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

For single packages, the value of d_e is usually 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. Measurement s show that RADTRAN is slightly conservative (Steinman, et al, 2002).

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_g = gamma dose rate at radial distance r (mSv/hr)
$DR_{p\text{ or }v}$ = maximum measured or calculated dose rate at 1 m from package or vehicle (mSv/hr)
r = radial distance from point source (m)
d_e = effective package dimension (m)

For large packages, at values of $r \leqq 2d_e$, 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:

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

where

$k_0^{'}$ = line-source package shape factor (m)

d_e = effective package dimension (m) [Equation 5].

The RADTRAN model does not consider the offset between the package and the vehicle or vehicle trailer holding the package or packages (packages on a single vehicle or vehicle trailer can be considered as a single package).

2.3 Neutron Radiation

The expression for neutron dose compatible with the expression for gamma dose describes neutron dose rate as a function of distance from an external isotropic point source. Reflection and absorption by the ground surface is neglected as before. Although neutron interactions with matter make transport through any medium, including air, more complex to model than gamma-radiation interactions, a relatively simple model that parallels the treatment of gamma radiation is used in RADTRAN. Since package dose rate is reported in mSv/hr, the relative biological effectiveness of 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.

The basic equation for dose rate at distance r from a point source is

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

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 mSv/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

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

(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

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

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 (mSv/hr)

p = index for package

v = index for vehicle (vehicle)

exp(-μr) = attenuation by the medium through which the radiation is travelling (m^{-1})

B(μr) = buildup factor for the medium through which the radiation is travelling

r = radial distance from point source (m).

The package shape factor for neutron radiation will be the same as 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:

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

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). Default 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. These values are

a_1 = 2.02E-02;
a_2 = 6.17E-05;
a_3 = 3.17E-08;
a_4 = 0. (13)

RADTRAN 6.0 and later versions of RADTRAN allow different values to be substituted for the default values.

Significant levels of neutron radiation are seldom encountered in radioactive materials transportation except in spent nuclear fuel transportation. The neutron coefficients are for fission neutrons and 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 Boltzmann 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 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

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

where
$DR_N(r)$ = neutron dose rate at distance r (mSv/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.

2.4 Final Expressions for Gamma and Neutron Radiation

The final form of the basic point-source expression used in RADTRAN 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 (mSv/hr)
r = radial distance from source (m)
Q_1 = units conversion factor = 2.8E-10 Sv-km-hr/mSv-m-sec
$DR_{p\ or\ v}$ = package or vehicle dose rate at 1 m (mSv/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 = 0

As noted previously, RADTRAN uses 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 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 (mSv/hr)
r = radial distance from source (m)
Q_1 = units conversion factor = 2.8E-10 Sv-km-hr/mSv-m-sec
$DR_{p\ or\ v}$ = package or vehicle dose rate (mSv/hr)
FN = fraction of package or vehicle 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 RADTRAN for gamma radiation is

$$DR_G(r) = Q_1 \cdot DR_{p\,or\,v} \cdot FG \cdot k_0' \exp(-\mu r) \cdot \frac{(1 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4)}{r} \qquad (17)$$

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 for neutron radiation is

$$DR_N(r) = Q_1 \cdot DR_{p\,or\,v} \cdot FN \cdot k_0' \exp(-\mu r)\frac{(1+a_1r+a_2r^2+a_3r^3+a_4r^4)}{r} \qquad (18)$$

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.

2.5 Dose to Members of the Public

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

An expression for the total integrated dose to a stationary individual receptor at a perpendicular distance x from the path of a moving source (i.e., a shipment in transit) with a dose-rate factor k (see equation 2), passing at a constant velocity V, has been derived from Equation (3) of AEC (1972) and is given by

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

where

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

where

$D(x)$ = total integrated dose absorbed by an individual at distance x (Sv)

k_0 = point-source package shape factor (m^2)

DR_v = vehicle dose rate at 1 m from surface (mSv/hr)

V = vehicle speed (km/hr)[5]

x = perpendicular distance of the individual receptor from shipment path (m)

μ = attenuation coefficient (m^{-1})

$B(r)$ = buildup factor expressed as a geometric progression

r = the distance between shipment and receptor along the route of travel (m).

In a separate calculation, the dose to an individual located at some user-specified distance from a shipment traveling at some user-specified velocity may be calculated. If the distance and velocity values are the smallest predicted for actual transportation conditions, then this will calculate a maximum value of individual dose.

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

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

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

---

[5] Equations 19 and 20 are not corrected for discrepancies in units.

D_{off} = integrated collective dose per km of transportation route (person-Sv)
Q = units conversion factor
PD = population density (persons/km^2)
min = minimum perpendicular distance from population to shipment (m)
max = maximum distance perpendicular to shipment (m).

The value of maximum distance (“max”) historically used in AEC (1972), and in RADTRAN applications, is 800 m (~ 0.5 mi.). However, NRC (2125, Chapter 2) shows that the collective radiation dose integrated over this band width is negligible compared to the background dose sustained by the exposed population. A value of max = 100 m encompasses collective doses of 0.1 percent of background or more, and is recommended. Retaining the 800-m value is extremely conservative and preserves parallelism and comparability with older analyses.

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

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

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

The population density term in Equation 22 is usually obtained from some census-based source; in the United States, U.S. Census Bureau is a good source, as is a web-based source like Google Maps. A geographic information system (GIS) can also be used to determine population densities. The routing code TRAGIS (TRAnsportation Geographic Information System), maintained by the Oak Ridge National Laboratory, can provide both population densities and route lengths.

The integration of Equation 22 is performed in RADTRAN 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

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

(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 ($x \cdot \mu_s$).

The collective dose along a route is also a function of the distance traveled. Equation 23 may be multiplied by a route or route segment length (DIST), which thereby incorporates the distance traveled. Route segment lengths may be obtained from a routing code like TRAGIS or estimated from a mapping program like Google Earth or any GIS system.

Varying population densities are accounted for by dividing a route into route segments, each segment associated with a population density. The length of each route segment is at the user's discretion. The total collective dose to the population along the route then becomes the sum of the doses received in each route segment. In the case of an urban area with sidewalks, the bandwidth (the perpendicular distance from min to max) may be subdivided into a pedestrian strip immediately adjacent to the transportation link and the remainder of the bandwidth, where residences are located. The pedestrian population density is estimated in urban areas by the product of the residential; population density and a ratio of the pedestrian (outside) population density to the resident population density. The integrated dose expression in Equation 22 then results in the following expression, equation 24, for the radiation dose sustained by people along the route (the "off-link dose").

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

(24)

where all variables are as defined for Equations 21 and 23, except for

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.
$RPD_{s\text{ or }u}$= ratio of pedestrian density to residential population density in suburban (s) or urban (u) route segments.
SF = residential shielding factor

The subscript “L” indicates the route segment in question.

Values of min, SW, and max (Madsen, Wilmot and Taylor,1986) are given in Table 2-1 and have been used in RADTRAN analyses in the absence of route-specific information. The maximum value of 800 meters (approximately ½ mile) is also used frequently. It is not listed in Table 2-1 because RADTRAN analyses show that at about 100 meters from the source, the dose is less than 0.1 percent of background. The collective dose calculated in this way is exceedingly conservative. Most of the variables in Equation 24 are user-defined; the user must enter values for each variable for each link in the input file.

Table 2-1. Typical U.S. Values For min and SW.

Population Zone	Highway Type	Value of min (m)	Value of SW (m)
Rural	Freeway	30	(none)[1]
Rural	Non-Freeway[2]	30	(none)
Suburban	Freeway	30	(none)
Suburban	Non-Freeway	27	30
Urban	Freeway	30	(none)
Urban	City Street	5	8

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).

Population Densities

Population densities may be estimated from census data or any available data base. Each population-density zone (urban, suburban, and rural) may be assigned a different, user-defined residential shielding factor. This factor is expressed by equation 25 and is the ratio of air (no shielding) to full shielding and represents the reduction in integrated exposure caused by shielding .

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

μ_m and B_m are the attenuation and buildup factors, respectively, for the shielding medium, μ_{air} and B_{air} are the attenuation and buildup factors, respectively, for air. When the shielding factor R=1, there is no shielding, and the attenuation and buildup factors for the shielding medium are equal to those for air. When R=0, the attenuation and buildup of the shielding material are so much larger than those for air that the shielding blocks 100 percent of the incoming ionizing radiation. Defining no shielding as R=1 allows this factor to be used in RADTRAN calculations.

Urban, suburban, and rural zones (RU, RS, and RR) are usually a function of population density and are related to construction methods and materials as shown in Table 2-2. Values that are applicable for many parts of the United States are given in Table 2-2, and do not generally apply worldwide. In rural Italy, for example, most houses are built of stone, and the value of RR suggested in Table 2-2 would be inappropriate; construction in many densely populated equatorial cities, on the other hand, is less substantial than indicated in Table 2-2.

Table 2-2. 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.

In practice, the designations rural, suburban, and urban are made on the following basis (Weiner, et al, 2013):

Rural: 0 to 139 persons/mi^2(0 to 55 persons/km^2)
Suburban : 139 to 3326 persons/mi^2(55 to 1300 persons/km^2)
Urban : more than 3326 persons/mi^2(1300 persons/km^2)

These bins were first proposed for the routing code TRAGIS (Johnson and Michelhaugh, 2000) and have been maintained in order to provide continuity with earlier analyses.

Figure 2.3 shows the population zones on a segment of Interstate 80 through Salt Lake City, UT.

Figure 2.3 A segment of I-80 through Salt Lake City, UT (from NRC, 2013, Figure 2-4).

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 173-178. State by state average highway speeds are available from the U.S. Bureau of Transportation Statistics; average rail speeds are available from the U.S. Federal Railroad Administration or the railroad companies themselves. Highway speeds during rush hour in urban areas are usually assessed at nominally half of the usual speed, but this is at the user's discretion.

National average traffic density data from 2002-2003 are presented in Table 2-3. State-specific data are presented in Weiner, et al. (2013, Appendix D) and show that these densities have changed considerably during the past 25 years.

Table 2-3: Average National Traffic Density (Vehicles/Hour)

Interstate and Limited-Access Highways			*US Primary Highways*		
Rural	Suburban	Urban	Rural	Suburban	Urban
1155	2414	5490	287	618	1711

State or local regulations may affect the choice of values for these parameters. These parameter values are different for countries other than the U.S.

Rail, Ship and Barge Modes

The collective doses received by persons along a rail transport link or waterway are computed in the same way as for highway modes. The limits of integration vary by mode. For rail mode, a value of 30 for minimum distance is often used in the absence of route-specific information.

Any link or route segment transiting an uninhabited area is assigned a population density of zero, as is open ocean travel. Routes along rivers, canals, congested port waters, etc. where a populated shoreline is within several hundred meters of the vessel have non-zero population densities. The minimum distance in such areas would be dictated by the minimum distance from the navigable channel to the shoreline. A suitable value in congested waterways in the absence of location-specific data is 200 m.

Air Transportation

For air transport, the entire in-transit incident-free dose calculation is 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.

2.5.2 Dose to Persons in Vehicles Sharing the Transport Link – Highway Modes

A schematic diagram of this situation is shown in Figure 2.4. All vehicles traveling on highways are assumed to be motorized vehicles. Figure 2.4 shows that the dose consists of three separate components:

- dose to occupants of vehicles traveling in the opposite direction to the shipment
- dose to occupants of vehicles traveling in the same direction as the shipment, and
- dose to occupants of 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 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 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:

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

where

D_{opp} = integrated dose to persons traveling in opposite direction (person-Sv or person-rem)

k_0 = point-source package shape factor (m^2)

DR_v = package dose rate at 1 m from surface (mSv/hr ; mrem /hr)

$I'(x)$ = integration function describing a 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. The population density (persons/km) is a function of vehicle density and vehicle occupancy. When combined with equation 26, the radiation dose to occupants of vehicles traveling in the opposite direction from the RAM shipment is:

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

which may be simplified to:

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

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)

$N' \cdot PPV$ = total number of persons traveling in the opposite direction

$DIST_L$ = distance traveled on link L

The values of x in Table 2-4 are suggested values for common types of highway and rail links in the United States. 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 2-4 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} is:

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

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

Q_2 = units conversion factor = 7.7E-08 Sv-hr^2-m/mSv-sec^2-km.

I'_G = dose integration function for gamma radiation

I'_N = dose integration function for neutron radiation.

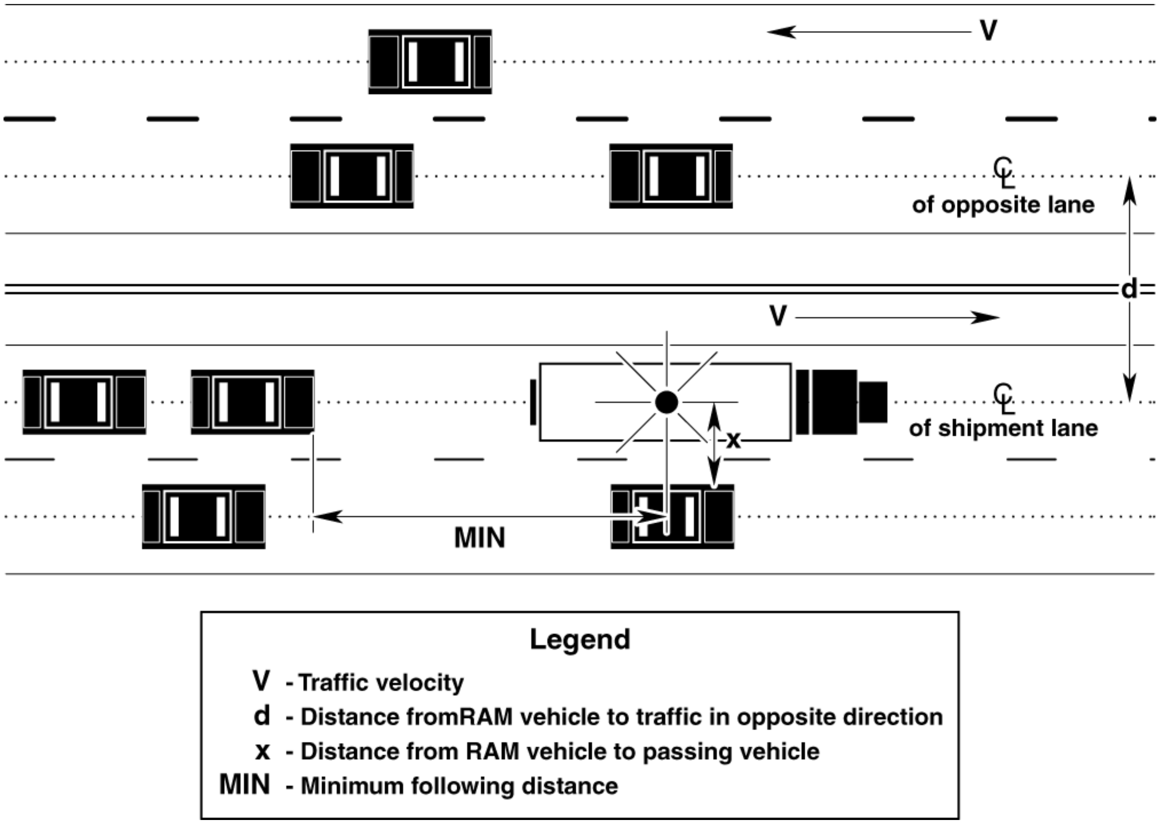

Figure 2.4 Illustration of Highway Traffic for Calculation of On-Link Dose

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 the exposure time t (hr).

For a given mode and link, the total exposure time t is given by

$$t = \frac{\mathrm{DIST_L}}{\mathrm{V_L}} \tag{30}$$

where V_L and $DIST_L$ are, respectively, the average speed on the route segment and the length of the route segment.

Occupants of vehicles are modeled as being distributed uniformly among the vehicles with a linear population density (as in equation 27a) 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:

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

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 occupants of vehicles both in front of and behind the RAM shipment, the case of a passing vehicle is considered. The traffic count N′ is used in Equation 31 to estimate dose to vehicles traveling in the same direction as the RAM shipment. This in effect counts all vehicles in all lanes but treats vehicles 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 vehicle occupancy per km, 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 (RADTRAN internally converts km/hr to m/sec). The integration in Equation 31 is performed with a Gaussian quadrature. If the integral from Equation 31 is $Y_{v,}$ then:

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

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:

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

where

Q_2 = units conversion factor = 7.7E-08 Sv -hr^2-m/mSv-sec^2-km

k_0 = point-source shape factor (m^2)

DR = dose rate at 1 m for the surface of vehicle v (mSv/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)

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.

$$F_1 = 2Y_vV_L \tag{35a}$$

and

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

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 links to obtain a total dose to persons traveling along the route in the same direction as the RAM shipment(s) being analyzed.

2.5.3 Dose to Population at Shipment Stops – All Modes

If a transport vehicle 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 external radiation from the shipment. The dose to any receptor at a stop is a function of the distance of the receptor from the source, the time the receptor is exposed, and shielding between the source and the receptor. Each receptor in a group of receptors can be modeled as a separate stop. Routing codes like TRAGIS identify train stops, and the stop model can be applied to them. The stop model for trucks is shown in Figure 2.5.

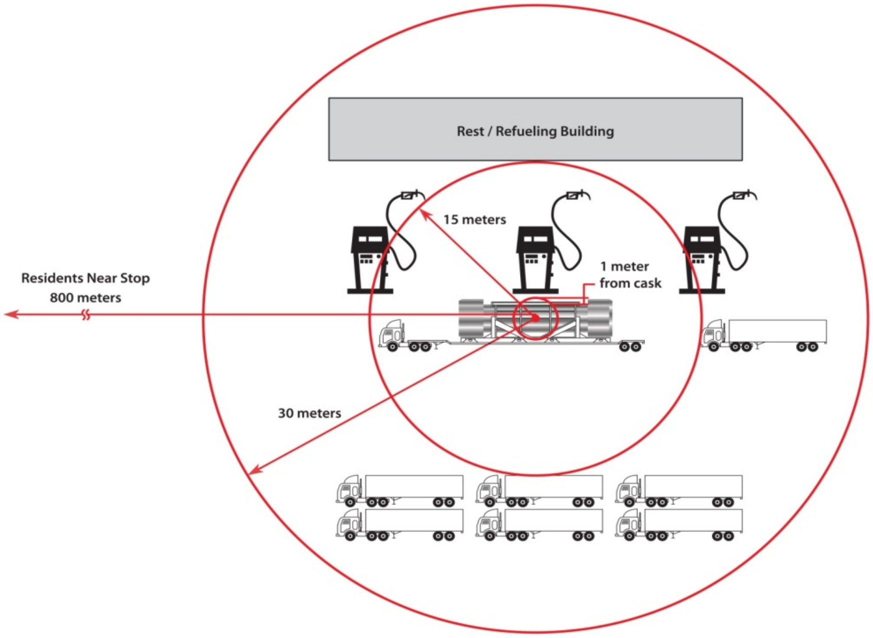

Figure 2.5. Stop model in RADTRAN (not to scale) (NRC, 20132, Figure 2-10)

RADTRAN presents the user with two possible ways to represent receptors (persons) at and near stops.

Option 1 – Average-Distance Method

The first option is based on a number of persons all at the same distance from the vehicle. This method is useful for modeling occupational doses that involve relatively few people. The equation for integrated population dose (D) for Option 1 is:

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

where

Q_4 = units conversion factor = 1.0E+03 Sv/mSv

k_{0_v} = point-source vehicle shape factor (m^2)

k'_{0_v} = line-source vehicle shape factor (m)

DR_v = vehicle dose rate at 1 m from surface (mSv/hr)

T_{st} = stop time (hr)

P_{st} = 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} = radial source-to-receptor distance (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:

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

and

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

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 2. Annular-Area Method

In this option, dose is calculated for a population density within an annular area. The population is modeled as a population uniformly distributed within the annulus; 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 by modeling a separate stop. Data developed by Griego, et al (1996) allow Option 2 to be applied to truck stops. If the number of people at the stop is provided, but the population density is not provided, the population density (in persons/km^2) may be calculated by dividing the number of people by the annular area. For example, if there are seven people in an annular ring around the gas pumps in Figure 2.5, and the inner and outer radii are, respectively, one meter and 15 meters,

Area of the annulus = $\Pi\ (15^2\text{-}1^2) = 703.72\ \text{m}^2$
Population density: $7/703.72 = 0.00995/\text{m}^2 = 9950$ persons/km^2

This calculation must usually be made offline.

The 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. This term (IR_S) involves a Taylor series expansion and is evaluated for gamma (S = G) and neutron (S = N) radiation as follows:

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

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 a positive, single precision argument ($\mu_S \cdot x$).

Evaluation of the integral at x_{max} and x_{min}, where max and min are the maximum and minimum radii, respectively, of the annular area, results in:

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

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:

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

where
Q_4 = units conversion factor = 1.0E-03 Sv/mSv
k_{0_v} = point-source shape factor for vehicle v (m^2)
DR_v = vehicle dose rate at 1 m from surface (mSv/hr)
PD_{st} = population density of annular area at stop (persons/km^2)
T_{st} = duration of stop (hr)
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.

Use of Stop Model to Estimate Storage-Related Dose

The handler dose in RADTRAN is essentially a stop dose; it has been retained for historical reasons. A period of handling and storage that may occur during the course of transportation is in fact a prolonged stop. Either of the two stop-dose models described in the preceding section 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, or use a code such as Microshield® to estimate shielding.

Use of Stop Model to Estimate An Accident Dose When There Is No Release of Radioactive Material

The most common type of traffic accident is one in which the radioactive cargo is not affected, in part because most radioactive material is very robustly packaged, and in part because the most common type of vehicle accident is one in which the damage to the vehicle is minor. In such an accident, however, the vehicle carrying the radioactive cargo can sit in one location for many hours. This situation is readily modeled as a stop. The stop model is used in calculating radiation doses when there is a loss of gamma shielding but no release of radioactive material.

Use of Stop Model to Estimate Dose to Airplane Passengers

If radioactive material is carried as cargo on a passenger plane, which happens only in rare instances of emergency transportation of medical radionuclides, the passengers are modeled as if they were at a stop. The geometry of the exposure would be specific to plane and cargo, so no general equation is given in addition to equation 41.

2.6 Dose to Workers

2.6.1 Dose to Crew Members – Highway, Rail and Air Modes

This section considers crew members on vehicles while the shipment is en route, and may also be used to calculate doses to airline personnel. Since crew members 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 crew members 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, e.g., spent fuel in a package whose long axis is parallel to the trailer or flatbed surface. The package dimension most appropriate for calculation of crew dose in this instance is package diameter rather than length.

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,

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

where

D_{crew} = integrated dose to crew (person-rem)

Q_1 = units conversion factor (2.8E-3 Sv-m-hr/mSv-km-sec)

$k_{o,end}$ = "crew-view" point-source package shape factor for $d_{e,\,end}$, where $d_{e,\,end}$ 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)

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.

The dose to the operating crew of a train while the train is in transit will be exceedingly small because of:

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

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

$$D_{\text{rail worker}} = Q_1 \cdot k_0' \cdot DR_v \cdot \left[\left(FG_v \cdot R_G \right) + \left(FN_v \cdot R_N \right) \right] \qquad (43)$$

where
$D_{\text{railworker}}$ = rail worker dose (person-rem)
Q_1 = units conversion factor (2.8E-3 Sv-m-hr/mSv-km-sec)
k_o' = line-source rail-car shape factor (m)
DR_v = dose rate at 1 m of rail car v (mSv/hr)
FG = fraction of rail-car dose rate from gamma radiation
FN = fraction of rail-car dose rate from neutron radiation
and

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

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

$$D_{CL} = D_{\text{rail worker}} \cdot NCL \qquad (44)$$

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

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

where
DIC = the number of distance-independent classifications per trip
DDC = the number of distance-dependent classifications per km
$\mathrm{DIST_L}$ = length of link (km)

DIC represents the inspections that occur regardless of total trip distance. The total worker dose for each classification stop is integrated ("hard-wired") into the RADTRAN code. The number of classification stops 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). The time of these classification stops currently in RADTRAN is 30 hours, but recent communications with the Federal Railroad Administration indicate that the average time has been decreased to 27 hours. Federal regulations (49 CFR) require that railcars carrying hazardous material, including radioactive material, be inspected at interchanges. The number of interchanges per link is generally dependent on the length of the link ($\mathrm{DIST_L}$). The recommended value for DDC is derived from Ostmeyer (1986) and is 0.018 inspections per km. Alternatively, if the number of inspections per trip and the time of each inspection are known, the worker dose may be calculated using the integrated classification stop data and the actual time of each stop.

Dose to Cargo Inspectors on Waterborne Vessels

As in the rail case, crew members 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 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

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

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
$k'_{0,\text{end}}$ = "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)
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 $k'_{0,\text{end}}$, 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).

Dose to Flight Attendants

The following equations are used to formulate dose to flight attendants under normal conditions of transport. 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

$$D_{\text{air}} = Q_3 \cdot k_p \cdot DR_v \cdot N_{\text{flatt}} \cdot \frac{DIST_L}{V_L} \qquad (48)$$

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
$DIST_L$ = distance traveled on link L (km)
V_L = average velocity on link L (m/sec)

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 vehicle;
- transfer from the final vehicle 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.

2.6.2 Small Packages ($d_p \leqq$ SMALLPKG)

A recent study of the transportation of small amounts of radioactive materials like smoke detectors (U.K. NRPB, 2001) cites a limiting dose rate of 5 μSv/hour (0.5 mrem/hour) for such packages. A new package shape factor k_H can be defied as

k_H = handling-to-dose conversion factor for small packages = 5E-02
Sv/handling-DR_p (5E-04 rem/handling-DR_p) (49a)

where DR_p, the dose rate per package, is in the appropriate units. The absorbed dose per handling to handlers of small packages is given by:

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

where

D_{Hsmall} = integrated dose to handlers of small packages (person-rem)
k_H = handling-to-dose conversion factor for small packages (equation 49a)
DR_p = package dose rate at 1 m from surface (mrem/hr)
PPS = number of packages per shipment
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:

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

where

D_H = integrated dose to handlers of medium and large packages (person-rem)
Q_4 = units conversion factor = 1.0E-03 Sv/mSv
k_0 = point-source shape factor (m^2)
DR_p = package dose rate at 1 m from package surface (mSv/hr)
T_H = average exposure time of handlers (hr)
PPS - number of packages per shipment
d_H = average package-to-handler distance (m)
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,

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

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.

2.6.3 Importance Analysis

Each incident-free analysis performed using RADTRAN is accompanied by an importance analysis. This analysis uses partial derivatives to determine the effect on the overall result of a one percent change in each input variable. The total incident-free dose, D, is given by

$$\mathrm{D} = \sum d(x_1, x_2 \ldots x_c) \tag{52}$$

The summation represents all dose subgroups. The importance measure, I_c, is defined as the change in D (ΔD), 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

$$\mathrm{I_c} = \mathrm{x_c}\frac{\partial \mathrm{D}}{\partial \mathrm{x_c}} = \sum \frac{\partial \mathrm{d_c}}{\partial \mathrm{x_c}} \tag{53}$$

This can be rewritten as,

$$\mathrm{I_c} = \mathrm{x_c}\frac{\partial \mathrm{D}}{\partial \mathrm{x_c}} = \sum \frac{\partial \mathrm{d_b}}{\partial \mathrm{x_c}}\frac{\mathrm{x_c}}{\mathrm{d_b}}\mathrm{d_b} \tag{54}$$

or as

$$\mathrm{I_c} = \mathrm{x_c}\frac{\partial \mathrm{D}}{\partial \mathrm{x_c}} = \sum_{\mathrm{a}} \frac{\partial \ln \mathrm{d_c}}{\partial \ln \mathrm{x_c}}\mathrm{d_b} \tag{55}$$

Values of Equation 55 for each input variable are printed in each RADTRAN output.

```
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 %
```

Figure 2.6. Example of Importance Analysis in RADTRAN.

3 MODELING TRANSPORTATION ACCIDENTS

Accident consequences and risks are determined by the properties and physical forms of the radioactive materials being transported and the specific radionuclides they contain. Other factors that affect consequence and risk are accident probability, accident severity, package response, and the dispersion environment.

Consequences and probabilities of vehicular accidents are calculated separately and then multiplied, to calculate transportation accident risks. The radiological consequences of an accident are the potential doses that might occur as a result of:

- dispersion of a specified quantity of radioactive material released from a compromised package, and/or
- direct exposure to material that has fallen on the ground, and/or
- direct exposure of persons to ionizing radiation following damage to package shielding (loss of shielding), or
- direct exposure of persons to external ionizing radiation from an undamaged cask on a damaged vehicle that cannot be moved for a significant period of time .

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 or more specified levels of damage to package integrity and/or shielding, including no damage.

A conditional probability is the probability, given that an accident occurs, that it will be of a specified severity. 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 in RADTRAN; each category is assigned a conditional probability. Conditional probabilities depend on the vehicle type, transportation mode, and package response. Package-response data (e.g., release fractions by accident-severity category) are package-dependent and are used to calculate risks and consequences.

3.1 Radionuclide Inventory and Properties of Package Contents

The material(s) in the package(s) being analyzed and the constituent radionuclides are used to estimate accident consequences. The variables for which input values must be supplied for each radionuclide in a package are:

- total number of becquerels (Bq) or curies (Ci)of each radionuclide per package;
- average photon energy disintegration per radionuclide (MeV);

- rate at which aerosol material is deposited on the ground (deposition velocity) (m/s);
- cloudshine dose factor (dose factor for immersion in a cloud of dispersed material) (Sv-m^3/Bq -sec);
- groundshine dose factor (dose factor for external exposure to ionizing radiation) (Sv-m^2/Bq-day)
- physiological characteristics (e.g., organ clearance time)
- half-life (days); and
- measures of the radiotoxicity of dispersed material (Sv/Bq inhaled, Sv/Bq ingested).

The internal radionuclide data library in RADTRAN supplies half-lives (in days), photon energies, and dose conversion factors for 149 radionuclides. The internal library is provided in Appendix XX. Dose conversion factors are the "M" values from ICRP Publication 72 (ICRP, 2002). The user may add "user-defined radionuclides" to define additional radionuclides or to use different dose conversion factors.

3.2 Accident Severity and Package Behavior

The universe of possible vehicle accidents can be described by an event tree, like that shown in Figure 3.1.

The event tree of Figure 3.1 encompasses the possible accident scenarios that could involve a truck. the probabilities reflect the documented frequency of each particular type of accident (Mills, et al, 2005). Each branching of the event tree includes all possible accident scenarios for that particular branch: e.g., an accident will either involve a collision or will not involve a collision; a collision will be either with a fixed object or with an object that is not fixed; and so on. Since probabilities are multiplied along each single branch, the probabilities listed in the column at the right side of the figure are the conditional probabilities that, if there is an accident, it will be an accident of that particular type. For example, from Figure 3-2, the conditional probability that a truck accident will involve a collision of the truck with a bus, another truck, or a train, is 0.77. The preferred method of developing severity categories is event-tree analysis.

The conditional probability of an accident scenario has been referred to, in older versions of RADTRAN, as s "severity fraction." The category definitions should cover the range of possible accident scenarios and the sum of the conditional probabilities of occurrence (severity fractions) of all of the categories should be approximately 1.0.

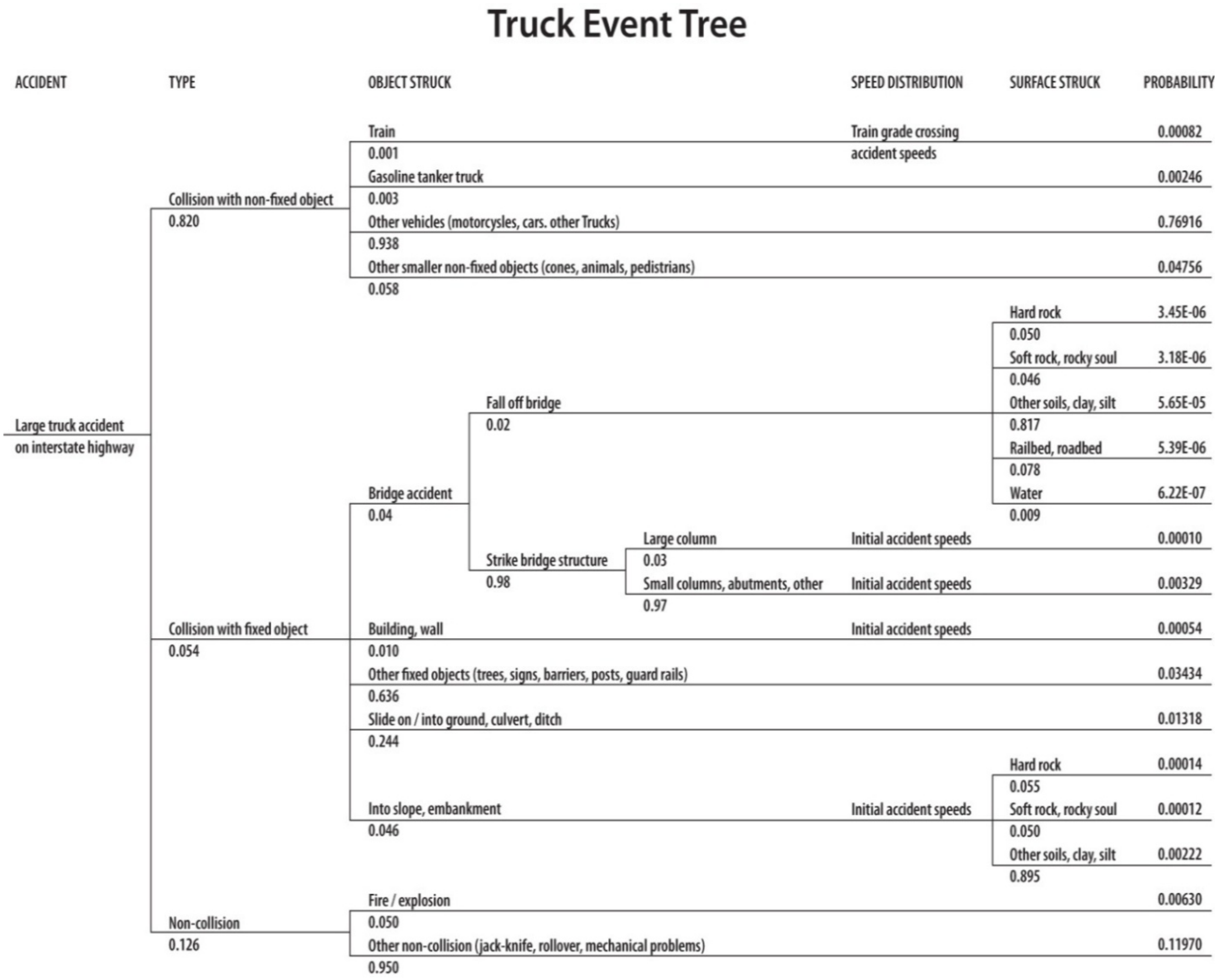

Figure 3.1. Truck accident event tree (from Mills, et al., 2005, Figure 7.3).

Behavior of the transported package in an accident determines whether there is any release of radioactive material or loss of shielding. The total radioactivity that can be carried in a Type A or industrial containers is such that exposure to this activity at a one meter distance for 30 minutes would result in a radiation dose no greater than 50 mSv (IAEA, 2002, Appendix I) (10 CFR Part 71 Appendix A). Type B containers and casks must meet the test conditions of 10 CFR 71.73 and are sufficiently robust that release of radioactive material in a traffic accident could occur only through the seals by seal failure.

For a given level of package response, actual releases, if any, are determined in part by the physical and chemical properties of the contents (not by the radioactivity). Several categorization schemes have been developed for spent fuel casks and other Type B packagings; the most recent are Sprung, et al, (2000), Chapter 7 and NRC (2013), Chapter 5 and Appendix E.

Each accident scenario has associated release fractions for each group of radionuclides in the package that exhibit similar physical and chemical properties (physical/chemical group). For example, the physical/chemical groups in spent nuclear fuel (SNF), a mixture of actinides and fission products, are gases, volatile materials, CRUD[6], and solid particulate matter. Release fractions for each physical/chemical group are applied to the radionuclides belonging to that group. The deposition velocity for each physical chemical group is also specified, as is the fraction of each nuclide that becomes airborne and the fraction of such airborne material that is respirable.

Deposition velocity of airborne particles depends on particle size and density. RADTRAN can accommodate only laminar (Stokes) flow; the deposition velocity for particles that can be modeled in RADTRAN is given by equation 56:

$$V_d = \frac{gd^2\rho}{18\mu} \tag{56}$$

where V_d is the deposition velocity (m/sec),
g is the gravitational constant (m/sec^2),
d is the particle aerodynamic diameter (AMAD) (m),
ρ is the particle density(kg/m^3), and
μ is the viscosity of air (kg/m-sec).

Values of settling velocity that RADTRAN accommodates well are between zero and 0.1 m/sec; for most particles and aerosols, 0.01 m/sec provides an adequate approximation.

Release, aerosolized, and respirable fractions are combined with deposition velocities and accident probabilities for each severity category, the number of packages, and the number of trips to calculate consequences and risks expected as a result of release of each material in each link.

3.3 Application of Meteorology to Dispersion[7]

The dispersion of a cloud of aerosol debris potentially released at the site of a severe accident also must be described in order to estimate consequences.

3.3.1 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

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[6] CRUD (Chalk River Unidentified Deposits) are corrosion products on the outside surface of the fuel rod cladding.

[7] A more detailed discussion of atmospheric dispersion can be found in Turner (1994) and Wark, et al, (1998)

(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.
- Dispersion is assumed to occur from a point or small area source.[8]
- 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 3.2). With few exceptions, source clouds for releases associated with transportation accidents should be modeled as puff releases. The Gaussian models for continuous releases such as those from smokestacks (elevated releases) or pipeline leaks (ground-level releases) may not be appropriate 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 the Greek letter CHI[9] and having units of Sv-sec/m^3 of the aerosol. For radioactive materials, the value of CHI 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 (Sv) in RADTRAN and is inversely proportional to the wind speed (u with units of m/sec). One way of describing the behavior of CHI as one moves away from a release location is to tabulate values of the dilution factor CHI/Q for a given wind speed and downwind distance or wind speed and isopleth area. Isopleths, or curves representing constant concentrations, are areas bounded by lines of equal CHI/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 CHI/Q are nested within isopleths with smaller CHI/Q values (Figure 3.3). In the case of an elevated release, the area of highest CHI/Q may be displaced some distance downwind. The shapes of the isopleths vary with atmospheric stability and other factors but are usually elliptical.

Pasquill (1961) classified atmospheric stability into six classes:

- A: strongly stratified air
- B: moderately unstable

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[8] Lagrangian and Eulerian models allow calculation of dispersion from a rising column of pollutant.

[9] "CHI" is written throughout instead of "X" in order to avoid confusion with the capital letter X.

- C: unstable
- D: neutral
- E: slightly stable
- F: very stable; temperature inversion

A seventh extremely stable Class G has been added, but RADTRAN treats F and G identically.

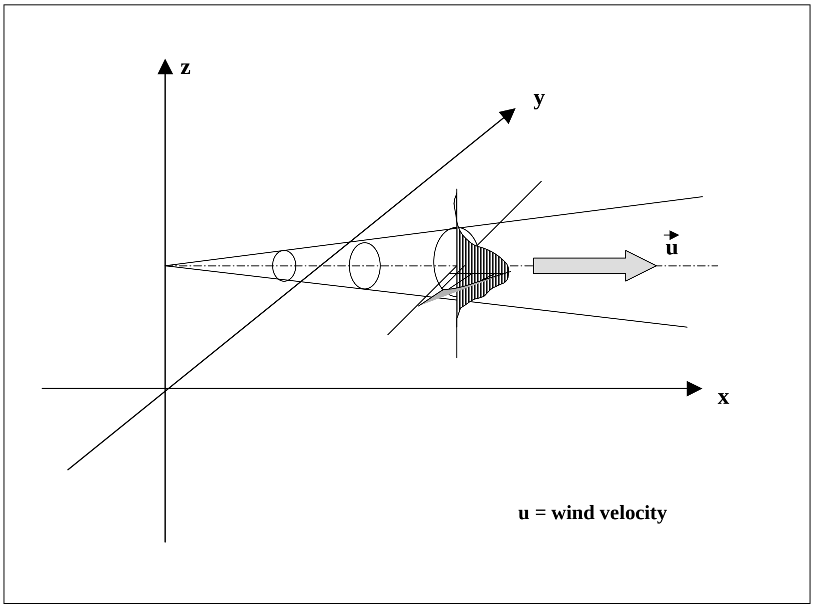

Figure 3.2 Diagram of Gaussian dispersion

Each atmospheric stability class is characterized by two meteorological constants (σ_y and σ_z) which are functions of the downwind distance and 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 (1994) and Till and Meyer (1983). The relationship between stability class and wind speed may be described by Table 3-1 (from Turner, 1994, Table 2.2).

Table 3-1 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

Dispersion associated with release into oceans or other bodies of water is not modeled in RADTRAN. 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 (Ensminger, et al., 1987).

3.3.2 Atmospheric Dispersion Calculations

The basic equation for Gaussian dispersion of radioactive materials in air, in terms of the dilution factor CHI/Q, is:

$$\frac{\mathrm{CHI}}{\mathrm{Q}} = \frac{1}{2\pi\pi u_y\ \sigma_z}\left[\exp\left\{-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right\}\right]\left[\exp\left\{\frac{-(z-H)^2}{2\sigma_z^2}\right\} + \alpha\exp\left\{\frac{-(z+H)^2}{2\sigma_z^2}\right\}\right] \qquad (57)$$

where

CHI = concentration of dispersed substance (Bq/m^3)

Q = rate of release of dispersed substance (Bq/sec)

u = wind speed (m/sec)

σ_y = crosswind meteorological constant (m) [y-axis Gaussian half-width (see Figure 3.4)]

σ_z = vertical meteorological constant (m) [z-axis Gaussian half-width (see Figure 3.5)]

H = release height (m)

α = reflection term; set equal to 1 for all materials [N.B. more commonly α = 0 for a completely depositing substance and α = 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, activity units (Bq) are used; other models that deal with non-radioactive materials usually express Q in grams or a similar mass unit. In RADTRAN , the dilution factor CHI/Q has units of Sv-sec/m^3-Bq released. RADTRAN includes an additional conservatism by setting α, the reflection term, to 1 for both depositing and non-depositing substances. Equation 57 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 57, as described later in this section. 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 CHI/Q is the quantity of interest, z is set to 0. Equation 57 then becomes[10]

$$\frac{\mathrm{CHI}}{\mathrm{Q}} = \frac{1}{\pi u \sigma_y \sigma_z} \left[\exp\left\{ -\frac{1}{2} \frac{y^2}{\sigma_y^2} \right\} \right] \qquad (58)$$

Figures 3.3 and 3.4 (from Turner, 1994) show the relationship between σ_y and σ_z and downwind distance. From the figures, it is evident that CHI/Q decreases rapidly as one moves laterally away from the plume centerline. The "footprint" of the plume is thus an ellipse with the semi-major axis in the direction of the wind and a relatively small semi-minor axis (this is shown in Section 3.6, Figure 3.6). 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 are isopleths – curves of constant CHI/Q that may be obtained by solving equation 58 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.

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[10] When α =1 in Equation 57, the factor of 2 in the denominator is cancelled.

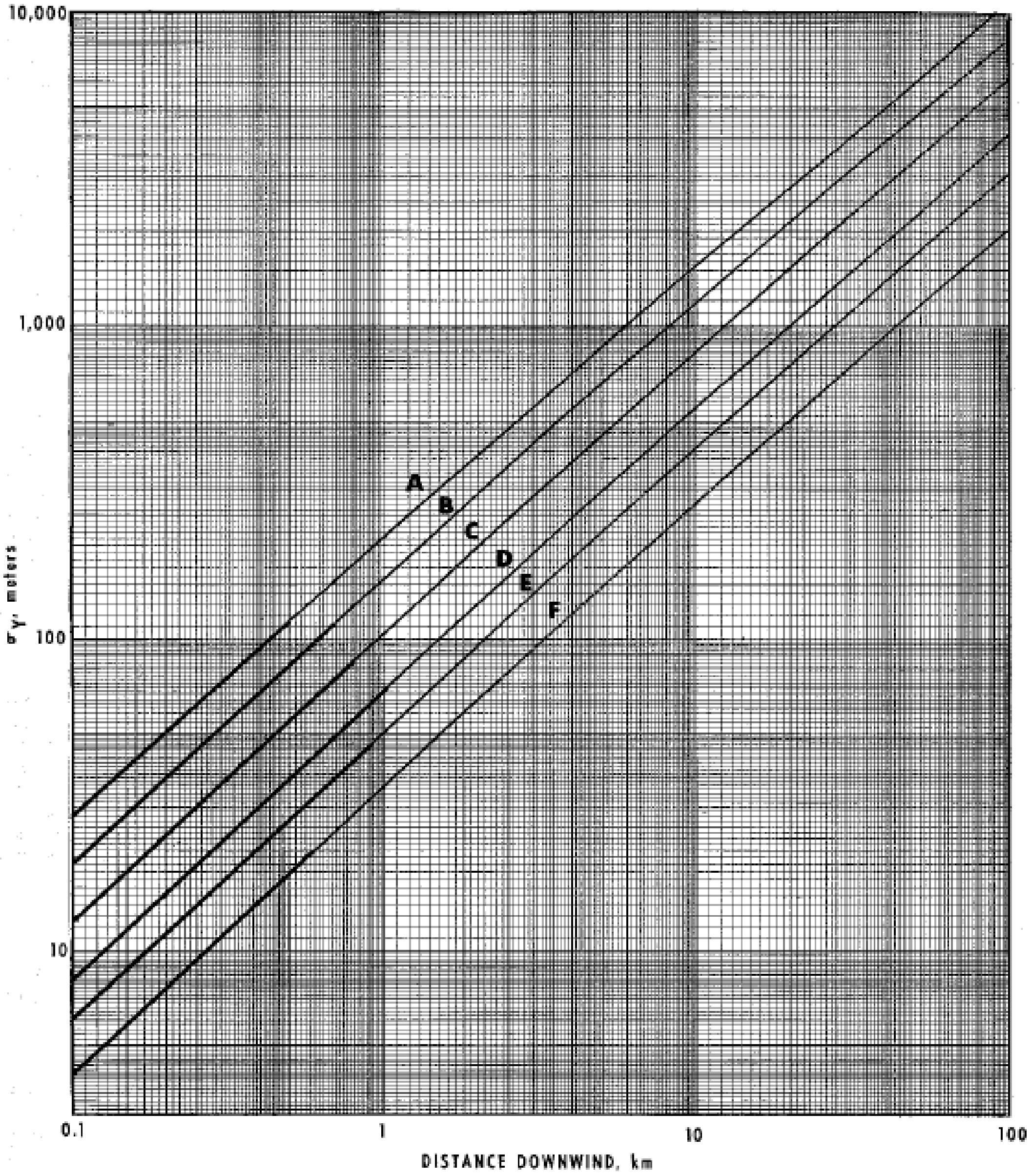

Figure 3.3. Crosswind Gaussian half-width (σy) as a function of downwind distance and meteorological stability. A, B, C, D, E, and F are the six Pasquill meteorological stability classes; from Turner (1994, reprinted by permission of Lewis Publishers).

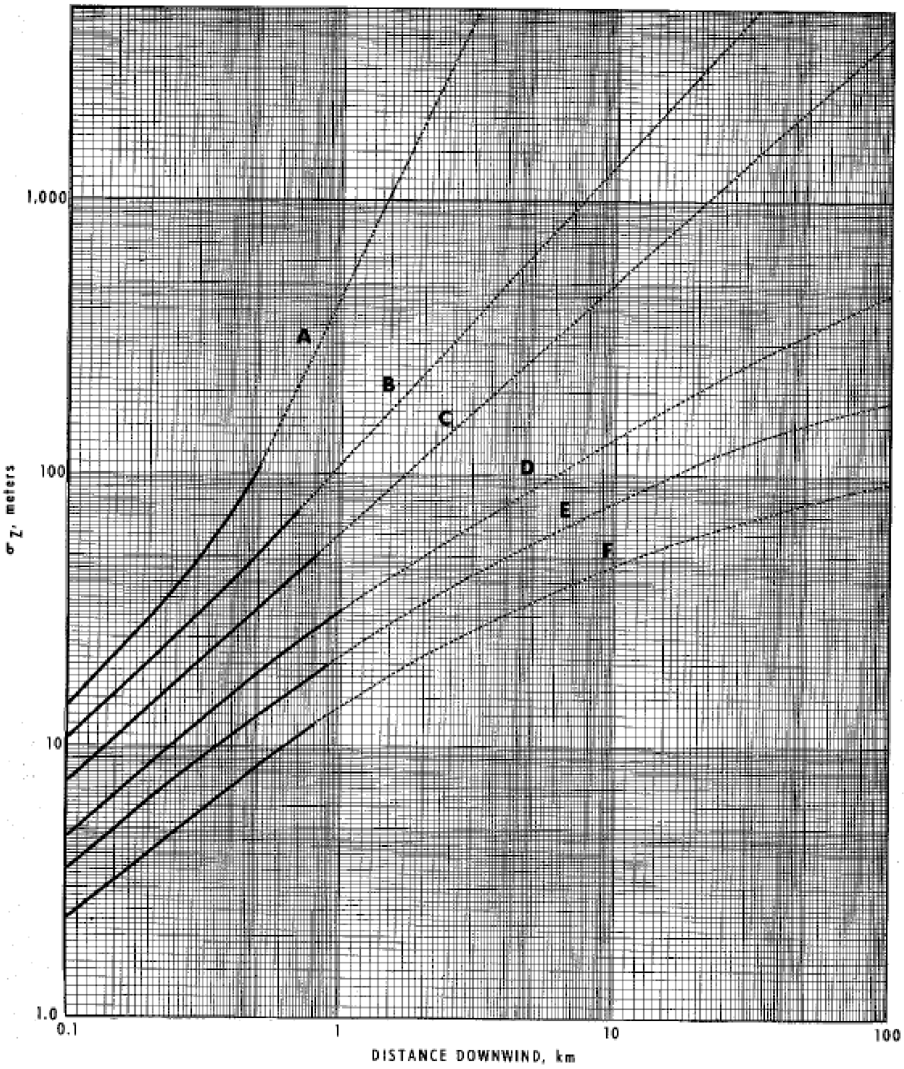

Figure 3.4. Vertical Gaussian half-width (σz) as a function of downwind distance and meteorological stability. A, B, C, D, E, and F are the six Pasquill meteorological stability classes; from Turner (1994, reprinted by permission of Lewis Publishers).

At ground level along the plume centerline (y=0), Equation 58 reduces to

$$\frac{CHI}{Q} = \frac{1}{\pi u \sigma_y \sigma_z} \tag{59}$$

Deposition of particles from an airborne plume is calculated by incorporating the deposition velocity of the particle, V_d (m/sec), to give equation 60:

$$\frac{CHI}{Q} = \frac{V_d}{\pi u \sigma_y \ \sigma_z} \qquad (60)$$

In equations 59 and 60, CHI/Q is expressed in units of Bq/m^2-Bq released. An elevated release is described by

$$\frac{CHI}{Q} = \frac{1}{\pi u \sigma_y \sigma_z} \exp\left\{-\frac{y^2}{2\sigma_y^2}\right\} \exp\left\{-\frac{H^2}{2\sigma_z^2}\right\} \qquad (61)$$

where all variables are previously defined.

Calculation of deposition requires incorporation of the settling velocity into equation 61,[11] which yields:

$$\frac{CHI}{Q} = \frac{V_d}{2\pi u \sigma_y \sigma_z} \exp\left\{-\frac{y^2}{2\sigma_y^2}\right\} \exp\left\{-\frac{\left[H - \frac{xV_d}{u}\right]}{2\sigma_z{}^2}\right\} \qquad (62)$$

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

3.3.3 RADTRAN Calculations

RADTRAN provides three alternate methods for calculating dispersion:

- using average U. S. weather data
- selecting a mix of Pasquill meteorological stability classes (Pasquill, 1961)
- using a dynamic dispersion model

Illustrations of these in RADTRAN maybe found in the RADTRAN 6/RadCat 6 User Guide (Weiner, et al., 2013)

The Average Method

The *Average* method uses a fixed set of isopleths, isopleth center-line distances, and dilution factors. These were calculated from 1980 U. S. average meteorological data, using a model of the equations discussed above. This method uses a single table of average or typical data (isopleth areas and CHI/Q values).

The *Average* method assumes release of radioactive material at ground level and cannot be used to calculate doses from an elevated release, such as a release combined with

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[11] For a derivation of this equation see Chapter 5 of Wark et al, 1998.

thermal loft from a fire. A ground-level release yields larger overall downwind concentrations and ground depositions than an otherwise comparable elevated release. Where there is lofting, the maximum ground-level aerosol concentration, while smaller than the maximum for the same release at ground level, will occur at some distance downwind from the accident site. The data included in the *Average* option are for a "puff" that is 10 m in diameter. Using a point source (i.e., an infinitely small source cloud) to model real releases would give erroneous and excessively high downwind concentrations for the innermost isopleths in particular.

When the *Average* method is used, any of the longer RADTRAN outputs will show a table of dilution factors for each severity category as a function of downwind distance. Analogous tables will be shown for deposition, ground contamination, and various doses and consequences.

The Pasquill Method

The *Pasquill* method uses tables of values for CHI/Q and isopleth areas for each of the six Pasquill stability classes and allows the user to specify the fraction of each Pasquill stability class that contributes to the overall meteorology. Each Pasquill stability class has a fixed associated wind speed, as shown in Table 3-2 (from Luna and Church, 1972). Lighter winds result in less dispersion and are therefore conservative, in that they yield larger values for downwind concentration than would greater wind speeds.

Table 3-2. Stability classes and associated wind speeds in the *Pasquill* option

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

RADTRAN contains tables of downwind distance, associated isopleths, and dilution factors for each of the six stability classes. These tables were calculated using models of the appropriate version of equation 59 with the wind speeds shown in Table 3-2. As in the *Average* method, the *Paquill* method is useful only for an instantaneous ground-level release and a small-diameter (10 m) source cloud.

The data in Tables 3-3 and 3-4 are the dilution factors, isopleth or "footprint" areas, and centerline downwind distances for the six Pasquill meteorological stability classes.

Table 3-3 Dilution factors in Bq-sec/m^3 for the six Pasquill categories

AREA	PASQUILL CATEGORY					
(m^2)	A	B	C	D	E	F/G
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 3-4. Areas and centerline distances for the six Pasquill meteorological classes

AREA	CENTERLINE DISTANCES (m)					
(m^2)	A	B	C	D	E	F/G
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

The *User-defined* option allows the user to model elevated releases and releases into wet as well as dry air. Most important, the user can specify the wind speed. This option provides a dynamic dispersion model, while the other two options provide static dispersion models.

The RADTRAN dispersion model assumes that the receptors are downwind from the release. Although this assumption is conservative, it is the only reasonable one to make, since the location of a potential accident with respect to wind direction is unknown. 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. These calculations were originally preserved by a separate code (TICLD) that now has been incorporated into RADTRAN (Weiner, Neuhauser and Kanipe, 1993). These individual-dose values are saved and printed in the output.

3.4 Dose and Dose Risk calculations

RADTRAN models external exposure when there is no release of radioactive material, and 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.

External doses calculated in RADTRAN, including incident-free doses, groundshine and cloudshine doses, and doses from loss-of-shielding accidents are expressed as effective dose equivalents (EDEs). Doses from inhaled or ingested radionuclides are retained in the various organs of the body and are expressed as committed effective dose equivalents (CEDEs). Dose commitments are calculated for periods of 1 year (for potential early effects, which would almost never occur from traffic accidents) and 50 years (for latent effects). Doses to individuals are usually expressed in Standard International Units (Sv). Collective doses are expressed in units of person-Sv. Organ doses (in Sv) also are computed for internal exposures via the inhalation and ingestion pathways. Latent effects may be calculated using published conversion factors (ISCORS, 2002).

3.4.1 Dose to an Individual from Inhalation of Dispersed Materials

In RADTRAN, the average individual inhalation dose attributed to a released amount of respirable aerosol of radionuclide i in material m within each downwind isopleth area is computed as follows:

$$D_{inh} = \sum_{m}^{\text{all materials}} \sum_{i}^{\text{all radionuclides}} \sum_{o}^{\text{all organs}} \left(Ci_i \cdot PPS_L \cdot RF_{i,j} \cdot AER_{i,j} \cdot RESP_{i,j} \cdot RPC_{i,o} \cdot \overline{X}_n \cdot BR \right) \qquad (63)$$

where
D_{inh} = individual inhalation dose (rem)
Bq_i = number of becquerels of radionuclide *i* in package (Bq)
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 (Sv per Bq) for *i*th radionuclide and *o*th organ (lung, marrow, and thyroid)
$\overline{X}_n$ = dilution factor (CHI) in nth isopleth area (Bq-sec/m^3 per Bq released; see Chapter 4)
BR = breathing rate (m^3/sec)

The subscript indices are defined in Table 3-5.

Table 3-5. Indices of RADTRAN Variables

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

3.4.2 Integrated Population Doses

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

$$D_{inh}^{pop} = Q_7 \cdot Ci_i \cdot PPS_L \cdot RF_{i,j} \cdot AER_{i,j} \cdot RESP_{i,j} \cdot RPC_i \cdot IF \cdot BR \cdot PD_L \cdot A_n \qquad (64)$$

where,
Q_7 = units conversion factor = 10^{-6} km^2/m^2
Bq_i = number of becquerels of radionuclide i per package (Bq)
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 (Sv per Bq inhaled)[12]
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 below.

In urban areas, persons both inside and outside of buildings may sustain an inhalation dose. To account for this, the population density term in equation 64, PD_L, is multiplied by the following term, which is invoked when a transportation link or route segment is characterized as U (urban):

$[(UBF \cdot BDF) + (USWF \cdot RPD)]$
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
UBF + USWF =1 since the people exposed are either inside the building or outside.

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 the 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. 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 to 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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[12] May be reset to zero for special-form materials with the DEFINE function of RADTRAN. The variable designation RPC_i has been retained in spite of the use of SI units, in orderto avoid problems in coding.

(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), and who occupy a sidewalk along the route. 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). Although some parts of cities (e.g., the Las Vegas, NV Strip or the Washington, DC Mall) could have a higher ratio of pedestrians to residents, the RPD is an average over an entire urban population, and is thus an adequate approximation in the absence of data.

Integrated Population Dose from Resuspension

An inhalation dose also result from deposited materials, because particulates can be resuspended by various mechanisms 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 dimensionless factor that is applied to the direct inhalation dose. Resuspension dose (D_{res}) can thus be expressed as

$$D_{res} = D_{inh} \cdot (RDF - 1) \tag{65}$$

where

D_{inh} = direct inhalation dose (from equation 64)

RDF = resuspension dose factor

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

$$RDF = 1 + V_d \left(8.64x10^4\right) \cdot \left[\frac{10^{-5}}{\lambda_1} \left(1 - e^{-18250\lambda_1}\right) + \frac{10^{-9}}{\lambda_2} \left(1 - e^{-18250\lambda_2}\right) \right] \tag{66}$$

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).

The period of dose integration is the same as the evacuation time (default = 24 hours); this is the time that the receptor would be exposed to resuspended radioactive material. The resuspension half-life is set to 15 days (Anspaugh, 2002) and the radioactive half-life is radionuclide-specific.

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. However, dose from an aerosol release of certain radionuclides that emit high-photon-energy gamma radiation, such as ^{24}Na and ^{60}Co, could be significant. Cloudshine Dose Factors (CDFs) are calculated for both photon- and neutron-emitting radionuclides (DOE, 1988; Eckerman & Ryman, 1993, Schleien, et al, 1996).[13] 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

$$D_{\mathrm{cld}}^{ind} = \sum^{\mathrm{materials}} \sum^{\mathrm{isotopes}} \sum^{\mathrm{organs}} \left(\mathrm{Ci}_{\mathrm{i}} \cdot \mathrm{PPS} \cdot \mathrm{CDF} \cdot \overline{\mathrm{X}}_{\mathrm{n}} \cdot \mathrm{RF}_{\mathrm{i,j}} \cdot \mathrm{AER}_{\mathrm{i,j}} \right) \tag{67}$$

where
$\mathrm{Bq_i}$ = number of curies of radionuclide i (Bq)
PPS = number of packages per shipment
$\mathrm{CDF_i}$ = cloudshine dose factor for radionuclide i (Sv-$\mathrm{m^3}$/Bq-sec)
$\overline{\mathrm{X}}_{\mathrm{n}}$ = time-integrated concentration of radionuclide i in nth isopleth (Bq-sec/$\mathrm{m^3}$)
$\mathrm{RF_{i,j}}$ = 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

$$D_{\mathrm{cld}_{\mathrm{i,j,L,m}}}^{pop} = \mathrm{Q_7} \cdot \mathrm{Ci_i} \cdot \mathrm{PPS_{L,m}} \cdot \mathrm{RF_{i,j}} \cdot \mathrm{AER_{i,j}} \cdot \mathrm{CDF_i} \cdot \mathrm{IF} \cdot \mathrm{PD_L} \tag{68}$$

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

Equation 68 is used without modification in rural and suburban areas. In urban areas, for urban links, the factor (UBF·BDF + USWF·RPD) is applied to account for air filtration in buildings and exposure of pedestrians. This yields the following equation:

$$D_{\mathrm{cld}_{\mathrm{i,j,L,m,u}}} = \mathrm{Q_7} \cdot \mathrm{Ci_i} \cdot \mathrm{PPS_{L,m}} \cdot \mathrm{RF_{i,j}} \cdot \mathrm{AER_{i,j}} \cdot \mathrm{CDF_i} \cdot \mathrm{IF} \cdot \mathrm{PD_L} \cdot (\mathrm{UBF} \cdot \mathrm{BDF} + \mathrm{USWF} \cdot \mathrm{RPD}) \tag{69}$$

where all variables are as defined in Equation 68 except for the last term, which is defined after equation 64.

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

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 Section 3.3. Persons living or working in the plume “footprint” will receive an external dose from this deposited material. This section describes the derivation of equations that relate gamma flux to dose rate and then expresses gamma flux in terms of deposited radionuclide concentrations.

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)

$$\phi_g = \frac{S}{2} E_1(\mu r) \tag{70}$$

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 (64) can then be restated as Bq per cm^2, since one beccquerel = one disintegration/sec = one photon/sec. 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).

$$DR_i = CL_i \cdot GDF_i \tag{71}$$

where

CL = contamination level of radionuclide i (3.7E4Bq/m^2)[14]

GDF = groundshine dose factor for radionuclide i (Sv-m^2/day-3.7E4Bq)

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[14] 1 μCi = 3.7 x 10^4 Bq. The equation is written this way for consistency with the RADTRAN internal calculation, which is done in historical units.

Groundshine dose factor values are taken from Eckerman and Ryman (1993;Federal Guidance Report 12) and are included in the RADTRAN radionuclide library for all radionuclides listed.[15] Equation 71 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 will generally be lower. 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:

$$\mathrm{DR(T)} = \mathrm{CL_i} \cdot \mathrm{GDF}\left[0.63\mathrm{e}^{-0.0031 t_{1/2}} + 0.37\mathrm{e}^{-0.000021 t_{1/2}}\right] \cdot \mathrm{e}^{\frac{-0.693\mathrm{ET}}{t_{1/2}}} \tag{71}$$

where

CL_i = contamination level of radionuclide i (3.7E4Bq/m^2)

GDF_i = groundshine dose factor for radionuclide i (Sv-m^2/day-3.7E4Bq)

$t_{1/2}$ = half-life of radionuclide i (days)

ET = elapsed time (days)

The term CL is derived from the deposited concentration, which has units of Bq/m^2 per Bq released, as follows:

$$\mathrm{CL_{i,j}} = \mathrm{Q_9} \cdot \mathrm{PPS} \cdot \mathrm{DC_{i,j}} \cdot \mathrm{Ci_{i,j}} \tag{72}$$

where

Q_9 = 3.7E10 Bq/Ci

PPS = number of packages per shipment

$DC_{i,j}$ = deposited concentration of radionuclide i from a single package in an accident of severity j (Bq/m^2 per Bq released). This term is calculated by RADTRAN from the deposition equation (equation 62). The RADTRAN calculation is described in Section 3.6.

CR_i = Bq of radionuclide i released from package in an accident of severity j (Bq) = $Bq_i \cdot RF_{i,j}$ (inventory and release fraction of radionuclide i in an accident of severity j)

The first two exponential terms in equation 72 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 (CL) and the contamination 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:

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[15] 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).

$$\mathrm{TDF} = \frac{\sum^{\text{all materials}} \sum^{\text{all radionuclides}} \mathrm{CL}_i}{\mathrm{CU}} \tag{73}$$

CL is calculated using RADTRAN, while CU is a number determined by the user, by regulation, or from some other source.

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

- An initial period of exposure to total deposition, which occurs regardless of any cleanup or other action.
- Selection of an interdiction level after clean up (CU) or no action.
- 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) (INTERDICT).

3.4.3 Action Levels

Action levels or thresholds represent a decision-making step in RADTRAN. 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 CL ≤ CU (TDF ≤ 1.0), then no action would be taken
- If CU ≤ CL (TDF > 1.0 ≤ INTERDICT}, then the area would be evacuated and cleaned-up.
- If TDF > INTERDICT, then the area will be evacuated and interdicted.

The recommended value for CU is the proposed EPA guideline of 0.2 $\mathrm{Bq/m^2}$ for total deposited activity (EPA, 1977). The recommended value for INTERDICT is 40, indicating that the numerator of Equation 73 is 40 times greater than CU (= 8 $\mu\mathrm{Bq/m^2}$ for the 0.2 $\mu\mathrm{Bq/m^2}$ threshold).

Calculation of Dose for No-Action Decision

When TDF ≤ 1.0, dose is calculated as follows:

$$D_{gnd} = Q_7 \cdot GDF_i \cdot t_{1/2_i} \cdot A_n \cdot PD_L \cdot CL_{n,j,i}\left[TRM1 + TRM2\right] \tag{74}$$

where

Q_7 = units conversion factor = 1.0E-6 $\mathrm{km^2/m^2}$

GDF_i = groundshine dose ($\mathrm{Sv\text{-}m^2/day\text{-}3.7E4Bq}$)

$t_{1/2i}$ = 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 by radionuclide i in nth isopleth area for an accident of severity j (Bq/m^2)
TRM1 = $\left[\lambda_1(1-e^{-\lambda_2 T_E})+\lambda_3(1-e^{-\lambda_4 T_E})\right]$
TRM2 = $\left[\lambda_1 e^{-(\lambda_2 \cdot T_S)}+\lambda_3(e^{-\lambda_4 \cdot T_S}-e^{-\lambda_4 \cdot 1.83E+4})\right]$

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

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

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

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

TRM 1 in equation 74 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 – an exceedingly conservative assumption, that fails to take into account weathering and other factors that disperse or cover the deposited material. As of this writing, the 50-year dose is still calculated by RADTRAN but not reported in the output. Without the 50-year exposure period, The incurred dose would be

$$D_{gnd} = Q_7 \cdot GDF_i \cdot t_{1/2_i} \cdot A_n \cdot PD_L \cdot CL_{n,j,i}\left[\mathrm{TRM1}\right] \qquad (75)$$

with all parameters defined as in equation 74.

Doses calculated with equations 74 and 75 are summed over all radionuclides to yield total dose per isopleth area. In the no-action case, there is no difference in the deposited concentration because no clean up is performed, and both terms are multiplied by CL_i.

Calculation of Dose for Evacuation and Clean-Up

When $1.0 < TDF \leq INTERDICT$, 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 smaller amount of residual radioactivity.

$$D_{gnd} = Q_7 \cdot GDF_i \cdot (A_n - A_{n-1}) \cdot PPS_L \cdot PD_L \cdot t_{1/2_i} \left[TRM1 \cdot CL_i \right] \qquad (76)$$

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-μBq)
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 radionuclide i (days)
TRM1 = see equation 74

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.

$$D_{gnd} = Q_7 \cdot GDF_i \cdot t_{1/2_i} \cdot PPS \cdot (A_n - A_{n-1}) \cdot PD_L \cdot TRM1 \cdot CL_{n,j,i} \qquad (77)$$

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-μBq)
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 (74)
$CL_{n,j,i}$ = contamination level of radionuclide i in nth area for accident of severity j

Calculation of Total Dose

The total dose from groundshine (per accident) is calculated by summing the results for all radionuclides in each isopleth.

$$D_{gnd\text{-}Total} = \sum_{n=1}^{NAREAS} D_{gnd} \qquad (78)$$

where
$D_{gnd\text{-}Total}$ = Total groundshine dose
D_{gnd} = Groundshine dose (person-Sv) for the ith radionuclide in the nth isopleth in accident of severity j on link l

3.4.4 Ingestion Dose

Food supplies may become contaminated by radionuclides deposited on agricultural products. This pathway is limited to accidents that result in the contamination of agricultural areas (i.e., rural links). 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 was used to develop estimates of ingestion dose for most radionuclides in the internal data library.

Because COMIDA runs fairly slowly, it is usually run outside of RADTRAN. COMIDA generates ingestion doses for a fixed radioactivity of each nuclide under consideration. An alternate model, INGEST (Weiner and Heames, 2013) has been developed, which runs within RADTRAN. Essentially COMIDA and RADTRAN are structured the same way, although programmed differently. COMIDA is based on Idaho agriculture, and the parameter values are not easily changed. INGEST considers agriculture in every state.

The Ingestion Dose Structure

If released radioactive material is deposited on any crop that is eaten by either people or animals, and radioactive material can be ingested. Exposure to ingested radioactive material is proportional to the following parameters.

(1) the quantity of radioactive material taken up by the agricultural commodity ingested; e.g., 1.2 percent of ^{137}Cs deposited on grass could be transferred to milk (Saricks, et al, 1989),
(2) the chemical form and activity of ingested radioactive material in any particular organ or tissue (the ingestion dose conversion factor); for example, the bone surface dose from dissolved ^{137}Cs is 1.4 x 10^{-8} Sv/Bq[1] (ICRP, 1996) ,
(3) the type and energy of ionizing radiation ingested (e.g. see ICRP, 1983), and
(4) the extent to which a target organ is saturated with stable (non-radioactive) isotopes of the radionuclide in question (Moeller, et al., 2005).

The ingestion dose model assumes that every radioactive atom is ingested by someone and therefore contributes to a collective, societal dose. The ingestion dose depends on the agricultural production of the local political jurisdiction (state, province) in which the accident occurs and not on the total agricultural production along the route. For the United States, the State is the political jurisdiction used in this model, because vehicle accident rates and similar statistics are available for each state.

Derivation of the Ingestion Dose Equations

Equation 79 is an expression of the collective ingestion dose potentially resulting from ingestion of radioactively contaminated food. The ingestion dose is a function of the radioactivity in food, and the equations in this and the succeeding sections reflect the pathway from release of radioactivity in the air to dose. The dose is collective, or “societal” because it is assumed that every radionuclide is ingested by some individual.

$$D_{ingest} = \sum_{i}^{Radionuclides} (INGEST_{i,j} \; x \; Clvl_{i,j,k} \; x \; Area_{k}) \qquad (79)$$

D_{ingest} = the total ingestion dose: units are Sv. The only summation is over the radionuclides (subscript i).
$INGEST_{i,j}$= ingestion dose due to ground contamination by radionuclide i in State j; units are $Sv/Bq_{deposited}$;
$Clvl_{i,j,k,}$ = deposited activity of radionuclide i in area k in State j: units are $Bq_{deposited}/m^2$;
$Area_k$ = area of k^{th} dispersion isopleth: units are m^2; for this calculation, 99.9% of the radioactive material is deposited in this area

The ingestion dose, $INGEST_{i,j}$, is given by equation (80)

$$INGEST_{i,j} = ft_{i,j} (DCF_{Ing,i}) \qquad (80)$$

$ft_{i,j}$, = the total food transfer factor for each radionuclide i deposited in State j,
DCF_{Ing}, = the ingestion dose conversion factor, DCF_{Ing}, for each radionuclide i. The ingestion DCF is the effective ingestion DCF for adults listed in ICRP 72 (ICRP, 1996). Units are Sv/Bq.

Calculation of the Total Food Transfer Factor

Radioactive material released to the environment either falls to the ground or becomes airborne and is dispersed. Material that is airborne does not enter the food chain; it can be inhaled and the inhalation and cloudshine doses are calculated separately in RADTRAN (Neuhauser, et al, 2000; Weiner, et al, 2009). Material deposited on the ground can enter the food chain only if it is deposited on agricultural crops; other deposited material either remains on the surface or is resuspended and is weathered, covered, or dispersed with the passage of time. Deposited radioactive material that enters the food chain is taken up in vegetation by three mechanisms: direct deposition from the initial passing plume, deposition onto the vegetation from resuspended contaminants, and retention by root uptake. Contaminated vegetation can then enter the human food chain either directly, in the case of vegetable crops, or indirectly in milk or meat.

NRC Regulatory Guide 1.109 (NRC, 1977b) divides doses into sources from animal products (milk and meat) and crops. Appendix D of USDOE (2002) associates each of the potential uptake sources (crops, milk, meat) with physical modes of uptake: direct deposition, resuspension, and root uptake. The total food transfer factor in equation 81, $ft_{i,j}$ is the fraction of the radioactive material i deposited in State j that is retained in foodstuff and available for human consumption. No crop interdiction (such as burial of contaminated food) or other treatment (such as washing) before consumption is assumed.

Local agricultural productivity, agricultural land use, and agricultural yield differ from state to state. The total food transfer factor for radionuclide *i* in State *j*, $ft_{i,j}$, is obtained by summing the three food chain pathways for that State.

$$ft_{i,j} = Agric_j\left((Crop_j)(fc_i) + (Milk_j)(fm_i) + (Meat_j)(fb_i)\right) \quad (81)$$

$Agric_j$ = fraction of land in State j that is agricultural (unitless).
$Crop_j$ = local annual crop yield in State j; the unit is kg/km^2-yr;
fc_i = food transfer factor for crops for radionuclide i; the unit is km^2-yr/ kg;
$Milk_j$ = local annual milk production in State j; the unit is liters/ km^2-yr;
fm_i = food transfer factor for milk for radionuclide i; the unit is km^2-yr/ liter;
$Meat_j$ = local annual meat production in State j; the unit is kg/ km^2-yr ;
fb_i = food transfer factor for meat for radionuclide i: the unit is km^2-yr/ kg

Crop, meat, and milk production are estimated on a yearly basis in order to account for seasonal variation. The state specificity accounts for different growing seasons and conditions in different states. Fractions of land in agricultural production and local crop yields (Saricks, et al, 1989) are presented in Table A1 (Appendix A) for the 48 contiguous States. The original source of these data is the U.S. Department of Agriculture (USDA, 2012).

The food transfer coefficient for crops, fc_i is the fraction of the radioactivity deposited on the crop area that is transferred to crops that are eventually consumed. DOE (2002) presents the food transfer coefficients in units of m^2-yr /kg; units (e.g., m^2 and km^2) are reconciled in the calculation. The transfer coefficient is:

$$fc_i = \frac{\langle C_i^c \rangle}{G_{i0}} \quad (82)$$

fc_i = food transfer coefficient via crops: units are m^2-yr/ kg;
$\langle C_i^c \rangle = \langle C^c_{di} \rangle + \langle C^c_{si} \rangle + \langle C^c_{ri} \rangle$, the total time-integrated concentration of radionuclide i in crops via direct deposition, resuspension, and the root uptake pathways: units are Bq-yr/ kg;
G_{i0} = initial ground deposition of radionuclide i: units are Bq/m^2.

The food transfer coefficient for milk, fm_i, is the fraction of deposited radioactive material that is transferred from animal feed and pasture grass to milk that then becomes available for human consumption. In the course of a year, the milk cow would feed on pasture grass half of the time and on stored feed half of the time (DOE, 2002). The transfer coefficient is:

$$fm_i = \frac{\langle C_i^p \rangle + \langle C_i^s \rangle}{2G_{i0}} Fm_i Q_f \quad (83)$$

fm_i = food transfer coefficient for milk via pasture grass and feed: units are m^2-yr/ liter;
$\langle C_i^p \rangle = \langle C^p_{di} \rangle + \langle C^p_{si} \rangle + \langle C^p_{ri} \rangle$, the time-integrated concentration of radionuclide i in pasture grass via direct deposition, resuspension, and the root uptake pathways: units are Bq-yr/kg;
$\langle C_i^s \rangle$ = the time-integrated concentration of radionuclide i in stored feeds. The feed is assumed to be the pasture grass that has decayed for 90 days, $\langle C_i^p \rangle e^{-90\lambda i}$ (DOE, 2002).

$\lambda = \ln 2/t_{1/2}$; $t_{1/2}$ = radiological half life
G_{i0} = initial ground deposition concentration of radionuclide i: units are Bq/m^2;
Fm_i = transfer coefficient from feed to milk for radionuclide i: units are Bq-day/liter$^-$ Bq from Table 2;
Q_f = total pasture grass and stored feed consumed by animal (assumed as 50 kg/day) (DOE, 2002)

The food transfer coefficient for meat, fb_i is the fraction of deposited radioactivity retained in animal feed and pasture grass and becomes available for human consumption as meat. In the course of a year, the beef cattle would feed on pasture grass half of the time and on stored feed half of the time (DOE, 2002). The transfer coefficient is:

$$fb_i = \frac{<C_i^p> + <C_i^s>}{2 * G_{i0}} Fb_i Q_f \qquad (84)$$

fb_i = food transfer coefficient for beef via pasture grass and feed.
$<C_i^p> = <C^p{}_{di}> + <C^p{}_{si}> + <C^p{}_{ri}>$, the time-integrated concentration of radionuclide i in pasture grass via direct deposition, resuspension, and the root uptake pathways: units are Bq-yr/kg;
Fb_i = transfer coefficient from feed to animal flesh for radionuclide i: units are Bq-day/kg-Bq from Table A2.

A few of the food transfer coefficients, primarily Fb_i, have been modified, based on the results from Kennedy & Strenge (1992). In general the transfer coefficient from Kennedy and Strenge (1992) is several orders of magnitude smaller and is more in line with coefficients for the transition elements, lanthanides, and actinides.

Calculation of Food Transfer Coefficients[2]

Radionuclide food transfer coefficients are the radionuclide-specific fractions of deposited radioactivity that are transferred from soil to plant to animal product and become available for human consumption. Food transfer coefficients are presented in Table 2, and the calculation is outlined in equations 81 through 88. Time-integrated concentrations in equations 81, 82, and 83 are from Saricks, et al (1989). Ground deposition of each radionuclide is calculated by RADTRAN and presented in RADTRAN output.

Food Pathway Calculations

Equations 85 through 92 provide algorithms for uptake by vegetation through direct deposition onto the vegetation, deposition of material resuspended in the air, and uptake by the plant roots. For the direct deposition from the initial plume, the amount of radioactive material retained on the vegetation is:

$$Cd_i = < x_i > V_d \frac{Pr}{Y_v} \exp[-(\lambda_{ei} t_e + \lambda_i t_h)] \qquad (85)$$

Cd_i = concentration of radionuclide i retained in vegetation: units are Bq/kg;
$<x_i>$ = time-integrated air concentration of radionuclide i in the initial passing plume: units are Bq-yrm^{-3};

V_d = deposition velocity^3 0.01 m/sec (Weiner, et al., 2009);
r = fraction of deposited activity intercepted and retained by the edible portion of the crop (dimensionless, assumed as 0.25) (DOE, 2002);
P = probability that an accident will occur during the growing season (assumed as 0.5, an approximate average of U.S. growing seasons);
Y_v = standing crop biomass of edible portion of vegetation at harvest, assumed to be 2 kg/m^2 for crops and 0.72 kg m^{-2} for pasture grass (DOE, 2002);
$\lambda_{\varepsilon\iota}$ = effective decay constant for removal of the radionuclide deposited on vegetation where $\lambda_{ei} = \lambda_i + \ln 2/t_w$, t_w = 0.0383 yr (14 days) (DOE, 2002);
t_e = time period of aboveground crop exposure to contamination during the growing season, assumed to be 0.165 yr (60 days) for crops and 0.082 yr (30 days) for pasture grass (DOE, 2002) ;
λ_i = radioactive decay constant ($\ln 2/t_{1/2}$) of radionuclide (units are yr^{-1}); and
t_h = time period between harvest of vegetation and consumption, assumed to be 0.038 yr (14 days) for crops by human consumption and zero for pasture grass for animals (DOE, 2002) .

Equation 85 (DOE, 2002, Section D.1.1) is the result of integrating over time, while equation 86 is an integral over the resuspension time. The deposited concentration Cd_i depends on the plume spread over the potentially affected area, which is assumed to occur relatively quickly, and results in the time-integrated concentration $<x_i>$ in Equation (7). The exponential term in equation 85 could have been written as appropriate integrals. However, DOE (2002) Section D.1.1 presents the length of the growing season and the time to consumption as constants.

Radioactivity initially deposited from the airborne plume can be resuspended and become available for deposition onto the vegetation. The concentration of resuspended material is expressed as an integral because resuspension of deposited material and integration of this material with already resuspended material is time-dependent process. The integrand of Equation 86 combines equation 85 with a resuspension factor (equation 87). The time-integrated concentration of radionuclide i retained in vegetation from resuspension is thus:

$$< C_{si} > = \int_0^{\infty} x_{Ri}(t)\, V_d\, \frac{r(1-e^{-\lambda_{ei} t_e})}{Y_v \lambda_{ei}} \exp(-\lambda_i t_h)\, dt \qquad (86)$$

$< C_{si}>$ = time-integrated concentration of radionuclide i in vegetation due to resuspension: units are Bq-yr/kg, and
$x_{Ri}(t)$ resuspended air concentration of radionuclide i at time t: units are Bq/m^3.

The resuspended air concentration in equation 86 is calculated by the following (Momeni, et al, 1979):

$$x_{Ri}(t) = G_i(t) R(t) \qquad (87)$$

$G_i(t)$ = deposited ground concentration of radionuclide i at time t
$R(t)$ = resuspension coefficient at time t.

$$G_i(t) = G_{io}\exp[-(\lambda_g + \lambda_i)t] \qquad (88)$$

G_{io} = <xi>Vd, = initial deposition of radionuclide i (units are Bq/m^2),
λg = ln2/ tg
tg = ground removal half-life, assumed to be 50 yr (Momeni. et al., 1979)

$$R(t) = \begin{Bmatrix} F_I e^{-\lambda_w t}, & 0 \leq t \leq t_s \\ F_E, & t_s \leq t \end{Bmatrix} \qquad (89)$$

F_I = initial resuspension factor (10^{-5}/m),
F_E = final resuspension factor (10^{-9}/m),
λ_w = ln2/tw,
tw = 0.1368 yr (50 d) (Momeni. et al., 1979)
t_s = 1.823 yr. (Momeni. et al., 1979)

The expressions for the resuspension factors and the resuspension decay constant, equations 87 through 89, were derived from experimental measurements (Volchok, 1971; Anspaugh, 1973; Phelps, et al., 1974; NRC, 1974) and are consistent with measured resuspension times in locations as different as the Nevada Test Site, the African bush, and a sheep farm (Anspaugh, et al., 2002).

By using equations 87 through 89, the time-integrated concentration for Equation (8) becomes

$$< C_{si} > = G_{io} < T_i > V_d \frac{r(1-e^{-\lambda_{ei} t_e})}{Y_v \lambda_{ei}} \exp(-\lambda_i t_h) \qquad (90)$$

$$< T_i > = \frac{F_I}{(\lambda_g+\lambda_i+\lambda_w)}\{1-\exp[-(\lambda_g+\lambda_i+\lambda_w)t_s]\} + \frac{F_E}{(\lambda_g+\lambda_i)}\exp[-(\lambda_g+\lambda_i)t_s] \qquad (91)$$

The time-integrated concentration of radioactivity in vegetation via root uptake is calculated by:

$$< C_{ri} > = \int_0^{\infty} G_i(t)\,\frac{B_v(i)}{\rho}\exp(-\lambda_i t_h)\,dt = G_{io}\frac{B_v(i)}{\rho(\lambda_g+\lambda_i)}\exp(-\lambda_i t_h) \qquad (92)$$

<Cri> = time-integrated radioactivity concentration in vegetation from root uptake: units are Bq- yr kg^{-1};
Gi(t) = ground concentration at time t, given in Equation (10);
Bv(i) = concentration ratio for the transfer of the element to the edible portion of a crop from dry soil: units are Bq/kg-plant per Bq/kg-soil from Table A2;
ρ = density for the effective root zone in dry soil, assumed to be 240 kg/m (Momeni. et al., 1979)

The implication of the calculated ingestion dose may be understood by comparison with a natural source of radioactivity. For example, the internal dose from ^{40}K and ^{14}C sustained by a 70 kg individual is about 2.8 mSv (Kramer, 2012). The radioactive material released in any of the sample accidents discussed would be deposited on a surface of about 30,100 m^2 (Table 4). If the crop is a leafy green like spinach, it would yield 330 one-cup (30 gm) servings of raw spinach (Table 5 and USDA, 2012). Each serving would deliver an average ingestion dose of about 4.2 μSv (0.42 mrem), about 0.15 percent of the naturally occurring internal dose from ^{40}K and ^{14}C.

Food transfer coefficients and food transfer factors are in Appendix A.

3.5 Accident Probability and Dose Risk

The term "dose risk" is a RADTRAN artifact, constructed to demonstrate the relationship between radiation dose and the probability of that dose occurring. The units of dose risk are radiation dose units, Sv or rem. In analyzing routine, incident-free transportation, it is recognized that the probability of such transportation is indistinguishable from unity, and the impact is referred to as "dose." However, the probability of an accident and the probability of a particular accident is not unity, and is usually much, much less than unity. "Dose risk" is essentially the product of overall accident probability, scenario-specific conditional probability, and radiation dose.

3.5.1 Probabilities of Accidents

Transportation accident probability has two parts: the probability (or likelihood) that a traffic accident will happen and the conditional probability that the accident will be of a particular severity. Thus, the equation describing accident probability on a route segment is:

$$\gamma_{j,L} = AR_L \cdot SV_{j,L} \cdot DIST_L \qquad (93)$$

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

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

3.5.2 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

$$\mathrm{RISK}_L^{\mathrm{INH}} = \sum_{i=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{\mathrm{inh}} \qquad (94)$$

where

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

D_{inh} = dose from inhalation of radionuclide i in material m in an accident of severity j on link L (person-Sv)

$$n = \sum_{m=1}^{k} \sum_{i=1}^{m}$$

m = number of radionuclides of material m

k = number of different materials

NSEV = number of different accident scenarios (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

$$\mathrm{RISK}_{\mathrm{L}}^{\mathrm{RES}} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot \mathrm{D}_{\mathrm{res}} \qquad (95)$$

where

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

D_{res} = dose from inhalation of radionuclides in an accident of severity j on link L (person-Sv)

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

$$\mathrm{RISK}_{\mathrm{L}}^{\mathrm{CLD}} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot \mathrm{D}_{\mathrm{cld}} \qquad (96)$$

where

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

D^{CLD} = dose from cloudshine of radionuclide i in an accident of severity j on link L (person-Sv)

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

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

where

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

D_{gnd} = dose from groundshine of radionuclide i in an accident of severity j on link L (person-Sv)

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

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

where

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

D_{ing} = dose from ingestion of radionuclide i an accident of severity j on link L (person-Sv)

n = number of radionuclides in package

NSEV = number of accident-severity categories

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.

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

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.

3.5.3 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. Neutron shields are usually organic polymers and are considered to be destroyed in any accident, so that no credit is taken for the neutron shield. Gamma shields are either depleted uranium (DU), steel, or lead. The forces on a Type B shielded cask that are developed in a traffic accident would cause at most negligible damage to a DU gamma shield or a monolithic steel cask (NRC, 2013, Chapters 3 and 4; Sprung, et al, 2000, Chapters 4 and 7). Lead, however, is relatively soft, and melts at a relatively low temperature (330 degrees C.). A sufficiently severe collision could cause the lead to slump and leave a void in the gamma shield (NRC, 2013, Chapter 5 and Appendix E; Sprung, et al, 2000, Chapter 7). A sufficiently hot, long duration fire could melt the lead shield, which, on cooling and contracting, could result in thinning of the shield. In either case, gamma shielding would be decreased. Figure 3.5 is a two-dimensional diagram of an undamaged and damaged cask

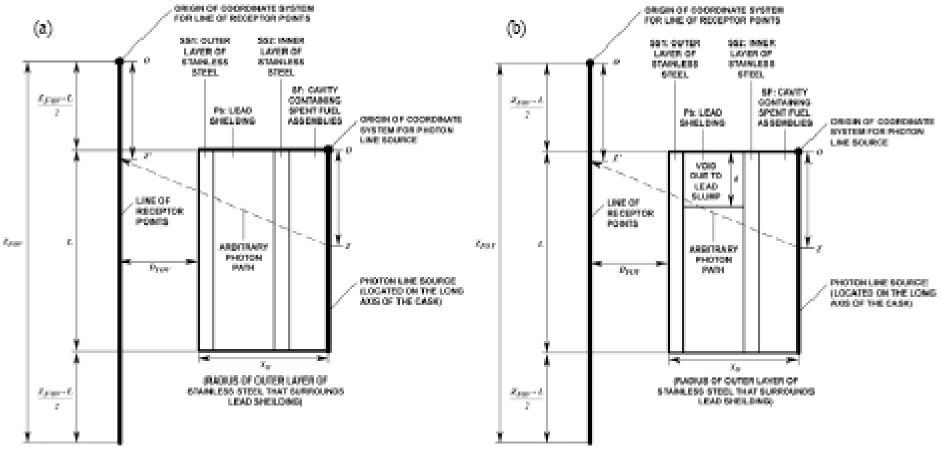

Figure 3.5. Diagram of a cask with (a) an undamaged lead gamma shield and (b) a damaged shield. (From O'Donnell et al, 2005).

The following discussion is an abbreviated version of the derivation of the LOS model of O'Donnell, et al (2005).

The dose rate to a receptor point is calculated by integrating the point-kernel fluence equation over a range of possible source points $zmin \leq z \leq zmax$, where $zmin \geq 0$ and $zmax \leq L$, and multiplying by a suitable factor to convert fluence to dose rate. Thus, for a receptor placed at an arbitrary point z. outside the cask, the dose rate from an isotope emitting photons with energy $E0$ will be approximately given by

$$D(z')_{mono} \cong S_L R(E_0) \int_{z_{min}}^{z_{max}} \frac{B(E_0, \mu_{Pb} x_{Pb}) \exp[-\mu_{Pb}(E_0) x_{Pb}(z,z') - \mu_{SS}(E_0) x_{SS2}(z,z')]}{4\pi r^2} dz, \quad (100)$$

where
$D(z.)_{mono}$ = the dose rate to a receptor located at z from the monoenergetic source,
S_L = the source photon emission rate per unit length of the source,
$R(E_0)$ = the dose response function
$B(E_0, \mu_{Pb} x_{Pb})$ = the buildup factor for photons in lead,
μ = the attenuation coefficient (appropriately subscritopted for each
x = the photon path length through each layer to be considered in the calculation.

The distance from arbitrary point *z* on the line source to receptor point *z.* is

$$r = \sqrt{\left(\left[\frac{Z_{FOV} - L}{2} + z\right] - z'\right)^2 + \left(x_0 + D_{FOV}\right)^2}. \quad (101)$$

Implicit in equations 100 and 101 are the assumptions that buildup is only significant in the lead shielding, and that the outer layer of stainless steel shielding is effectively transparent to photons. Buildup is only taken into account in the lead shielding because the lead layer is much thicker and has a higher attenuation coefficient than either of the two stainless steel layers. The inner layer of stainless steel was accounted for by constraining the limits of integration (*zmin* and *zmax*) such that the only photons considered are those that traverse its entire thickness (i.e., photons do not travel through the corners). A single equation suffices for the photon pathlengths through the inner layer in the integration, which makes it simple to account for this layer, and the outer layer may be neglected without significant error.

The dose response function is assumed to be that for the monoenergetic photons of energy *E0* emitted from the source. However, because of buildup, a spectrum of photons with unknown energy range Δ*E* will emerge from the cask. The expression for dose rate *D* fits the form

$$D(z') = \int_{\Delta E} R(E)\Phi(E,z')dE, \quad (102)$$

where *R*(*E*) is the continuous energy dose response function, and Φ(*E*, z.) is the photon fluence rate per unit energy as a function of energy (spectrum) at the receptor point of interest. Since the continuous energy response function and the spectrum are both unknown quantities, an expression for dose rate that fits the following form is desired

$$D(z') = A\int_{\Delta E} \Phi(E,z')dE \cong A S_L \int_{z_{min}}^{z_{max}} \frac{B(E_0, \mu_{Pb} x_{Pb}) \exp[-\mu_{Pb}(E_0) x_{Pb}(z,z') - \mu_{SS}(E_0) x_{SS2}(z,z')]}{4\pi r^2} dz, \quad (103)$$

where *A* is a constant factor quantifying the dose response. Thus, from equations 102 and 103, *A* is given by

$$A = \frac{\int\limits_{\Delta E} R(E)\Phi(E,z')dE}{\int\limits_{\Delta E} \Phi(E,z')dE}.$$

(104)

Therefore, with no approximation, the constant *A* is given by the fluence-weighted average of the continuous energy response function. Since the continuous energy response function and the emerging photon spectrum are both unknown, the constant *A* is approximated by assuming that the fluence is very small at every energy except for the photon source emission energy *E0* and that *E0* does, in fact, fall within the energy range ΔE. Making these assumptions, the integrands in equation 104 are very small at every point except *E0*, and the expression for *A* becomes

$$A \cong \frac{R(E_0)\Phi(E_0,z')}{\Phi(E_0,z')} = R(E_0).$$

(105)

Combining equations 103 and 105 gives equation 100.

A factor *F* by which the dose rate from the monoenergetic source is increased due to shielding loss from lead slumping is

$$F(z')_{mono} \cong \frac{\left(\int\limits_{z_{min}}^{z_{max}} \frac{B(E_0,\mu_{Pb}x_{Pb})\exp[-\mu_{Pb}(E_0)x_{Pb}(z,z') - \mu_{SS}(E_0)x_{SS2}(z,z')]}{4\pi r^2}dz\right)_{damaged}}{\left(\int\limits_{z_{min}}^{z_{max}} \frac{B(E_0,\mu_{Pb}x_{Pb})\exp[-\mu_{Pb}(E_0)x_{Pb}(z,z') - \mu_{SS}(E_0)x_{SS2}(z,z')]}{4\pi r^2}dz\right)_{undamaged}}.$$

(106)

The only parameters needed for the monoenergetic treatment are those describing the physical dimensions of the undamaged and damaged casks, the source energy, and the receptor location.

In order to estimate *F* at an arbitrary receptor location for a source emitting multiple photon energies, Equation 100 is averaged over the multiple emission energies using activity fractions for a set of key isotopes and branching ratios for the photon energies emitted by each isotope. Some results for a representative truck cask (single assembly steel-lead -steel cask) are shown in Figure 3-6.

The model suggests that if the line of receptor points is close to the cask (within 1m), the increase in dose is very large for points near the shielding gap created by the lead slump, but very rapidly drops off to unity for points near more shielded locations (e.g., near the bottom of the cask). However, as the distance from the cask increases, the dose increase begins to converge to a value greater than unity for receptors within the bounds of the cask. As the line of receptor points moves away from the cask, more and more receptor points experience dose contributions from photons traveling through at least some portion of the gap in the lead shielding. In other words, the receptors have more of a .view. of the source through the gap. Overall, the model suggests that when one is very close to the cask, the dose increase is quite large near the gap in the lead shielding, but not at other points. However, when one is far from the cask, the dose increase is moderate at many points.

The model was benchmarked against MCNP calculations.

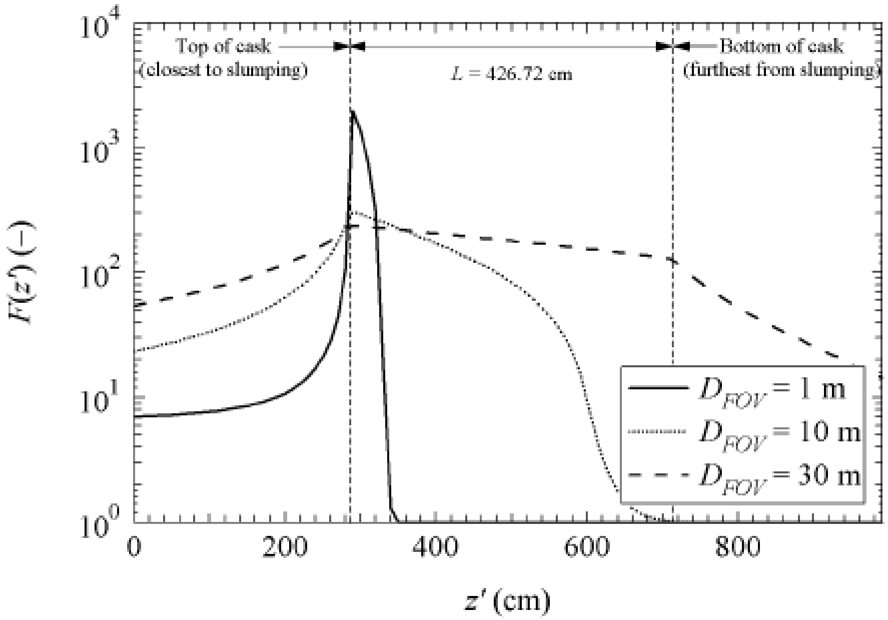

Figure 3.6. The factor F(z) for a representative truck cask at variable distances from the cask. (From O'Donnell et al, 2005)

The factor F is used by RADTRAN to multiply the external dose rate in the stop model, as described in Section 2.4.3. Conditional probabilities are derived in the same way as for accidents involving a release of radioactive material. Thus, the dose-risk per link for LOS is expressed as

$$\mathrm{RISK}_{\mathrm{L}}^{\mathrm{LOS}} = \sum_{\mathrm{j=1}}^{\mathrm{NSEV}} \gamma_{j,L} \cdot \mathrm{D}_{\mathrm{LOS}} \tag{107}$$

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-Sv)

3.5.4 Non-radiological Risks

RADTRAN contains a subroutine that calculates expected traffic accidents and fatalities that are independent of any radioactive cargo. This routine multiplies the traffic accident rate for the appropriate vehicle by the link length, and reports traffic accidents and fatalities for each link.

RADTRAN can also be configured to estimate risks from non-radiological emissions, like hazardous chemical emissions, by creating a “dummy” radionuclide with an extremely long half life and writing a DEFINE statement for that radionuclide.

3.6 RADTRAN Calculations

Figure 3.7 shows the plume footprint and illustrates the RADTRAN calculation that is described below. For the remainder of this section X, the Greek symbol for CHI, is used instead of CHI.

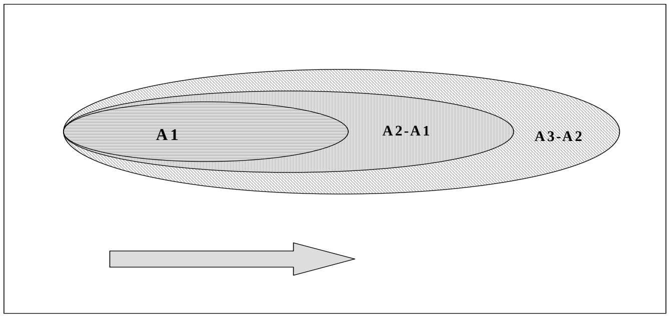

Figure 3.7. Typical Plume Footprint. The arrow represents wind direction. The shaded areas are, respectively, the area of the smallest isopleth (ellipse A1), the area of the second isopleth (ellipse A2 –ellipse A1), and the area of the third isopleth (ellipse A3 – ellipse A2).

For a release of one Bq (Q = 1 Bq), X/Q is equal to X. For each meteorological stability class, the value of X at the downwind edge of of A_1 (Figure 3.7) is 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 of X at the downwind end of the area.

The dilution factor for the area A_2-A_1 is the geometric mean of the largest and smallest dilution factors for that area:

$$\overline{X}_2^0 = \sqrt{X_2 - X_1} \qquad (108)$$

The nth dilution factor is thus

$$\overline{X}_n^0 = \sqrt{X_n - X_{n\text{-}1}} \qquad (109)$$

Equations 96 and 97 are used in RADTRAN for non-depositing materials (e.g., gases). Deposition velocity is introduced into the calculation in two places, as described below.

3.6.1 First introduction of V_d

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

$$DEP_1^0 = \overline{X}_1 \cdot V_d \cdot A_1 \qquad (110)$$

where

X (or CHI) = concentration of dispersed material (Bq/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

$$DEP_n^0 = \overline{X}_n \cdot V_d \cdot [A_n - A_{n-1}] \qquad (111)$$

where all variables are previously defined.

The total amount of material deposited out to A_n is then

$$DEP_n^0 = DEP_1^0 + \sum_{i=2}^{n} DEP_i^0 \qquad (112)$$

where all variables are previously defined.

3.6.2 Second introduction of V_d:

Deposition of material results in depletion of the airborne puff or plume. 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:

$$\overline{X}_n^1 = \sqrt{\left(\overline{X}_n \cdot \left(1 - DEP_n^N\right) \cdot \overline{X}_{n\text{-}1}^0 \cdot \left(1 - DEP_{n\text{-}1}^N\right)\right)} \qquad (113)$$

where all variables have been 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

$$DEP_n^1 = \overline{X}_n^0 \cdot V_d \cdot [A_n - A_{n-1}] \qquad (114)$$

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.

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

$$\mathrm{DC}_n = V_d \cdot \overline{X}_n \tag{115}$$

3.6.3 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). This integration is performed by the AVINT subroutine of RADTRAN, 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 at smaller intervals than isopleths at greater distance from the release point.[16] 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:

- 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).
- 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.

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[16] 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.

4 HEALTH EFFECTS

4.1 Acute Health Effects

Acute health effects are those that occur when individual dose exceeds some threshold value and a health effect is observed. Acute effects are also called prompt effects since the symptoms appear shortly after exposure rather than after a latent period.

Dose rate is as important as dose. 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 means that there is not a single dose threshold for mortality. Instead, a dose and dose rate that results in death to half of the exposed population – a "lethal dose to 50%" or LD_{50} -- is often used to describe lethal effects. For a single short whole-body exposure to external low-LET[17] radiation and minimal post-exposure medical treatment, the National Council on Radiation Protection (NCRP) gives an $LD_{50/30}$[18] 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, or 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 in RADTRAN and used to model the effects of external whole body radiation.

In RADTRAN the potential occurrence of early effects is estimated by comparing the calculated dose to estimated doses to individuals and populations that have exhibited early health effects. 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 several models (Evans et al., 1985; NRC, 1990; ICRP, 1991). The early-effects values used in RADTRAN for acute effects are taken from Evans et al. (1985) for an intermediate level of care since no values were calculated for minimal care. Since acute radiation effects have never been observed to result from transportation accidents, and the calculated doses from potential accident scenarios are usually well below those causing acute effects, the values used in RADTRAN have not been updated

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[17] 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.

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

Table 4-1. Probabilities of Early Fatality – Marrow and Lung Doses

Marrow Dose (Sv)	Fatality Incidence	Marrow Dose (Sv)	Fatality Incidence	Lung Dose (Sv)	Fatality Incidence
<1.60	0.00000	5.70	0.99482	<5.00	0.00000
1.60	0.00913	5.80	0.99679	5.25	0.00759
1.70	0.01234	5.90	0.99808	5.50	0.01050
1.80	0.01639	6.00	0.99889	5.75	0.01430
1.90	0.02143	6.10	0.99938	6.00	0.01922
2.00	0.02761	6.20	0.99967	6.25	0.02549
2.10	0.03510	6.30	0.99983	6.50	0.03341
2.20	0.04408	6.40	0.99992	6.75	0.04329
2.30	0.05475	6.50	0.99996	7.00	0.05548
2.40	0.06729	6.60	0.99998	7.25	0.07038
2.50	0.08188	6.70	0.99999	7.50	0.08837
2.60	0.09872	>6.70	1.00000	7.75	0.10988
2.70	0.11797			8.00	0.13529
2.80	0.13977			8.25	0.16498
2.90	0.16425			8.50	0.19925
3.00	0.19150			8.75	0.23830
3.10	0.22155			9.00	0.28218
3.20	0.25438			9.25	0.33077
3.30	0.28990			9.50	0.38372
3.40	0.32798			9.75	0.44042
3.50	0.36838			10.00	0.50000
3.60	0.41078			10.25	0.56130
3.70	0.45481			10.50	0.62293
3.80	0.50000			10.5	0.68335
3.90	0.54583			11.00	0.74095
4.00	0.59172			11.25	0.79420
4.10	0.63706			11.50	0.84178
4.20	0.68123			11.75	0.88274
4.30	0.72363			12.00	0.91656
4.40	0.76371			12.25	0.94326
4.50	0.80096			12.50	0.96331
4.60	0.83499			12.75	0.97755
4.70	0.86552			13.00	0.98709
4.80	0.89237			13.25	0.99306
4.90	0.91551			13.50	0.99653
5.00	0.93502			13.75	0.99840
5.10	0.95111			14.00	0.99933
5.20	0.96406			14.25	0.99974
5.30	0.97423			14.50	0.99991
5.40	0.98199			14.75	0.99997
5.50	0.98776			15.00	0.99999
5.60	0.99192			>15.00	1.00000

Table 4-2 Comparison of RADTRAN Values with Previous Fatality Values (abbreviated listing)

Dose (Sv)	*Bone Marrow*	*Lung*
1000	1.0	1.0
800	1.0	1.0
700	1.0	1.0
400	1.0	1.0
300	1.0	1.0
250	1.0	1.0
200	1.0	1.0
100	1.0	1.0
80	1.0	1.0
60	1.0	1.0
40	1.0	1.0
30	1.0	1.0
20	1.0	1.0
10	1.0	0.50000
8.0	1.0	0.13529
7.0	1.0	0.05548
6.0	1.0	0.01922
5.0	0.999	0
	1.0 if > 680	
4.0	0.978	0
3.0	0.770	
2.0	0.356	
1.5	0.083	0
1.0	0.012	0
<1.0	0	0

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

Table 4-3. Early Morbidity Threshold Values (derived from Evans et al., 1985, except where noted)

Organ Index (o)	Organ	Organ-Dose Morbidity Threshold (Sv)	Physiological Effect
1	Lung (internal)[a]	5.0	Radiation Pneumonitis
2	Bone Marrow[b]	0.5	Depression of Hematopoesis[c]
3	Gastrointestinal Tract (stomach)	0.5	Prodromal Vomiting
4	Thyroid (radioiodines)	2.0	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 presentation of morbidity symptoms is not discussed here. Discussion of these symptoms may be found in the cited references.

4.2 Model for Acute Health Effects from Inhalation of Dispersed Material

4.2.1 Early Fatalities

For each downwind isopleth, A_n, the lung and bone marrow organ doses are compared to the P^{EF}, the probability of early fatality (see Table 4-1). 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

$$N_{j,L}^{EF\text{-}INH} = \sum_{o=1}^{2} \sum_{n=1}^{NAREAS} \left(EXP_n \cdot P_{j,L,n,o,i}^{EF}\right) \tag{116}$$

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

4.2.2 Early Morbidities

Early morbidity doses are estimated by comparison of the organ doses with the thresholds in Table 5-3. The organs included are the lung, bone marrow, gastrointestinal tract, and thyroid (radioiodines only). Table 5-3 gives threshold dose values for manifestation of physiological effects. The number of early morbidities is estimated by summing over these organs.

$$N_{j,L}^{EM\text{-}INH} = \sum_{o=1}^{4} \sum_{n=1}^{NAREAS} \left(EXP_n \cdot P_{j,L,n,o}^{EM}\right) \tag{117}$$

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)

4.3 Latent Health Effects

The linear, no-threshold (LNT) model of the stochastic dose-effect relationship has been used to estimate stochastic latent effects of ionizing radiation exposure. 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 excessively conservative for and inapplicable to, doses of the order of background (approximately 3.1 mSv/year in the United States) (Muckerheide, 1995; McMahon et al, 2010; Tubiana, et al, 2006; NRC, 2013). The doses for incident-free transportation and for transportation accidents lie well within this range. RADTRAN provides an option that multiplies the calculated dose units by 0.06 LCF/person-Sv (0.0006 LCF/person-rem (ISCORS, 2002).

5 SPECIAL TOPICS

5.1 Regulatory Checks

A check sequence is included in RADTRAN to assess compliance with exclusive-use shipment criteria and applicable regulation. The regulatory checks that RADTRAN performs tell the user whether the RADTRAN parameter values for a shipment of radioactive material comply with Federal regulations for maximum permissible dose rates to population or crew, and with exclusive-use criteria. If the user designs a shipment that does not meet these regulations, a message stating that the regulatory checks have been disabled will be printed in the output.

5.2 Exclusive Use Shipments

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 0.10 mSv/hr (49 CFR 173.441(b))
2. The surface dose rate of the package is greater than 2 mSv/hr (49 CFR 173.441(b));
3. The sum of all dose rates for the packages in a shipment would exceed 2 mSv/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 10 mSv/hr (49 CFR 173.441(b)(1));
5. The dose rate at any surface of the vehicle cannot exceed 2 mSv/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 0.10 mSv/hr (49 CFR 393.441(b)(3)); or

7. The dose rate in the crew compartment must be less than 0.02 mSv/hr (49 CFR 173.441(b)(2))

An exclusive-use package is one that must be shipped without other freight or cargo present in the same vehicle or ship hold. Appropriate messages are also printed in the output:

- For all modes except air, if a shipment is designated as exclusive-use but is not required to be, and
- If a shipment is designated as exclusive-use and is by air mode, and
- If a shipment has not been designated as exclusive-use, but is required to be.

5.3 Regulation of External Dose Rate

By regulation, the dose rate at any point on the outer surface of a vehicle cannot exceed 2 mSv/hr [10 CFR 71.47 and 49 CFR 173.441(b)]. RADTRAN 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

$$DR_{surface} = DR_v \frac{1 + 0.5 d_{e_v}}{0.5 d_{e_v}} \tag{118}$$

where

$DR_{surface}$ = dose rate a vehicle surface (mSv/hr)

DR_v = vehicle dose rate at 1 m from surface (mSv/hr)

d_{e_v} = effective dimension of shipment vehicle (m)

In this case, if the regulatory limit of 2 mSv/hr for vehicle surface dose rate is exceeded, then DR_v is reset to the result of the following expression for all subsequent calculations[19]

$$DR_v = 200 \left[\frac{0.5 d_{e_v}}{1 + 0.5 d_{e_v}} \right] \tag{119}$$

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 0.02 mSv/hr by evaluating the following expression.

$$DR_{crew} = k_{0,end} \cdot DR_v \cdot CSF_v \left[\left[\frac{FG_v \cdot TR_{G,r}}{r_{end}^2} \right] + \left[\frac{FN_v \cdot TR_{N,r}}{r_{end}^2} \right] \right] \tag{120}$$

where

DR_{crew} = dose rate in the crew compartment (mSv/hr)

$k_{0,end}$ = point-source crew-view shape factor (m)

DR_v = vehicle dose rate (mSv/hr)

CSF_v = crew shielding factor for vehicle v

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[19] Since RADTRAN performs internal calculations in historic units, the coefficient of 200 is retained in Equation 109.

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 a value of d_e derived from the characteristic dimension of the package surface closest to the crew compartment. If the dose rate is acceptable, then the actual value is used for calculating dose to crew members. If the dose rate is calculated to be greater than 0.02 mSv/hr, then the value is reset to 0.02 mSv/hr for the calculation of crew dose.

If this test is satisfied, then RADTRAN 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

$$DR_v(2\text{ m}) = DR_v \cdot \left[\frac{1+0.5d_{e_v}}{2+0.5d_{e_v}}\right], \tag{121}$$

where
$DR_v(2\text{ m})$= 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 0.1mSv/hr (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 an appropriate informational message is printed in the RADTRAN output. Otherwise, DR_v is used directly. Special Topics

5.4 Uncertainty

Uncertainty may be introduced RADTRAN calculations using the MELCOR uncertainty engine (DOE, 2004; Weiner, et al., 2006) by distributing input parameters. The MELCOR uncertainty engine has been adapted for use in RADTRAN to determine the shape, parameters, and minimum and maximum of the distribution and to sample on the distribution and create an appropriate RADTRAN batch file. Coupling input parameters is not possible in this initial application.

An input file with the extension "*.unc" is created by appending a RADTRAN input file to the following script:

```
*eor* melgen
*r*i*f  gen_files\AP1000-3BE.gen
*r*i*f  Gen_Files\RN_Output.gen
*allowreplace
*
***Comments on mandatory definition section
* Variable definitions (%DEF%) are mandatory.
* Use one-word variable names. Spaces are allowed in the description.
* Other optional specifications:
*    Title string
*    Sample size between 5 and 500.
*    Base file and folder name, default 'Run'.
*    Initial distribution and inputs for a variable.
*
* The order of initial values required for each distribution type is:
*          %INIT%varname=BETA, p, q, xlow, xhigh
*          %INIT%varname=NORMAL1, mean, sd
*          %INIT%varname=NORMAL2, x05, x95
*          %INIT%varname=LOGNORMAL, mean, geo_sd
*          %INIT%varname=LOGUNIFORM, xlow, xhigh
*          %INIT%varname=TRIANGLE, xlow, xmidpt, xhigh
*          %INIT%varname=UNIFORM, xlow, xhigh
***Begin mandatory definition section
[Insert variable definitions here]
***End mandatory definition section
```

In the RADTRAN text input file, for each distributed variable,% *#variable_name*#% of the appropriate variable (i.e. %#PACKAGE#%, %#VEHICLE%#, %#STOP#%, etc.) is inserted. The MELCOR engine then creates RADTRAN input files in which a number randomly selected from the desired distribution is substituted for each %#*variable_name*#%. Up to 500 RADTRAN can be executed with a batch file.

5.5 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 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, only on the size of the affected population.

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APPENDIX A

Table A1. State Dependent Food Transfer Factors; Equation 1 (Saricks 1989)

State	Agric	Crop	Milk	Meat
		kg/km^2-yr	liters/km^2-yr	kg/km^2-yr
AL	0.31	1.76 x 10^4	2.00x10^3	7.19x10^3
AZ	0.52	4.15 x10^3	1.85 x10^3	6.36 x10^2
AR	0.44	3.58 x 10^4	2.78 x10^3	9.77 x10^3
CA	0.32	4.29 x 10^4	1.63 x 10^4	3.41 x10^3
CO	0.51	2.52 x 10^4	1.64 x10^3	2.24 x10^3
CT	0.14	4.36 x10^3	2.32 x 10^4	5.97 x10^3
DE	0.53	1.45 x 10^5	1.24 x 10^4	4.98 x 10^4
FL	0.37	5.94 x 10^4	6.82 x10^3	3.47 x10^3
GA	0.33	3.15 x 10^4	4.26 x10^3	8.84 x10^3
IA	0.91	3.17 x 10^5	1.25 x 10^4	1.74 x 10^4
ID	0.26	5.37 x 10^4	4.79 x10^3	1.22 x10^3
IL	0.81	3.29 x 10^5	8.36 x10^3	6.70 x10^3
IN	0.71	2.54 x 10^5	1.14 x 10^4	1.00 x 10^4
KS	0.90	9.40 x 10^4	2.90 x10^3	6.01 x10^3
KY	0.56	5.05 x 10^4	1.04 x 10^4	3.14 x10^3
LA	0.31	2.17 x 10^4	3.84 x10^3	1.98 x10^3
MA	0.12	4.55 x10^3	1.35 x 10^4	1.57 x10^3
MD	0.41	8.79 x 10^4	2.81 x 10^4	1.59 x 10^4
ME	0.74	1.51 x 10^4	4.11 x10^3	1.62 x10^3
MI	0.30	7.84 x 10^4	1.62 x 10^4	2.24 x10^3
MN	0.54	1.46 x 10^5	2.28 x 10^4	5.83 x10^3
MO	0.66	6.76 x 10^4	7.38 x10^3	5.56 x10^3
MS	0.41	2.70 x 10^4	3.34 x10^3	4.65 x10^3
MT	0.65	1.84 x 10^4	4.11 x10^2	8.39 x10^2
NC	0.33	4.65 x 10^4	6.05 x 10^3	9.51 x 10^3
ND	0.91	9.23 x 10^4	2.58 x 10^3	1.14 x 10^3
NE	0.92	1.31 x 10^5	3.06 x10^3	7.51 x10^3
NH	0.82	1.04 x10^3	7.11 x10^3	6.62 x10^2
NJ	0.19	3.23 x10^4	1.15 x10^4	1.59 x10^3
NM	0.61	2.60 x10^3	1.17 x10^3	6.61 x10^2
NV	0.14	1.03 x10^3	3.59 x10^2	1.58 x10^2
NY	0.30	2.72 x10^4	4.10 x10^4	2.07 x10^3
OH	0.59	1.49 x 10^5	1.94 x 10^4	5.55 x 10^3
OK	0.74	3.10 x 10^4	2.97 x 10^3	3.87 x 10^3
OR	0.29	1.47 x 10^4	2.37 x 10^3	9.18 x 10^2
PA	0.29	3.62 x 10^4	3.61 x 10^4	6.13 x 10^3
RI	0.093	1.28 x 10^4	7.64 x 10^3	2.06 x 10^3
SC	0.29	2.78 x 10^4	3.29 x 10^3	3.22 x 10^3
SD	0.90	5.04 x 10^4	4.06 x 10^3	3.20 x 10^3

State	**Agric**	**Crop**	**Milk**	**Meat**
		kg/km^2-yr	**liters/km^2-yr**	**kg/km^2-yr**
TN	0.47	3.34×10^4	9.90×10^3	3.72×10^3
TX	0.78	2.19×10^4	2.53×10^3	3.26×10^3
UT	0.19	2.66×10^3	2.48×10^3	5.72×10^2
VA	0.37	2.75×10^4	9.08×10^3	4.61×10^3
VT	0.27	2.48×10^3	4.50×10^4	1.27×10^3
WA	0.39	5.13×10^4	8.48×10^3	1.71×10^3
WV	0.23	5.41×10^3	2.53×10^3	1.62×10^3
WI	0.50	7.53×10^4	7.47×10^4	4.20×10^3
WY	0.54	5.77×10^3	2.47×10^2	6.39×10^2
US AVERAGE	0.44	5.58×10^4	6.71×10^3	3.07×10^3

Table A2. Radionuclide Food Transfer Coefficients

ATOMIC NUMBER	ELEMENT	TRANSFER COEFFICIENTS		
		SOIL-TO-PLANT	GRASS-TO-MEAT(d/kg)	GRASS-TO-MILK(d/liter)
1	Hydrogen	4.8	$1.20x10^{-02}$	$1.00x10^{-02}$
2	Helium	0	0	0
3	Lithium	$8.30x10^{-04}$	$1.00x10^{-02}$	$5.00x10^{-02}$
4	Beryllium	$4.20x10^{-04}$	$1.00x10^{-03}$	$1.00x10^{-04}$
5	Boron	$1.20x10^{-01}$	$8.00x10^{-04}$	$2.70x10^{-03}$
6	Carbon	5.5	$3.10x10^{-02}$	$1.20x10^{-02}$
7	Nitrogen	7.5	$7.70x10^{-02}$	$2.20x10^{-02}$
8	Oxygen	1.6	$1.60x10^{-02}$	$2.00x10^{-02}$
9	Fluorine	$6.50x10^{-04}$	$1.50x10^{-01}$	$1.40x10^{-02}$
10	Neon	0	0	0
11	Sodium	$5.20x10^{-02}$	$3.00x10^{-02}$	$4.00x10^{-02}$
12	Magnesium	$1.30x10^{-01}$	$5.00x10^{-03}$	$1.00x10^{-02}$
13	Aluminum	$1.80x10^{-04}$	$1.50x10^{-03}$	$5.00x10^{-04}$
14	Silicon	$1.50x10^{-04}$	$4.00x10^{-05}$	$1.00x10^{-04}$
15	Phosphorus	1.1	$4.60x10^{-02}$	$2.50x10^{-02}$
16	Sulfur	$5.90x10^{-01}$	$1.00x10^{-01}$	$1.80x10^{-02}$
17	Chlorine	5	$8.00x10^{-02}$	$5.00x10^{-02}$
18	Argon	0	0	0
19	Potassium	$3.70x10^{-01}$	$1.20x10^{-02}$	$1.00x10^{-02}$
20	Calcium	$3.60x10^{-02}$	$4.00x10^{-03}$	$8.00x10^{-03}$
21	Scandium	$1.10x10^{-03}$	$1.60x10^{-02}$	$5.00x10^{-06}$
22	Titanium	$5.40x10^{-05}$	$3.10x10^{-02}$	$5.00x10^{-06}$
23	Vanadium	$1.30x10^{-03}$	$2.30x10^{-03}$	$1.00x10^{-03}$
24	Chromium	$2.50x10^{-04}$	$2.40x10^{-03}$	$2.20x10^{-03}$
25	Manganese	$2.90x10^{-02}$	$8.00x10^{-04}$	$2.50x10^{-04}$
26	Iron	$6.60x10^{-04}$	$4.00x10^{-02}$	$1.20x10^{-03}$
27	Cobalt	$9.40x10^{-03}$	$1.30x10^{-02}$	$1.00x10^{-03}$
28	Nickel	$1.90x10^{-02}$	$5.30x10^{-03}$	$6.70x10^{-03}$
29	Copper	$1.20x10^{-01}$	$8.00x10^{-03}$	$1.40x10^{-02}$
30	Zinc	$4.00x10^{-01}$	$3.00x10^{-02}$	$3.90x10^{-02}$
31	Gallium	$2.50x10^{-04}$	$5.00x10^{-04}$	$5.00x10^{-05}$
32	Germanium	$1.00x10^{-01}$	$1.00x10^{-01}$	$5.00x10^{-04}$
33	Arsenic	$1.00x10^{-02}$	$2.00x10^{-03}$	$6.00x10^{-03}$

Table A2. Radionuclide Food Transfer Coefficients -- continued

Atomic Number	**Element**	**Transfer Coefficients**		
		Soil-to-Plant	**Grass-to-Meat(d/kg)**	**Grass-to-Milk(d/liter)**
34	Selenium	$2.50\text{x}10^{-02}$	$1.50\text{x}10^{-02}$	$4.50\text{x}10^{-03}$
35	Bromine	$7.60\text{x}10^{-01}$	$2.60\text{x}10^{-02}$	$5.00\text{x}10^{-02}$
37	Rubidium	$1.30\text{x}10^{-01}$	$3.10\text{x}10^{-02}$	$3.00\text{x}10^{-02}$
38	Strontium	$1.70\text{x}10^{-02}$	$6.00\text{x}10^{-04}$	$8.00\text{x}10^{-04}$
40	Zirconium	$1.70\text{x}10^{-04}$	$3.40\text{x}10^{-02}$	$5.00\text{x}10^{-06}$
41	Niobium	$9.40\text{x}10^{-03}$	$2.80\text{x}10^{-01}$	$2.50\text{x}10^{-03}$
42	Molybdenum	$1.20\text{x}10^{-01}$	$8.00\text{x}10^{-03}$	$7.50\text{x}10^{-03}$
43	Technetium	$2.50\text{x}10^{-01}$	$4.00\text{x}10^{-01}$	$2.50\text{x}10^{-02}$
44	Ruthenium	$5.00\text{x}10^{-02}$	$4.00\text{x}10^{-01}$	$1.00\text{x}10^{-06}$
45	Rhodium	1.30	$1.50\text{x}10^{-03}$	$1.00\text{x}10^{-02}$
46	Palladium	$1.50\text{x}10^{-01}$	$4.00\text{x}10^{-03}$	$1.00\text{x}10^{-02}$
47	Silver	$1.50\text{x}10^{-01}$	$1.70\text{x}10^{-02}$	$5.00\text{x}10^{-02}$
48	Cadmium	$3.00\text{x}10^{-01}$	$5.30\text{x}10^{-04}$	$1.20\text{x}10^{-04}$
49	Indium	$2.50\text{x}10^{-01}$	$8.00\text{x}10^{-03}$	$1.00\text{x}10^{-04}$
50	Tin	$2.50\text{x}10^{-03}$	$8.00\text{x}10^{-02}$	$2.50\text{x}10^{-03}$
51	Antimony	$1.10\text{x}10^{-02}$	$4.00\text{x}10^{-03}$	$1.50\text{x}10^{-03}$
52	Tellurium	1.30	$7.70\text{x}10^{-02}$	$1.00\text{x}10^{-03}$
53	Iodine	$2.00\text{x}10^{-02}$	$2.90\text{x}10^{-03}$	$6.00\text{x}10^{-03}$
54	Xenon	0	0	0
55	Cesium	$1.00\text{x}10^{-02}$	$4.00\text{x}10^{-03}$	$1.20\text{x}10^{-02}$
56	Barium	$5.00\text{x}10^{-03}$	$3.20\text{x}10^{-03}$	$4.00\text{x}10^{-04}$
57	Lanthanum	$2.50\text{x}10^{-03}$	$2.00\text{x}10^{-04}$	$5.00\text{x}10^{-06}$
58	Cerium	$2.50\text{x}10^{-03}$	$1.20\text{x}10^{-03}$	$6.00\text{x}10^{-04}$
59	Praseodymium	$2.50\text{x}10^{-03}$	$4.70\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
60	Neodymium	$2.40\text{x}10^{-03}$	$3.30\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
61	Promethium	$2.50\text{x}10^{-03}$	$4.80\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
62	Samarium	$2.50\text{x}10^{-03}$	$5.00\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
63	Europium	$2.50\text{x}10^{-03}$	$4.80\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
64	Gadolinium	$2.60\text{x}10^{-03}$	$3.60\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
65	Terbium	$2.60\text{x}10^{-03}$	$4.40\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
66	Dysprosium	$2.50\text{x}10^{-03}$	$5.30\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
67	Holmium	$2.60\text{x}10^{-03}$	$4.40\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
68	Erbium	$2.50\text{x}10^{-03}$	$4.00\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
70	Ytterbium	$2.50\text{x}10^{-03}$	$4.00\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
71	Lutetium	$2.60\text{x}10^{-03}$	$4.40\text{x}10^{-03}$	$5.00\text{x}10^{-06}$
72	Hafnium	$1.70\text{x}10^{-04}$	$4.00\text{x}10^{-01}$	$5.00\text{x}10^{-06}$

Table A2. Radionuclide Food Transfer Coefficients -- continued

Atomic Number	Element	Transfer Coefficients		
		Soil-to-Plant	Grass-to-Meat(d/kg)	Grass-to-Milk(d/liter)
73	Tantalum	6.30x10^{-03}	6.00x10^{-04}	2.50x10^{-02}
74	Tungsten	1.80x10^{-02}	1.30x10^{-03}	5.00x10^{-04}
75	Rhenium	2.50x10^{-01}	8.00x10^{-03}	2.50x10^{-02}
76	Osmium	5.00x10^{-02}	4.00x10^{-01}	5.00x10^{-03}
77	Iridium	5.50x10^{-02}	1.50x10^{-03}	5.00x10^{-03}
78	Platinum	5.00x10^{-01}	4.00x10^{-03}	5.00x10^{-03}
79	Gold	2.50x10^{-03}	8.00x10^{-03}	5.00x10^{-03}
80	Mercury	3.80x10^{-01}	2.60x10^{-01}	3.80x10^{-02}
81	Thallium	2.50x10^{-01}	4.00x10^{-02}	2.20x10^{-02}
82	Lead	6.80x10^{-02}	2.90x10^{-04}	6.20x10^{-04}
83	Bismuth	1.50x10^{-01}	1.30x10^{-02}	5.00x10^{-04}
84	Polonium	1.50x10^{-01}	1.20x10^{-02}	3.00x10^{-04}
85	Astatine	2.50x10^{-01}	3.00x10^{-04}	5.00x10^{-02}
86	Radon	0	0	0
87	Francium	1.00x10^{-02}	2.00x10^{-02}	5.00x10^{-02}
88	Radium	3.10x10^{-04}	3.40x10^{-02}	8.00x10^{-03}
89	Actinium	2.50x10^{-03}	6.00x10^{-02}	5.00x10^{-06}
90	Thorium	4.20x10^{-03}	2.00x10^{-04}	5.00x10^{-06}
91	Protactinium	2.50x10^{-03}	1.00x10^{-05}	5.00x10^{-06}
92	Uranium	2.50x10^{-03}	3.40x10^{-04}	5.00x10^{-04}
93	Neptunium	2.50x10^{-03}	2.00x10^{-04}	5.00x10^{-06}
94	Plutonium	2.50x10^{-04}	1.40x10^{-05}	2.00x10^{-06}
95	Americium	2.50x10^{-04}	2.00x10^{-04}	5.00x10^{-06}
96	Curium	2.50x10^{-03}	2.00x10^{-04}	5.00x10^{-06}
97	Berkelium	2.50x10^{-03}	2.00x10^{-04}	5.00x10^{-06}
98	Californium	2.50x10^{-03}	2.00x10^{-04}	5.00x10^{-06}
99	Einsteinium	2.50x10^{-03}	2.00x10^{-04}	5.00x10^{-06}
100	Fermium	2.50x10^{-03}	2.00x10^{-04}	5.00x10^{-06}
