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RADTRAN 6 Technical Manual

Ruth F. Weiner, K. Sieglinde Neuhauser, Terence J. Heames, Brandon M. O'Donnell, Matthew L. Dennis

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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.

Acknowledgements

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).

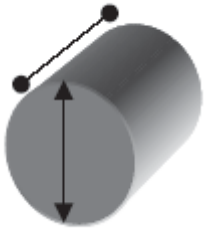


Figure 1a

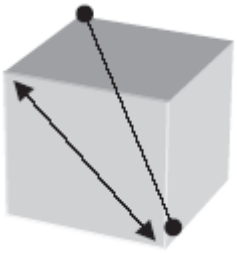


Figure 1b

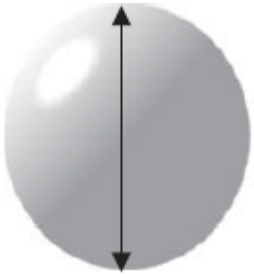


Figure 1c

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.

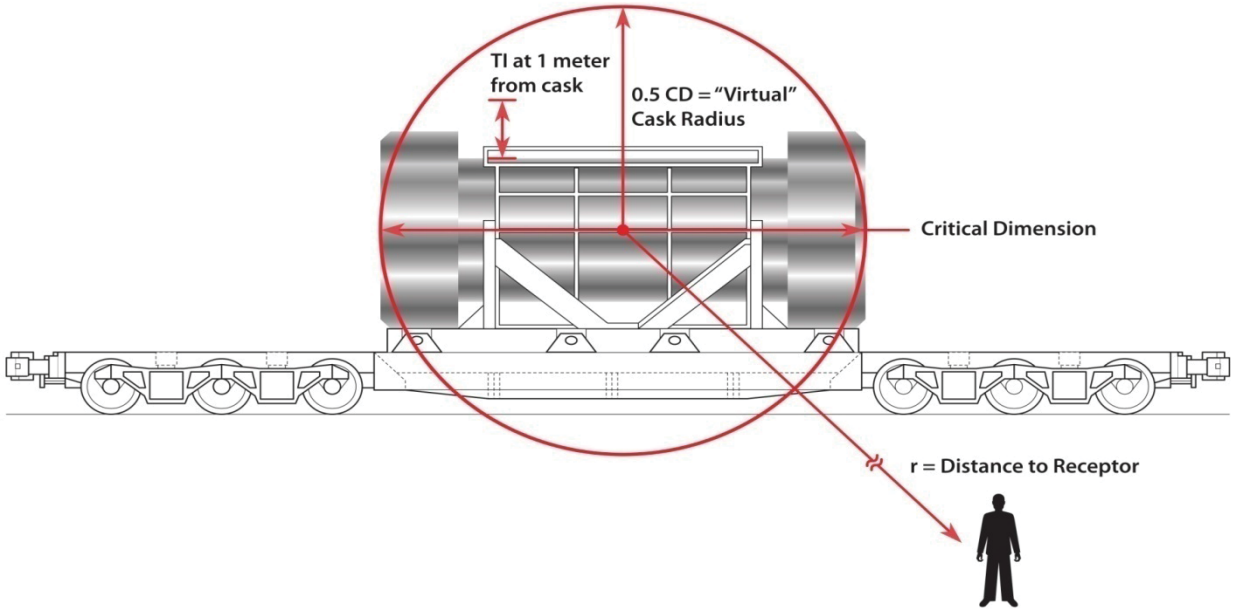


Figure 2.2. RADTRAN model of the vehicle in routine, incident-free transportation. The cask in this diagram is positioned horizontally and the critical dimension is the cask length (NRC, 2013, Figure 2-2).

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:

$$k_0' = 1 + 0.5 d_e \quad (8)$$

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

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

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

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

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

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

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
$DR_{p \text{ or } v}$ = maximum measured dose rate at 1 m from package or vehicle (mSv/hr)
p = index for package
v = index for vehicle (vehicle)
$\exp(-\mu r)$ = 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 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:

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

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

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

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

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

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

$$DR_N(r) = Q_1 \cdot DR_{p\,or\,v} \cdot FN \cdot k_0' \exp(-\mu r) \frac{(1 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4)}{r} \quad (18)$$

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

(19)

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

where

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

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:

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

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

$$= \begin{cases} \dfrac{\pi}{2 \cdot x}; \text{if } \mu_s = 0. \end{cases}$$

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").

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

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

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 .

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

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:

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

which may be simplified to:

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

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:

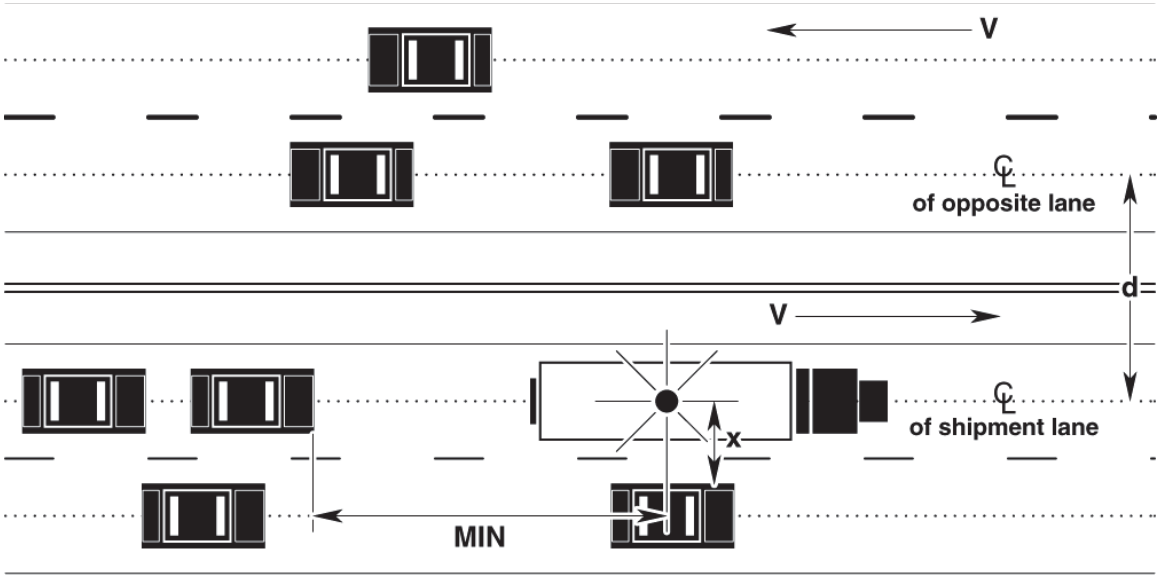
$$D = Q_2 \cdot k_0 \cdot DR_v \cdot DIST_L \cdot PPV_L \cdot \frac{N'}{V_L^2} \cdot \left[\left(FG_v \cdot I'_G(x)\right) + \left(FN \cdot I'_N(x)\right)\right] \quad (28)$$

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.



Legend

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

Figure 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):

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

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

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

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:

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

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

In addition to 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

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

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:

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

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.

$$F_1 = 2Y_v V_L \qquad (35a)$$

and

$$F_2 = \frac{1}{x}\cdot Y_v V_L \qquad (35b)$$

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.

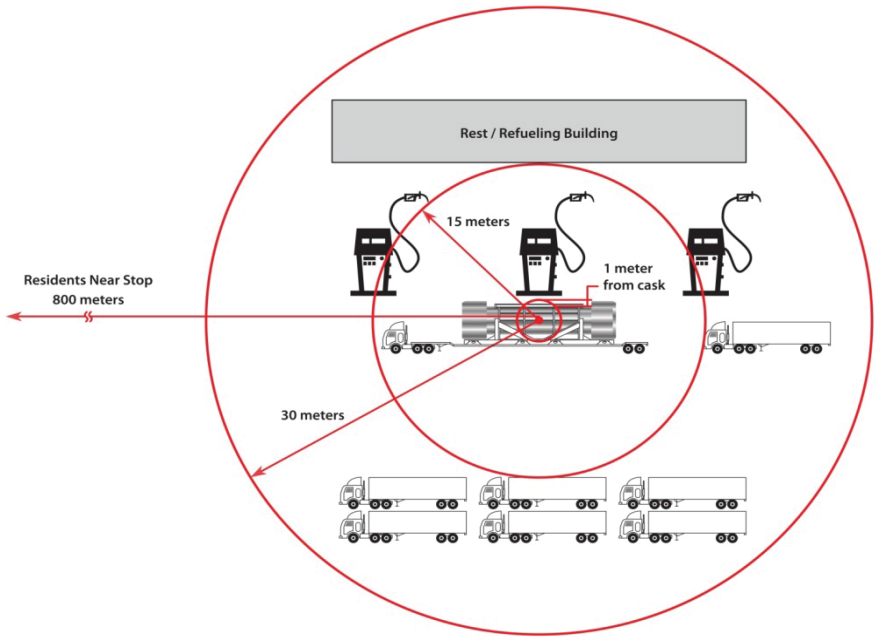


Figure 2.5. Stop model in RADTRAN (not to scale) (NRC, 20132, Figure 2-10)

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:

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

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 = Π (15^2-1^2) = 703.72 m^2
Population density: 7/703.72 = 0.00995/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:

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

where

μ_S = attenuation coefficients for gamma (S = G) or neutron (S = N) radiation in air (m^{-1})

$a_1 ... a_4$ = 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 (μ_S·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

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

where
$D_{railworker}$ = 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

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

where
$D_{\text{rail worker}}$= dose to rail worker per classification or inspection from Equation 43
NCL = number of classifications or inspections per trip

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

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

where

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

DIC represents the inspections that occur regardless of total trip distance. 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 ($DIST_L$). 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.

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

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:

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

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:

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

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,

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

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

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

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

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

This can be rewritten as,

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

or as

$$I_c = x_c \frac{\partial D}{\partial x_c} = \sum_a \frac{\partial \ln d_c}{\partial \ln x_c} d_b \tag{55}$$

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.

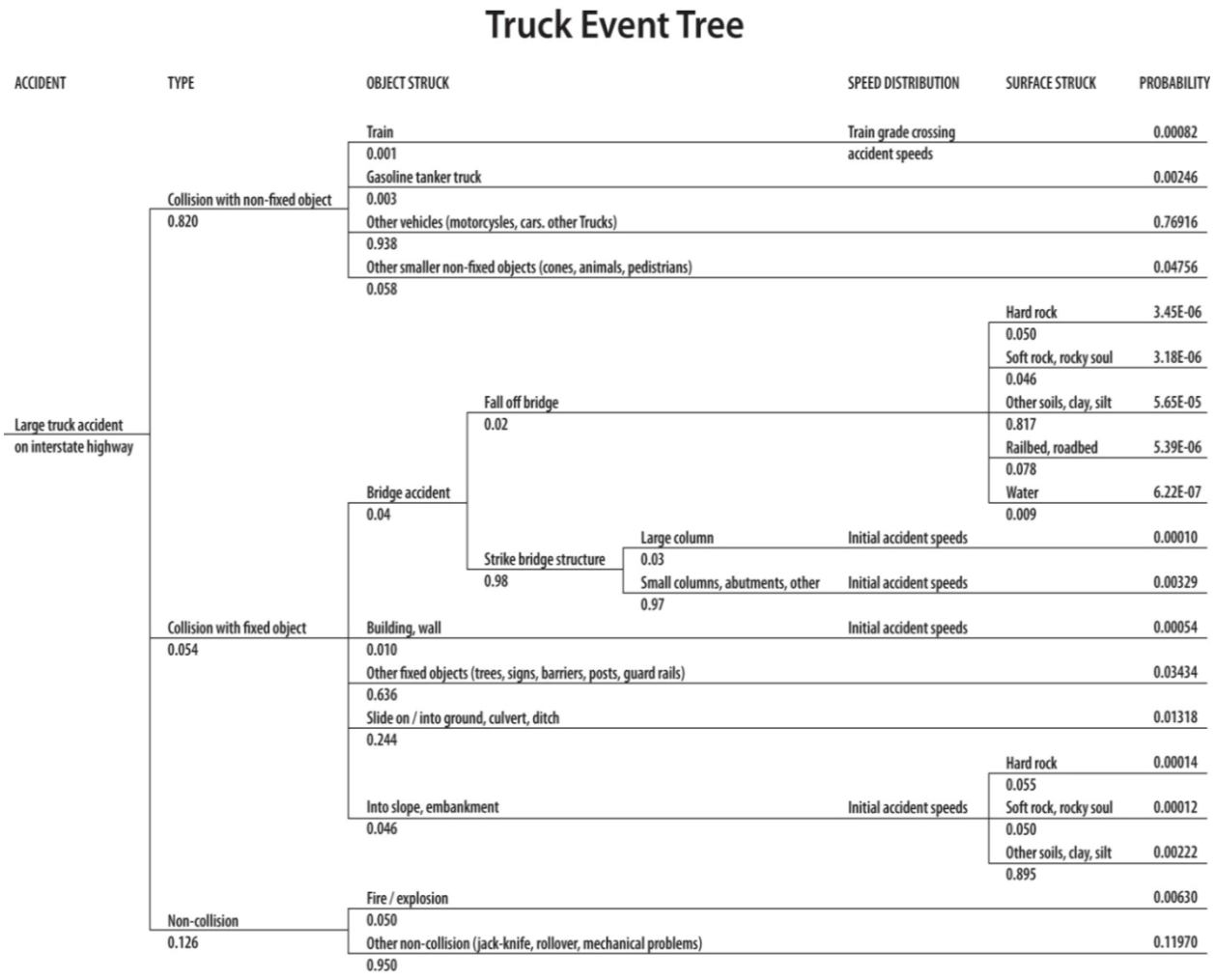


Figure 3.1. Truck accident event tree (from Mills, et al., 2005, Figure 7.3).

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:

$$V_d = \frac{gd^2\rho}{18\mu} \qquad (56)$$

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

[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

[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.

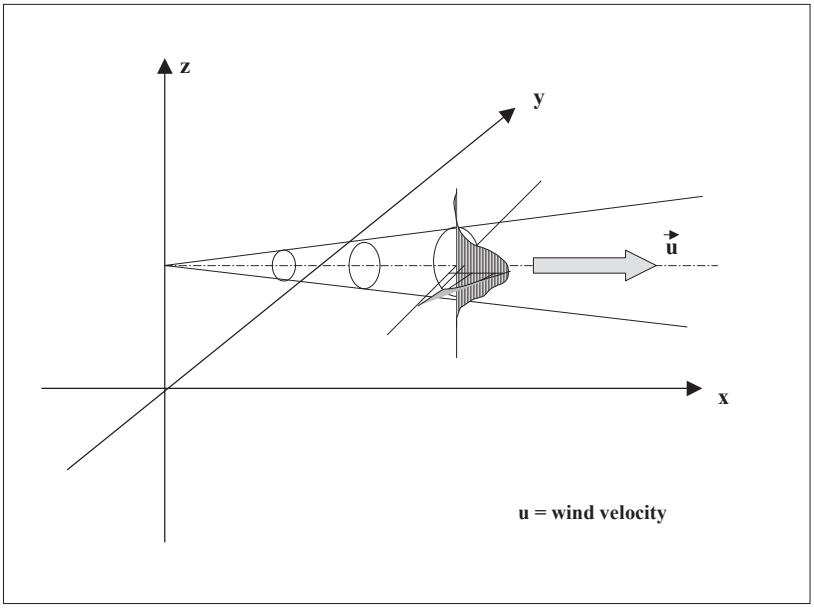


Figure 3.2 Diagram of Gaussian dispersion

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:

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

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]

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

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.

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

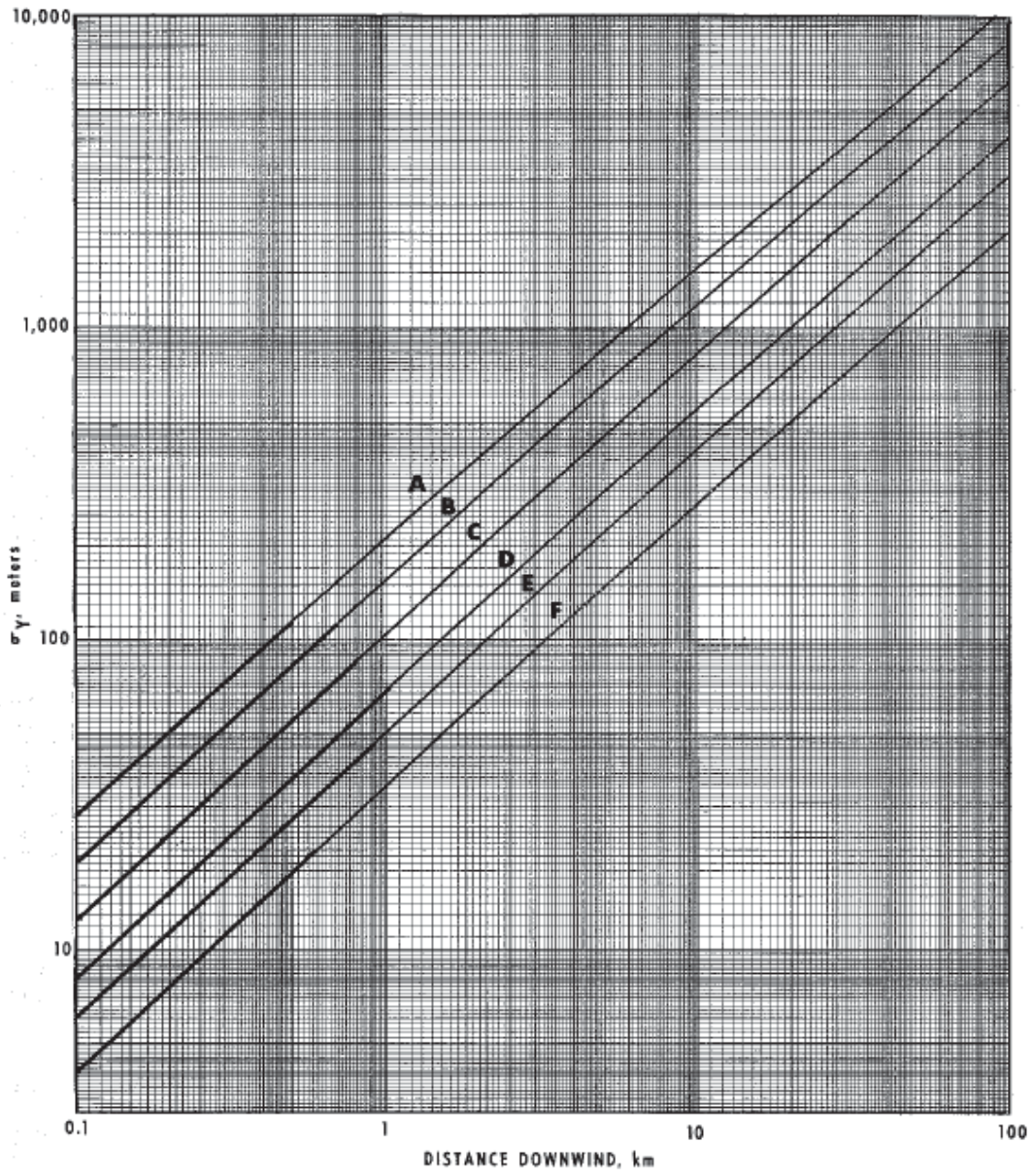


Figure 3.3. Crosswind Gaussian half-width (σy) as a function of downwind distance and meteorological stability. A, B, C, D, E, and F are the six Pasquill meteorological stability classes; from Turner (1994, reprinted by permission of Lewis Publishers).

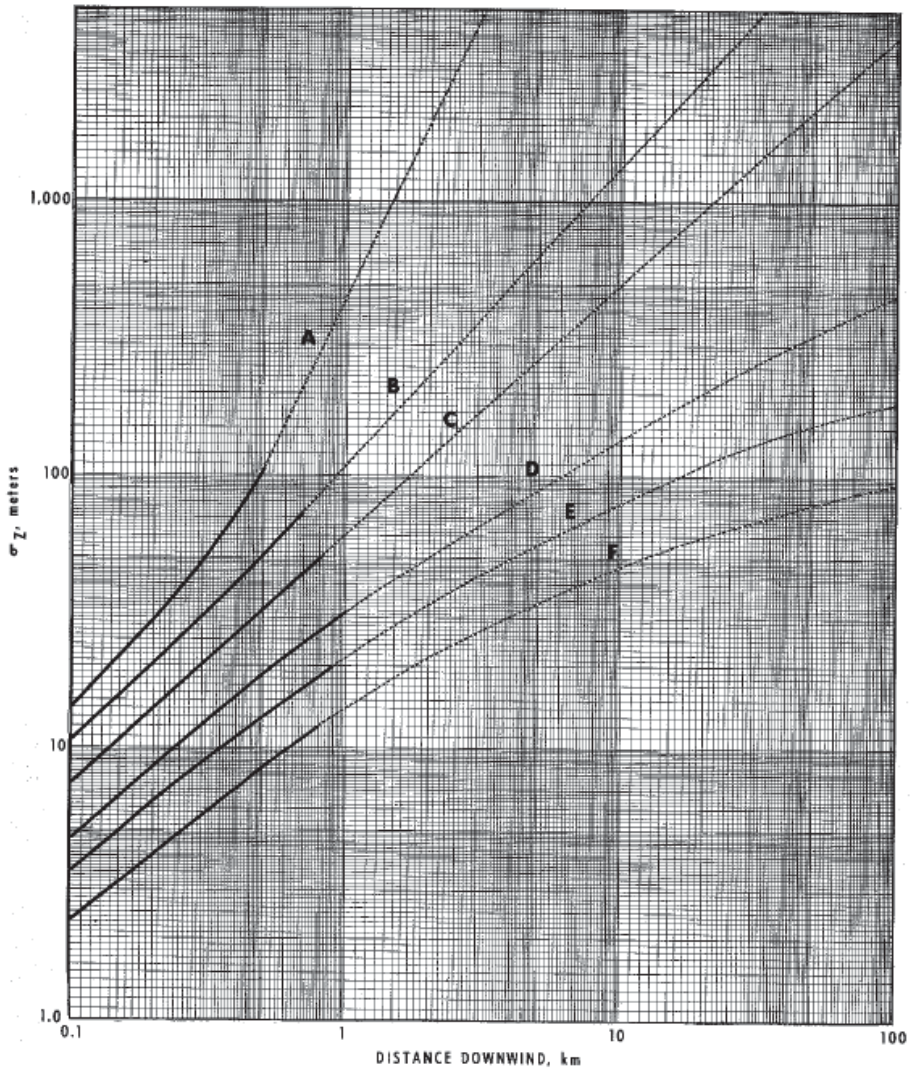


Figure 3.4. Vertical Gaussian half-width (σz) as a function of downwind distance and meteorological stability. A, B, C, D, E, and F are the six Pasquill meteorological stability classes; from Turner (1994, reprinted by permission of Lewis Publishers).

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:

$$\frac{CHI}{Q} = \frac{V_d}{\pi u \sigma_y \sigma_z} \tag{60}$$

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

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

where all variables are previously defined.

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

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

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

[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:

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

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

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

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.

[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

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

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).

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

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

$$D_{cld}^{ind} = \sum^{materials} \sum^{isotopes} \sum^{organs} \left(Ci_i \cdot PPS \cdot CDF \cdot \overline{X}_n \cdot RF_{i,j} \cdot AER_{i,j} \right) \qquad (67)$$

where

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

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

$$D_{cld_{i,j,L,m}}^{pop} = Q_7 \cdot Ci_i \cdot PPS_{L,m} \cdot RF_{i,j} \cdot AER_{i,j} \cdot CDF_i \cdot IF \cdot PD_L \qquad (68)$$

where

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

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

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

[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)

[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:

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

where

CL_i = contamination level of radionuclide i ($3.7E4 Bq/m^2$)

GDF_i = groundshine dose factor for radionuclide i ($Sv\text{-}m^2/day\text{-}3.7E4 Bq$)

$t_{1/2}$ = 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:

$$CL_{i,j} = Q_9 \cdot PPS \cdot DC_{i,j} \cdot Ci_{i,j} \quad (72)$$

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:

[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).

$$TDF = \frac{\sum^{\text{all materials}} \sum^{\text{all radionuclides}} CL_i}{CU} \qquad (73)$$

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 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 μBq/m^2 for the 0.2 μBq/m^2 threshold).

Calculation of Dose for No-Action Decision

When TDF ≤ 1.0, dose is calculated as follows:

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

where

Q_7 = units conversion factor = 1.0E-6 km^2/m^2
GDF_i = groundshine dose (Sv-m^2/day-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)

$$TRM1 = \left[\lambda_1(1-e^{-\lambda_2 T_E}) + \lambda_3(1-e^{-\lambda_4 T_E})\right]$$

$$TRM2 = \left[\lambda_1 e^{-(\lambda_2 T_S)} + \lambda_3(e^{-\lambda_4 \cdot T_S} - e^{-\lambda_4 \cdot 1.83E+4})\right]$$

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

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

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

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

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

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

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≤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.

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

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.

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

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.

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

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 1.4×10^{-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:

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

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);
$\lambda_{\varepsilon t}$ = 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)

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

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

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

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.

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

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

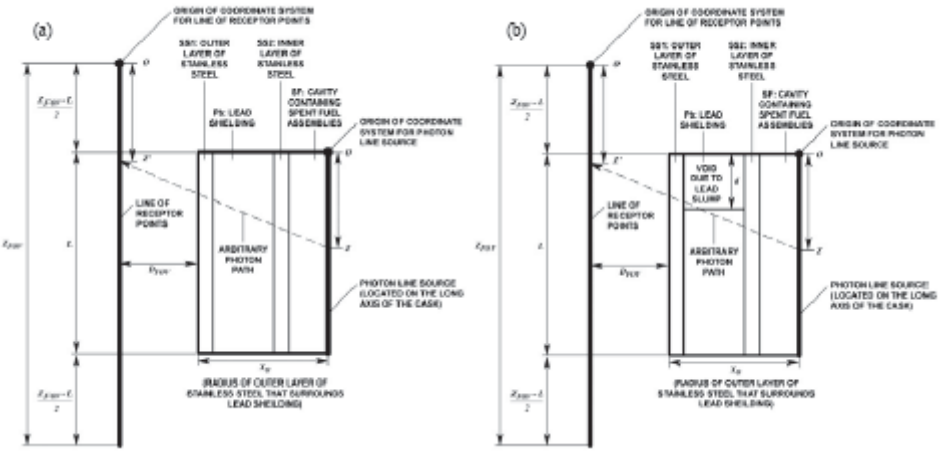


Figure 3.5. Diagram of a cask with (a) an undamaged lead gamma shield and (b) a damaged shield. (From O'Donnell et al, 2005).

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 $zmin \le z \le zmax$, where $zmin \ge 0$ and $zmax \le L$, 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

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

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

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

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 ΔE 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 $\Phi(E, z.)$ 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

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

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

given by

$$A = \frac{\int_{\Delta E} R(E)\Phi(E,z')dE}{\int_{\Delta E} \Phi(E,z')dE}. \qquad (104)$$

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

$$A \cong \frac{R(E_0)\Phi(E_0,z')}{\Phi(E_0,z')} = R(E_0). \qquad (105)$$

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

$$F(z')_{mono} \cong \frac{\left(\int_{z_{min}}^{z_{max}} \frac{B(E_0,\mu_{Pb}x_{Pb})\exp\left[-\mu_{Pb}(E_0)x_{Pb}(z,z') - \mu_{SS}(E_0)x_{SS2}(z,z')\right]}{4\pi r'^2}dz\right)_{damaged}}{\left(\int_{z_{min}}^{z_{max}} \frac{B(E_0,\mu_{Pb}x_{Pb})\exp\left[-\mu_{Pb}(E_0)x_{Pb}(z,z') - \mu_{SS}(E_0)x_{SS2}(z,z')\right]}{4\pi r'^2}dz\right)_{undamaged}}. \qquad (106)$$

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.

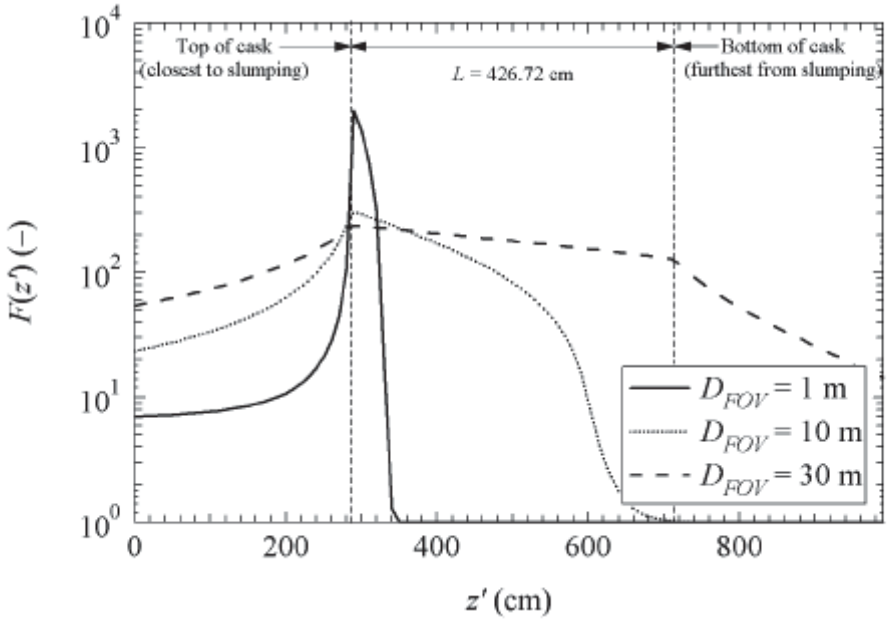


Figure 3.6. The factor F(z) for a representative truck cask at variable distances from the cask. (From O'Donnell et al, 2005)

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

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

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.

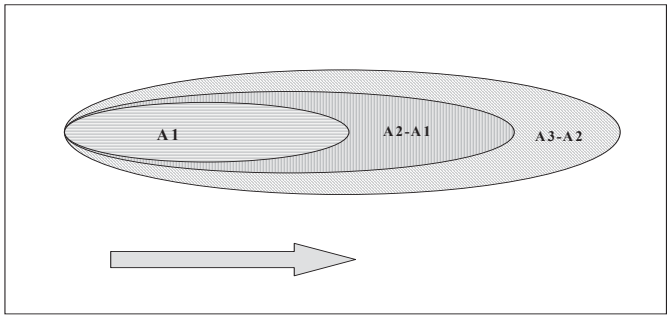


Figure 3.7. Typical Plume Footprint. The arrow represents wind direction. The shaded areas are, respectively, the area of the smallest isopleth (ellipse A1), the area of the second isopleth (ellipse A2 –ellipse A1), and the area of the third isopleth (ellipse A3 – ellipse A2).

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

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

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

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

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:

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

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

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

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:

$$DC_n = V_d \cdot \overline{X}_n \qquad (115)$$

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.

[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

[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

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

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.

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

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

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

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]

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

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

[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

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

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

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

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	1.20×10^{-02}	1.00×10^{-02}
2	Helium	0	0	0
3	Lithium	8.30×10^{-04}	1.00×10^{-02}	5.00×10^{-02}
4	Beryllium	4.20×10^{-04}	1.00×10^{-03}	1.00×10^{-04}
5	Boron	1.20×10^{-01}	8.00×10^{-04}	2.70×10^{-03}
6	Carbon	5.5	3.10×10^{-02}	1.20×10^{-02}
7	Nitrogen	7.5	7.70×10^{-02}	2.20×10^{-02}
8	Oxygen	1.6	1.60×10^{-02}	2.00×10^{-02}
9	Fluorine	6.50×10^{-04}	1.50×10^{-01}	1.40×10^{-02}
10	Neon	0	0	0
11	Sodium	5.20×10^{-02}	3.00×10^{-02}	4.00×10^{-02}
12	Magnesium	1.30×10^{-01}	5.00×10^{-03}	1.00×10^{-02}
13	Aluminum	1.80×10^{-04}	1.50×10^{-03}	5.00×10^{-04}
14	Silicon	1.50×10^{-04}	4.00×10^{-05}	1.00×10^{-04}
15	Phosphorus	1.1	4.60×10^{-02}	2.50×10^{-02}
16	Sulfur	5.90×10^{-01}	1.00×10^{-01}	1.80×10^{-02}
17	Chlorine	5	8.00×10^{-02}	5.00×10^{-02}
18	Argon	0	0	0
19	Potassium	3.70×10^{-01}	1.20×10^{-02}	1.00×10^{-02}
20	Calcium	3.60×10^{-02}	4.00×10^{-03}	8.00×10^{-03}
21	Scandium	1.10×10^{-03}	1.60×10^{-02}	5.00×10^{-06}
22	Titanium	5.40×10^{-05}	3.10×10^{-02}	5.00×10^{-06}
23	Vanadium	1.30×10^{-03}	2.30×10^{-03}	1.00×10^{-03}
24	Chromium	2.50×10^{-04}	2.40×10^{-03}	2.20×10^{-03}
25	Manganese	2.90×10^{-02}	8.00×10^{-04}	2.50×10^{-04}
26	Iron	6.60×10^{-04}	4.00×10^{-02}	1.20×10^{-03}
27	Cobalt	9.40×10^{-03}	1.30×10^{-02}	1.00×10^{-03}
28	Nickel	1.90×10^{-02}	5.30×10^{-03}	6.70×10^{-03}
29	Copper	1.20×10^{-01}	8.00×10^{-03}	1.40×10^{-02}
30	Zinc	4.00×10^{-01}	3.00×10^{-02}	3.90×10^{-02}
31	Gallium	2.50×10^{-04}	5.00×10^{-04}	5.00×10^{-05}
32	Germanium	1.00×10^{-01}	1.00×10^{-01}	5.00×10^{-04}
33	Arsenic	1.00×10^{-02}	2.00×10^{-03}	6.00×10^{-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	$2.50x10^{-02}$	$1.50x10^{-02}$	$4.50x10^{-03}$
35	Bromine	$7.60x10^{-01}$	$2.60x10^{-02}$	$5.00x10^{-02}$
37	Rubidium	$1.30x10^{-01}$	$3.10x10^{-02}$	$3.00x10^{-02}$
38	Strontium	$1.70x10^{-02}$	$6.00x10^{-04}$	$8.00x10^{-04}$
40	Zirconium	$1.70x10^{-04}$	$3.40x10^{-02}$	$5.00x10^{-06}$
41	Niobium	$9.40x10^{-03}$	$2.80x10^{-01}$	$2.50x10^{-03}$
42	Molybdenum	$1.20x10^{-01}$	$8.00x10^{-03}$	$7.50x10^{-03}$
43	Technetium	$2.50x10^{-01}$	$4.00x10^{-01}$	$2.50x10^{-02}$
44	Ruthenium	$5.00x10^{-02}$	$4.00x10^{-01}$	$1.00x10^{-06}$
45	Rhodium	1.30	$1.50x10^{-03}$	$1.00x10^{-02}$
46	Palladium	$1.50x10^{-01}$	$4.00x10^{-03}$	$1.00x10^{-02}$
47	Silver	$1.50x10^{-01}$	$1.70x10^{-02}$	$5.00x10^{-02}$
48	Cadmium	$3.00x10^{-01}$	$5.30x10^{-04}$	$1.20x10^{-04}$
49	Indium	$2.50x10^{-01}$	$8.00x10^{-03}$	$1.00x10^{-04}$
50	Tin	$2.50x10^{-03}$	$8.00x10^{-02}$	$2.50x10^{-03}$
51	Antimony	$1.10x10^{-02}$	$4.00x10^{-03}$	$1.50x10^{-03}$
52	Tellurium	1.30	$7.70x10^{-02}$	$1.00x10^{-03}$
53	Iodine	$2.00x10^{-02}$	$2.90x10^{-03}$	$6.00x10^{-03}$
54	Xenon	0	0	0
55	Cesium	$1.00x10^{-02}$	$4.00x10^{-03}$	$1.20x10^{-02}$
56	Barium	$5.00x10^{-03}$	$3.20x10^{-03}$	$4.00x10^{-04}$
57	Lanthanum	$2.50x10^{-03}$	$2.00x10^{-04}$	$5.00x10^{-06}$
58	Cerium	$2.50x10^{-03}$	$1.20x10^{-03}$	$6.00x10^{-04}$
59	Praseodymium	$2.50x10^{-03}$	$4.70x10^{-03}$	$5.00x10^{-06}$
60	Neodymium	$2.40x10^{-03}$	$3.30x10^{-03}$	$5.00x10^{-06}$
61	Promethium	$2.50x10^{-03}$	$4.80x10^{-03}$	$5.00x10^{-06}$
62	Samarium	$2.50x10^{-03}$	$5.00x10^{-03}$	$5.00x10^{-06}$
63	Europium	$2.50x10^{-03}$	$4.80x10^{-03}$	$5.00x10^{-06}$
64	Gadolinium	$2.60x10^{-03}$	$3.60x10^{-03}$	$5.00x10^{-06}$
65	Terbium	$2.60x10^{-03}$	$4.40x10^{-03}$	$5.00x10^{-06}$
66	Dysprosium	$2.50x10^{-03}$	$5.30x10^{-03}$	$5.00x10^{-06}$
67	Holmium	$2.60x10^{-03}$	$4.40x10^{-03}$	$5.00x10^{-06}$
68	Erbium	$2.50x10^{-03}$	$4.00x10^{-03}$	$5.00x10^{-06}$
70	Ytterbium	$2.50x10^{-03}$	$4.00x10^{-03}$	$5.00x10^{-06}$
71	Lutetium	$2.60x10^{-03}$	$4.40x10^{-03}$	$5.00x10^{-06}$
72	Hafnium	$1.70x10^{-04}$	$4.00x10^{-01}$	$5.00x10^{-06}$

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	6.30×10^{-03}	6.00×10^{-04}	2.50×10^{-02}
74	Tungsten	1.80×10^{-02}	1.30×10^{-03}	5.00×10^{-04}
75	Rhenium	2.50×10^{-01}	8.00×10^{-03}	2.50×10^{-02}
76	Osmium	5.00×10^{-02}	4.00×10^{-01}	5.00×10^{-03}
77	Iridium	5.50×10^{-02}	1.50×10^{-03}	5.00×10^{-03}
78	Platinum	5.00×10^{-01}	4.00×10^{-03}	5.00×10^{-03}
79	Gold	2.50×10^{-03}	8.00×10^{-03}	5.00×10^{-03}
80	Mercury	3.80×10^{-01}	2.60×10^{-01}	3.80×10^{-02}
81	Thallium	2.50×10^{-01}	4.00×10^{-02}	2.20×10^{-02}
82	Lead	6.80×10^{-02}	2.90×10^{-04}	6.20×10^{-04}
83	Bismuth	1.50×10^{-01}	1.30×10^{-02}	5.00×10^{-04}
84	Polonium	1.50×10^{-01}	1.20×10^{-02}	3.00×10^{-04}
85	Astatine	2.50×10^{-01}	3.00×10^{-04}	5.00×10^{-02}
86	Radon	0	0	0
87	Francium	1.00×10^{-02}	2.00×10^{-02}	5.00×10^{-02}
88	Radium	3.10×10^{-04}	3.40×10^{-02}	8.00×10^{-03}
89	Actinium	2.50×10^{-03}	6.00×10^{-02}	5.00×10^{-06}
90	Thorium	4.20×10^{-03}	2.00×10^{-04}	5.00×10^{-06}
91	Protactinium	2.50×10^{-03}	1.00×10^{-05}	5.00×10^{-06}
92	Uranium	2.50×10^{-03}	3.40×10^{-04}	5.00×10^{-04}
93	Neptunium	2.50×10^{-03}	2.00×10^{-04}	5.00×10^{-06}
94	Plutonium	2.50×10^{-04}	1.40×10^{-05}	2.00×10^{-06}
95	Americium	2.50×10^{-04}	2.00×10^{-04}	5.00×10^{-06}
96	Curium	2.50×10^{-03}	2.00×10^{-04}	5.00×10^{-06}
97	Berkelium	2.50×10^{-03}	2.00×10^{-04}	5.00×10^{-06}
98	Californium	2.50×10^{-03}	2.00×10^{-04}	5.00×10^{-06}
99	Einsteinium	2.50×10^{-03}	2.00×10^{-04}	5.00×10^{-06}
100	Fermium	2.50×10^{-03}	2.00×10^{-04}	5.00×10^{-06}

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RADTRAN 6/RadCat 6 User Guide

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ABSTRACT

This document provides a detailed discussion and a guide for the use of the RadCat 6.0 Graphical User Interface input file generator for the RADTRAN code, Version 6. RadCat 6.0 integrates the newest analysis capabilities of RADTRAN 6.0, including an economic model, updated loss-of-lead shielding model, a new ingestion dose model, and unit conversion. As of this writing, the RADTRAN version in use is RADTRAN 6.02.

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ACRONYM LIST

CFR	Code of Federal Regulations
DCF	Dose conversion factor
DOE	[U.S.] Department of Energy
DOT	[U.S.] Department of Transportation
EPA	[U.S.] Environmental Protection Agency
GIS	Geographic Information System
GUI	Graphical user interface
ICRP	International Commission on Radiation Protection
ISCORS	Interagency Standing Committee on Radiation Safety
JRE	Java Runtime Environment
LCF	Latent cancer fatalities
LOS	Loss of shielding
MEI	Maximally exposed individual
NRC	[U.S.] Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PC	Personal computer
SI	Standard International [units]
SNL	Sandia National Laboratories

1. WELCOME TO RADTRAN/RADCAT

RADTRAN is an internationally accepted program and code for calculating the risks of transporting radioactive materials. The first versions of the program, RADTRAN I and II, were developed for NUREG-0170 (NRC, 1977), the first environmental statement on transportation of radioactive materials. RADTRAN and its associated software have undergone a number of improvements and advances consistent with improvements in both available data and computer technology.

RadCat is a Graphical User Interface (GUI) which generates an input file for RADTRAN. The version of RADTRAN currently bundled with RadCat 6 is RADTRAN 6.

2. ORGANIZATION OF THIS USER GUIDE

This User Guide provides step by step instructions for creating an input file using RadCat. The topics in the Table of Contents reflect the tabs and screen names for the RadCat screens. Some details and sample input data are discussed in the appendices at the end. A very brief explanation is presented with each topic. For an in-depth discussion of the technical details of the program, anyone using RADTRAN is advised to consult the appropriate bibliographic references or (when it becomes available) the forthcoming technical Appendix.

3. DOWNLOADING AND CHECKING FOR THE LATEST VERSION

The RADTRAN/RadCat package may be downloaded from:
https://radtran.sandia.gov/radcat.

On the web page, click on click here and fill out the application. You will be notified by email when you are approved. When you are approved, you can click on Download RadCat. You will be asked for your username, which is the email address you listed in the application.

When you sign in, you must download the Java Runtime Environment if it is not already on your computer. To do this, go to http://www.java.com and click on Java Software Download. Download the Windows online installation. (You may want to download and read the instructions, but it isn't absolutely necessary.) The download installs the Java Runtime Environment (JRE) on your PC. The most recent version of the Runtime Environment will download to your computer. If you are on a network, you may get a message indicating that you can't install. If this happens, you will need help from your network administrator to install it, or to give you access through a firewall. If you have a firewall (like ZoneAlarm) on the computer you are using, turn it off before installing the JRE. To gain access through a network firewall you'll need the proxy access and port number as shown in Figure 1. The proxy and port settings can be obtained from your network administrator (the port is usually Port 80).

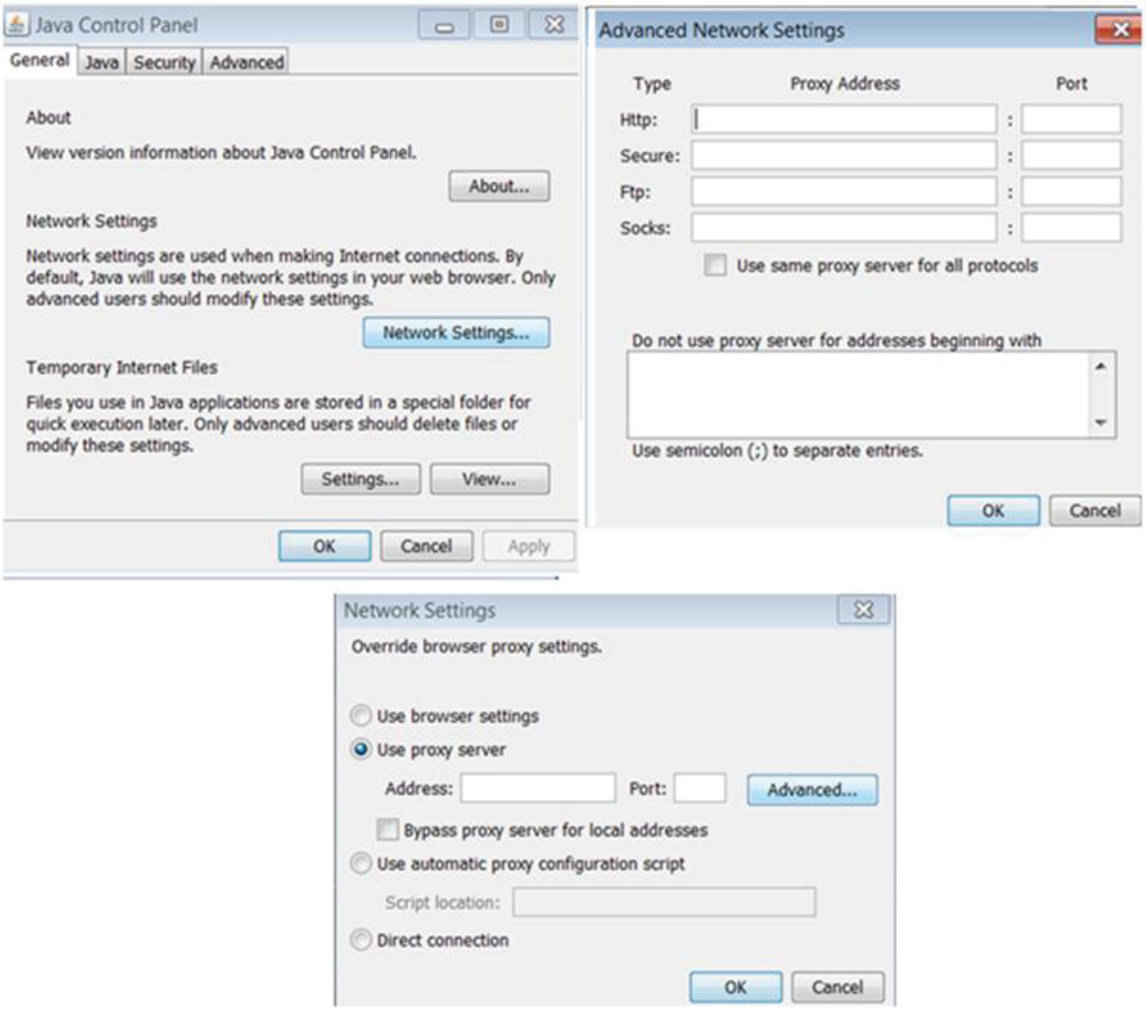


Figure 1: Proxy and Port Settings

Once JRE is installed, you can go back to Download RadCat on the Main Menu and click on Launch the application to download RadCat. When you launch RadCat (the application), you may get a notice that says there is no certificate of authenticity or that there is a risk in running the program; launch the application anyway. The process for applying for the certificate may not be complete. If you wish to put the Java Runtime Environment icon on your desktop, go to C:\Program Files\Java, open the *bin* folder, find the coffee cup javacpl.exe icon, and copy the icon or create a shortcut to your desktop. To access RadCat from the Java Control Panel, click on "View" in the Temporary Internet Files section of the General tab.

Once you have installed JRE, you can launch RadCat either from the Java cache or from the RadCat icon. JRE maintains a cache of recent RadCat downloads with the associated date of download. To view the cache or start RadCat from the cache, go to C:\Program Files\Java\, open the bin folder, and click on the coffee cup javacpl.exe icon. The Java Control Panel dialog box will open. Click on "View" in the Temporary Internet Files

section of the General tab and the Java Cache Viewer will open and show your cached RadCats. If you have difficulty downloading, try emptying your cache.
If you want to download the latest version, go back to https://radtran.sandia.gov/radcat and click on Download RadCat. You may see more than one version of RadCat. The latest version is RadCat 6. RadCat 3 does not include all of the most recent features, but does include the basic RadCat. RadCat 2.3 is bundled with an obsolete version of RADTRAN and should not be used. Click on Launch the application, and the latest version will be downloaded.

When RADTRAN/RadCat is downloaded, the RADTRAN 6 executable is downloaded to c:/users/*your computer username*/radcat along with the text files used by RADTRAN.

RADTRAN 6.02 will expire automatically two years after download. If the RADTRAN that you have downloaded expires, simply reapply and you will be given a different password and can download again. Earlier versions of RADTRAN do not contain the latest enhancements and will gradually become obsolete, even though you can continue to use them.

4. RUNNING RADTRAN WITH RADCAT

RadCat will only **open** "*.rml" files. If you are using a "*.in5" or ".input" file, **import** the file instead of opening it (see Section 4.1). Please note that a file using more than one transportation mode (e.g., both truck and rail in a single file) will not open in RadCat. RadCat will only open files that have only one transportation mode and can run only one mode at a time. RadCat 6 will open files created with RadCat 3.0, but these files do not include all of the features in RadCat 6.

To open an existing input file with RadCat and run it, follow these steps:

1. Open RadCat.

2. In RadCat, choose the file to be run, either by using the **File** pull-down menu or by clicking on the **Open** icon. This can be seen in Figure 2. The directory will appear and you may choose the file to be run. When the file has been selected, the title of the file will appear in the **Title** space.

3. Click on the **Run RADTRAN** icon (the icon showing a computer monitor). The output file will appear and can be saved.

Versions of RADTRAN 6 earlier than RADTRAN 6.02 will open in RadCat 6 but will not provide access to the alternate ingestion dose model INGEST.

4.1 Importing RADTRAN 5 Files

RadCat has the ability to import RADTRAN 5 input files and convert them to be run by RADTRAN 6.0 or later versions. This feature can be selected from the **File** pull-down

menu by clicking on the **Import** icon. You must ensure that your input files are listed as a **"*.**in5,**"**"*.dat," or ".input**"** file for RadCat to import and convert it properly.

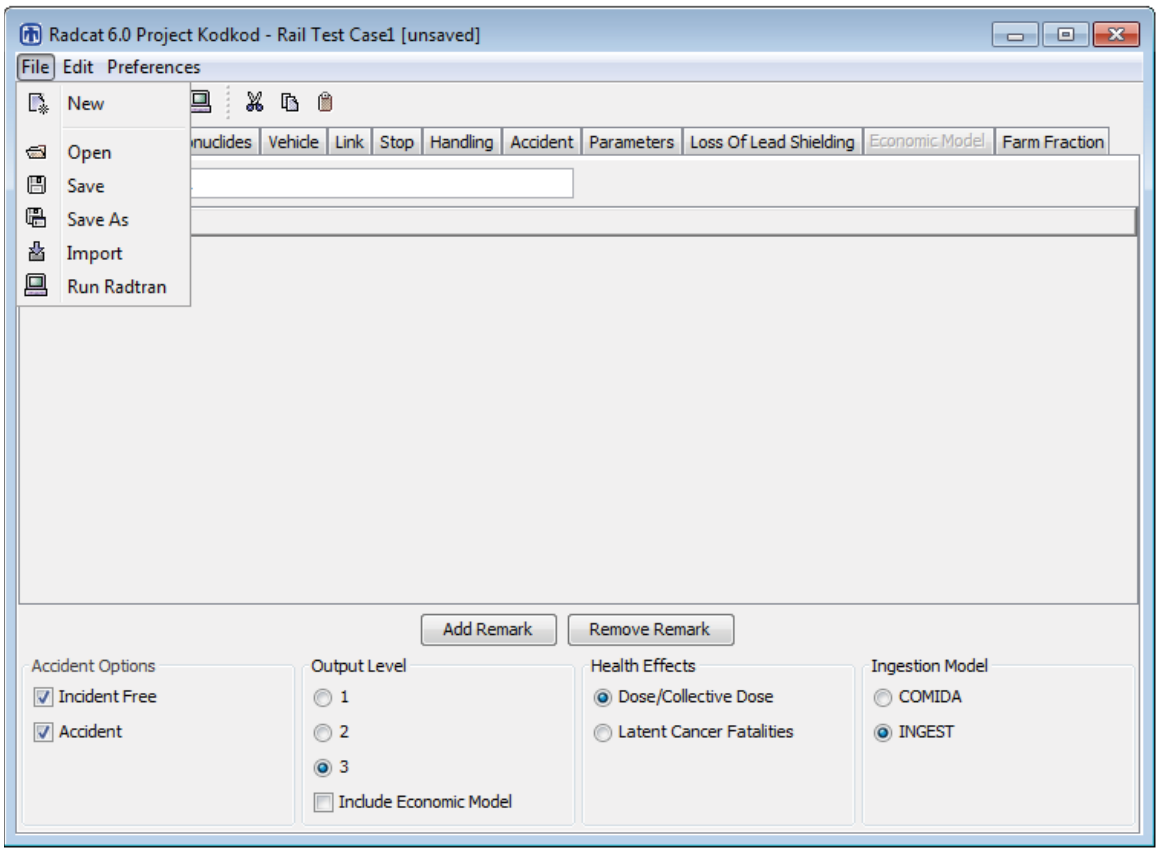


Figure 2: File pull-down menu.

4.2 Saving An Input File

An input file may be saved at any time by clicking on the **Save** icon (the floppy disk icon). The **Save As** window will open and you can save the file in the normal Windows manner. Your file should be saved as a **"***filename*.rml" file, and you will need to add the **"*.rml"** extension to your filename when saving it. RADTRAN will run the file even if it isn't saved. Save often.

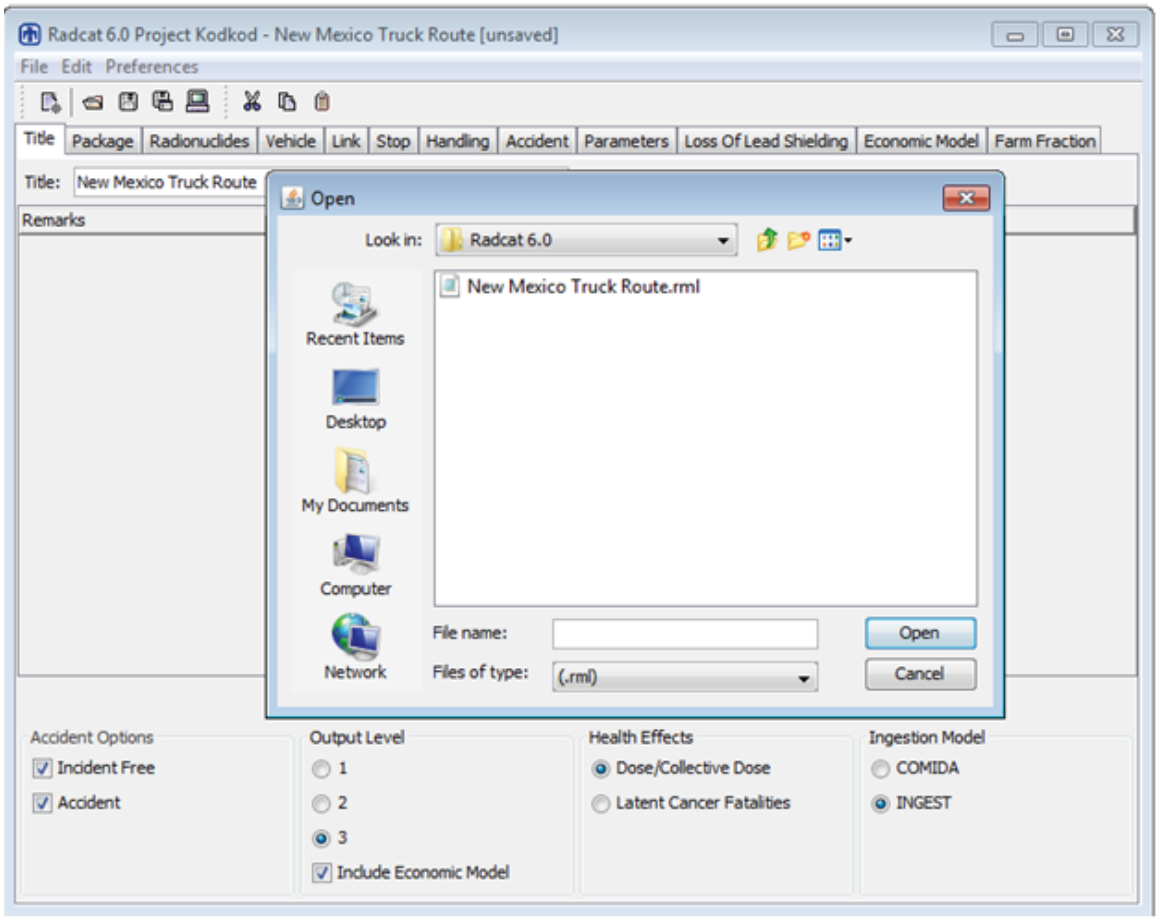


Figure 3: Saving a file

4.3 Generating An Input File With RadCat

4.3.1 New

When the **New** icon is selected to create a new file, the **Mode Selection** dialog box appears. An example of the **Mode Selection** dialog box can be seen in Figure 4. Selection of a transportation mode (highway, rail, or barge) must be made before a new file can be created. A file cannot be created in RadCat with more than one mode. The mode is selected from the pull-down menu.

If a file is already open, selecting the **New** icon will open a second Java window from which you will be able to select another transportation mode from the **Mode Selection** dialog box. This will not change or otherwise affect any of the information in the first open file.

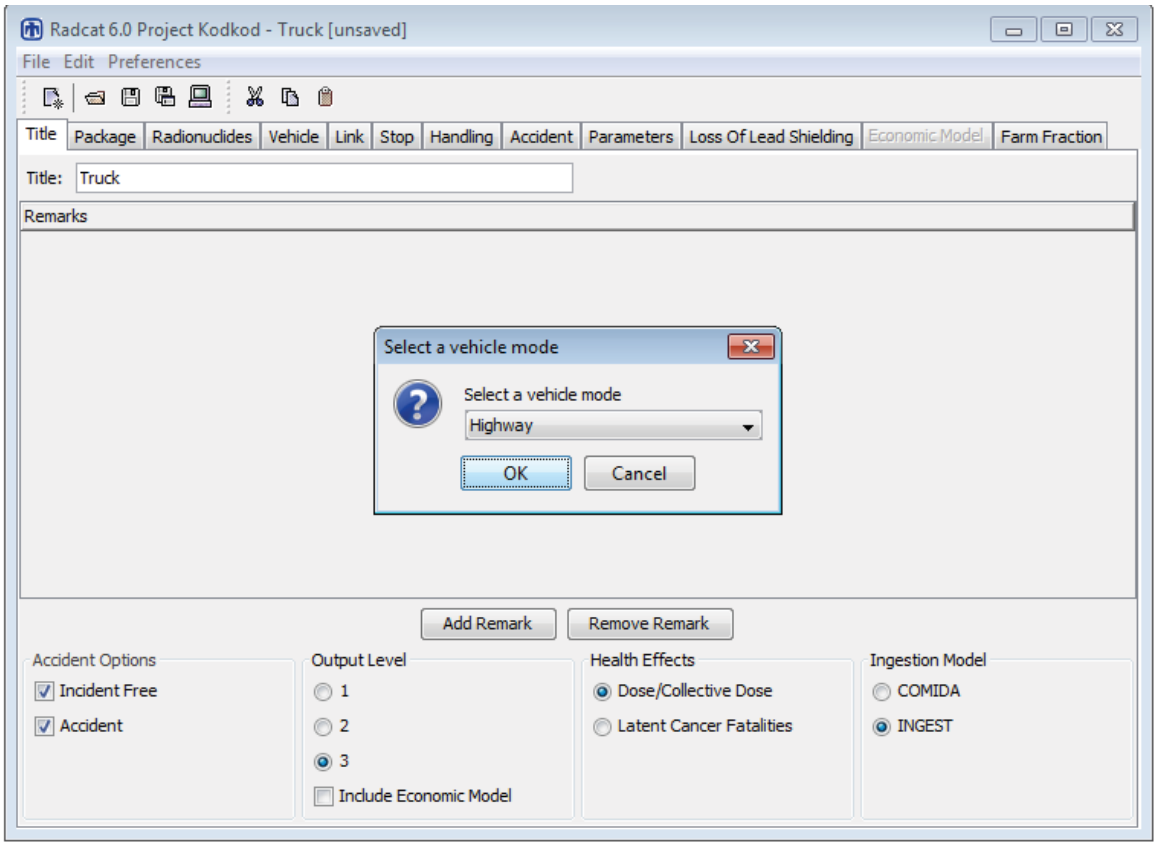


Figure 4: Vehicle Mode selection

4.3.2 Preferences (Unit Conversion)

RadCat automatically defaults to historical units, i.e. rems and curies. However, due to increased international use and the need for unit flexibility, RadCat 6 will accept for input either historical (rem, curie) or international (SI, sievert, becquerel) units, and will output either, at your discretion. If you wish to change units, you can do so only for an active file.

In the **Preferences** heading on the main toolbar, you can select **Convert Units**. This will display a dialog box that will instruct you to select **Convert to SI Mode and Change the Existing Values** or **Convert to SI mode without changing the Existing Values** (Figure 5). The first option automatically converts any historical numerical value in RadCat. The latter is meant to allow for changing unit headings in the event you accidentally enter values in SI units. Once in SI mode, you can convert back to historical units by again selecting the **Preferences, Convert Units.** Table 1 show the input and output units for the two systems:

Table 1 Historic and SI units and conversions.

Parameter	Historic Units	SI Units
Source strength	curies (Ci)	becquerel (Bq)

Conversion	1 Ci = 3.7 x 10^{10} Bq	1 Bq = 2.7 x 10^{-11} Ci*
Transferred energy	rad	gray (Gy)
Conversion	1 rad = 0.01Gy	1 Gy = 100 rad
Dose	rem	sievert (Sv)
Conversion	1 rem = 0.01Sv	1 Sv = 100 rem
Collective dose	person-rem	person-Sv

- 1 Bq = one disintegration per second

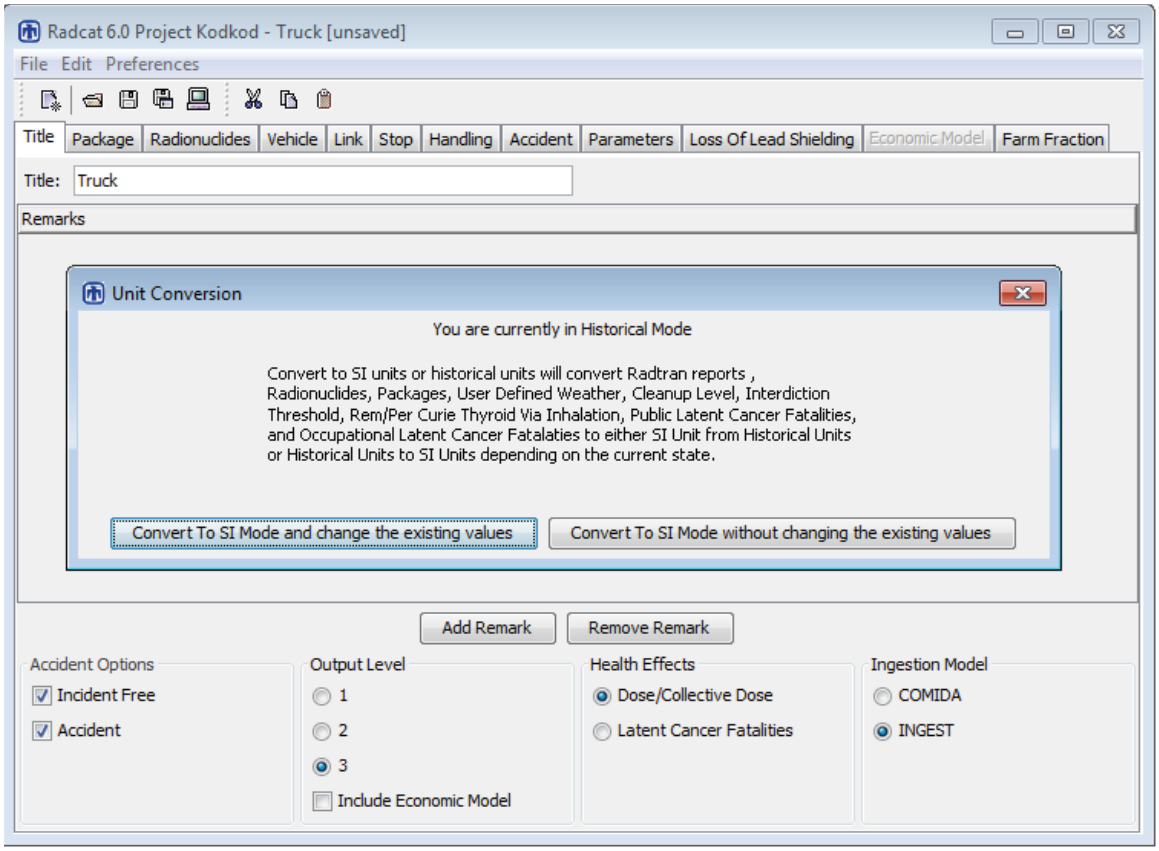


Figure 5: Unit Conversion

4.3.3 Entering Data

Whenever an entry is made on a RadCat tab, you must hit ENTER (depress the ENTER key).

4.3.4 Title

You may type any name for your file in the **Title** box and hit "ENTER" to give your file a title. Your file must have a title. The **Title** box can be seen in Figure 4.

4.3.5 Remarks

The **Remarks** screen is for you to annotate your file; e.g., give a brief description of the scenario, the sources of your input parameters, etc. When you click on **Add Remark** a line appears in the remarks screen. The word "REMARK" is on this line. You can delete it and enter your own remark. You must hit "ENTER" for your remarks to be added for each line. Click on **Add Remark** to append additional remarks. **Remarks** can be seen in Figure 6.

4.3.6 Incident-Free and Accident Options

Checking the **Incident Free** box will result in analysis of routine, incident-free transportation. Checking the **Accident** box will result in analysis of transportation accidents. Even if you only wish to have accident output, you must enter non-zero data on the **Package, Vehicle,** and **Link,** and **Stop** tabs. Checking both the **Incident Free** and **Accident,** boxes results in a full analysis of incident-free transportation and transportation accidents. These options can be seen in Figure 6.

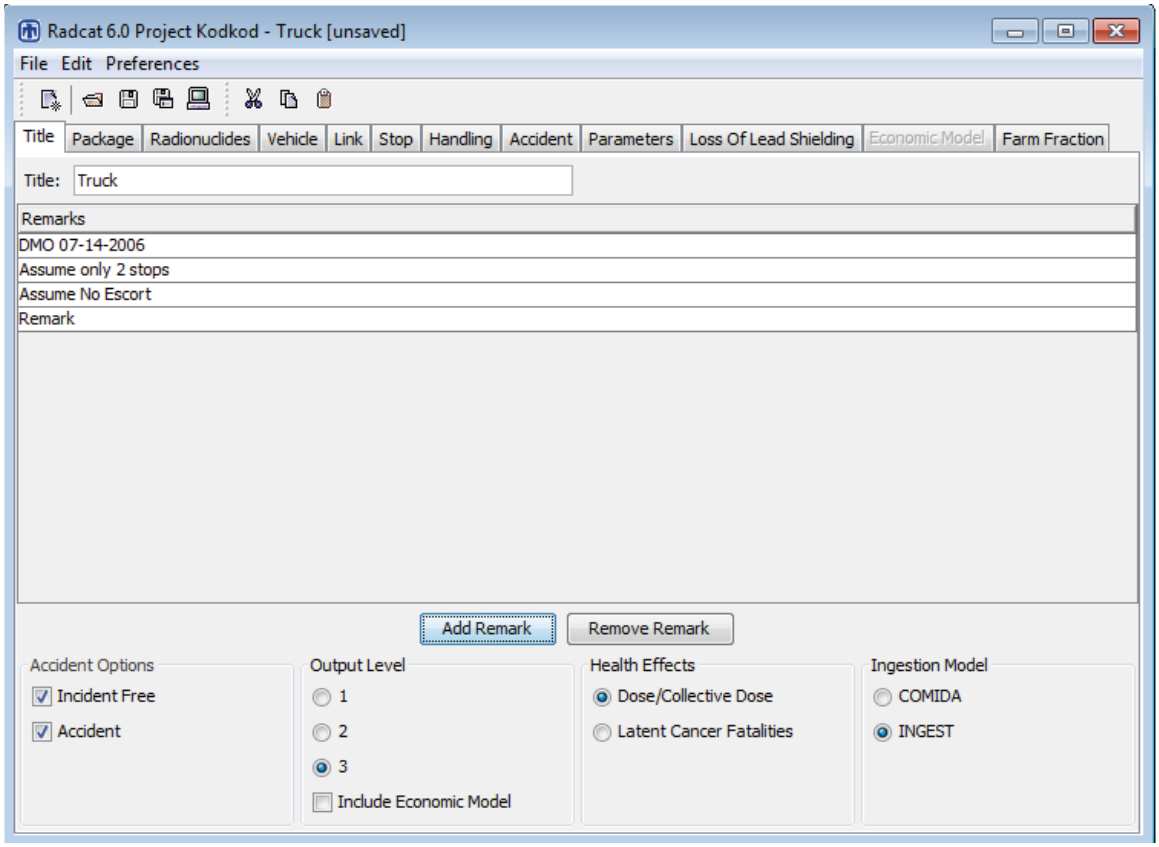


Figure 6: Title tab showing Incident Free and Accident options and outputlevel.

4.3.7 Output Level

Three options are available for controlling output size:

Short output. The input echo, incident-free, and accident and non-radiological risk tables are printed. The output file is approximately 10 pages long.

Intermediate Output. Short output plus input tables, early effects values, ground contamination tables, intermediate tables, and total expected population dose tables are printed. The output file is approximately 28 pages long.

Full Output. Intermediate output plus consequence tables and sensitivity analysis. The output file is approximately 33 pages long. This option can be seen in Figure 6. If you are importing an older file which used the four-level output, your output level will be adjusted automatically to match the new three-level output structure.

A checkbox for the **Economic Model** is included on the **Title** tab. When unchecked (as shown in Figure 6), the Economic Model Tab remains grayed out, and results from the Economic Model will not be included in the RADTRAN output. However, if the box is checked, the Economic Model Tab will become functional, allowing for default value editing and inclusion in the RADTRAN output.

4.3.8 Health Effects

Health effects may be reported in the output either as individual and collective doses or as latent cancer fatalities (LCF). RADTRAN can calculate the risk of latent cancer fatalities (LCF) by multiplying the dose by a linear conversion factor; the default factor in RADTRAN, is 6×10^{-2} LCF/Sv (6×10^{-4} LCF/rem) (DOE 2002a, ISCORS 2002). The validity of this linear conversion for small individual or average doses has been called into question (Tubiana and Aurengo, 2005; Raabe, 2011, Gonzalez, et al., 2013) and it is included only because it has been used extensively. Reporting results in units of dose rather than LCF [1] is encouraged.

4.3.9 Ingestion Dose Model

RADTRAN calculates ingestion dose by two different models, COMIDA and INGEST. COMIDA (Abbott and Rood, 1993) and the new model, INGEST (Weiner and Heames, 2013). INGEST uses state specific food transfer factors. Select the ingestion dose model you wish to use. If you select **INGEST**, be aware that it only works with **User-Defined Weather** (Section 11 – Accidents) and will not work with either of the other **Weather** options. COMIDA works with all **Weather** options.

5. PACKAGE

When making a new input file or adding or deleting a package in an existing file, select the **Package** tab. When editing an existing file without adding or deleting a package, the

[1] Use of a linear conversion factor has been the subject of skepticism for some time. The papers by Tubiana and Aurengo and Gonzalez et al. present a summaries and reviews of peer-reviewed molecular biologic and epidemiologic studies that support this skeptical view.

order in which the tabs are opened will not make any difference. This can be seen in Figure 6.

5.1 Name

Give your package a name in the left-hand column. You may delete "PACKAGE_1" and substitute any name that you like. A package name must be a continuous text string and may not contain any spaces.

If you wish to transport more than one package, click the **Add Package** bar and add as many packages as you wish. You can give your added packages any names that you want to give them. You will be adding packages to vehicles in a later tab. The package tab can be seen in Figure 7. RadCat 6 includes some spreadsheet functionality; cells can be copied to a new location using the copy and paste icons at the top of the GUI, the pull-down "Edit" menu, or CTRL+C and CTRL+V. A line can be copied to another line, but cannot be copied where no line exists. Lines can be added or deleted only with the buttons at the bottom of the tab.

List all the packages that you will want for this run on this tab. You can add or delete packages only on this tab; you cannot add them or delete them from other tabs.

5.2 Long Dimension

Enter the largest dimension of the package in meters, e.g. length of a cylinder if larger than the diameter. In RADTRAN literature, for historical reasons, this dimension is called the "critical dimension," although it is not critical in the sense of nuclear criticality.

5.3 Dose Rate

Enter the external dose rate at one meter from the package surface, in units of mrem/hr or Sv/hr. External dose rate can often be obtained by measurement or from the cask Safety Analysis Report (SAR), or can be estimated by calculating package shielding. The regulations of 10 CFR Part 71 specify that the external dose rate *at two meters* from the package surface should not exceed 10 mrem/hour. This is equivalent to about 14 mrem/hr at one meter from the package surface for a "critical dimension" of about 5 meters. The package parameters, including dose rate, are shown in Figure 7.

The **Parameters** tab (Section 12) includes a flag that reads "Imposed regulatory limit on vehicle external dose." When the flag is on, a regulatory constraint is imposed on the shipment. Selecting **YES** will cause RADTRAN to adjust the package length and dose rate internally so that the external dose rate at two meters does not exceed 10 mrem/hr, and thus may be modeling a different dose rate than the one you entered. If the regulatory constraint is in place, RADTRAN will print a message noting this in the output. If you want to lift this regulatory constraint, select **NO**. Some analysts prefer to lift this regulatory constraint (by selecting **NO)** so they always know exactly what they are modeling.

RADTRAN models the external dose rate as a virtual source at the center of the package. The distance between the source and the receptor must take this into account. The dose rate at one meter from the surface may be calculated from the dose rate at two meters using RADTRAN, remembering to take into account the distance between the cask surface (the actual radiation source) and the center of the cask (location of the virtual source).

5.4 Gamma and Neutron Fractions

When you enter a value into either of these cells, RadCat will automatically adjust the other cell so that the sum is equal to one. This can be seen in Figure 7.

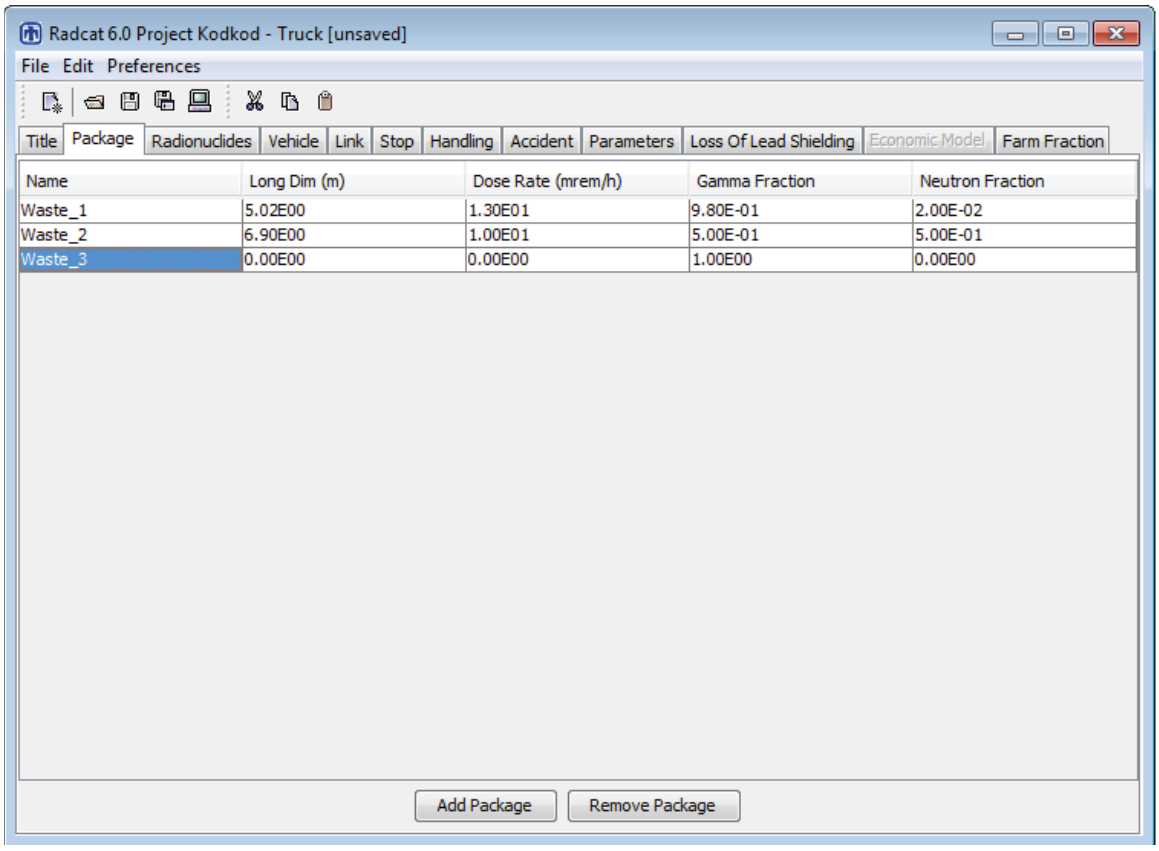


Figure 7: Package tab

6. RADIONUCLIDES

Select the **Radionuclides** tab next after the **Package** tab (Figure 8). When editing an existing file without adding or deleting a package, the order in which the tabs are opened will not make any difference.

At the top of the **Radionuclides** tab is a pull-down menu of the packages you have created. Select the package whose inventory you wish to specify.

6.1`Adding Radionuclides from the Internal Library

The window just below the package pull-down menu lists all of the radionuclides in the internal RADTRAN library. Radionuclides from the internal library may be added to your package by clicking on the **Add Library Radionuclide** arrow. The radioisotope name will then appear on the right-hand screen. Name the **Physical/Chemical Group** to which the radionuclide belongs. You may use any name you like, but the name can have no more than eight alpha-numeric characters and cannot contain any spaces. Remember that the release behavior in the event of an accident depends on the physical/chemical group (gas, particle, volatile substance, etc.). RADTRAN will accept up to 15 different physical chemical groups. Once you have added a **Physical/Chemical Group** name to your first radionuclide, the **Physical/Chemical Group** entry will become a pull-down menu that reflects your additions, so that you can select existing physical/chemical groups for other entries without re-typing the name each time. Physical/chemical groups must be entered at this tab; they cannot be entered on any other tab (Figure 8). Enter the number of curies of the radionuclide in the **Curies** column.

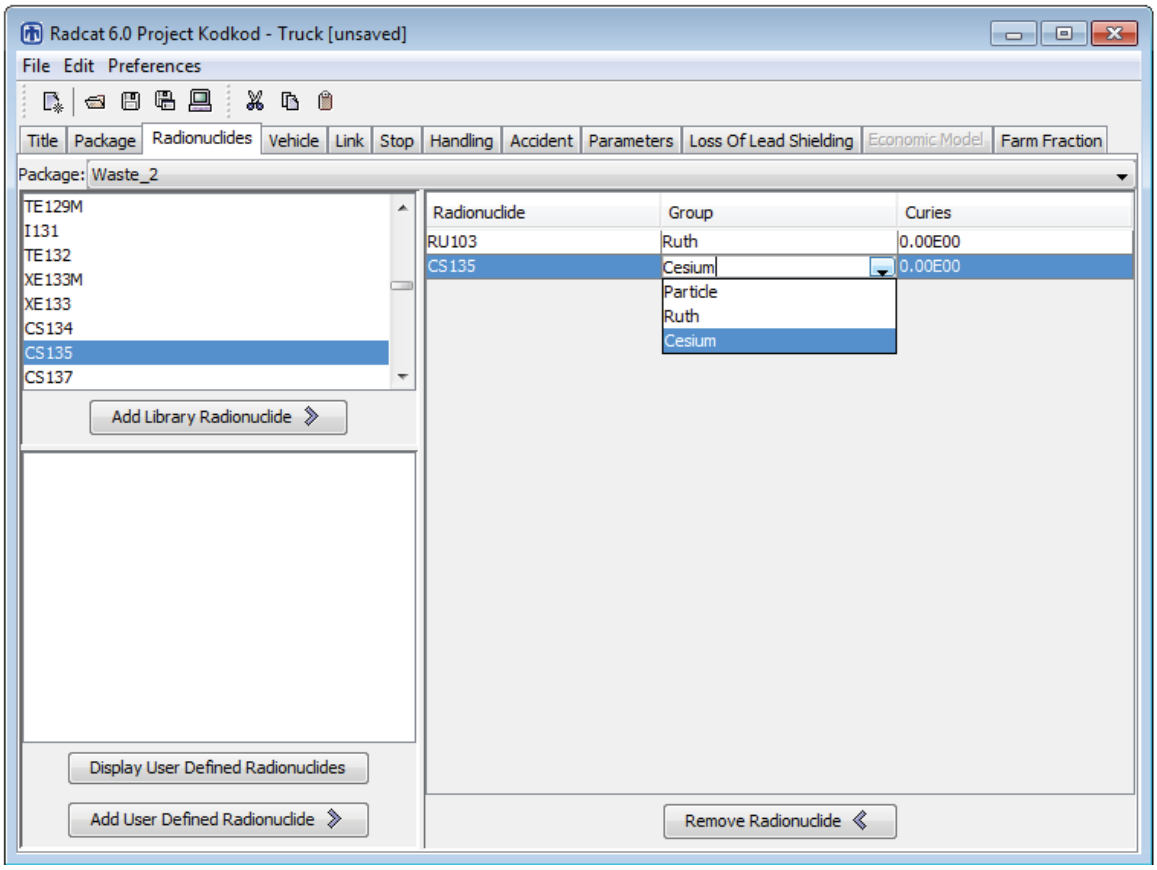


Figure 8: Radionuclides tab.

6.2. Adding User-Defined Radionuclides

If the radionuclide you wish to add is not in the internal library, it may be added to your package. To do this, first click on the **Display User-Defined Radionuclides** bar. The **User Defined Radionuclides** screen will open. In this tab, you can click on the **Add User Defined Radionuclides** bar. You may then enter the name of the radionuclide in the left-hand cell (in place of ISOTOPE_1. The name can be up to eight characters long and may not contain any spaces. This can be seen in Figure 9.

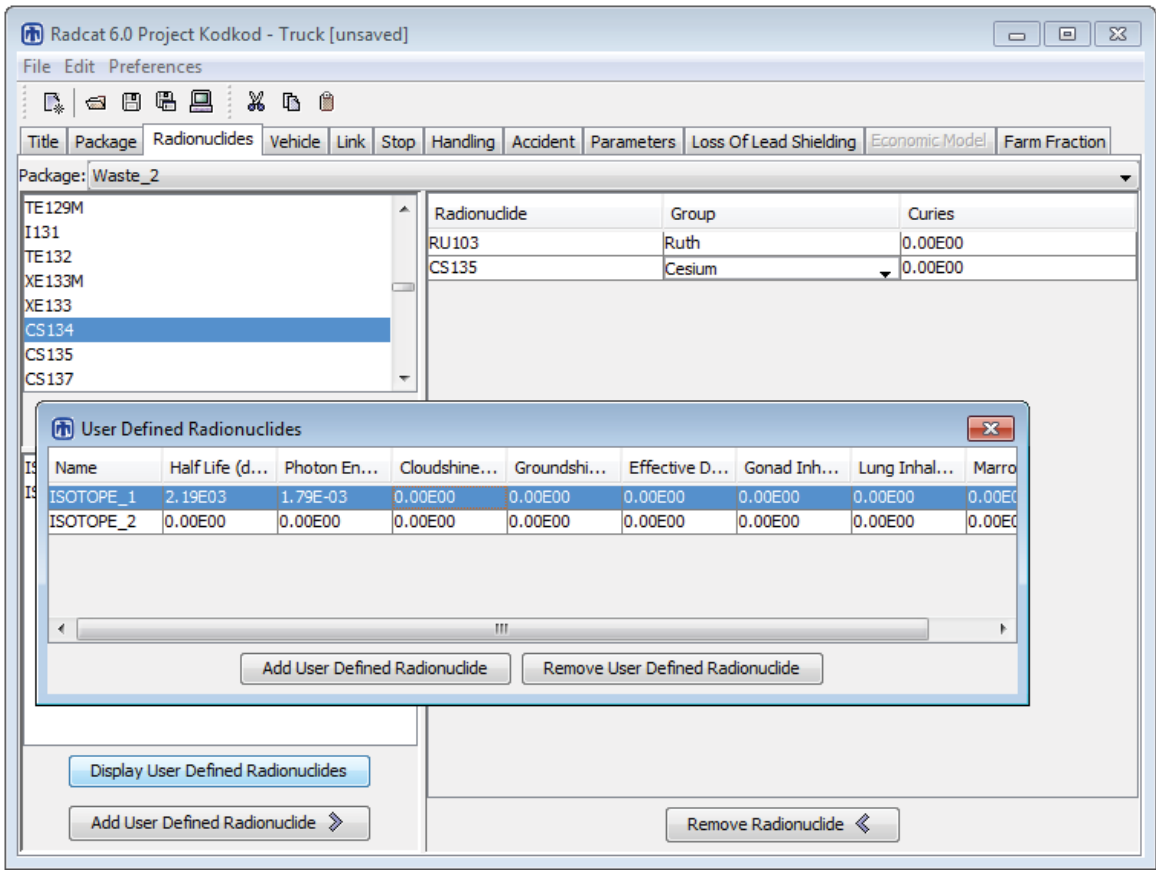


Figure 9: Radionuclides tab with user defined radionuclides window

Half-lives may be found in the Chart of the Nuclides (KAPL, 2003) or the International Commission on Radiological Protection (ICRP) Publication 38 (ICRP, 1983), and dose conversion factors may be found in the Health Physics Handbook (Shleien et al, 1996), Federal Guidance Report 12 (Eckerman and Ryman, 1993), ICRP Publication 72 (ICRP, 1996), and similar references. Dose conversion factors for radionuclides in the internal RADTRAN library are provided in Appendix B. Enter values for:

- Half-life in days,
- Photon Energy in MeV = Groundshine DCF/0.000304,
- Cloudshine Dose Conversion Factor (DCF) in rem-m^3/Ci-sec or Sv-m^3/Bq-sec,
- Groundshine DCF in rem-m^2/μCi-day or Sv-m^2/Bq-day ,

- Effective DCF in rem/Ci or Sv/Bq (called Inhalation Dose in the output),
- Gonad Inhalation DCF in rem/Ci or Sv/Bq,
- Lung Inhalation DCF in rem/Ci or Sv/Bq, and
- Marrow Inhalation DCF in rem/Ci or Sv/Bq.

Make sure you use the appropriate units. A value larger than zero for the half-life must be used for every user-defined radionuclide. RADTRAN will not run if there is a radionuclide with a half-life of zero or with a negative half-life.

If values for the **Cloudshine** dose conversion factor, the **Groundshine** dose conversion factor, and/or the **Inhalation** dose conversion factor are not entered, RADTRAN will run but will report zero for the appropriate doses. If values for the **Gonad Inhalation**, **Lung Inhalation**, and/or **Marrow Inhalation** dose conversion factors are not entered, there will be no effect on cloudshine, groundshine, inhalation, or resuspension collective doses, but specific gonad inhalation, etc., doses will not be reported.

When you have added a user-defined radionuclide, the name of that radionuclide appears on the lower part of the **Radionuclides** tab. Using the **Add User Defined Radionuclide** arrow under that screen, you add the user-defined radionuclide to your package, and indicate the physical/chemical group and number of curies as before. If you wish to include a radionuclide in more than one **Physical/Chemical Group** (e.g., Co-60 as both CRUD and particulate), give the radionuclide a different name for each **Physical/Chemical Group** (e.g., CO60CRUD, CO-60P) and include one or both as **User-Defined Isotope(s)**.

Inhalation, resuspension, groundshine, and cloudshine doses are calculated for all radionuclides: both those in the internal library and those that are user-defined. However, the ingestion dose is calculated by RADTRAN only for radionuclides in the internal library and not for those radionuclides that are user-defined.

7. VEHICLE

The **Vehicle** parameters (external dose rate, length, etc.) determine the dose to residents along the route and near stops, to occupants of vehicles sharing the route, to people sharing stops, to inspectors and to the vehicle crew. The analogous **Package** parameters determine doses to handlers. If there is only one package per vehicle, as for a spent fuel or UF_6 package, or if all the packages can be modeled as one, as for the TRUPACT-II (which is actually three cylinders standing adjacent to each other), the largest dimension, external dose rate, and gamma and neutron fraction should be the same for the vehicle and package.

When making a new input file or adding or deleting a vehicle in an existing file, select the **Vehicle** tab after the **Radionuclides** tab, because screens that come after the **Package** and **Radionuclides** screens require a vehicle name. When editing an existing file without adding or deleting a vehicle, the order in which the tabs are opened doesn't make any difference. This can be seen in Figure 10.

7.1 Vehicle Name

Provide a vehicle name in the left-hand column. The defaulted name may be substituted with any other name and additional vehicles can be given any name you wish to give them. A vehicle name must be a continuous text string and must not contain any spaces.

To analyze more than one vehicle, click the **Add Vehicle** bar and add the desired number of vehicles. This can be seen in Figure 10. Add packages to vehicles as follows:

1. Click on the vehicle to which the desired package is to be added.

2. Then click on the package to be added, and enter the number of those packages that are to be added to the vehicle.

Adding the package to the vehicle adds the radionuclide contents of the package to the analysis. The radionuclide content is important to the accident analysis, though not to the incident-free analysis. Different packages may be added to a vehicle. When selecting the vehicle, the number of each of the packages on that vehicle shows up in the **Number of Packages** column. If a package is not on a particular vehicle, the **Number of Packages** column will show a zero. This can be seen in Figure 10.

List all the desired vehicles on this tab. Vehicles cannot be added on other tabs, nor can they be deleted from other tabs. RADTRAN can handle as many as 20 vehicles in a single analysis.

7.2 Number of Shipments

Enter the number of shipments. This can be seen in Figure10. RADTRAN calculates doses and dose risks for one shipment and multiplies that result by the number of shipments. The same result can be obtained, as many analysts prefer to do, by performing the RADTRAN analysis for one shipment and multiplying externally by the number of shipments.

7.3 Vehicle Size

Enter the largest dimension of the cargo section of the vehicle, or of the part of the vehicle holding the packages, in meters. This is the “critical dimension” of the vehicle in RADTRAN. This can be seen in Figure 10.

7.4 Vehicle Dose Rate

Enter the external dose rate at one meter from the edge of the cargo-carrying part of the vehicle, in units of mrem/hr or Sv/hr. The regulations of 10 CFR Part 71 specify that the external dose rate *at two meters* from this edge should not exceed 0.01 mSv/hour (10 mrem/hour). This is equivalent to 0.014 mSv/hr (14 mrem/hr) at one meter if the largest

dimension is approximately 5 meters. If the actual dose rate is not known, and one assumes that the shipper is abiding by regulations, one may use the regulatory maximum, 14 mrem/hr, as the external dose rate, recognizing that this value is conservative. This can be seen in Figure 10.

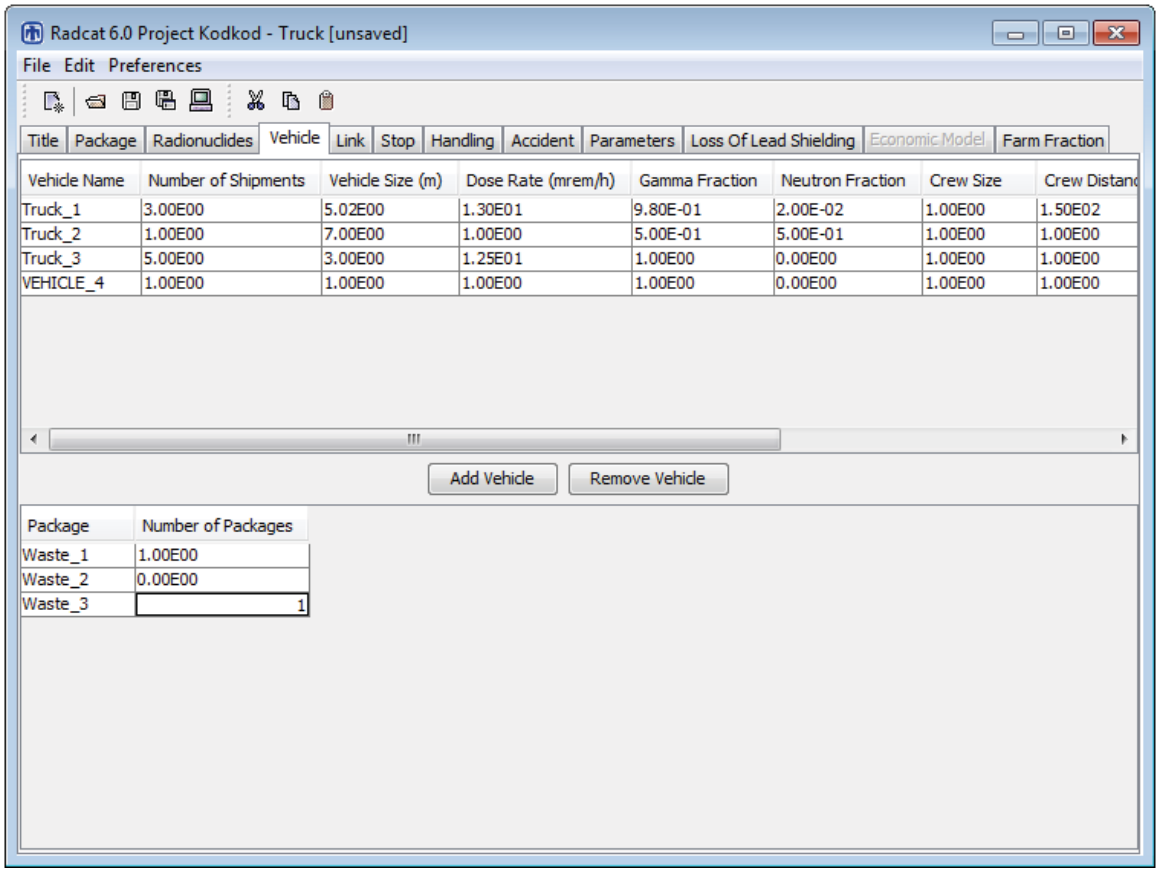


Figure 10: Vehicle tab

RADTRAN has a flag on the **Parameters** tab (Section 12), "Imposed regulatory limit on vehicle external dose," that imposes a regulatory constraint on the shipment. As it was explained in Section 5.3 (Package tab), Selecting **YES** will cause RADTRAN to internally adjust the critical dimension and the dose rate so that the external dose rate at two meters does not exceed 10 mrem/hr, and thus may not use the dose rate you entered into the calculations. If you want to lift this regulatory constraint, select **NO**.

RADTRAN models the external dose rate as a virtual source at the center of the package. The distance between the source and the receptor must take this into account.

7.5 Gamma and Neutron Fractions

Enter a value into either of these cells; RadCat will automatically adjust the other cell so that the sum of both is equal to 1. This can be seen in Figure 10.

7.6 Crew Size

Enter the number of crew members traveling on the vehicle. This can be seen in Figure 11.

7.7 Crew Distance

For highway and barge travel, enter the **Distance** in meters from the crew to the nearest surface of the cargo in the **Crew Distance (m)** column. This distance is about 2 to 3 meters for large trailer rigs but may be much longer for heavy haul trucks. This can be seen in Figure 10. The crew on a train in transit is at least 150 m (several railcar lengths) from the radioactive cargo, and is shielded by intervening rail cars

Occupational dose for rail shipments includes the dose to the crew on the moving train and the dose sustained by rail yard workers at stops along the route. The dose to the train crew is usually small compared to the dose to railyard workers. The dose to railyard workers at classification stops is calculated internally by RADTRAN and the result is in the output, RADTRAN calculates and reports in-transit yard worker dose using the distance-dependent rail worker exposure factor per km (DDRWEF) listed on the **Parameters** tab (Section 12). The details on DDRWEF are provided in Section 12 under the **Minimum number of rail classification stops** subsection. Railyard worker dose can also (and preferably) be calculated from rail stops (Section 9) when the information on the number of classification stops and their duration is available.

A barge usually has a crew of 10. Enter the average distance of the crew from the cargo.

7.8 Crew Shielding Factor

Enter a factor between 0 and 1 for crew shielding. This factor is the fraction of ionizing radiation to which the crew is exposed (the inverse of the shielding fraction). This means that 1 = no shielding, and 0 = 100% shielding. This can be seen in Figure 10.

If RADTAN is run with regulatory constraints (see the **Parameters** screen, Section 12) the maximum crew dose will automatically not be greater than 2 mrem (0.02 mSv) per hour. If RADTRAN is run without regulatory constraints, the crew shielding factor, if the crew distance from the package is 3 meters, is 0.38. This value was calculated using RADTRAN from the using the 2 mrem per hour standard

7.9 Crew View

The **Crew View** is the largest dimension, in meters, of the cargo that faces toward the crew. This is usually the diameter of a cylindrical cask or the diagonal end dimension of a rectangular container or array. This can be seen in Figure 10 in the **Crew View (m)** column.

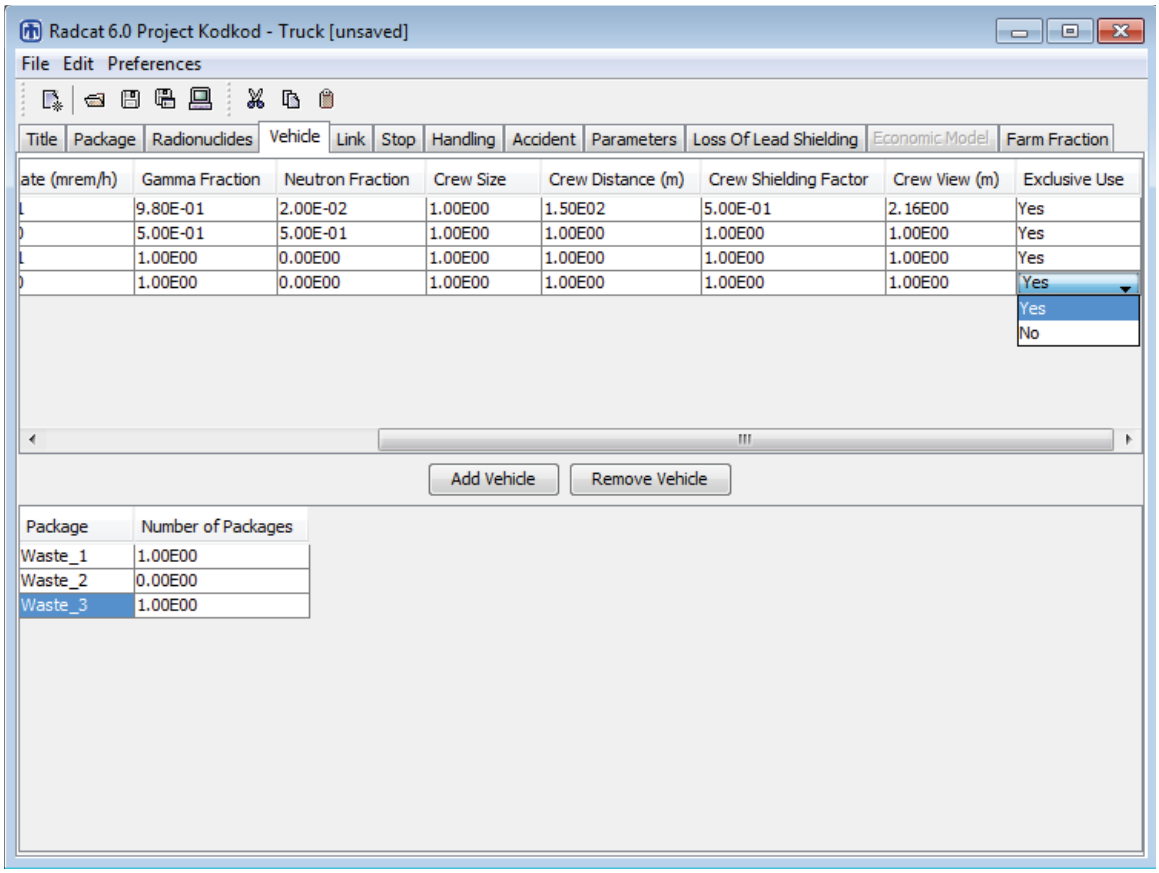


Figure 11: Vehicle tab continued

7.10 Exclusive Use

A pull-down menu allows you to indicate whether the vehicle is exclusive use or not. This can be seen in Figure 11 in the **Exclusive Use** column.

8. LINK

A "link" is a route segment. Links are designated as rural, suburban, and urban, based on population density (Johnsons and Michelhaugh, 2000). Each segment with a different population density can be designated as rural, suburban, or urban, as shown in Figure 12. The route shown in Figure 12 was produces using TRAGIS. the rural, suburban, urban designation affects the use of some default parameters as described in section 8.10.

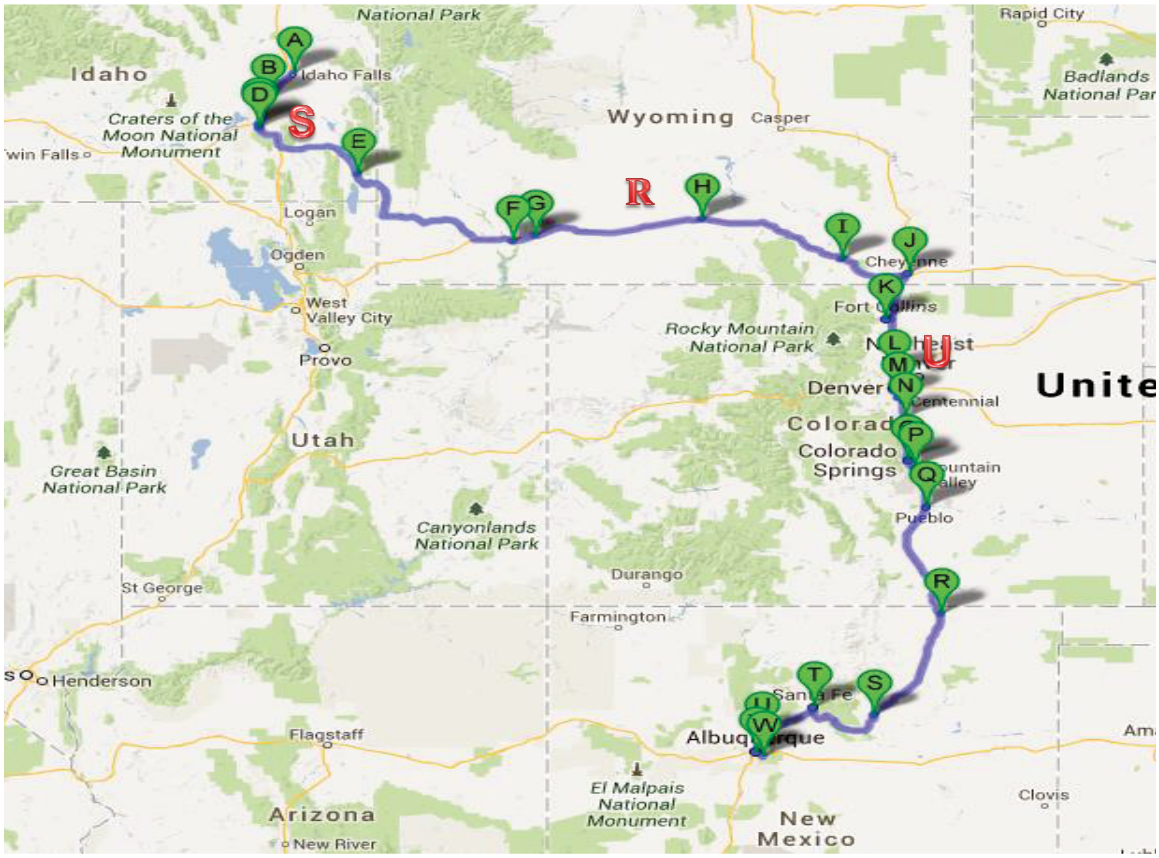


Figure 12: A possible truck route from Idaho Falls, ID to Albuquerque, NM (courtesy of ORNL). A rural segment (R), a suburban segment (S), and an urban segment(U) are indicated.

Routing codes like TRAGIS provide the population along the route. RADTRAN assumes a bandwidth (usually 800 meters) along each link and integrates the population density over this bandwidth for each link. RADTRAN adjusts internally for a band on both sides of the route. Links may be designated as rural, suburban, or urban according to the following population densities:

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)

The population density classification is not automatic; i.e., any link can be designated as rural, suburban, or urban, independently of the population density.

Figure 13 is another example of a route using a different mapping system: Interstate 80 through Salt Lake City, UT. Urban, suburban, and rural segments are indicated in the figure.

Figure 13: Interstate Truck Route generated by a SNL GIS.

When making a new input file or adding or deleting a vehicle in an existing file, select the **Link** tab next after the **Vehicle** tab since the vehicle name is required on the Link tab. If editing an existing file without adding or deleting a package, the order in which the tabs are opened doesn't make any difference. This can be seen in Figure 14.

8.1 Link Name

Give each link a name in the left-hand **Link Name** column. A link name must be a continuous text string and must not contain any spaces. Links do not need to be consecutive, but listing them the same order in which they occur along the route helps to visualize the route. Rush-hour periods can also be separate links to take into account different vehicle speeds and vehicle densities on these segments.

8.2 Vehicle

Available vehicle names are on a pull-down menu in the **Vehicle** column. Vehicle names cannot be added or deleted at this tab. This can be seen in Figure 14 in the Vehicle column.

8.3 Length

Enter the length of the route segment – the link – in kilometers, as obtained from a routing code like WebTRAGIS or from a GIS system or from a map. This can be seen in Figure 14 in the **Length (km)** column.

Useful conversion factors are:
1 km = 0.62137 mile
1 mile = 1.60934 km.
1 person/mi^2 = (1 person/mi^2)*(1 mi/1.608 km)^2 = 1 person/2.59 km^2

8.4 Speed

Enter the average speed of each vehicle on each link, in km/hr. This can be seen in Figure 14 in the **Speed (km/h**) column. You may use any speeds you choose. Several options for speed are available:

- State highway speed limits as of 2012, in km/hour for various types of roads, are shown in Table 2. Suburban interstate highway speeds are usually the same as rural speeds.
- WebTRAGIS currently outputs the length and transit time for each link. The speed of the vehicle on the link can be calculated directly from this output.
- The state traffic reports available on www.bts.gov allow direct calculation of allowed maximum speed for each state transited.

Rail speed depends on the track class and type of cargo. Trains carrying hazardous materials, including radioactive materials, are often limited to 50 mph (80 km/hr) in rural areas and 40 mph (64 km/hr) in suburban and urban areas. When the slowing at curves is considered, the national average speed is approximately 35 kph. Rail speed on each link can also be calculated directly from WebTRAGIS data.,

Table 2. State truck speed limits (National Motorists Association, 2012)*.

Speed Limit (kilometers/hour)							
State	Interstate		Other	State	Interstate		Other
	Rural	Urban			Rural	Urban	
AL	113	105	105	NE	121	105	105
AZ	89	89	89	NV	121	105	113
AR	121	105	105	NH	105	105	89
CA	105	89	97	NJ	105	89	105
CO	89	89	89	NM	121	105	105
CT	121	105	105	NY	105	89	89
DE	105	89	105	NC	113	113	113
DC	89	89	105	ND	121	121	105
FL	113	89	105	OH	105	105	89
GA	113	105	113	OK	121	113	113
ID	105	105	105	OR	89	89	89
IL	105	89	89	PA	105	89	105
IN	105	89	97	RI	105	89	89
IA	113	89	105	SC	113	113	89
KS	121	121	121	SD	121	121	113
KY	105	105	105	TN	113	113	113
LA	113	113	113	TX	121	121	121
ME	105	105	105	UT	121	105	121
MD	105	105	105	VT	105	89	80
MA	105	105	105	VA	64	89	32
MI	105	105	105	WA	113	113	105
MN	113	105	105	WV	97	97	97
MS	113	113	113	WI	113	105	105
MO	113	97	105	WY	105	105	105
MT	105	105	105				

*Some states have different speed limits for night and day. In these cases, the lower of the speeds is the value in the table.

8.5 Population Density

RADTRAN requires population along a route to be entered in the appropriate column as a population density (persons/km^2), which may be calculated for each link from WebTRAGIS. WebTRAGIS provides, for each route segment, the length of the segment the population, and the band width, and may in some cases provide the population density directly. Population density may also be calculated from the City/County data book, or some other GIS system or source. Population density is shown in Figure 14.

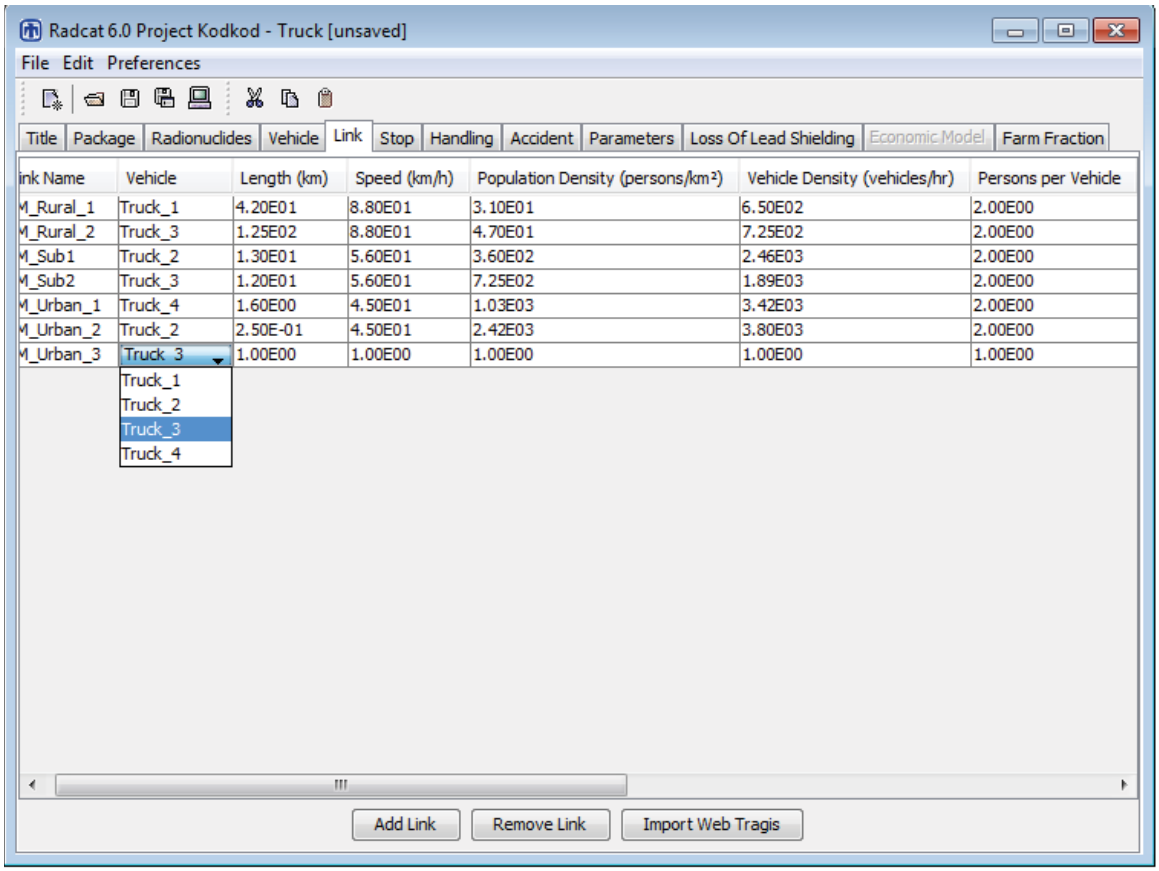


Figure 14: Link tab

8.6 Vehicle Density

Enter the vehicle density – the vehicles per hour sharing the route with the radioactive cargo. This can be seen in Figure 14 in the **Vehicle Density (vehicles/hr)** column. National average vehicle densities from 2003 to 2005 are (Appendix D):

Interstate Highways

* rural: 1155 vehicles/hr
* suburban: 2414 vehicles/hr
* urban: 5490 vehicles/hr

U.S. Highways

* rural: 287 vehicles/hr
* suburban: 618 vehicles/hr
* urban: 1711 vehicles/hr

The study from which these numbers are extracted is provided in Appendix D, which includes average regional vehicle densities from the ten Environmental Protection

Agency (EPA) regions and average vehicle densities from 21 states. More accurate vehicle densities can usually be obtained from state traffic counts.

Average rail densities, except for trains carrying passengers, are

Rail

- rural: 1 vehicle/hr
- suburban: 5 vehicles/hr
- urban: 5 vehicles/hr

8.7 Persons per Vehicle (Vehicle Occupancy)

Enter the average persons per vehicle for the route in the **Persons per Vehicle** column (Figure 14). For highway transportation, this is usually 1.5 or 2 persons per vehicle . For rail, since most rail transportation is freight, the number is usually 3 (the train crew). If passenger trains share the route, the average vehicle occupancy can be estimated.

The vehicle density and the vehicle occupancy are important parameters in determining the on-link incident-free dose from transportation of radioactive materials.

8.8 Accident Rate (How RADTRAN Analyzes Accidents)

RADTRAN analyzes only one accident, because only one accident would occur during a trip on any route. The accident analysis is based on the package and vehicle, because the package contains the radionuclides potentially released, and the location of the accident – the link – is identified by the vehicle. If the vehicle is in an accident, it goes no further than the accident location. However, the accident could occur on any segment of the route, so RADTRAN reports accident risks and consequences on every route segment (link). If you wish to model the accident on several links, but not on all links, enter accident rated in the "Accident Rate (accidents/veh-km") only for the links on which you wish to model an accident. Enter zero in the "Accident Rate (accidents/veh-km") column for those links on which you do not want an accident (don't leave the cell empty: RADCAT hangs up if the cell is empty).

Enter the vehicle accident rate for each route segment in accidents per vehicle-km in the **Accident Rate (accidents/veh-km)** column (Figure 14a). Accident rates are usually reported by state and type of road or rail. A useful reference for accident rates is the Bureau of Transportation Statistics web site: http://www.bts.gov. Table 3 shows the data from that site.

8.9 Fatalities per Accident

Enter the number of fatalities per accident (Figure 14a). Fatality rates are usually reported by state and can be found at www.bts.gov. The fatalities per accident value is 0.00353, an approximately constant number in the U.S.

Table 3 Highway and rail accident rates [a]

State	Highway accidents/ vehicle km	Rail accidents/ railcar-km	State	Highway accidents/ vehicle km	Rail accidents/ railcar-km
AL	2.61E-06	2.27E-07	NE	1.96E-06	1.20E-07
AZ	1.7E-05	1.82E-07	NV	8.37E-06	1.80E-08
AK	2.07E-06	3.05E-07	NH	3.46E-06	7.82E-07
CA	3.98E-06	3.14E-07	NJ	5.19E-06	1.58E-07
CO	9.58E-07	2.53E-07	NM	4.78E-06	2.72E-07
CT	2.08E-06	9.61E-07	NY	1.21E-06	6.33E-08
DE	1.90E-06	3.36E-07	NC	4.78E-06	9.62E-08
DC	6.83E-06	4.42E-06	ND	1.15E-06	1.97E-07
FL	1.27E-05	1.81E-07	OH	1.63E-06	2.08E-07
GA	1.40E-06	1.74E-07	OM	7.61E-06	2.70E-07
ID	6.69E-06	3.39E-07	OR	1.22E-06	2.19E-07
IL	5.68E-06	1.89E-07	PA	2.45E-06	3.77E-07
IN	1.32E-06	2.15E-07	RI	2.18E-06	1.14E-07
IA	1.63E-06	2.03E-07	SC	1.59E-06	1.14E-07
KS	2.50E-06	2.01E-07	SD	5.36E-06	2.57E-07
KY	3.29E-06	3.16E-07	TN	3.00E-06	3.44E-07
LA	2.85E-06	7.60E-08	TX	1.11E-05	2.25E-07
ME	2.91E-06	4.27E-07	UT	2.04E-06	7.56E-08
MD	4.09E-06	1.97E-07	VT	1.16E-06	1.47E-07
MA	1.57E-06	1.03E-07	VA	2.67E-06	1.93E-07
MI	1.20E-06	1.39E-07	WA	6.91E-06	1.34E-07
MN	1.43E-06	1.84E-07	WV	1.55E-06	8.53E-08
MS	1.50E-06	1.73E-07	WI	1.79E-06	2.57E-07
MO	3.98E-06	1.05E-07	WY	5.21E-06	3.15E-07
MT	3.78E-06	3.24E-07	US	3.72E-06	1.82E-07

[a]From BTS (200**6**), Table 1-23

8.10 Population Zone

A pull-down menu allows the designation of each link as rural, suburban, or urban. These designations affect certain RADTRAN calculations within the code. For example, rural, suburban, and urban areas have different shielding for residents, only a rural link can be associated with a non-zero farm fraction, urban links allow consideration of non-resident populations, urban links allow for a mixture of indoor and outdoor air, etc. Any link can be designated as rural, suburban, or urban regardless of the population density on the link, as discussed earlier.

Since about 1995, the following population density classification has been used in RADTRAN:

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)

The **Population Zone** column is shown in Figure 14a.

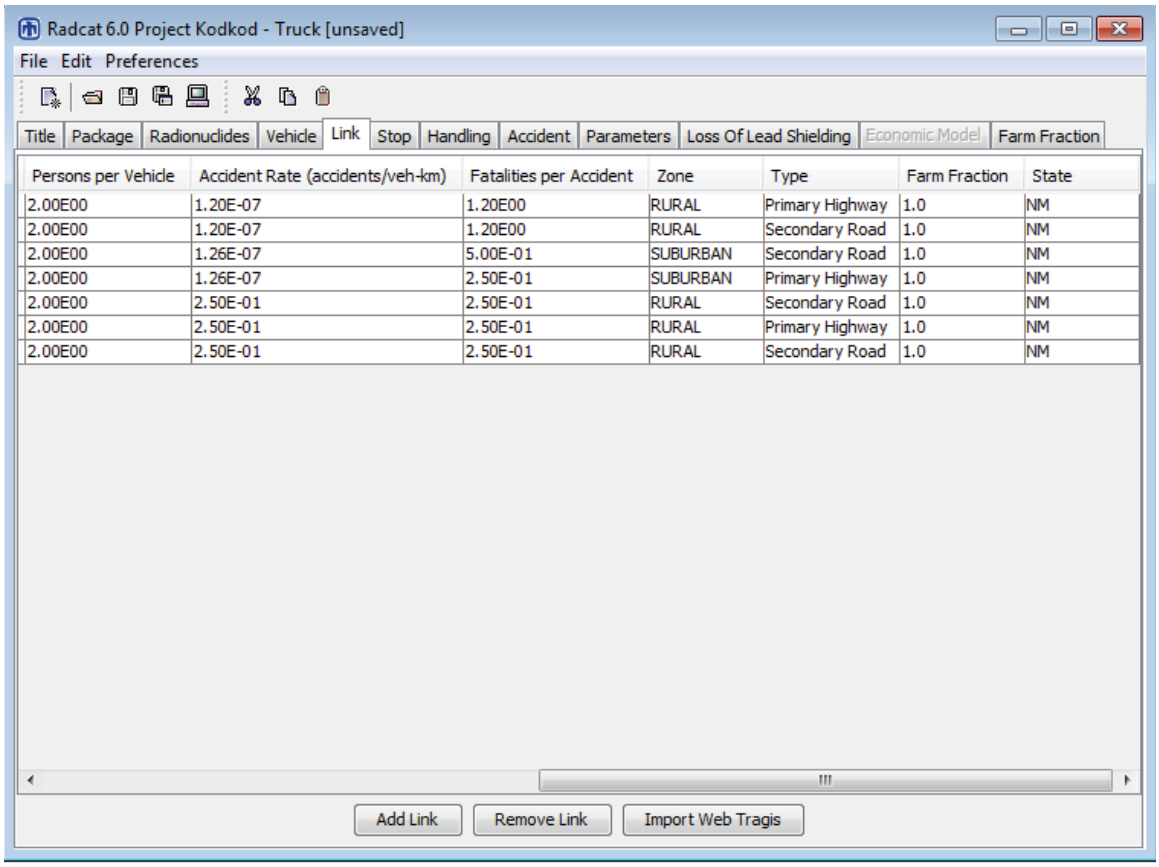


Figure 14a: Link tab -- continued

8.11 Road Type

A pull-down menu allows the designation of the road type as Interstate (Primary Highway) or Secondary Road for the Highway Mode (the **Type** column in Figure 14a). The designation "Other" is for rail and barge routes only. The RADTRAN code uses this designation.

8.12 Farm Fraction and State

There are two alternate methods that RADTRAN uses to calculate ingestion dose; COMIDA and INGEST. These are discussed in detail in the section on accidents, Section 11, but the input is on the LINKS tab. Input parameters for the two methods are different.

Farm Fraction is activated when COMIDA is selected (selection is made on the Title tab). It is the fraction of land along rural route segments that is farmland. COMIDA internally calculates, for each radionuclide that is released and dispersed, the activity that would be taken up by foodstuffs and then applies the fraction of the link along which the

uptake occurs. A farm fraction is only read by RADTRAN if it is on a rural route segment (if you wish to designate a farm fraction for a suburban or urban link, designate that link as rural). Farm fraction is shown in Figure 14a in the **Farm Fraction** column. The fraction of rural routes in agriculture is usually 0.4 or 0.5, but is at the user's discretion.

State is used if INGEST is selected on the Title tab). In order to calculate ingestion dose using INGEST, enter the two-letter state abbreviation in the **State** column (e.g.: MD, NY, IL) on the same line as the rural link of the state transited. This entry invokes agricultural parameters for the rural route segments in that particular state. If you wish to use INGEST on a suburban or urban link, designate that link as rural. This will affect the other parameters associated with this designation as described in Section 8.10.

9. STOPS

Select the **Stop** tab next after the **Link** tab. If editing an existing file without adding or deleting a package or vehicle, the order in which the tabs are opened will not make any difference. Figure 15 shows the **Stop** tab.

9.1 Name

Give each **Stop** a **Name** in the left-hand column. A stop name must be a continuous text string and must not include any spaces. Aggregation of all stops of a particular type (e.g., inspection stops, refueling stops) may be done if the parameters associated with these stops, except stop time, are the same. The total time for those stops is entered in the **Time** column. Each different receptor (e.g., other people at a refueling stop, residents near the stop, truck crew, an inspector) should be structured as a different stop. This difference can be seen in Figure 15. It is helpful to name the stop appropriately, e.g. inspector, resident, population sharing stop, etc.

9.2 Vehicle

Available vehicle names are on a pull-down menu in the Vehicle column. This can be seen in Figure 16 in the Vehicle column. Vehicle names cannot be added or deleted at this tab.

9.3 Minimum and Maximum Distances and People or People/km^2

The columns labeled **Min(imum)** and **Max(imum) Distance** (Figure 16) refer to the shortest and longest distance, respectively, between the receptor and the radioactive cargo. Enter these distances for each receptor (each stop) The **Min(imum) Distance** cannot be less than 1.0 meter.

The **Min** and **Max** distances determine what should be entered into the **People or People/km^2** column. When the **Min** and **Max** distances are equal (e.g., for an inspector who is 2 meters from the truck cargo) the number entered into the **People or People/km^2**

column will be read as the number of people at that distance (1 in the case of the inspector). When the **Max** distance is larger than the **Min** distance (and it cannot be smaller), RADTRAN reads the number in the **People or People/km^2** column as a population density (**People/km^2**) in an annulus around the radioactive cargo, as shown in Figure 15.

Before being entered into RadCat, this population density must be calculated, since RADTRAN does not perform this calculation. For example, if there are 20 people around the cargo between one meter and 10 m, the population density in this annular ring may be calculated as follows:

Inner radius = 1 meter.
Outer radius = 10 meters.

Area of annulus = $\pi*[(10)^2 - (1)^2] = 99\pi = 311 m^2 = 3.11 \times 10^{-4}$ km^2

Population density in the annulus = $20/(3.11 \times 10^{-4}) = 6.43 \times 10^4$ people/ km^2

In RadCat, you would then enter 1 meter for the **Min(imum) Distance,** 10 meters for the **Max(imum) Distance**, and 6.43×10^4 for **People or People/km^2**.

For areas surrounding the stop, for which the population density is given on the **Links** tab or is otherwise known, that population density may be entered directly into the **People or People/km^2** of the stop model (Figure 15). The receptors in this case are the residents living in vicinity of the stop.

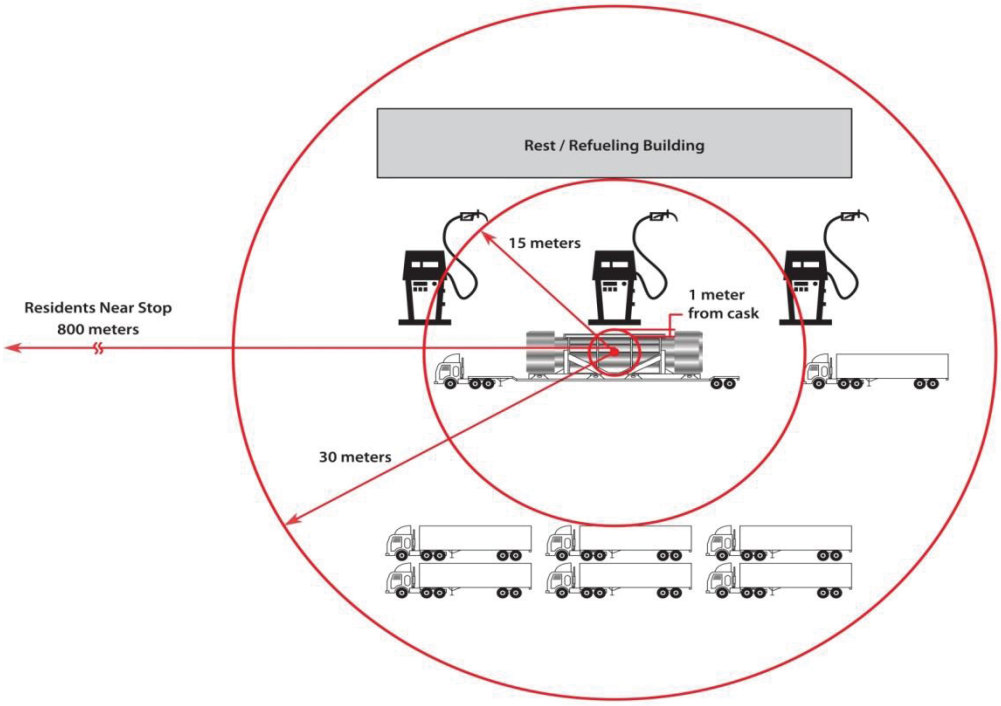


Figure 15: Truck Stop Model

9.4 Shielding Factor

The **Shielding Factor** is the fraction of ionizing radiation to which the receptors are exposed; that is, the inverse of the amount of shielding: 1 = no shielding and 0 = 100% shielding. Enter a number between 0 and 1 for the shielding factor for each stop. This can be seen in Figure 16 in the **Shielding Factor** column.

9.5 Time

Enter the total time in hours for each stop (Figure 16).

10 HANDLING

Handling refers to a potential package dose sustained by a handler during storage, loading, and unloading, and similar activities. The handling dose was related to the package rather than the vehicle in an early version of RADTRAN. The handler dose is calculated the same way as for a stop in which the minimum and maximum distances are the same. Modeling handling as a stop using the **Stop** tab allows more flexibility and is more accurate. The input parameters **Name, Vehicle, Time,** and **Shielding** are the same as those parameters would be in the **Stop** model. **Distance** is the average distance of handlers from the source, and the **Number of Handlers** is the number of people at that distance. Figure 17 shows the **Handler** tab.

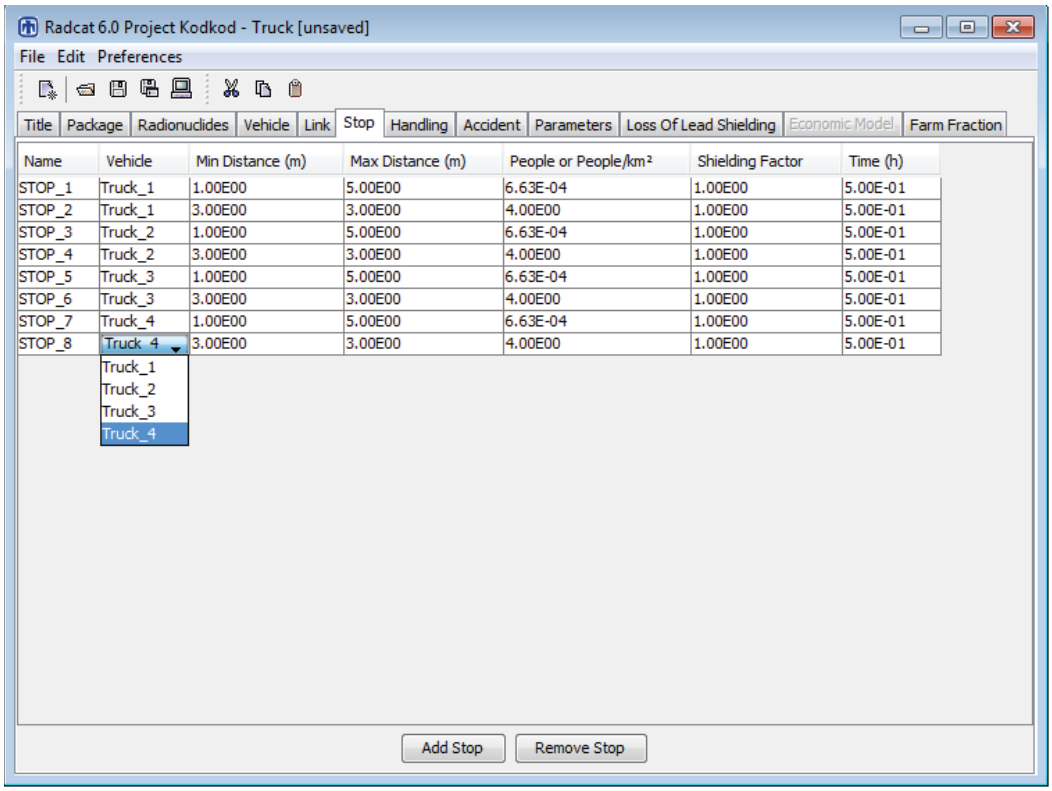


Figure 16: Stop Tab

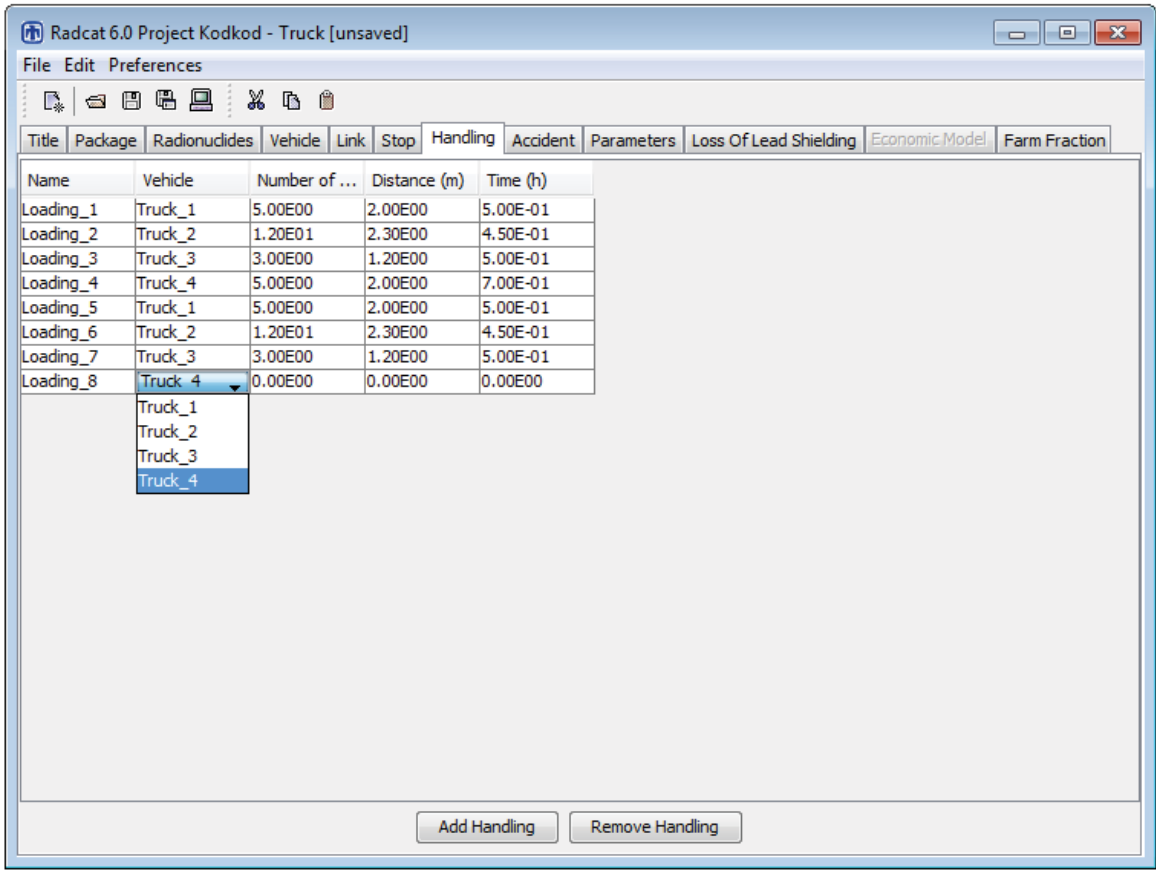


Figure17: Handling Tab

11. ACCIDENTS

The following types of accidents are modeled in RADTRAN

- accidents in which the radioactive cargo is not damaged or affected
    - minor traffic accidents (e.g., fender-benders, flat tires) that result in minor damage to the vehicle—usually called "incidents"[2]
    - accidents that damage the vehicle or trailer enough that the vehicle cannot move from the scene of the accident under its own power, but which do not result in damage to the cargo
    - accidents that involve a death or injury, but no damage to the cargo
- accidents in which the radioactive cargo is affected
    - accidents in which there is a release of radioactive material
    - accidents that result in loss of gamma shielding but no release of radioactive material

<u>Accidents in which the radioactive cargo is not damaged or affected</u>

These accident are modeled as **Stops** (Section 9, above). The stop time can be estimated by you; for very large casks it is often estimated as ten hours.

<u>Accidents in which the cargo is affected and radioactive material may be released.</u>

The accident analysis requires a radionuclide inventory to have been entered at the **Radionuclides** tab for each package, and accident rates and population densities at the **Link** tab. If no radionuclides have been put in the **Package** tab of the input file, or if the **Package** with the radionuclides has not been put on the **Vehicle** involved in the accident, RADTRAN will run but the accident outputs will be zeros. When the **Accident** tab is opened, the following tabs appear:

- Probability
- Deposition Velocity
- Release
- Aerosol
- Respirable
- Isopleth P
- Weather

[2] In U.S. Department of Transportation parlance, an "accident" is an event that results in a death, an injury,or enough damage to a vehicle that it cannot move under its own power. All other non-routine transportation events are termed "incidents." This document uses the term "accident" for both accidents and incidents.

11.1 Conditional Probabilities (Severity Fractions)

The **Probability** tab allows you to specify the conditional probability of an accident of a particular severity, given that an accident happens. Earlier versions of RADTRAN referred to conditional probabilities as "severity fractions". The probability tab is shown in Figure 19.

The **Index** is a numbering system for conditional probabilities and enumerates them (note that the **Index** begins with zero). The conditional probabilities should include the all possible accidents; references that may be used for Type B packages are NRC, 2013 and DOE, 2002. The most likely accidents are those in which there is neither a release of radioactive material nor loss of gamma shielding.

Conditional probabilities are often based on event trees, like the one shown in Figure 18 (Mills, et al., 2006).

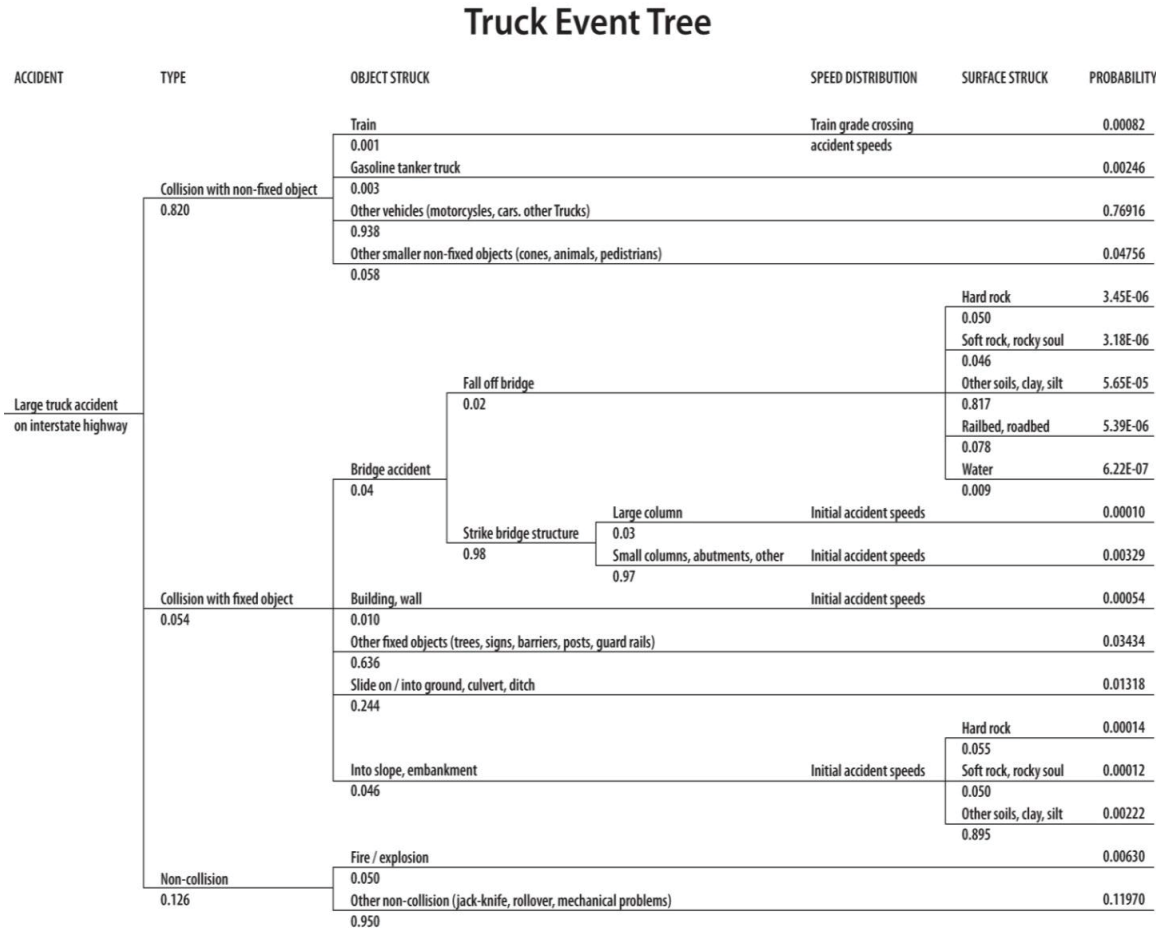


Figure 18: Truck Event Tree (from Mills, et al., 2006)

Event trees are obtained from studies of accidents as described most recently in NRC, 2013, Appendix E, and in Sprung, J.L., et al. (2000 DOE (U.S. Department of Energy), 2002b, and Fischer, L.E., et al. 1987. Tables 4 and 5, adapted from NRC, 2013 and DOE (2002b), respectively, show the relationship between the index, severity fractions (conditional probabilities) and release fractions. The reader is encouraged to consult the source documents for these tables to learn how they were arrived at.

Table 4. Severity and release fractions for rail-transported, uncanistered PWR spent fuel (adapted from NRC, 2013) .

Index	Conditional Probability	Gas	Volatiles	Particulates	CRUD
0	0.99993	0	0	0	0
1	5.96E-12	0.80	0.50	0.70	0.001
2	3.57E-11	0.80	0.50	0.70	0.001
3	1.79E-11	0.80	0.50	0.70	0.001
4	1.79E-11	0.80	0.50	0.70	0.001
5	3.4E-10	0.80	0.50	0.70	0.001
6	3.4E-10	0.80	0.50	0.70	0.001
7	1.13E-10	0.80	0.64	0.45	0.001

Table 5. Severity and release fractions for ucanistered truck-transported PWR spent fuel (adapted from DOE, 2002b) .

Index	Conditional Probability	Gas	Volatiles	Particulates	CRUD
0	0.99993	0	0	0	0
1	6.06E-05	0.136	4.09E-09	1.02E-07	1.36E-03
2	5.86E-06	0.839	1.68E-05	6.71E-08	2.52E-03
3	4.95E-07	0.449	1.35E-08	3.37E-07	1.83E-03
4	7.49E-08	0.835	3.60E-05	3.77E-06	3.16E-03
5	3.00E-10	0.84	2.40E-05	5.01E-06	3.17E-03

Conditional probabilities should add to 1.00, though this is sometimes difficult to see with very small probability fractions. RadCat does not force addition to 1.00. Enter the conditional probabilities in the right-hand column. Conditional probabilities may only be added and deleted on this tab. This can be seen in Figure19.

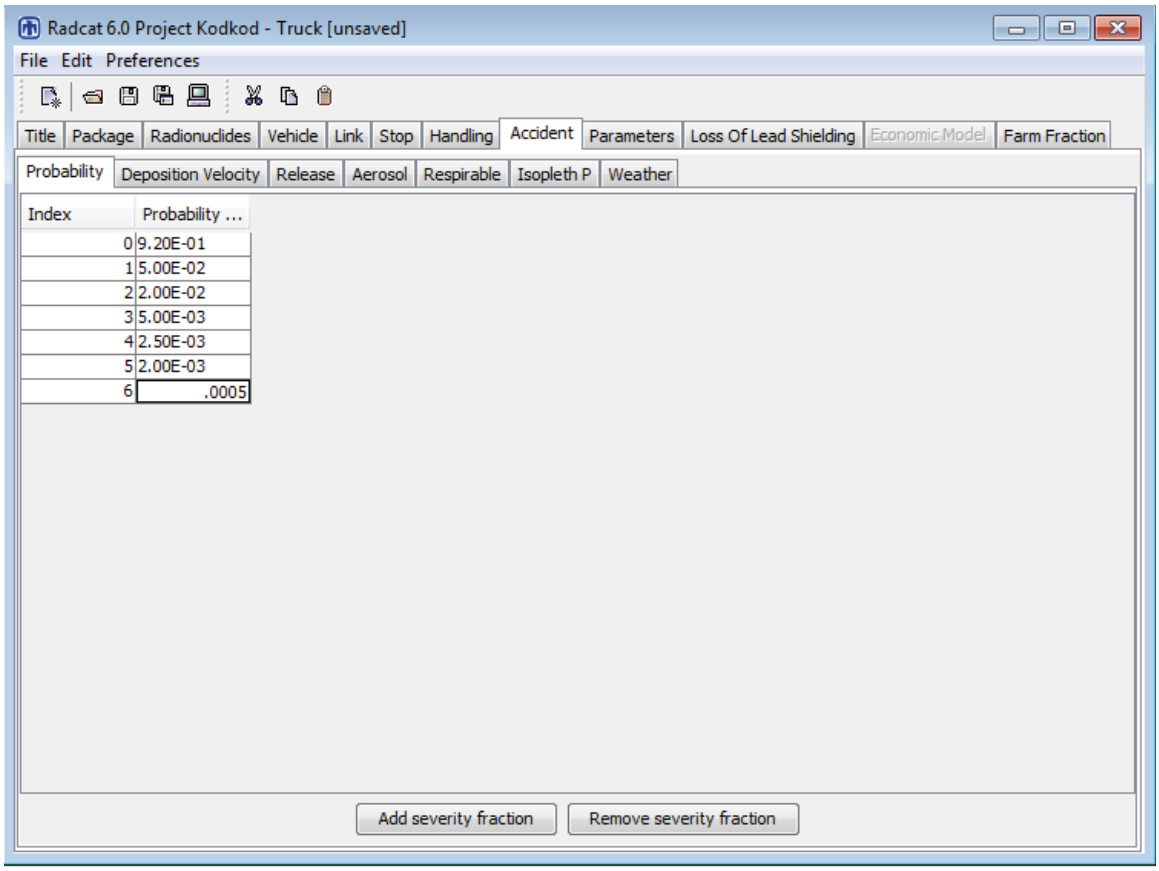


Figure19: Accident/probability tab

11.2 Deposition Velocity

Deposition Velocity (Figure 20) depends on the size, density, and shape of the radionuclides that are released into the environment as a result of the accident. The **Group** column on the left has a pull-down menu of the physical chemical groups entered at the **Radionuclides** tab. Enter a **Deposition Velocity** in meters/sec for each **Group.** Gases do not deposit and thus have a **Deposition Velocity** = 0. A **Deposition Velocity** of 0.01 m/sec is often used as being generally representative of the aerodynamic diameter of aerosol particles that can be dispersed over long distances. The **Deposition Velocity** should be small enough that the material is deposited in at least two isopleths. If the **Deposition Velocity** is too large RADTRAN will abort reading the input file at that point.. It is recommended that the **Deposition Velocity** be no larger than 0.1 m/sec for proper results. **Groups** may not be added or deleted at this tab.

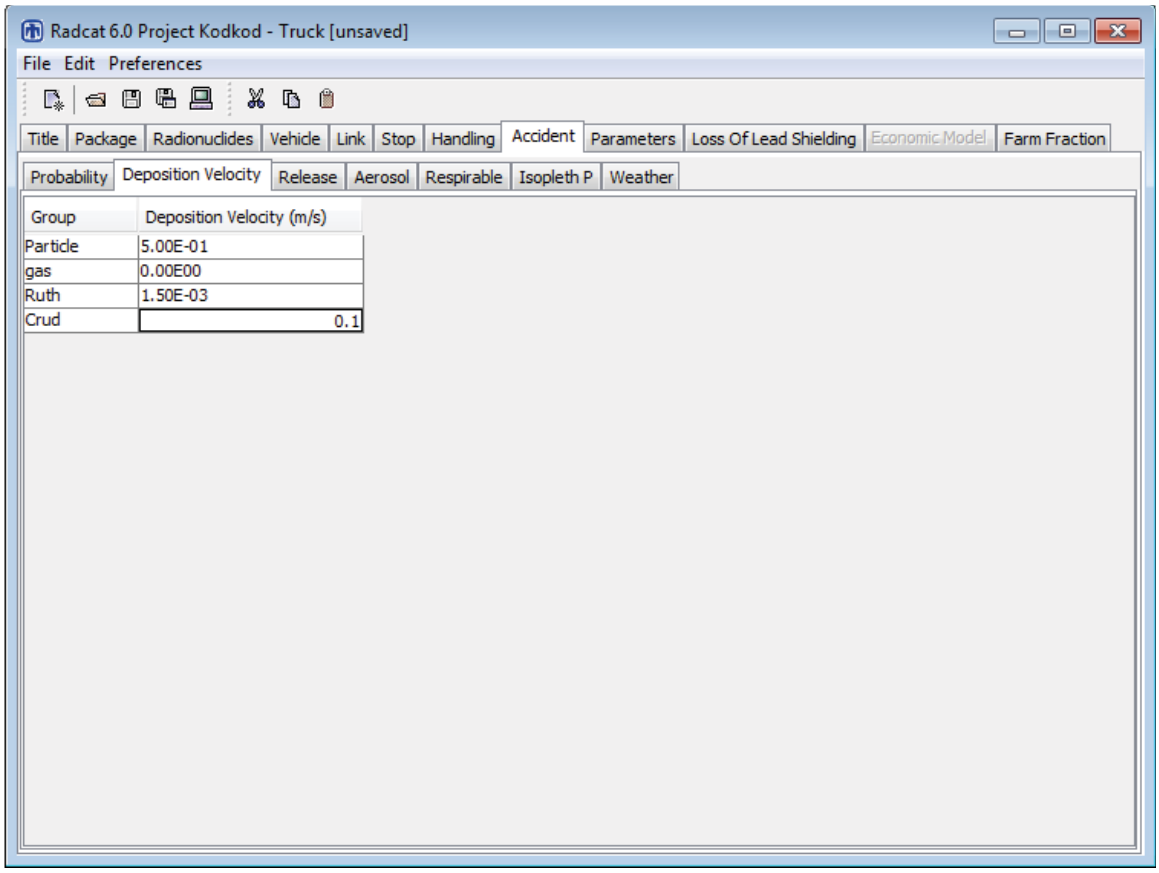


Figure 20: Accident/deposition velocity tab

11.3 Release Fraction

Release Fraction, the fraction of each radionuclide in the cargo that could be released in an accident, depends on the physical and chemical behavior of the radionuclides and on the severity of the accident. These are shown in Tables 4 and 5.

The pull-down menu at the top allows selection of the physical/chemical **Group.** Groups may not be added or deleted at this tab. Select a physical/chemical **Group** from the pull-down menu. This can be seen in Figure 21.

The left-hand column shows the **Index** number which is associated with each conditional probability**.** Enter a **Release Fraction** for each **Index** and each **Group.** Indices may not be added or deleted at this tab.

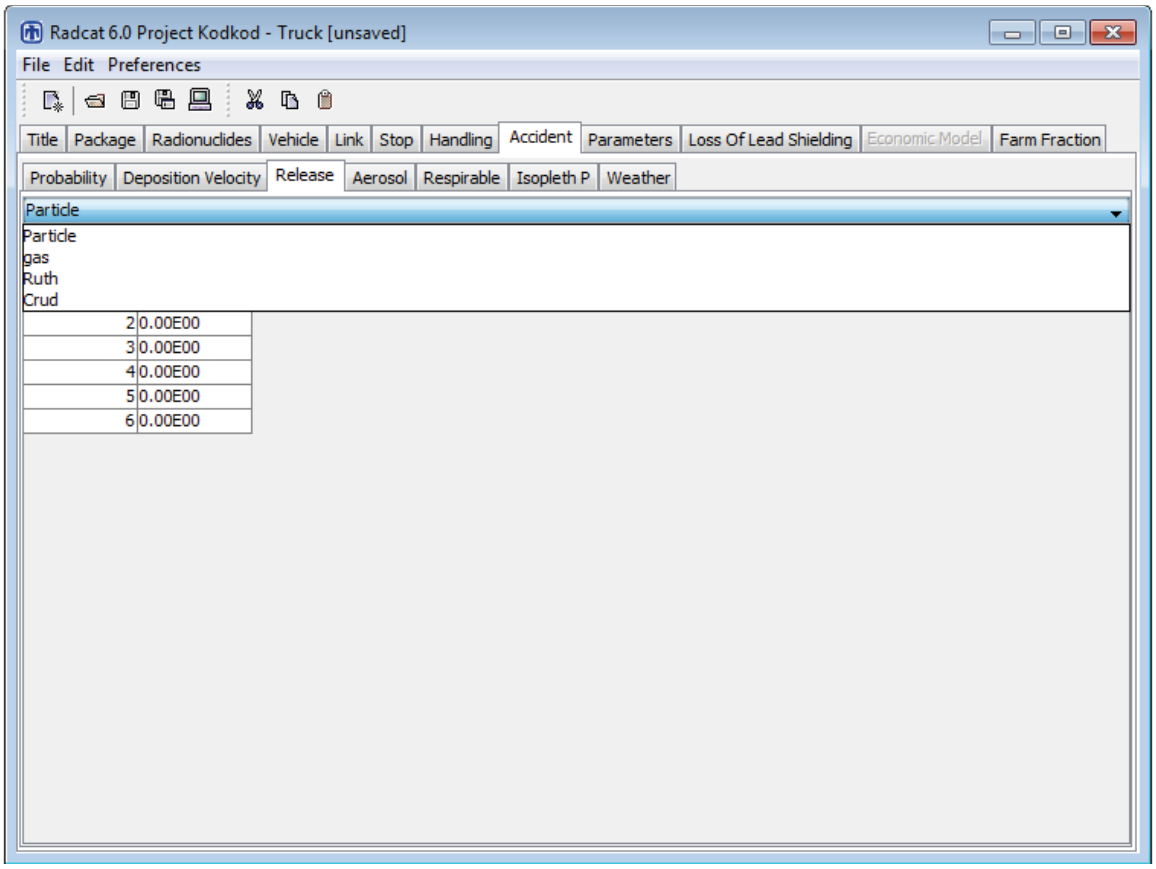


Figure 21: Accident/release tab

11.4 Aerosol Fraction

The **Aerosol Fraction,** the fraction of each **Release Fraction** that would be aerosolized in an accident, depends on the physical behavior of the radionuclides and on the severity of the accident. The pull-down menu at the top allows selection of the physical/chemical **Group.** Groups may not be added or deleted at this tab. Select a physical/chemical **Group** from the pull-down menu seen in Figure 22.

The left-hand column shows the **Index** number which is associated with each conditional probability. Enter an **Aerosol Fraction** for each **Index** and each **Group.** In most accidents involving Type B casks or containers, only very small particles are released; in such cases, the **Aerosol Fraction** = 1. Indices may not be added or deleted at this tab.

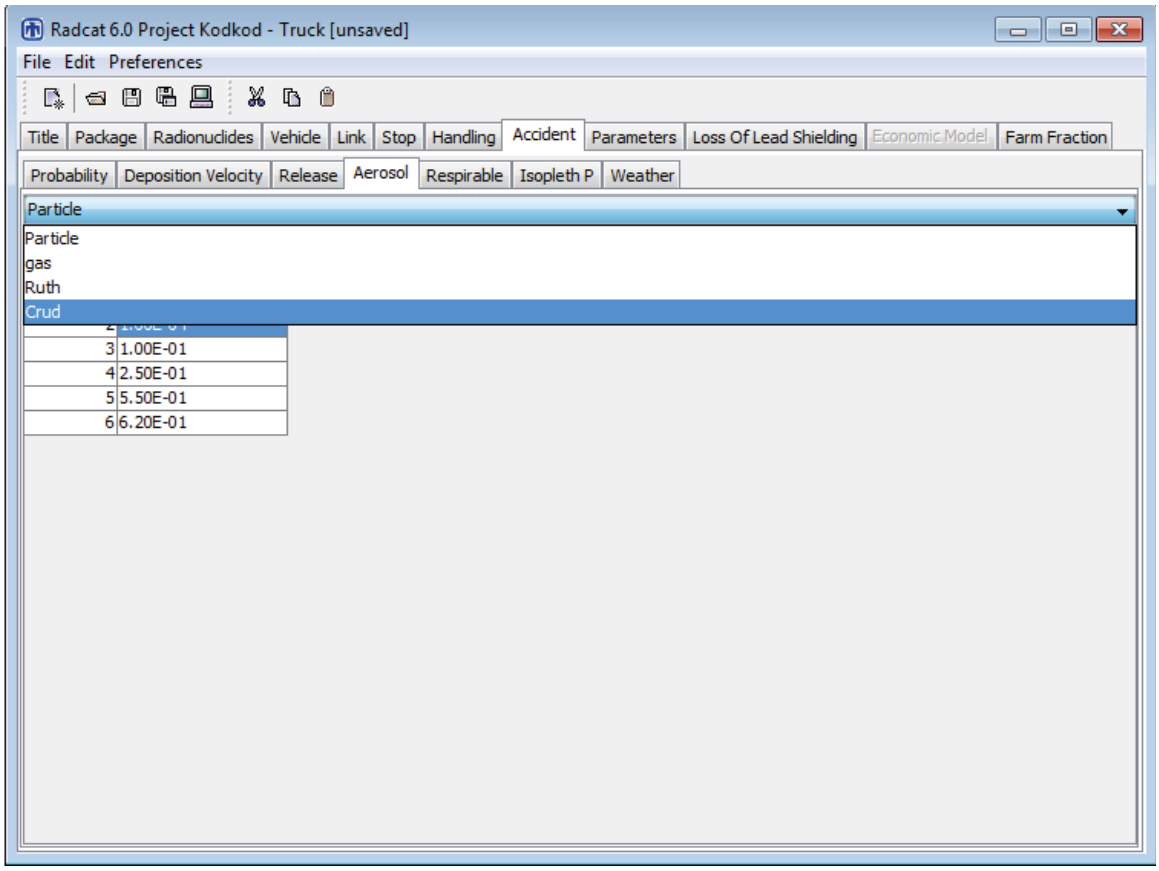


Figure 22: Accident/aerosol tab

11.5 Respirable Fraction

The **Respirable Fraction,** the fraction of each **Aerosol Fraction** that consists of particles or droplets small enough to enter the lung alveoli (usually considered to be less than 10 microns in diameter)[3], depends on the physical and chemical behavior of the radionuclides and on the severity of the accident. The pull-down menu at the top allows selection of the physical/chemical **Group.** Groups may not be added or deleted at this tab. Select a physical/chemical **Group** from the pull-down menu seen in Figure 23.

The left-hand column shows the **Index** number which is associated with each conditional probability**.** Enter a **Respirable Fraction** for each **Index** and each **Group.** The **Respirable Fraction** is usually between 0.02 and 0.05. Indices may not be added or deleted at this tab.

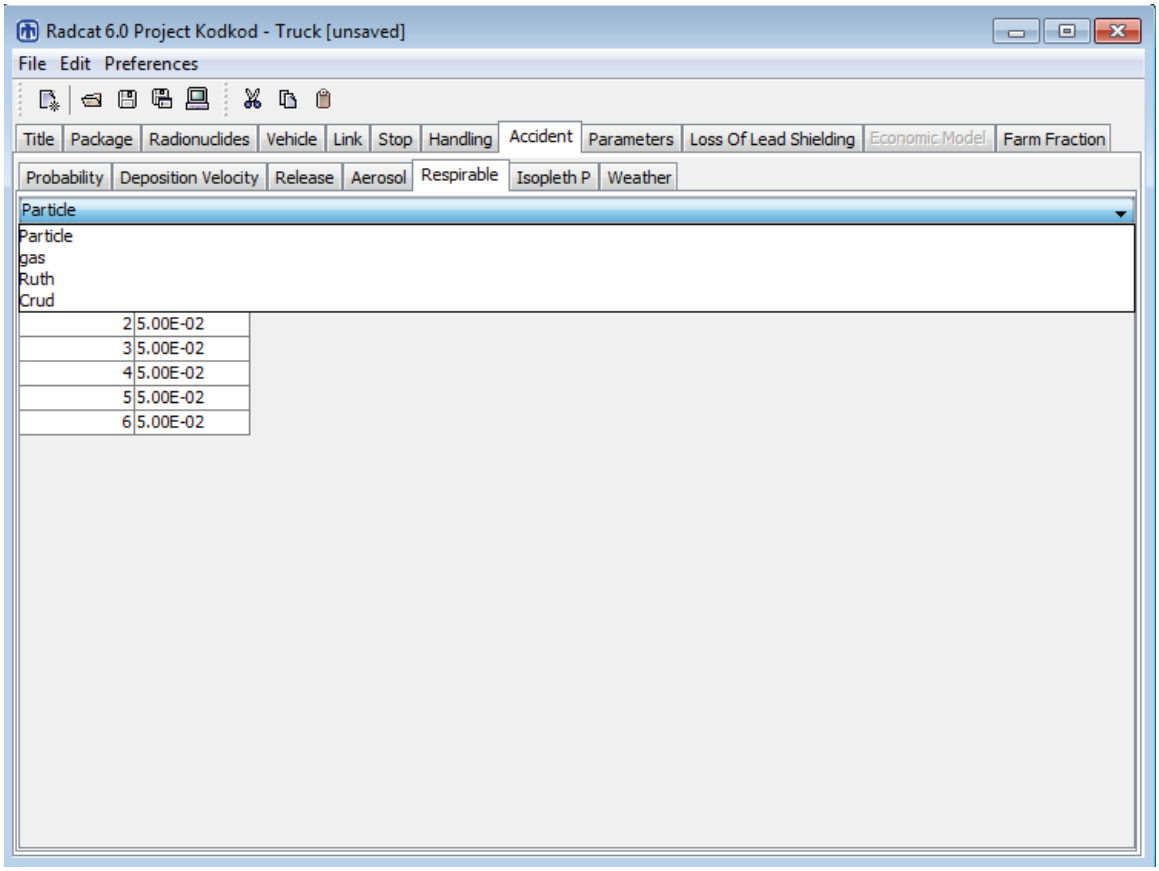


Figure 23: Accident/respirable tab

[3] The inhalation dose conversion factors used in RADTRAN, which are from ICRP 72, include contributions from larger particles in the nasopharyngeal system

11.6 Isopleth P

RADTRAN provides two alternative methods of identifying the population that could experience the fallout from an accidental release of radioactive material. The default method takes the population density in the 800-meter band on either side of the transportation route, from the **Links** tab, and applies it to the footprint of the entire plume, encompassing all selected isopleths. The alternate method allows a different population density to be associated with (and entered for) each isopleth; the population densities must be obtained offline from a GIS system or some other population map. The **Isopleth P** tab provides you with a choice between the default and the alternate method. Open the **Isopleth P** tab before you open the **Weather** tab. The two buttons at the top of the tab provide the choice between the default population density (the density in the 800-meter band) and user-supplied population densities. This can be seen in Figure 24. User-supplied population densities in **Isopleth P** may only be used with the **Average** option on the **Weather** tab. If **Specify your own population densities** is selected, a population density must be added for each isopleth area by adding or removing population densities with the "Add Isopleth P" or "Remove Isopleth P" buttons respectively. If **Use the default population densities** is selected, you can choose any of the options listed in the **Weather** tab, and the population densities listed in the **Link** tab will be used for the isopleth areas. Isopleth areas may not be added or deleted at this tab. As RADTRAN is currently configured, the user-supplied population densities option in Isopleth P can be used only with National Average weather (**Average Option** in the **Weather** tab).

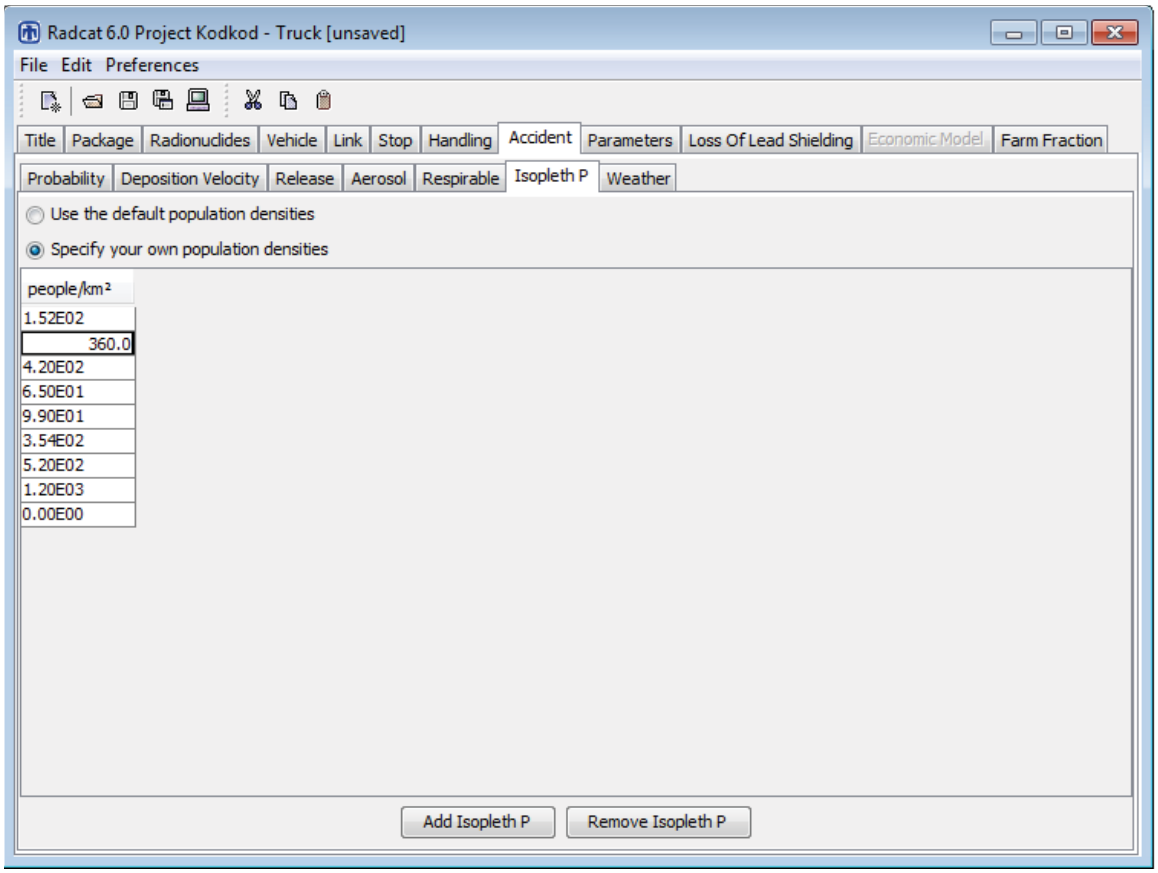


Figure 24: Accident/isopleth P tab

11.7 Weather

Open the **Weather** tab after you open the **Isopleth P** tab. If **Specify your own population densities** is selected on the **Isopleth P** tab, you must select the **Average Weather** tab and the same number of dispersion areas as **Isopleth P** population densities. The number of dispersion areas may be added or removed using the bars at the bottom of the tab. This can be seen in Figure 25. If desired, **Isopleth Areas**, maximum **Centerline Distances** for each area, and corresponding **Time Integrated Concentrations** may be calculated externally using any Gaussian dispersion program, and can be entered manually into the table on this tab. You cannot add or delete population densities in this tab.

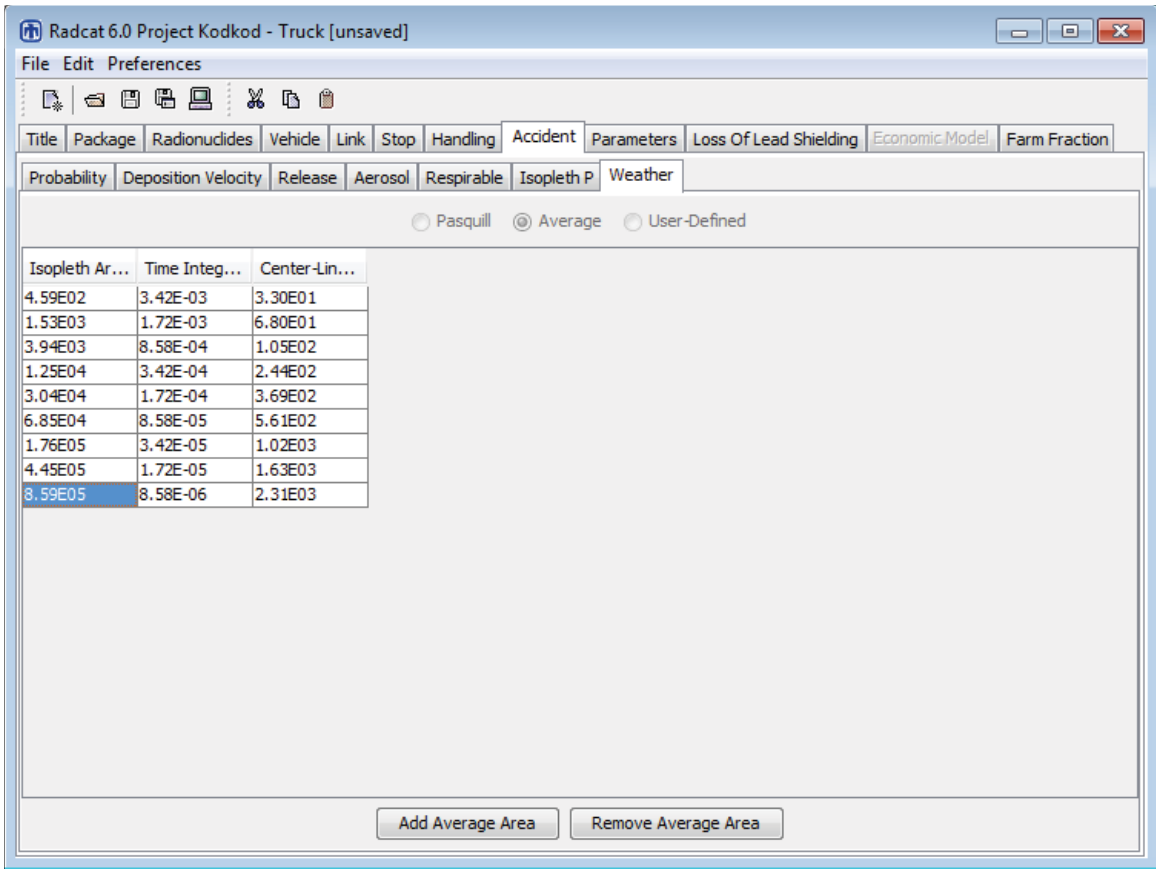


Figure 25: Accident/weather tab with user-defined dispersion option

11.7.1 The Average Option

Choosing the **Average** option selects a set of **Isopleth areas**, maximum **Centerline Distances** for each area, and corresponding **Time Integrated Concentration** (dilution, or Chi/Q, factors) based on U. S. national average meteorology (NRC, 1977) and wind speed (Figure 26). Areas may be added to or withdrawn using the bars at the bottom of the tab. RADTRAN cannot handle more than 18 isopleth areas. This option cannot be used if INGEST ingestion dose model is selected (the selection is made on the **Title** tab).

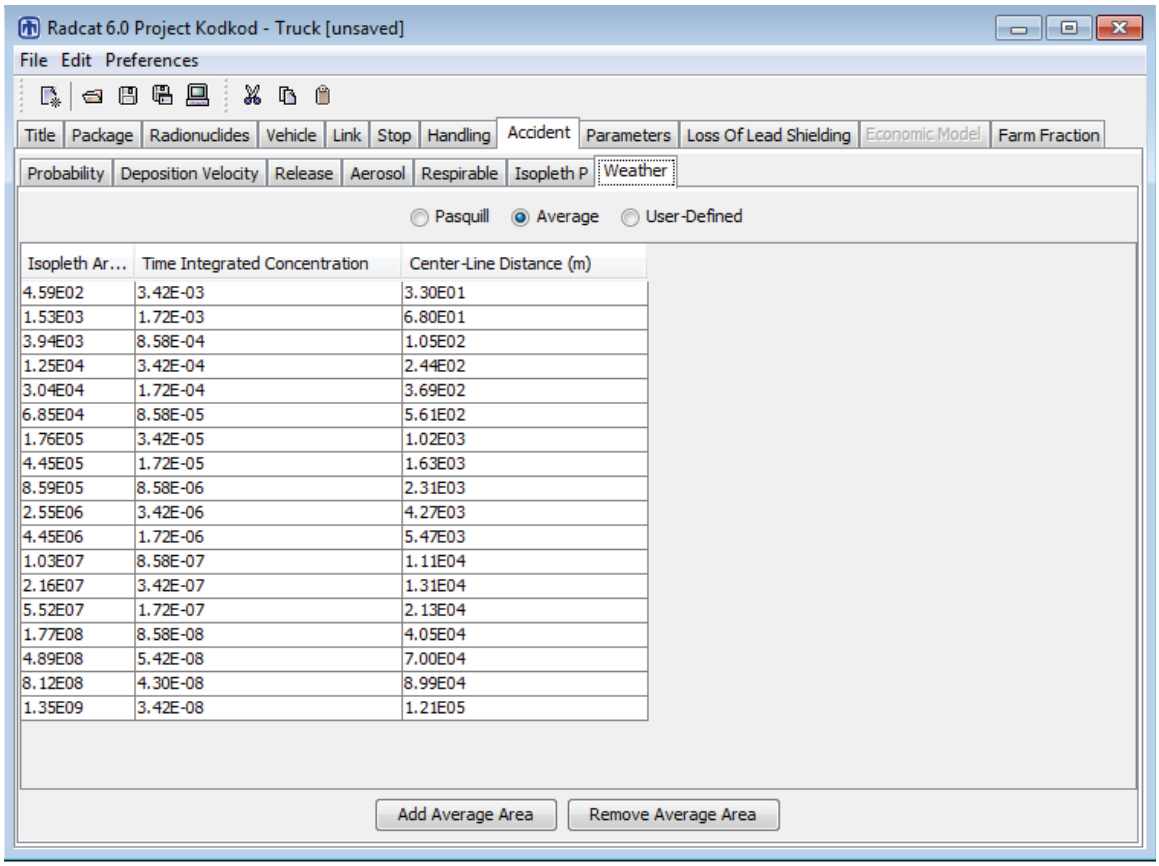


Figure 26: Accident/weather tab with national average weather option

11.7.2 The Pasquill Option

Choosing the **Pasquill** option opens a tab listing the six meteorological **Pasquill Stability Classes** in the left-hand column and allows you to enter the fraction of occurrence of each **Stability Class** in the **Fraction** column as seen in Figure 27. These fractions must total exactly 1 or RADTRAN will not execute in this option, each **Stability Class** has an associated fixed wind speed**,** as shown in Table 6. This option cannot be used if INGEST ingestion dose model is selected (the selection is made on the **Title** tab).

Table 6: Pasquill Wind Speeds for Each Stability Class

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

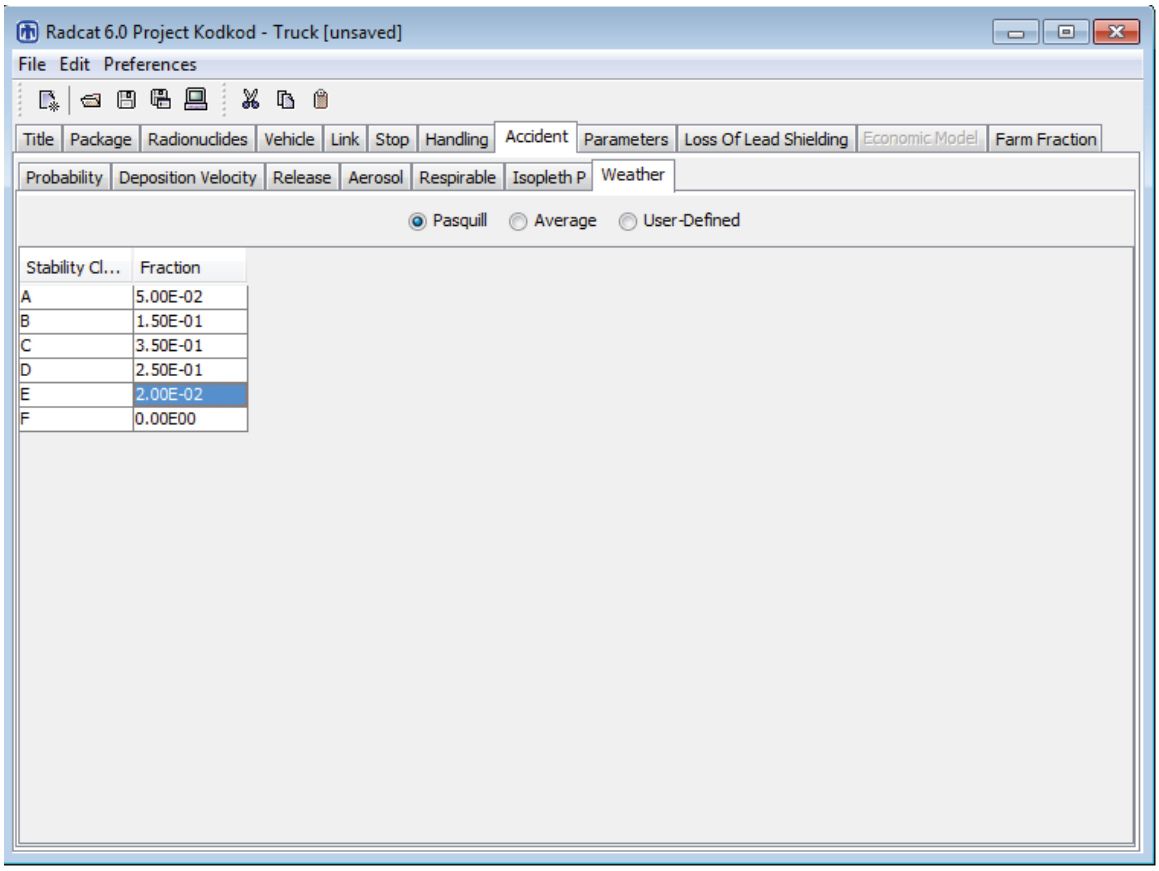


Figure 27: Accident/weather tab with Pasquill option

11.7.3 The User-Defined Option

The User-Defined option allows modeling of higher temperature and elevated releases, rainout, and the application of user-defined wind speeds. Choosing the User-Defined option opens a tab listing the input parameters listed below and shown in Figure 28. You can only use this option for one specific type of cask, release location, and wind stability class. Use of the INGEST ingestion dose model requires the User-Defined weather option.

Release Height (m) – This parameter allows you to specify the release height for an atmospheric dispersion. "Effective release height" is generally the elevation at which the plume begins to move downwind.

1. **Heat Release (calories/sec)** – This parameter allows you to incorporate thermally-induced buoyancy and momentum that will affect the effective release height.

2. **Cask Length (m)** – This cask length should be the same as the largest cask dimension indicated on the **Package** tab.

3. **Cask Radius (m)** – This cask radius should be the same as indicated on the **Package** tab.

4. **Wind Speed at Anemometer (m/sec)** – This parameter will allow you to specify the wind speed at an anemometer reading site.

5. **Anemometer Height (m)** – This parameter will allow you to correlate the anemometer wind speed with the wind speed at the effective release height, usually 10 meters.

6. **Ambient Temperature (degrees Kelvin, ^{o}K)** – This parameter adjusts the plume rise accordingly to adiabatic and potential temperature lapse rates. 293 ^{o}K = 20 ^{o}C = 68 ^{o}F; 273 ^{o}K = 0 ^{o}C = 32 ^{o}F

7. **Atmospheric Mixing Height (m)** – This parameter will allow you to define the height to which the atmosphere is uniformly mixed, which is the *de facto* height to which the plume will rise. The mixing height can be determined analytically by finding the height above the ground of the intersection of the ambient temperature profile with the dry adiabatic lapse rate. If there is no temperature inversion, the mixing height can be infinite, but is often entered as a kilometer (1000 meters) or more.

8. **Rainfall Rate** – This parameter will allow you to incorporate wet deposition into the dispersion model. It is recommended that this parameter be used for light and medium rainfall (a few millimeters per hour) since this model does not incorporate the surface runoff or washout which is experienced with heavy rainfall. The Solar and Meteorological Surface Observation Network has the following definitions for rainfall rates:

    - Light Drizzle: Up to 0.25 mm/hr
    - Medium Drizzle: 0.25 to 0.51 mm/hr
    - Heavy Drizzle: Greater than 0.51 mm/hr

    - Light Rainfall: Up to 2.5 mm/hr
    - Medium Rainfall: 2.5 to 7.6 mm/hr
    - Heavy Rainfall: Greater than 7.6 mm/hr

The website http://precip.fsl.noaa.gov/beta/precip7.html can provide hourly rain data from the National Oceanic and Atmospheric Administration (NOAA) Forecast System Laboratory:

9. **Dispersion Model** – This parameter allows a choice between the Pasquill-Gifford dispersion coefficients and the Briggs dispersion coefficients. The former is suitable for rural areas and the latter, for urban areas (Turner, 1967).

10. **Stability Category** – This parameter will allow you to determine which Pasquill stability class (A-F) will be used. In general, classes A, B, and C are consistent with increasing wind speed and unstable atmospheric conditions, class D is neutral (the ambient lapse rate is the same as the adiabatic lapse rate) and consistent with wind speeds about 4 to 5 m/sec, and classes E and F are consistent with very light winds, poor dispersion, and temperature inversions. Any text on air pollution can provide a complete discussion of Pasquill stability class. References that may be consulted are Turner (1967), Randerson (1984) and Wark, et al (1998).

11. **Release Location** – This parameter allows you to designate whether the release will be in a rural or suburban/urban location. This option provides different dispersion results, but at present RADTRAN models only one accident. If some links on a route are rural and some, urbanorsuburban, two different RADTRAN analyses can be conducted. Both the COMIDA and INGEST ingestion dose models apply only to rural links.

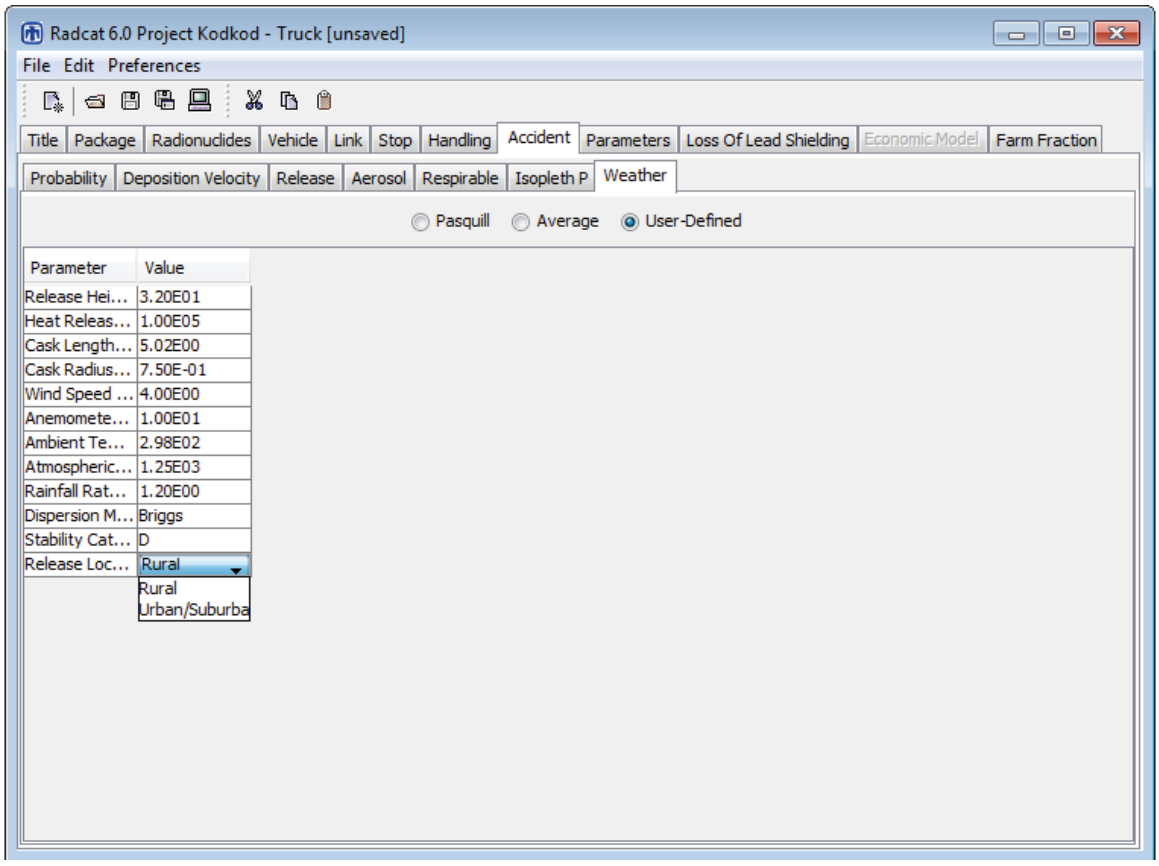


Figure 28: Accident/weather tab with user-defined option

12. PARAMETERS

Figures 29, 30, and 31 lists values that have historically been used in RADTRAN for a variety of parameters. They are referred to as "default" values but are not true defaults, because any or all of them can be overwritten. These parameter values are presented for the RADTRAN user's convenience. Figure 29 shows the **Parameters** tab for highway routes, Figure 30 shows the **Parameters** tab for rail routes and Figure 31 shows the **Parameters** tab for barge routes.

Shielding factor for residences

The shielding factor is the fraction of ionizing radiation to which residents along the route are exposed in their homes or other buildings. It is the inverse of the shielding fraction; i.e., a shielding factor of 1 indicates no shielding, and a shielding factor of zero indicates 100% shielding. The shielding factor is different for rural, suburban, and urban zones because building materials differ. Figures 29, 30, and 31 show the default values for shielding factors: 1.0 (i.e., no shielding) for rural buildings, 0.87 for suburban buildings, and 0.018 for urban buildings. You can substitute any number for these values.

Fraction of outside air in urban buildings

This is the fraction of aerosol particles in the outside air which may be entrained in building ventilation systems (i.e., the fraction of particles of an external aerosol that remain in aerosol form after passing through a ventilation system) to which people in urban structures are exposed. The fraction of outside air in urban buildings is used to calculate the inhalation dose to that population. The default value of 0.05 represents a conservative average across a series of building types, including residential, office, and industrial structures (Engelmann, 1990) and is possibly outdated.

Fraction of population occupying the sidewalk

This parameter applies only to sidewalks on an urban link (a city street)the abuts the strees on whici the vehicle travels, and specifies the fraction of population that is not inside buildings. The default value of 0.48 is for the latter model, and is taken from Finley et al. (1980). This value is suitable for large cities and conservative for smaller cities. This parameter and the **Fraction of urban population inside buildings** automatically add to 1.00.

Fraction of urban population inside buildings

This parameter describes either the fraction of the population that is indoors or the fraction of the area that is occupied by buildings, depending on the type of population model being used. The default value of 0.52is for the latter model, and is taken from Finley et al. (1980).

Ratio of pedestrians/km^2 to residential population/km^2

This ratio is used to calculate the exposure of unshielded persons on sidewalks in urban areas. This parameter applies only to sidewalks that line the transportation route on an urban link. The ratio can also serve as a surrogate for the ratio of non-resident (e.g., tourist) urban population to resident urban population since the U. S. Census, the source of population densities used in RADTRAN, includes only resident population. The default value is 6.0, which is based on empirical data from New York City (Finley et al., 1980).

Minimum small package dimension for handling

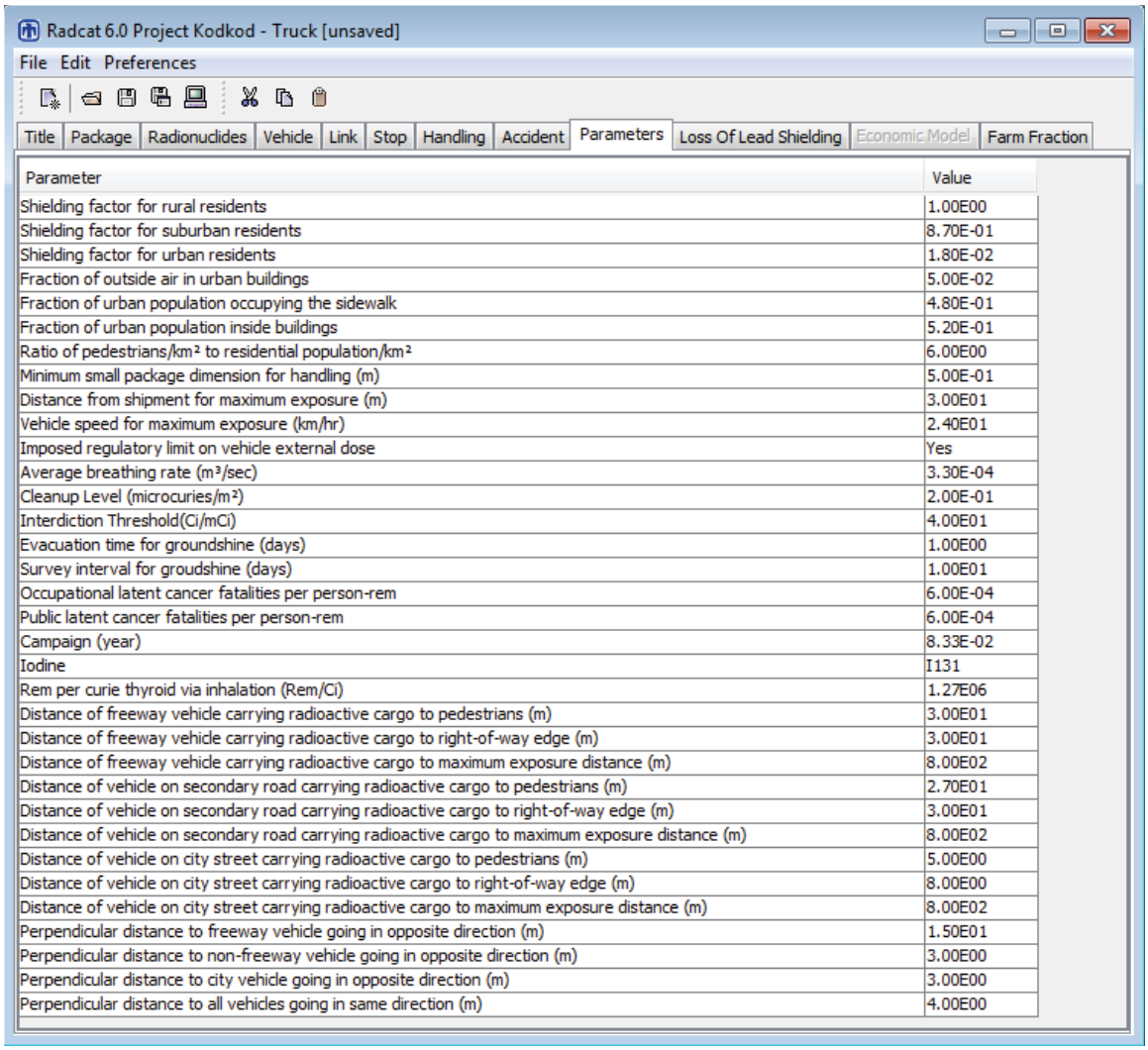
This parameter specifies the package size threshold, which determines the calculation of handler dose in RADTRAN. If a package is designated as "small," i.e., smaller than the default threshold, the dose to the handler is calculated as originating in a uniform source. If package dimensions exceed the threshold, handler dose is calculated as described in Section 10. The default value is 0.5 m (Javitz, 1985)

Distance from shipment for maximum exposure

This parameter is used to calculate the maximum individual "in-transit" off-link dose. It is the minimum distance, in meters, perpendicular to the route, from the shipment centerline to an individual standing beside the route right-of-way while a shipment passes. The default value is 30 meters (NRC, 1977).

Vehicle speed for maximum exposure

This parameter is also used to calculate the maximum individual "in-transit" dose. It is the minimum speed of a shipment in km/hr. The default value is 24 km/hr (15 mph) (NRC, 1977), which is probably conservative. The appropriate table on the Bureau of Transportation Statistics web site (www.bts.gov) should be consulted for more realistic values for this parameter.



Parameter	Value
Shielding factor for rural residents	1.00E00
Shielding factor for suburban residents	8.70E-01
Shielding factor for urban residents	1.80E-02
Fraction of outside air in urban buildings	5.00E-02
Fraction of urban population occupying the sidewalk	4.80E-01
Fraction of urban population inside buildings	5.20E-01
Ratio of pedestrians/km² to residential population/km²	6.00E00
Minimum small package dimension for handling (m)	5.00E-01
Distance from shipment for maximum exposure (m)	3.00E01
Vehicle speed for maximum exposure (km/hr)	2.40E01
Imposed regulatory limit on vehicle external dose	Yes
Average breathing rate (m³/sec)	3.30E-04
Cleanup Level (microcuries/m²)	2.00E-01
Interdiction Threshold(Ci/mCi)	4.00E01
Evacuation time for groundshine (days)	1.00E00
Survey interval for groudshine (days)	1.00E01
Occupational latent cancer fatalities per person-rem	6.00E-04
Public latent cancer fatalities per person-rem	6.00E-04
Campaign (year)	8.33E-02
Iodine	I131
Rem per curie thyroid via inhalation (Rem/Ci)	1.27E06
Distance of freeway vehicle carrying radioactive cargo to pedestrians (m)	3.00E01
Distance of freeway vehicle carrying radioactive cargo to right-of-way edge (m)	3.00E01
Distance of freeway vehicle carrying radioactive cargo to maximum exposure distance (m)	8.00E02
Distance of vehicle on secondary road carrying radioactive cargo to pedestrians (m)	2.70E01
Distance of vehicle on secondary road carrying radioactive cargo to right-of-way edge (m)	3.00E01
Distance of vehicle on secondary road carrying radioactive cargo to maximum exposure distance (m)	8.00E02
Distance of vehicle on city street carrying radioactive cargo to pedestrians (m)	5.00E00
Distance of vehicle on city street carrying radioactive cargo to right-of-way edge (m)	8.00E00
Distance of vehicle on city street carrying radioactive cargo to maximum exposure distance (m)	8.00E02
Perpendicular distance to freeway vehicle going in opposite direction (m)	1.50E01
Perpendicular distance to non-freeway vehicle going in opposite direction (m)	3.00E00
Perpendicular distance to city vehicle going in opposite direction (m)	3.00E00
Perpendicular distance to all vehicles going in same direction (m)	4.00E00

Figure 29: Parameters tab for highway mode

Imposed regulatory limit

The default setting is "**YES"** which causes a series of regulatory checks to be performed. If any circumstances are identified that violate the regulatory requirements (e.g., package dose rate exceeds regulatory maximum), then the appropriate parameter values are reset to the regulatory maximum (the critical package dimension may be adjusted as well) and the calculation continues. A message informing you is printed in the output. You may adjust the setting to "**NO**" which will bypass the regulatory check subroutine, and ensure that the package dose rate and package critical dimension used in RADTRAN calculations are those that you intended to use.

Average breathing rate

This parameter is used to calculate inhalation doses. The default is 3.30×10^{-4} m^3/sec. This breathing rate is taken from the Reference Man (70-kg adult male at light work

derived from Shleien et al, 1996; Table 12.6). The value in the cited table, 20 liters/minute, has been converted to m^3/sec.

Cleanup level

This parameter is the desired concentration, in microcuries/m^2or mSv/m^2, to which a contaminated surface should be cleaned. The parameter is the total allowed activity of all deposited radionuclides. The default value is the EPA guidance of 0.2 μCi/m^2 (EPA, 1977).

Interdiction threshold

This parameter specifies the threshold value for interdiction of contaminated land. The default value is 40, i.e., a value 40 times greater than the **Cleanup Level** (NRC (1977).

Evacuation time for groundshine

This is the evacuation time in days following a dispersal accident. The default value is 1.0 day (24 hours). Mills et al. (1995) analyzed 66 verified HazMat accidents in which evacuations were carried out and found that the mean evacuation time was approximately one hour. The resuspension model also uses this parameter as the time that the receptor is exposed to resuspended material. This time is an input to the calculation of the resuspension dose. If you wish to use a time for exposure to resuspended material different from the groundshine exposure time, you can run RADTRAN separately with a different groundshine exposure time.

Survey interval for groundshine

This parameter is the time (in days) required to survey contaminated land following a dispersal accident. None of the residents of the area are exposed to the released radioactive material during the survey interval. The default value for the survey interval is 10 days (NRC, 1977).

Occupational latent cancer fatalities per person-rem

This parameter specifies the occupational Latent Cancer Fatality (LCF) conversion factor for worker exposure; units are LCF per rem. The default value for workers is 6.0E-04 LCF/rem (0.06 LCF/Sv) and is consistent with the recommendations from the Interagency Steering Committee on Radiation Standards (DOE 2002a, ISCORS 2002). The uncertainties surrounding the use of the linear non-threshold theory to calculate potential LCF are discussed in the section below.

Public latent cancer fatalities per person-rem

This parameter specifies the non-occupational LCF conversion factor for public exposure; units are LCF per rem. The default value is 6.0E-04 LCF/rem (0.06 LCF/Sv) (ISCORS 2002).

No empirical evidence exists to support the default value. The joint report of the French Academies of Science and Medicine, cited in Tubiana and Aurengo (2005) states:

> *Epidemiological studies have clearly shown that the carcinogenic risks of low doses (< 100 mSv) are very small, if any.... [Radiobiological] data show that the use of a linear no-threshold relationship is not justified for assessing by extrapolation the risk of low doses...since this extrapolation relies on the concept of a constant carcinogenic effect per unit dose, which is inconsistent with radiobiological data. [100 mSv = 10,000 mrem = 10 rem]*

Moreover, Gonzalez, et al (2013), in an extensive discussion of the misapplication of the linear non-threshold theory of radiation damage to predict "latent cancer fatalities," state

> *In some low dose radiation exposure situations, particularly after accidents, nominal risk coefficients have been improperly used to ascribe hypothetical future deaths. Speculative, unproven, undetectable and 'phantom' numbers are obtained by multiplying the nominal risk coefficients by an estimate of the collective dose received by a huge number of individuals theoretically incurring very tiny doses that are hypothesized from radioactive substances released into the environment….(Gonzalez, et al, 2013, Section 2.2, p. 508)*

The conversion to LCF is, however, commonly used and is therefore included as an option in RADTRAN output. Analysts are encouraged to report results in dose units and not in LCF.

Campaign

This is the duration of the shipping campaign in years, and is used to calculate the total number of off-link persons exposed, using the Census Bureau algorithm for the average length of residence in the U.S. The default value is 0.0833 years, an average month in an average year or $1/12^{th}$ of a year. Although the total number of exposed persons is calculated, neither the time that each person is exposed nor the exposure time for the total group is calculated.

Rem per curie thyroid via inhalation

This is the one-year committed effective dose equivalent (CEDE) in rem per curie to the thyroid from inhalation of iodine isotopes to estimate early-mortality risk. The default values are 1.27×10^6 for Iodine-131, 5.77×10^6 for Iodine-129, and 9.25×10^5 for Iodine-125. Currently only I-131 is called out in the input file.

The following parameters apply to traffic on highways.

Distance of freeway vehicle carrying radioactive cargo to pedestrians
Distance of freeway vehicle carrying radioactive cargo to right-of-way edge
Distance of freeway vehicle carrying radioactive cargo to maximum exposure distance

These are the distances between a vehicle that is transporting radioactive material on a limited access highway (a freeway) or U.U. primary highway and, respectively, pedestrians on the sidewalk along the route, residents along the route at the edge of the right-of-way, and the outer boundary of band along the route occupied by the residents. The default value for the right of way edge is 30 meters and for the outer boundary, it is usually 800 meters. The distance to a sidewalk (valid only for urban areas) is 27 meters, allowing for a 3-meter sidewalk (NRC, 1977). These distances are for truck travel and are shown in Figure 29.

Distance of non-freeway vehicle carrying radioactive cargo to pedestrians
Distance of non-freeway vehicle carrying radioactive cargo to right-of-way edge
Distance of non-freeway vehicle carrying radioactive cargo to maximum exposure distance

These are the distances between a vehicle that is transporting radioactive material on a secondary road and, respectively, pedestrians on the sidewalk along the route, residents along the route at the edge of the right-of-way, and the outer boundary of band along the route occupied by the residents. The default value for the right of way edge is 30 meters and for the outer boundary, it is usually 800 meters. The distance to a sidewalk (valid only for urban areas) is 27 meters, allowing for a 3-meter sidewalk (NRC, 1977). These distances are for truck travel and are shown in Figure 29.

Distance of city street vehicle carrying radioactive cargo to pedestrians
Distance of city street vehicle carrying radioactive cargo to right-of-way edge
Distance of city street vehicle carrying radioactive cargo to maximum exposure distance

These are the distances between a vehicle that is transporting radioactive material on a city street and, respectively, pedestrians on the sidewalk along the route, residents along the route at the edge of the right-of-way, and the outer boundary of band along the route occupied by the residents. The default value for the right of way edge is 8 meters and for the outer boundary, it is usually 800 meters. The distance to a sidewalk is 5 meters, allowing for a 3-meter sidewalk (NRC, 1977). Although Type B and most Type A casks would not be transported on city streets, radiopharmaceuticals, blood irradiators, and research materials are transported in cities. These distances are shown in Figure 29.

Perpendicular distance to freeway vehicle going in the opposite direction

The default value is 15 meters (Madsen et al.,1986, pp. 36-37). This parameter specifies the average perpendicular distance (i.e. a distance measured along a line at right angles to the line of travel of the radioactive materials shipment) between the radioactive

materials shipment and lanes of traffic traveling in the opposite direction, in meters. The value is based on a configuration of four lanes with an average lane width of 5 meters, with the radioactive materials shipment in the outside lane, oncoming traffic in the corresponding outside lane, and passing vehicles in the inner lanes.

Perpendicular distance to non-freeway vehicle going in the opposite direction
Perpendicular distance to city vehicle going in the opposite direction

The default value is 3 meters (Madsen et al. 1986 p. 36-37), based on a road configuration of two lanes with an average lane width of 3 meters, in the most typical traffic configuration.

Perpendicular distance of all vehicles going in the same direction

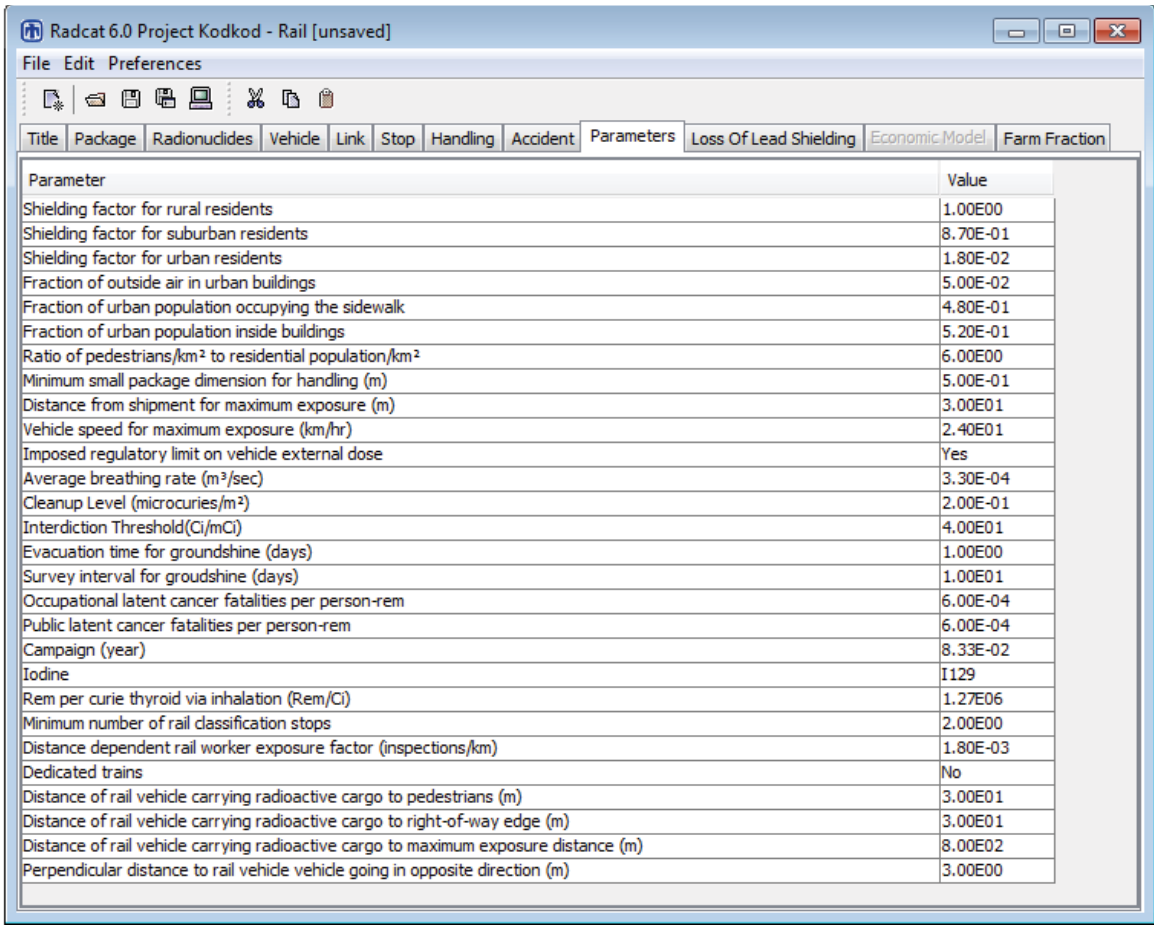
The default value is 4 meters (Madsen et al., 1986). This value is based on the median value for all interstate and secondary-road lane widths.

The following parameters apply to rail transportation.

Minimum number of rail classification stops

This applies to rail mode only and specifies the minimum number of railcar classifications per trip. The default value is 2 since there are at least two inspections per trip – one at the beginning and one at the end of each trip (Wooden 1986). The collective dose to railyard workers at a 30-hour classification stop has been integrated into RADTRAN, and is multiplied by this number to give the dose to yard workers at classification stops. The dose is the weighted sum of the doses for railyard worker groups, and is calculated primarily with a line-source model, though a point-source model is used when appropriate. For general freight, dose is calculated with the modifying factors b_1 through b_7, which have units of person-hr/km and are derived from Wooden (1987) as described in Appendix B of Neuhauser, et al (2000) (Figure 30).

Although there are always classification stops at the origin and terminus of a trip, the residential population around the stop may differ. In this case it may, for clarity, be better to use one classification stop.



Parameter	Value
Shielding factor for rural residents	1.00E00
Shielding factor for suburban residents	8.70E-01
Shielding factor for urban residents	1.80E-02
Fraction of outside air in urban buildings	5.00E-02
Fraction of urban population occupying the sidewalk	4.80E-01
Fraction of urban population inside buildings	5.20E-01
Ratio of pedestrians/km² to residential population/km²	6.00E00
Minimum small package dimension for handling (m)	5.00E-01
Distance from shipment for maximum exposure (m)	3.00E01
Vehicle speed for maximum exposure (km/hr)	2.40E01
Imposed regulatory limit on vehicle external dose	Yes
Average breathing rate (m³/sec)	3.30E-04
Cleanup Level (microcuries/m²)	2.00E-01
Interdiction Threshold(Ci/mCi)	4.00E01
Evacuation time for groundshine (days)	1.00E00
Survey interval for groudshine (days)	1.00E01
Occupational latent cancer fatalities per person-rem	6.00E-04
Public latent cancer fatalities per person-rem	6.00E-04
Campaign (year)	8.33E-02
Iodine	I129
Rem per curie thyroid via inhalation (Rem/Ci)	1.27E06
Minimum number of rail classification stops	2.00E00
Distance dependent rail worker exposure factor (inspections/km)	1.80E-03
Dedicated trains	No
Distance of rail vehicle carrying radioactive cargo to pedestrians (m)	3.00E01
Distance of rail vehicle carrying radioactive cargo to right-of-way edge (m)	3.00E01
Distance of rail vehicle carrying radioactive cargo to maximum exposure distance (m)	8.00E02
Perpendicular distance to rail vehicle vehicle going in opposite direction (m)	3.00E00

Figure 30: Parameters Tab with Rail Mode

Distance dependent rail worker exposure factor

In the event that the actual data on rail stops along a route is not available, this factor can used to calculate the railyard worker dose at stops along the route. Ostmeyer (1986) estimated an average of 0.0018 inspections/km. The 30-hour collective railyard worker dose is multiplied by this number and by the total shipment distance in kilometers to give the in-transit railyard worker dose.

Dedicated Trains

If a shipment is by general freight or key trains, this switch should read **NO**; if by dedicated rail, **YES**. The default setting is **NO**. This can be seen in Figure 30. The main difference between the two options is the exposure of rail workers in rail yards. For dedicated rail, worker dose is calculated with factors b_8 through b_{11} of Appendix B of Neuhauser, et al (2000).

Distance of rail car carrying radioactive cargo to pedestrians
Distance of rail car carrying radioactive cargo to right-of-way edge

These two distances are the same, since there is no pedestrian walkway or sidewalk along a rail route. The default value is 30 meters (NRC, 1977). This parameter is the minimum perpendicular distance over which the off-link dose calculation will be integrated.
no sidewalk available.

Distance of rail car carrying radioactive cargo to maximum exposure distance

The default value is 800 meters (NRC, 1977). This parameter is the maximum perpendicular distance over which the off-link dose calculations will be integrated.

Perpendicular distance to rail car vehicle going in the opposite direction

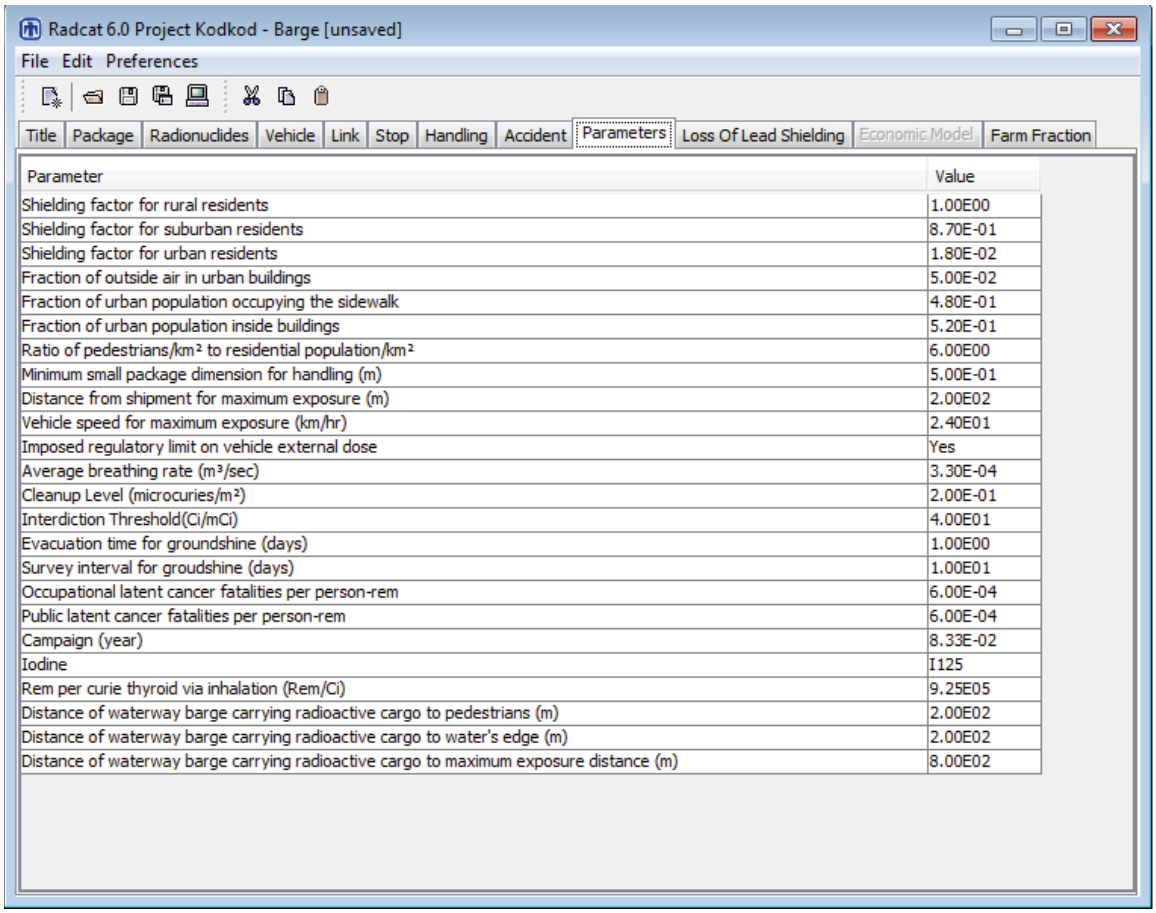
The default value is 3 meters (Madsen et al. (1986 p. 36-37). This parameter specifies the perpendicular distance between the radioactive materials shipment and other traffic lanes, in meters and is based on a minimum clearance between passing trains on double rail segments.

Distance of waterway barge carrying radioactive cargo to pedestrians
Distance of waterway barge carrying radioactive cargo to right-of-way edge

These two distances are the same, since there is no pedestrian walkway or sidewalk along a barge route. The default value is 200 meters (NRC, 1977). This parameter the minimum perpendicular distance over which the off-link dose calculation will be integrated. This can be seen in Figure 31.

Distance of waterway barge carrying radioactive cargo to maximum exposure distance

The default value is 1 km (NRC, 1977). This parameter is the maximum perpendicular distance over which the off-link dose calculations will be integrated



Parameter	Value
Shielding factor for rural residents	1.00E00
Shielding factor for suburban residents	8.70E-01
Shielding factor for urban residents	1.80E-02
Fraction of outside air in urban buildings	5.00E-02
Fraction of urban population occupying the sidewalk	4.80E-01
Fraction of urban population inside buildings	5.20E-01
Ratio of pedestrians/km² to residential population/km²	6.00E00
Minimum small package dimension for handling (m)	5.00E-01
Distance from shipment for maximum exposure (m)	2.00E02
Vehicle speed for maximum exposure (km/hr)	2.40E01
Imposed regulatory limit on vehicle external dose	Yes
Average breathing rate (m³/sec)	3.30E-04
Cleanup Level (microcuries/m²)	2.00E-01
Interdiction Threshold(Ci/mCi)	4.00E01
Evacuation time for groundshine (days)	1.00E00
Survey interval for groudshine (days)	1.00E01
Occupational latent cancer fatalities per person-rem	6.00E-04
Public latent cancer fatalities per person-rem	6.00E-04
Campaign (year)	8.33E-02
Iodine	I125
Rem per curie thyroid via inhalation (Rem/Ci)	9.25E05
Distance of waterway barge carrying radioactive cargo to pedestrians (m)	2.00E02
Distance of waterway barge carrying radioactive cargo to water's edge (m)	2.00E02
Distance of waterway barge carrying radioactive cargo to maximum exposure distance (m)	8.00E02

Figure 31: Parameters tab with barge mode

13. LOSS OF LEAD SHIELDING (LOS)

Loss of Lead Shielding is modeled in a manner analogous to the modeling of an accident. The radiation dose from a loss of lead gamma shielding is calculated by RADTRAN using a multiplier of the external radiation dose from the shielded cask (O'Donnell, et al, 2004). The conditional probability of a particular loss of shielding is the probability, given an accident, that a particular fraction of lead shielding will be lost. The dose from that particular shielding loss is calculated using the RADTRAN Stop model (Section 9).

13.1 LOS probability

The **Probability** tab allows you to specify the conditional probability of an accident of a particular severity, given that an accident happens (just as with an accident involving a release). The probability tab is shown in Figure 32.

The **Index** is a numbering system for conditional probabilities and simply enumerates them (note that the **Index** begins with zero). One conditional probability (usually the zeroth) should represent an accident in which there is no loss of lead gamma shielding.

Conditional probabilities for LOS events may be obtained from studies of accidents as described in Sprung, et al (2000), DOE (2002b), NRC (2013), and similar references.Table 7 (from NRC 2013, Table V-2) shows some typical conditional probabilities and slump fractions for a Type B spent fuel cask. These are different from the parameter values shown in Figure 32.

Table 7. Sample conditional probabilities and LOS fractions (adapted from NRC (2013, Table V-2)

Index	Conditional probability of LOS	Maximum lead slump (mm)	Slump Fraction
0	0.9999	0.0	0.0
1	1.9E-06	0.09	0.017
2	4.3E-07	0.37	3.7E-03
3	3.4E-10	20.9	1.3E-03
4	1.8E-11	15.5	0.063
5	3.8E-6	1.65	0.023
6	8.6E-7	25.1	5.1E-03
7	6.8E-10	114.5	3.4E-04
8	3.6E-11	310.5	3.2E-03
9	6.3E-7	6.43	4.3E-03
10	1.4E-7	18.3	2.8E-04
11	1.1E-10	83.2	1.8E-05

Slump fraction

RADTRAN can only model removal (loss) of gamma shielding, and therefore uses removal as a surrogate for thinning or other distortions of the gamma shield. The **Slump Fraction** is the fractional portion of the lead gamma shielding that is removed during an LOS event. Each index and probability fraction will have an associated slump fraction as shown in Table 7 and Figure 32.

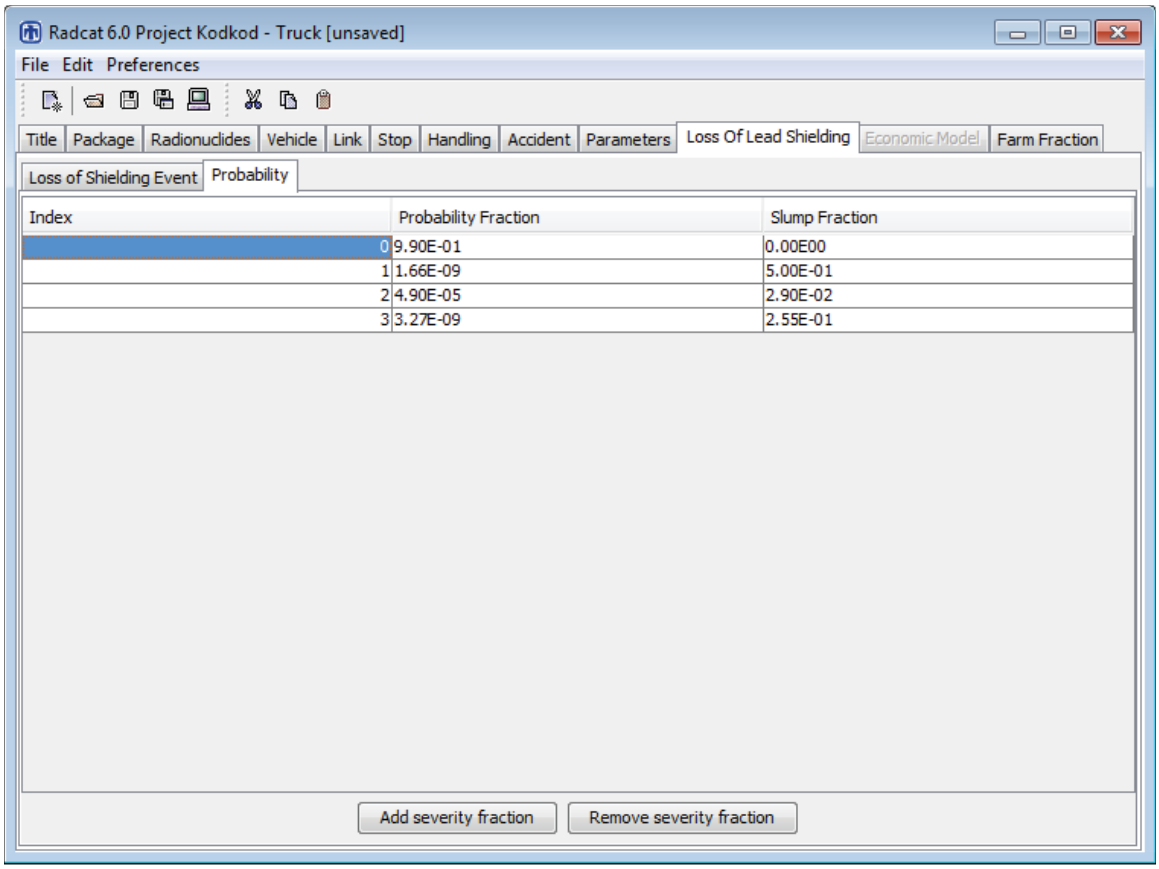


Figure 32. Loss of lead shielding tab, probability

13.2 Loss of Shielding Event

The input for a loss of shielding event is structured in part like the input for a stop, like the input for an accident that does not involve a release.

Name

Give each **Loss of shielding event** a **Name** in the left-hand column. An event name must be a continuous text string and must not include any spaces. Different dose receptors (e.g., public near the event, emergency first responders) and different population densities can be structured as different events.

Vehicle

Available vehicle names are on a pull-down menu in the **Vehicle** column, as shown in. Figure 33 in the **Vehicle** column. Vehicle names cannot be added or deleted at this tab.

Minimum distance

Enter the shortest distance at the LOS event from the radioactive cargo to the receptor(s) whose dose will be calculated. The **Min(imum) distance** cannot be less than 1.0 meters and must be less than or equal to the **Max(imum) distance**.

Maximum distance

Enter the longest distance at the LOS event from the radioactive cargo to the receptor(s) whose dose will be calculated. The **Max(imum) Distance** must be greater than or equal to the **Min(imum) distance**.

People

This parameter defines the number of radiation receptors at each particular LOS Event as seen in Figure 33. If the **Min(imum)** and **Max(imum) distance** are the same, RADTRAN will report the dose for the given number of receptors at that distance. If the **Min(imum)** and **Max(imum) distance** are different, the number in the "People" column will be read as a population density, usually the population density along the route. The **Min(imum)** and **Max(imum) distance** will usually be 30 and 800 meters, respectively.

Shielding factor

The **Shielding factor** is the fraction of ionizing radiation to which the receptors are exposed; that is, the inverse of the amount of shielding. Thus 1 = no shielding and 0 = 100% shielding. Enter a number between 0 and 1 for the shielding factor for each stop. This can be seen in Figure 33 in the **Shielding Factor** column.

Time

Enter the total time in hours for each LOS event. The total time represents the duration of potential radiation exposure, and can be indicative of an emergency services first responder or the public awaiting evacuation. This is seen in Figure 33 in the **Time (h)** column.

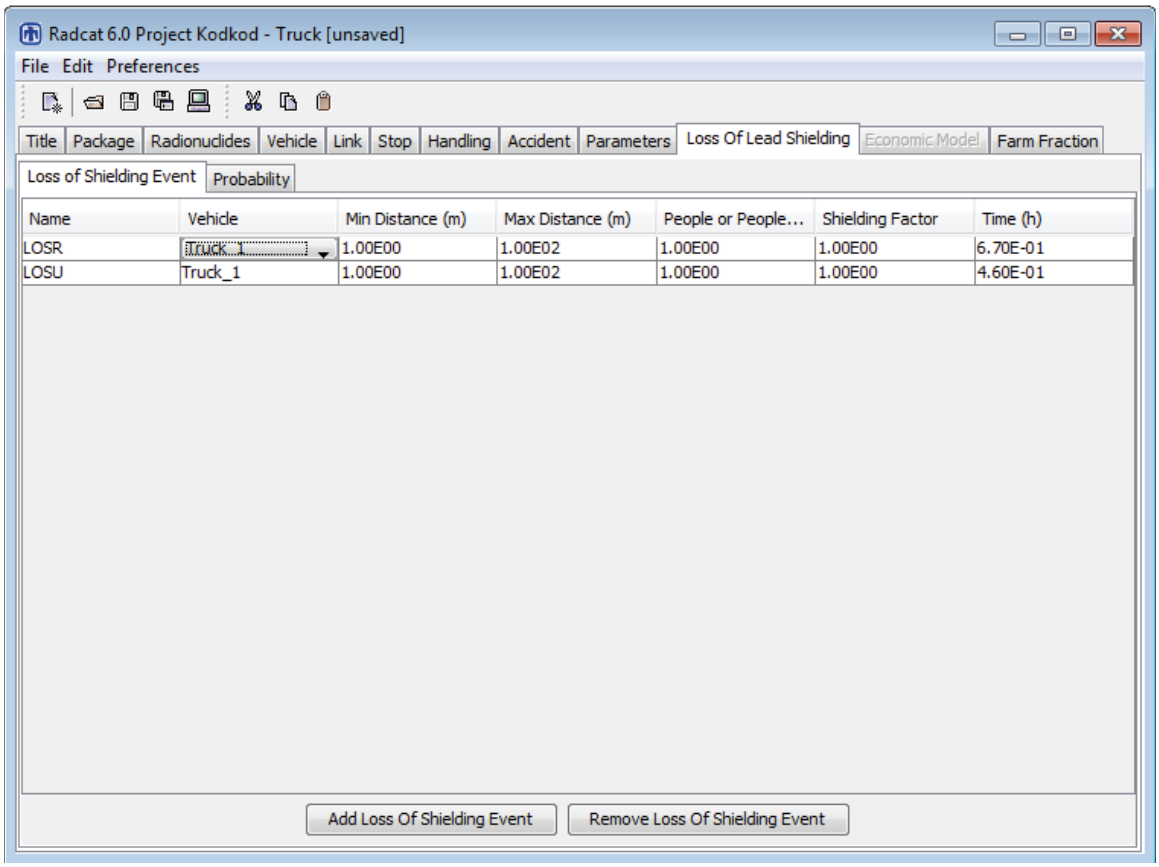
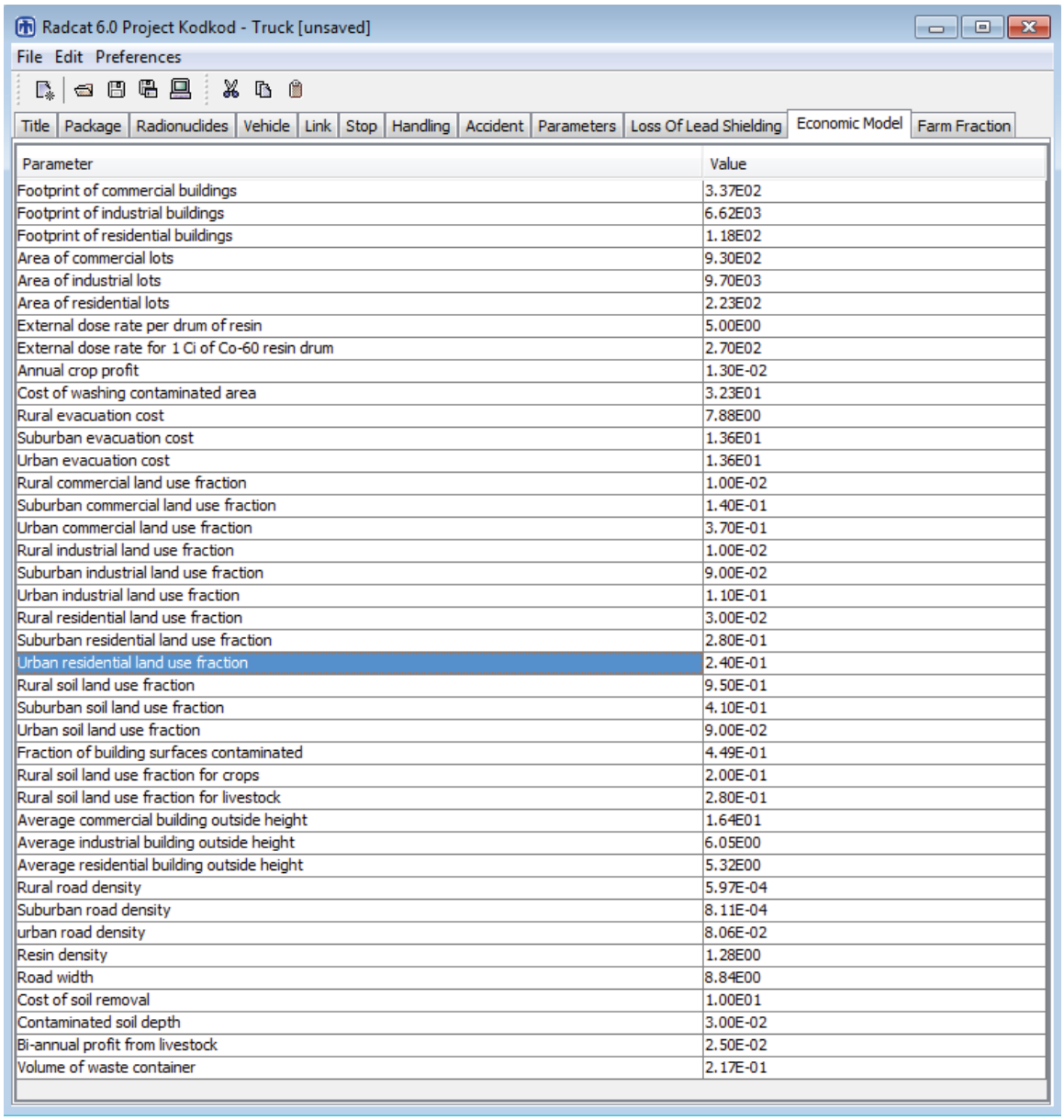


Figure 33: Loss of lead shielding tab, LOS event

14. ECONOMIC MODEL

An accidental release and dispersal of radioactive material during transportation could require evacuation of the population and decontamination of the affected area. The economic model in RADTRAN 6 estimates the cost of evacuation and decontamination.

A checkbox for the **Economic Model** is included on the **Title** tab. When unchecked, the **Economic Model** tab remains grayed out, and results from the **Economic Model** will not be included in the RADTRAN 6.0 output. However, if the box is checked, the Economic Model Tab will become functional. Figure 34 lists default values for the Economic Model, which can be overwritten. A listing of economic model parameter names, descriptions, average values and units can be found in Appendix B. Derivation of the economic model parameters is discussed in Osborn, et al (2007).



Parameter	Value
Footprint of commercial buildings	3.37E02
Footprint of industrial buildings	6.62E03
Footprint of residential buildings	1.18E02
Area of commercial lots	9.30E02
Area of industrial lots	9.70E03
Area of residential lots	2.23E02
External dose rate per drum of resin	5.00E00
External dose rate for 1 Ci of Co-60 resin drum	2.70E02
Annual crop profit	1.30E-02
Cost of washing contaminated area	3.23E01
Rural evacuation cost	7.88E00
Suburban evacuation cost	1.36E01
Urban evacuation cost	1.36E01
Rural commercial land use fraction	1.00E-02
Suburban commercial land use fraction	1.40E-01
Urban commercial land use fraction	3.70E-01
Rural industrial land use fraction	1.00E-02
Suburban industrial land use fraction	9.00E-02
Urban industrial land use fraction	1.10E-01
Rural residential land use fraction	3.00E-02
Suburban residential land use fraction	2.80E-01
Urban residential land use fraction	2.40E-01
Rural soil land use fraction	9.50E-01
Suburban soil land use fraction	4.10E-01
Urban soil land use fraction	9.00E-02
Fraction of building surfaces contaminated	4.49E-01
Rural soil land use fraction for crops	2.00E-01
Rural soil land use fraction for livestock	2.80E-01
Average commercial building outside height	1.64E01
Average industrial building outside height	6.05E00
Average residential building outside height	5.32E00
Rural road density	5.97E-04
Suburban road density	8.11E-04
urban road density	8.06E-02
Resin density	1.28E00
Road width	8.84E00
Cost of soil removal	1.00E01
Contaminated soil depth	3.00E-02
Bi-annual profit from livestock	2.50E-02
Volume of waste container	2.17E-01

Figure 34: Economic model default values

15. RADTRAN OUTPUT

Once all the necessary input data has been entered to run RADTRAN, click on the Run RADTRAN icon, as shown in Figure 35. Once RADTRAN has run, a new Java window will open. If RADTRAN has run properly, SUCCESSFUL COMPLETION will be shown at the bottom of the Java window as shown in Figure 36.

8

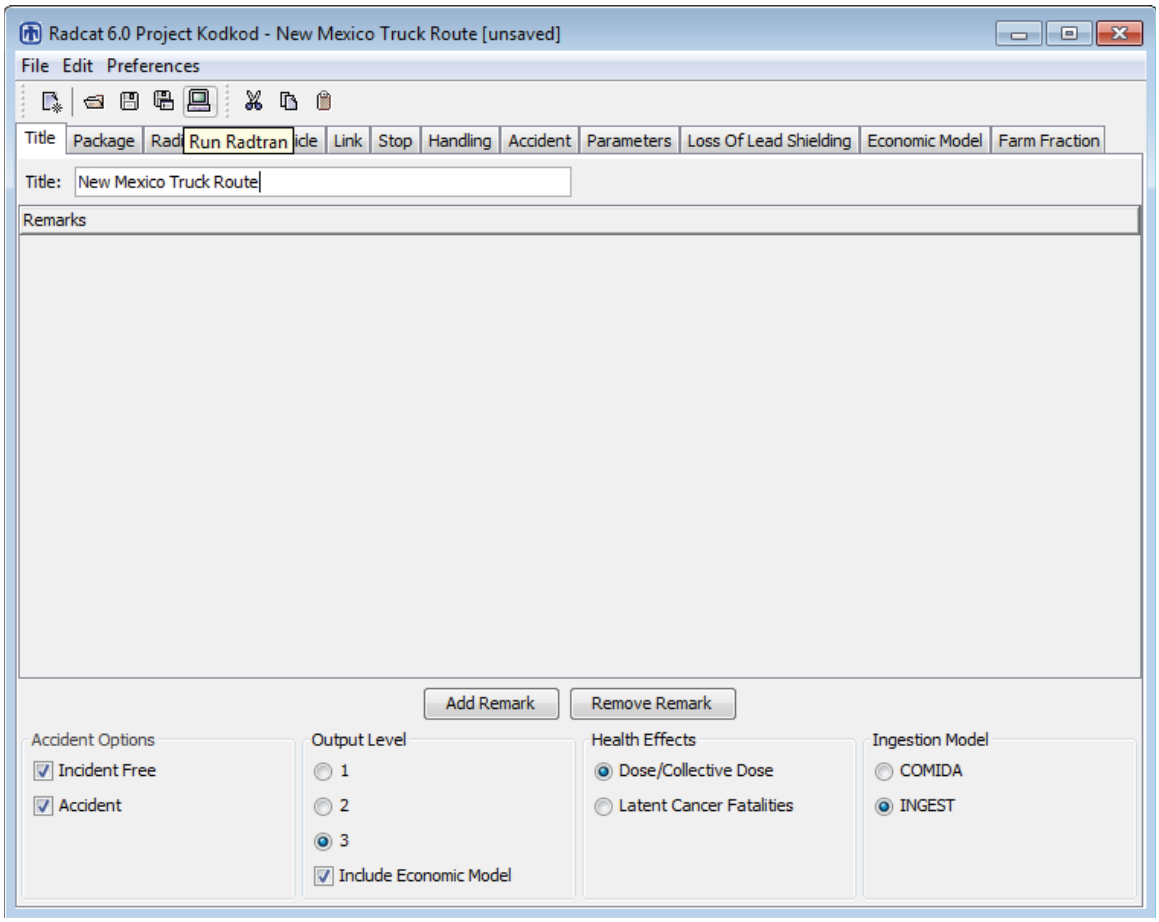


Figure 35: Run RADTRAN

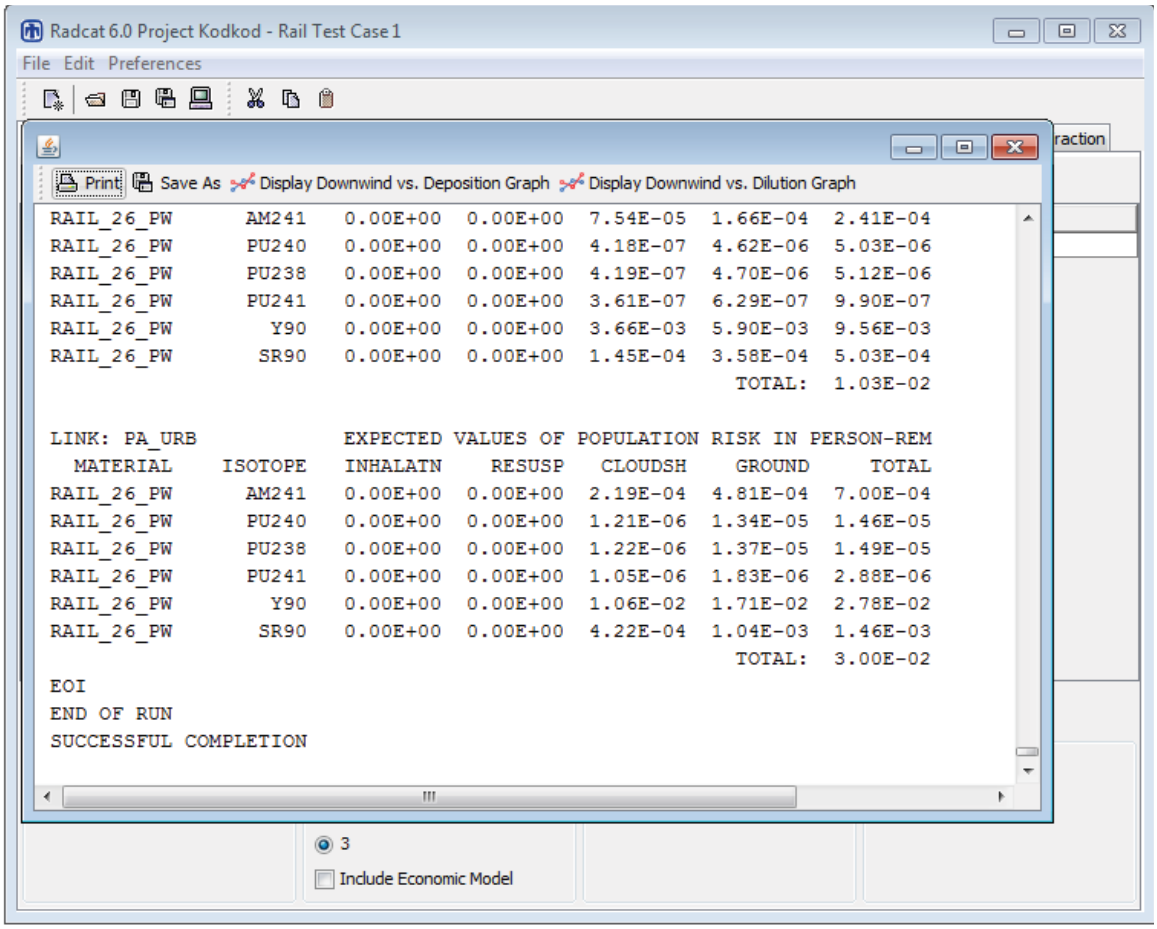


Figure 36: End of RADTRAN Output

The output is a text file that can be saved in text form. It can also be saved as, or imported into, an EXCEL spreadsheet so that you can work with the numbers in the output. An annotated copy of the RADRAN output is provided in Appendix E.

The incident-free output is self-explanatory. “No release” accidents are modeled as stops, and are part of the incident-free stop output.

The output for an accident involving a release of radioactive material lists accident dose risks for each link, as shown in Figure 37. The links on which there is no accident (these are the links for which the user specified zero accident rate) show zero for all accident risks for that link. In versions of RADTRAN before RADTRAN 6.02, the total rural, suburban and urban accident risks were listed. These totals are meaningless and should be ignored, since only one accident will occur on each route.

On the bar at the top of the output screen is an icon titled “Display Downwind vs. Deposition Graph” as shown in Figure 38. These graphical displays plot the downwind distance vs. deposition and the downwind distance vs. dilution for National Average and User-defined weather only; results using the Pasquill option cannot be displayed as

graphs. Figure 38 shows an example of a graphical output. The graphical outputs are made with every successful RADTRAN run.

When RADTRAN is run, the output appears immediately on the screen, and may be printed and/or saved. The file that appears on the screen starts with an echo of the input file. The beginning of the output file is clearly marked. The file in Figure 37 can be saved as a text file, an excel file, or a Word document. It can be saved to any folder on the computer or LAN. An incomplete output file indicates some error in the input file that caused RADTRAN to abort. The error message that appears at the end of the output file in these cases is usually self-explanatory.

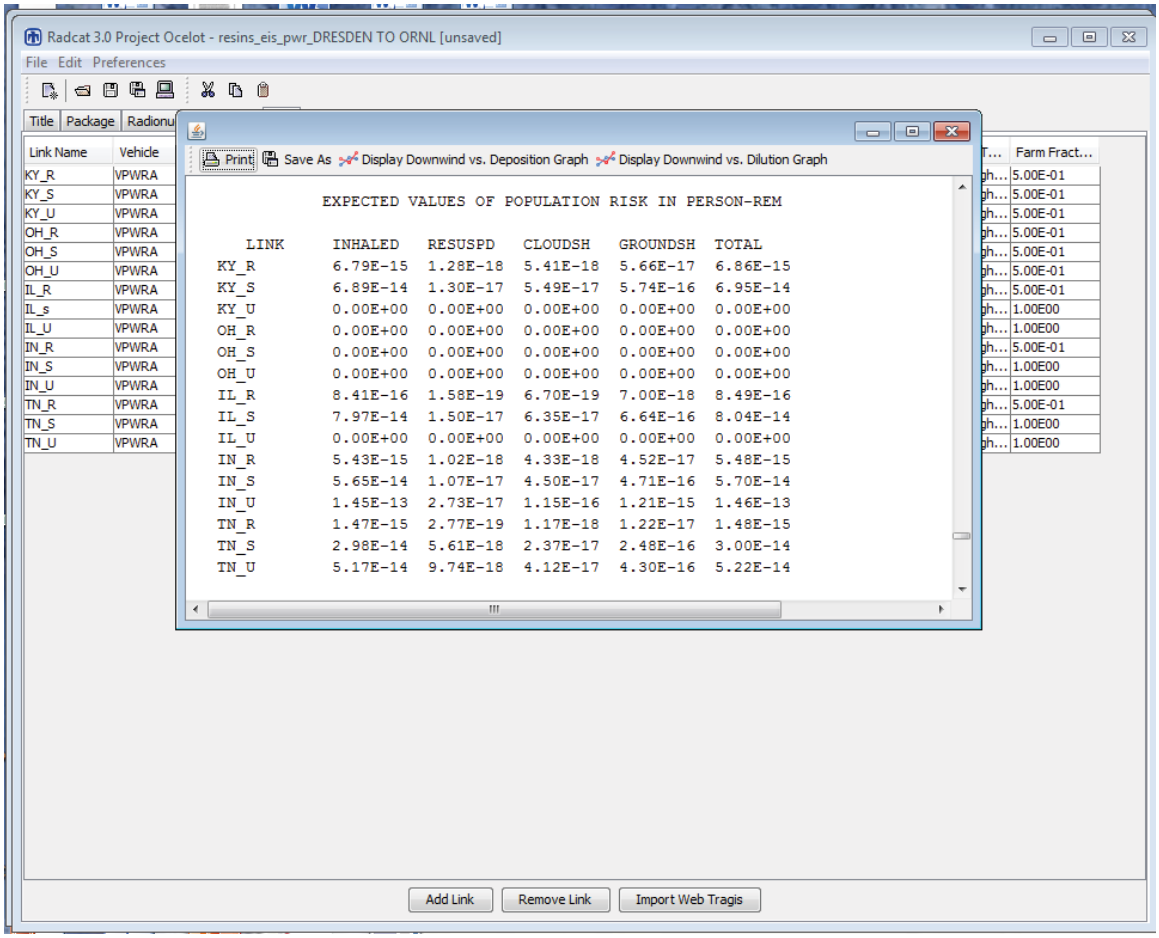


Figure 37: Accident output.

Figure 38 shows the accident output graphically. Changes can be made in the appearance of the output and graphical outputs can be saved. Left click over the graph window and select “Properties” or “Save as”, as shown in Figure 38. The graphical outputs can be saved as PNG Image Files. The properties that can be changed are:

- Title

- y-axis Name
- y-axis Range
- x-axis Name
- x-axis Range
- Background color

The legend and line colors cannot be changed. An example of these changes can be seen in Figure 40.

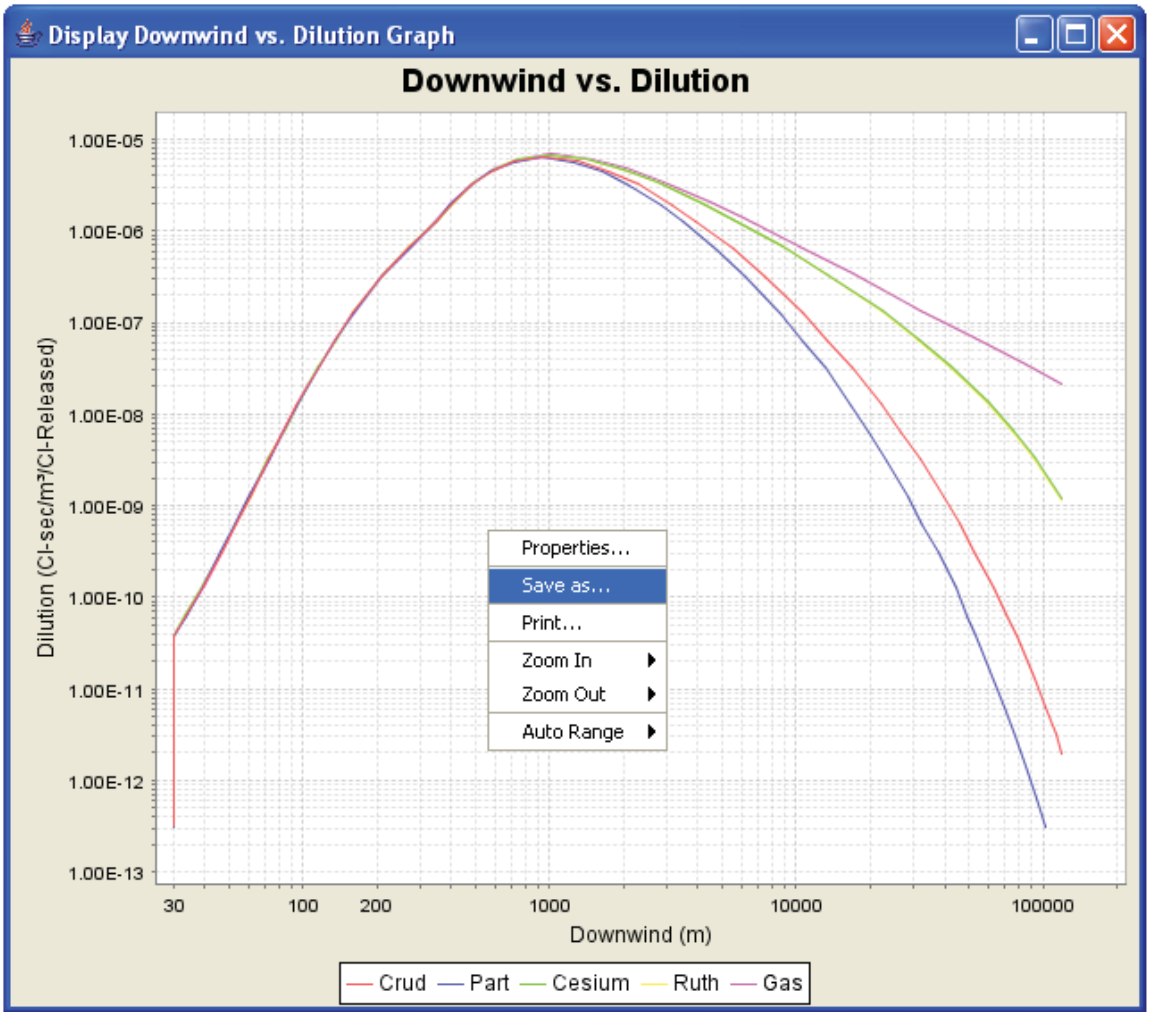


Figure 38: Graphical output.

An example of these changes can be seen in Figure 39.

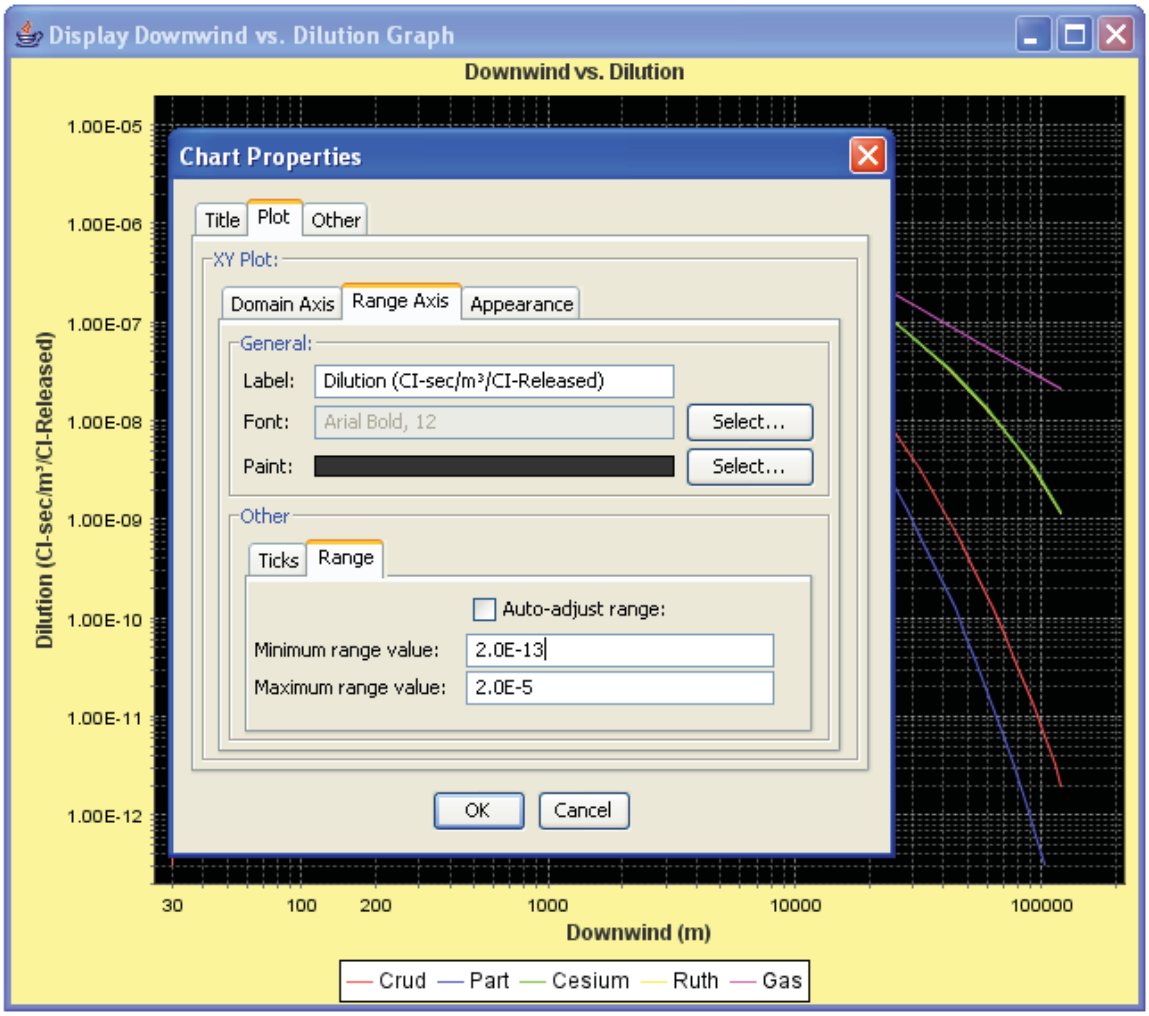


Figure 39: Graphical output property changes

16. SAVING, RUNNING RADTRAN, EXITING

The input file can be saved with either the **Save** or the **Save As** icon. Your input file should be saved as a **".rml**" file. You will need to add this extension to your filename when saving it, because RadCat does not automatically add the "**.rml**" extension when saving the file. The file may be run in RADTRAN by clicking on the **Run RADTRAN** icon (the computer icon). RADTRAN can be run without saving

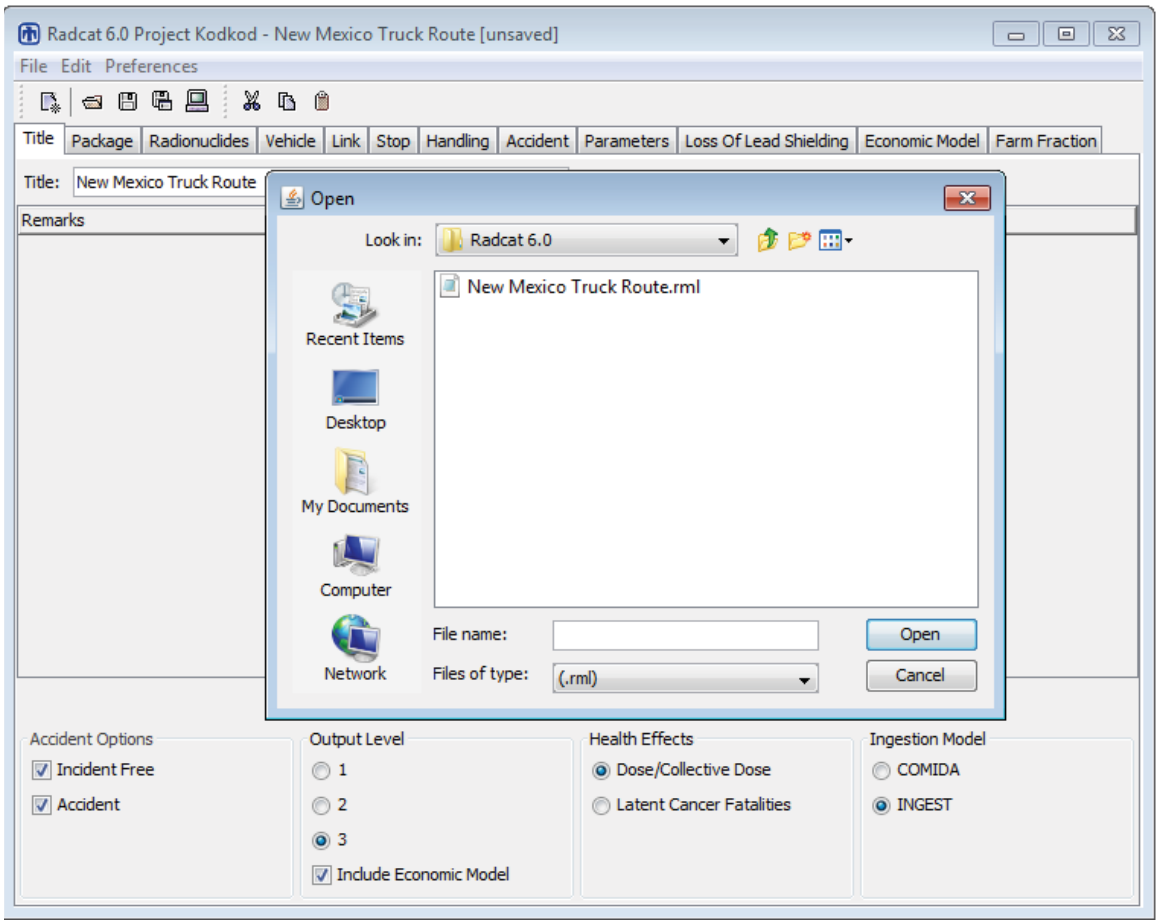


Figure 40: Saving a RadCat Input File

Exit from RADTRAN/RadCat by clicking on the “x” in the upper right-hand corner of the screen, as with any file.

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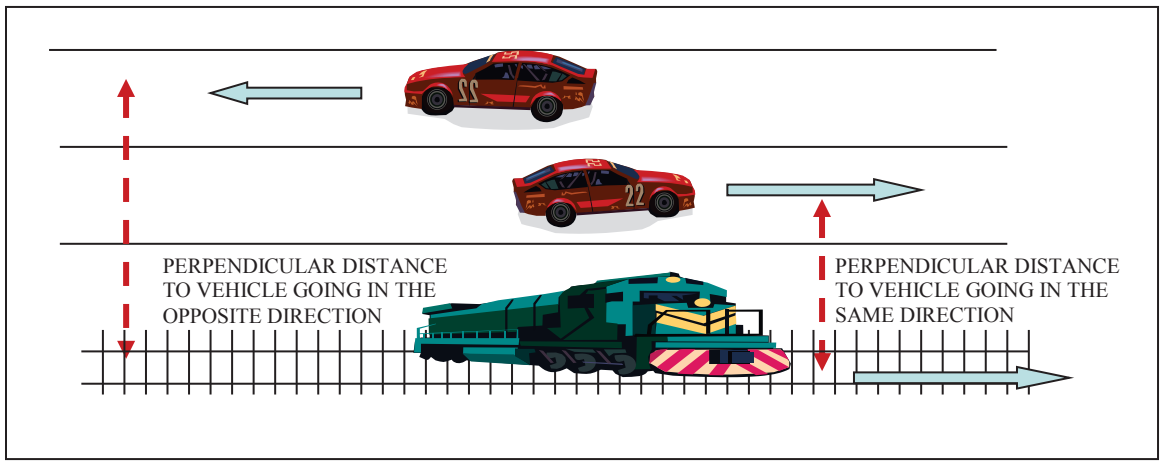
APPENDIX A. A SPECIAL CASE

The parameter ADJACENT specifies the average perpendicular distance (at right angles to the line of travel) between the radioactive materials shipment centerline and the center of other traffic lanes, in meters.

There are times when rail shipments will travel on a route parallel to an adjacent highway. In such a case, occupants of vehicles on the highway going both in the same direction as the rail shipment, as well as in the opposite direction, may receive an external dose from the rail shipment. Although you will be in Rail Mode for your calculation, you may wish to use **Highway Mode** to determine the incident-free dose to the occupants of vehicles on the parallel highway.

Figure 20 is a diagram of the situation you are modeling.



FigureA-1. Diagram for the on-link dose on a highway that parallels a rail route

Structure your supplemental **Highway Mode** calculation as follows:

- Create a new RadCat **Highway** file. This file will include some parameters from your rail (or barge) file and some that you will create for this file.
- You cannot just import the **Rail** (or **Barge**) file. Create a new package and vehicle that are the same as your rail package and vehicle: use the rail
    - package size,
    - package dose rate,
    - package gamma and neutron fractions,
    - add at least one radionuclide. It does not figure in the calculation, but RADTRAN hangs up without it.
    - vehicle size,
    - vehicle dose rate,
    - vehicle gamma and neutron fractions.
- What you put for crew parameters is up to you – they do not enter into this calculation.

    - Make a link for each segment for which the train (or barge) parallels the highway. On the LINKS tab, the Vehicle Speed will be the relative speed of the train and the vehicles on the highway because you are calculating only the on-link dose.
    - "Vehicle Density" is the vehicle density -- vehicles **per hour --** on the highway
    - "Persons per Vehicle" is the average occupancy of the vehicles on the highway,
    - "Type" will be the type of highway you are considering: primary highway or secondary road.
- The parameters on the **Parameter** tab that affect your calculation are:
    - Perpendicular distance to freeway vehicle going in opposite direction (m)
    - Perpendicular distance to non-freeway vehicle going in opposite direction (m)
    - Perpendicular distance to city vehicle going in opposite direction (m)
    - Perpendicular distance to all vehicles going in the same direction (m)

  The default values for these parameters are 15m, 3m, 3m, and 4m, respectively , and refer to the lane widths and distances between lane centers. RADTRAN will call the first parameter if your LINK is designated as "primary highway," the second and third if your LINK is designated as "secondary road."

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- Estimate the distance, in meters, between the center of the highway lane closest to the train (or barge) and change the "perpendicular distance to all vehicles going in the same direction (m)" from its default of 4-meters to the value you have estimated.
- Add the distance between your highway lanes to that estimate, and substitute that sum for the default values for the other three "perpendicular distance..." parameters.

The only output result that should be taken from this modified Highway Mode is the **ONLINK** population dose for each link. This dose is taken from the **Incident-Free**

APPENDIX B. VARIABLE NAMES IN RADTRAN

Table B-1. Flag chart and default values

Flag Name	Flag Description	Default Value
IACC	Setting this flag to 2 directs the code to work through all exposure pathways associated with atmospheric dispersal of package contents during an accident. The alternative value of IACC = 1 denotes non-dispersal and is no longer used in RADTRAN	2
ITRAIN	This flag, used only for rail mode, denotes whether shipment is by general freight (ITRAIN = 1) or by dedicated rail (ITRAIN = 2).	1
IUOPT	This flag is used to select a building shielding option. For the STANDARD value, persons in rural buildings are not shielded (100% exposure), persons in suburban dwellings are 87% exposed, and persons in urban dwellings are 1.8% exposed. Setting the IUOPT flag to 1 is equivalent to full shielding (everyone indoors is fully shielded and receives no dose). Setting the IUOPT flag to 3 is equivalent to no shielding.	2
REGCHECK	Setting this flag to 1 causes a series of regulatory checks to be performed. If any circumstances are identified that violate the regulatory requirements, then the appropriate parameter values are reset to the regulatory maximum and the calculation continues. REGCHECK = 0 bypasses the regulatory-check subroutine.	1
BDF	The Building Dose Factor describes the entrainment of aerosol particles in ventilation systems (i.e., the fraction of particles of an external aerosol that remain in aerosol form after passing through a ventilation system). The BDF is used to modify inhalation doses to persons in urban structures. The default value of 0.05 is about five times higher than the value for high-rise buildings with air-conditioning systems used by Finley et al., (1980) for New York City, which has been used in RADTRAN in the past.	0.05

BRATE	This factor represents breathing rate and is used for calculation of inhalation doses. The breathing rate (BRATE = 3.30E-04 m^3/sec) of the Reference Man (70-kg adult male at light work) derived from Shleien, et al 1996; Table 12.6) has been used as the default value. The value in the cited table has been converted from liters per hour to m^3/sec.	3.30E-04
CULVL	This factor describes Clean-Up Level, which is the required level to which contaminated surfaces must be cleaned up. The default value is the EPA guideline of 0.2 $\mu Ci/m^2$ (EPA, 1977). This value applies to the sum of deposited activity over all radionuclides of a multi-radionuclide material. Analysts who can justify use of more realistic values are urged to do so.	0.2
EVACUATION	This parameter specifies evacuation time in days following a dispersal accident, where this includes time to respond to the accident and carry out a course of action. The default value is 24 h (1 day). Mills et al. (1995) analyzed 66 verified hazmat accidents in which evacuations were carried out and found that the mean evacuation time was approximately 1 hour. Even when response time is added, a 24-hour (1-day) value for this variable is conservative. This parameter defined the time of exposure to groundshine and to resuspended material.	1.0
INTERDICT	This parameter specifies the threshold value for interdiction of contaminated land. The default value is 40, i.e., a value 40 times greater than CULVL, and it was taken from NUREG-0170 (NRC, 1977).	40
LCFCON	This parameter specifies the Latent Cancer Fatality (LCF) Conversion Factors; units are LCFs per rem. The default values are 5.0E-04 LCF/rem for the general public and 4.0E-04 LCF/rem for workers. They have been adjusted for low-dose and low-dose-rate decrease in effects with a DDRRF (Dose and Dose Rate Reduction Factor) of 2. These values are consistent with the recommendations of BEIR VII (NRC/NAS, 2005) and ICRP 60 (ICRP, 1991). The dose-response relationship is assumed to be linear with no threshold in order to agree with current regulations. However, the majority of available data indicate that the actual dose-response relationship at very low doses is likely to be considerably less and, as noted in BEIR VII, is not incompatible with zero (NRC/NAS, 2005). Thus, cancer risk estimates obtained from RADTRAN 5 will be generally conservative.	6.0E-04
LOS	The parameter was used to analyze loss-of-shielding accidents. It is no longer used in RADTRAN analyses.	

RADIST	This parameter is used to specify an array of Radial Distances, which are used to define annular areas for dose-calculation purposes when the IACC Flag is set to 1. It is no longer used in RADTRAN.	
RPCTHYROID	This parameter is used to specify 1-year CEDE (rem per curie) to the thyroid from inhalation of radionuclides of iodine for estimation of early-mortality risk. Radioiodine mainly travels to and irradiates a single organ, the thyroid. In previous releases of RADTRAN, however, the 50-year CEDE was used to approximate the 1-year dose. One-year committed doses to the thyroid have been calculated directly for RADTRAN 5. This new parameter was not included in the internal radionuclide database, since it would have meant adding a new column containing zeros for all radionuclides but the radioiodines. The information has been included under the RPCTHYROID keyword instead. The default values are 1.27E+06 for iodine-131, 5.77E+06 for iodine-129, and 9.25E+05 for iodine-125.	1.27E+06 for I-131 5.77E+06 for I-129 9.25E+05 for I-125
SURVEY	This parameter is used to specify the time (in days) required to survey contaminated land following a dispersal accident. The amount of deposited material removed by radioactive decay is calculated beginning with time of initial deposition. The longer a deposited material remains on the ground, the more is removed by decay and spread by forces such as wind and rain. The actual elapsed time between accident occurrence and completion of a survey is impossible to determine in advance, but is likely to be prolonged because of governmental and regulatory complexities. The default value is set to an unrealistically brief, but radiologically conservative, 10 days (NRC, 1977).	10
TIMENDE	This parameter specifies the time, in days, required to effect evacuation following a non-dispersal accident. It is no longer used in RADTRAN.	
UBF	This parameter is the Urban Building Fraction; it describes either the fraction of the population that is indoors or the fraction of the area that is occupied by buildings, depending on the type of population model being used. The default value of 0.52 is for the latter model, and is taken from Finley et al. (1980). The value is most accurate for large cities such as New York and is somewhat conservative for smaller cities.	0.52
USWF	This parameter is the Urban Sidewalk Fraction; it specifies the fraction of the population that is out of doors or the fraction of the population that occupies sidewalks, depending on the type of population model being used. The default pre-assigned value of 0.1 is for the latter model, and is taken from Finley et al. (1980). As with the UBF, this value is suitable for large cities and is conservative for smaller cities.	0.1

ADJACENT	See DISTON	
CAMPAIGN	This keyword specifies the duration of the shipping campaign in years. The value calculated with CAMPAIGN is the total number of off-link persons exposed. This result may be used to perform external calculations of annual off-link dose. Annual dose values may be compared with total dose in multi-year shipping campaigns and are useful for assessing regulatory compliance with standards based on annual doses. The default value is 0.0833 years. This is an average month in an average year, or $1/12^{th}$ of a year.	0.0833
DDRWEF	This keyword applies to rail mode only and specifies the Distance Dependent Rail Worker Exposure Factor. This factor is used to calculate the component of rail-worker dose that depends on distance traveled (e.g., exposure related to engine changes, crew shift-changes, etc., while en route). The default value of 0.0018 inspections/km is taken from Ostmeyer (1986).	0.0018
DISTOFF	This keyword specifies a set of three distances, in meters, used in off-link dose calculations for highway, rail, and barge modes. The three distances are: (1) the minimum perpendicular distance over which the off-link dose calculation will be integrated; (2) the minimum pedestrian-walkway width, for instances in which dose to pedestrians beside the link is calculated (see RPD for discussion of pedestrian density); and (3) the maximum perpendicular distance over which the off-link dose calculation will be integrated. DISTOFF must be followed one or more keywords that specify values for various link types. The default values, which are supplied for each link type, are from NUREG-0170 (NRC, 1977). The link types and values for each are:	
	FREEWAY Any limited-access divided highway. [30, 30, 800]	30, 30, 800
	SECONDARY Any non-limited-access highway that is not a city street (27, 30, 800)	27, 30, 800
	STREET Any city street. [5, 8, 800]	5,8,800
	RAIL Any rail right-of-way in the U.S. [30, 30, 800]	30, 30, 800
	WATER Any vessel. [200,200,800]	200, 200, 1000
DISTON	FREEWAY Any limited-access, divided highway [15.0 m];	15
	SECONDARY Any non-limited access highway [3 m];STREET Any city street [3 m];	3 for secondary roads 3 for city streets

	RAIL Any rail right-of-way [3 m].	3
	An additional parameter for highway mode only is ADJACENT It represents the minimum perpendicular distance between shipment centerline and centerline of adjacent passing vehicles [4 m].	4
FMINCL	This keyword is applied to rail mode only and specifies the minimum number of railcar classifications or inspections per one-way trip. The default value is 2 since there are always at least two inspections per one-way trip - one at the beginning and one at the end of each trip (Wooden, 1986).	2
FNOATT	This parameter is applied to passenger-air mode only and specifies the Number of Flight Attendants. The default value is 4 (NRC, 1977).	4
FREEWAY	See DISTOFF and DISTON	
MITDDIST	This parameter is used to calculate the maximum individual "in-transit" dose to a member of the public; it represents the minimum perpendicular distance, in meters, from the shipment centerline to an individual standing beside the road or railroad while a shipment passes. The default value is 30.0 m (NRC, 1977).	30
MITDVEL	This parameter is used to calculate the maximum individual "in-transit" dose; it represents the minimum velocity, in km/hr, of a shipment. The default value is 24.0 km/hr (15 mph) (NRC, 1977).	24
RAIL	See DISTOFF and DISTON	
RPD	This parameter is the Ratio of Pedestrian Density. It is used to calculate the density of unshielded persons on sidewalks and elsewhere in urban areas when the IUOPT Flag is not equal to 3 by indexing it to the population density of the surrounding area. RPD is also used in the calculation of accident consequences. The default is 6.0, which is based on empirical data from New York City (Finley, 1980). It means that the pedestrian density is six times the residential population density. This figure is likely to be conservative for most other urban areas, but similar data are seldom collected in other cities.	6.0

RR	This parameter specifies the Rural Shielding Factor. The default value is 1.0 (i.e., no shielding). Although even wood-frame construction provides some shielding, the Rural Shielding Factor is set to 1.0 to conservatively account for the fact that rural economies involve a relatively large fraction of outdoor employment (farming, ranching, etc.). RR is used in incident-free dose and in dose-risk calculation for non-dispersal accidents.	1.0
RS	This parameter specifies the Suburban Shielding Factor. The default value is 0.87, which represents a residential structure of wood-frame construction (Taylor and Daniel, 1982, p.12). RS is used in incident-free dose and in dose-risk calculations for non-dispersal accidents.	0.87
RU	This parameter specifies the Urban Shielding Factor. The default value is 0.018, which represents an urban commercial building constructed of concrete block (Taylor and Daniel, 1982, p.12). RU is used in incident-free dose and in dose-risk calculations for non-dispersal accidents.	0.018
SMALLPKG	This parameter specifies the first Package Size Threshold. This parameter is used to determine the handling method that will be used for a package, which, in turn, is used in the calculation of handler dose. If a package is designated as "small" then an empirical algorithm for handling dose is used; if package dimensions exceed the threshold then another method is used. The default value for SMALLPKG is 0.5 m (Javitz, 1985). Although it is highly unlikely that this value will need to be altered, you has the option to do so.	0.5

Mode	Mode Number	Conveyance Types Associated with Mode
HIGHWAY	1	Any truck; usually a tractor-trailer(also called a "semi" or a combination truck)
RAILWAY	2	One or more railcars in a single train
WATERWAY	3	Any vessel; usually barge

Table B-2: Definitions for Input to the RISKIND Dispersion Model

USE_RADTRAN:	0 use RISKIND center line distances – **preferred**
	1 use RADTRAN distances (only if REL_HT < 3 meters)
REL_HT:	Release Height (m)
HEAT_REL:	Heat Release (cal/sec)
SRC_WDTH:	Source Width or Cask Length (m)
SRC_HT:	Source Height or Cask Radius (m)
WS:	Wind Speed (m/sec)
ANEM_HT:	Anemometer Height (m)
AMB_T:	Ambient Temperature (K)
HT_MIX:	Atmospheric Mixing Height (m)
Pasquill/Briggs:	1 use the Pasquill-Gifford dispersion model with coefficients
	2 use the Briggs dispersion model with coefficients
Stability:	Pasquill Stability Category A=1 through F=6
Rural – or –	1 use the rural terrain coefficients
Suburban/Urban	2 use the suburban/urban terrain coefficients

Table B-2: Economic Model Default Values

Parameter Name	Description	Average Value	Units
AF_C	Footprint of commercial buildings	337	m^2
AF_I	Footprint of industrial buildings	6620	m^2
AF_R	Footprint of residential buildings	118	m^2
ALOT_C	Area of commercial lots	930	m^2
ALOT_I	Area of industrial lots	9700	m^2
ALOT_R	Area of residential lots	223	m^2
BARL_DR_LM	External dose rate per barrel of resin	5.0	mrem/hour
CO_BARL_DR	External dose rate per 1 Ci of Co-60	269.7	mrem/hour
CROP_PROFT	Annual crop profit	0.01303	$/$m^2$
C_WASH	Cost of washing contaminated area	32.29	$/$m^2$
EVAC_CST_R	Rural evacuation cost	7.88	$/person-$km^2$
EVAC_CST_S	Suburban evacuation cost	13.61	$/person-$km^2$
EVAC_CST_U	Urban evacuation cost	13.61	$/person-$km^2$
F_CR	Rural commercial land use fraction	0.01	
F_CS	Suburban commercial land use fraction	0.14	
F_CU	Urban commercial land use fraction	0.37	
F_IR	Rural industrial land use fraction	0.01	
F_IS	Suburban industrial land use fraction	0.09	
F_IU	Urban industrial land use fraction	0.11	
F_RR	Rural residential land use fraction	0.03	
F_RS	Suburban residential land use fraction	0.28	
F_RU	Urban residential land use fraction	0.24	
F_SR	Rural soil land use fraction	0.95	
F_SS	Suburban soil land use fraction	0.41	
F_SU	Urban soil land use fraction	0.09	
FBC	Fraction of building surfaces contaminated	0.449	
FR_C	Rural soil land use fraction for crops	0.20	
FR_L	Rural soil land use fraction for livestock	0.28	
OH_C	Average commercial building outside height	16.40	m
OH_I	Average industrial building outside height	6.05	m
OH_R	Average residential building outside height	5.32	m
RHO_RD_R	Rural road density	5.97E-04	m of road/m^2 of land
RHO_RD_S	Suburban road density	8.11E-04	m of road/m^2 of land
RHO_RD_U	urban road density	8.06E-02	m of road/m^2 of land
RHO_RESIN	Resin density	1.28	g/cm^3
ROAD_W	Road width	8.84	m
SOIL COST	Cost of soil removal	10	$/$m^3$
SOIL_DPTH	Contaminated soil depth	0.03	m
STCK_PROFIT	Bi-annual profit from livestock	0.02499	$/$m^2$
VOL_BARREL	Volume of waste container	0.2167	m^3

APPENDIX C. DOSE CONVERSION FACTORS

Correspondence for the radionuclide arrays:

1. Half-Life (days). Source: ICRP 38 (as reported in Federal Guidance Report (FGR) 13)

2. Photon Energy (MeV). Source: ICRP 72 (this value is not used in RADTRAN 5.5)

3. Cloud/Immersion Dose Factor (rem-m^3/Ci-sec). Source: FGR 12 (multiply by $3.7x10^{12}$ to convert from SI units to historical units)

4. Groundshine Dose Factor (rem-m^2/μCi-day). Source: FGR 12 (multiply by $3.197x10^{11}$ to convert from SI units to historical units)

5. 50-year Effective Inhalation Dose Factor (rem/Ci). Source: ICRP 72 – 50-year Effective Inhalation Dose Type M to adult obtained from ICRP-DOSE CD v. 2.0.1 (multiply by $3.7x10^{12}$ to convert from SI units to historical units)

6. 50-year Gonad Inhalation Dose Factor (rem/Ci). Source: ICRP 72 – 50-year Testes Inhalation Dose Type M to adult obtained from ICRP-DOSE CD v. 2.0.1 (multiply by $3.7x10^{12}$ to convert from SI units to historical units)

7. 1-year Lung Inhalation Dose Factor (rem/Ci). Source: ICRP 72 – 1-year Lung Inhalation Dose Type M to adult obtained from ICRP-DOSE CD v. 2.0.1 (multiply by $3.7x10^{12}$ to convert from SI units to historical units)

8. 1-year Marrow Inhalation Dose Factor (rem/Ci). Source: ICRP 72 – 1-year Red Marrow Inhalation Dose Type M to adult obtained from ICRP-DOSE CD v. 2.0.1 (multiply by $3.7x10^{12}$ to convert from SI units to historical units)

9. Nuclide Name for Ingestion Data. Source: COMIDA2 – Names must match RT5INGEST.BIN

10. A1 Activity Limit Values (Ci). Source: 10CFR71 Appendix A – Revised 1/1/2004

11. A2 Activity Limit Values (Ci). Source: 10CFR71 Appendix A – Revised 1/1/2004

The inhalation dose conversion factors use a 1.0-micron AMAD particle as a conservative value. ICRP-66 uses a distribution from 1 to 5 microns and the occupational respirable size is 5.0-microns. The upper limit for truly respirable particles is 10.0-microns.

ICRP 72 gives dose commitments to adult members of the public at age 20 that are assumed to live another 50 yrs.

All dose conversion factors (DCFs) and photon energies are calculated for each individual radionuclide with the exception of the following radionuclides which have their progenies included:

- Mo-99 includes the weighted contribution from the short half-life of its Tc-99m daughter.
- Ru-103 includes the weighted contribution from its short half-life Rh-103m daughter.
- Ru-106 includes the weighted contribution from the short half-life of its Rh-106 daughter. Inhalation DCFs were determined with Ru-106 only. There is no information for Rh-106.
- Cs-137 includes the weighted contribution from the short half-life of its Ba-137m daughter. Inhalation DCFs were determined with Cs-137 only. There is no information for Ba-137m.
- Ce-144 includes the weighted contributions from the short half-lives of its Pr-144 and Pr-144m daughters. Inhalation DCFs were determined with Ce-144 and Pr-144. There is no information for Pr-144m.

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Nuclide Name	Half Life (days)	Photon Energy (MeV)	Cloudshine (rem-m^3/Ci-sec)	Groundshine (rem-m^2/μCi-day)	Effective Inhalation (rem/Ci)
H-3 (WTR)	4.51E+03	0.00E+00	1.22E-06	0.00E+00	6.66E+01
H-3 (GAS)	4.51E+03	0.00E+00	1.22E-06	0.00E+00	6.66E-03
Be-10	5.84E+08	0.00E+00	4.14E-05	1.32E-07	3.55E+04
C-14 (ORG)	2.09E+06	0.00E+00	8.29E-07	5.15E-09	2.15E+03
C-14 (GAS)	2.09E+06	0.00E+00	8.29E-07	5.15E-09	2.29E+01
Na-22	9.49E+02	2.19E+00	4.00E-01	6.71E-04	4.81E+03
P-32	1.43E+01	0.00E+00	3.66E-04	9.30E-07	1.26E+04
S-35	8.74E+01	0.00E+00	8.99E-07	5.37E-09	5.18E+03
Cl-36	1.10E+08	1.55E-04	8.25E-05	2.15E-07	2.70E+04
Ca-41	5.11E+07	4.19E-04	0.00E+00	0.00E+00	3.52E+02
Ca-45	1.63E+02	4.35E-08	3.19E-06	1.47E-08	9.99E+03
Sc-46	8.38E+01	2.01E+00	3.69E-01	6.17E-04	2.52E+04
Cr-51	2.77E+01	3.26E-02	5.59E-03	9.85E-06	1.18E+02
Mn-54	3.13E+02	8.35E-01	1.51E-01	2.60E-04	5.55E+03
Fe-55	9.86E+02	1.69E-03	0.00E+00	0.00E+00	1.41E+03
Co-57	2.71E+02	1.25E-01	2.08E-02	3.68E-05	2.04E+03
Co-58	7.08E+01	9.75E-01	1.76E-01	3.04E-04	5.92E+03
Fe-59	4.45E+01	1.19E+00	2.21E-01	3.58E-04	1.37E+04
Ni-59	2.74E+07	2.41E-03	0.00E+00	0.00E+00	4.81E+02
Co-60	1.92E+03	2.50E+00	4.66E-01	7.51E-04	3.70E+04
Ni-63	3.50E+04	0.00E+00	0.00E+00	0.00E+00	1.78E+03
Zn-65	2.44E+02	5.84E-01	1.07E-01	1.77E-04	5.92E+03
Ga-67	3.26E+00	1.58E-01	2.66E-02	4.76E-05	8.88E+02
Kr-85	3.91E+03	2.21E-03	4.40E-04	8.44E-07	0.00E+00
Rb-86	1.87E+01	9.45E-02	1.78E-02	2.98E-05	3.44E+03
Rb-87	1.72E+13	0.00E+00	6.73E-06	2.81E-08	1.85E+03
Sr-89	5.05E+01	8.45E-05	2.86E-04	7.26E-07	2.26E+04
Sr-90	1.06E+04	0.00E+00	2.79E-05	9.08E-08	1.33E+05
Y-90	2.67E+00	1.69E-06	7.03E-04	1.70E-06	5.18E+03
Y-91	5.85E+01	3.61E-03	9.62E-04	1.84E-06	2.63E+04
Zr-93	5.58E+08	0.00E+00	0.00E+00	0.00E+00	3.70E+04
Zr-95	6.40E+01	7.39E-01	1.33E-01	2.31E-04	1.78E+04
Nb-94	7.41E+06	1.57E+00	2.85E-01	4.89E-04	4.07E+04
Nb-95m	3.61E+00	6.83E-02	1.08E-02	2.00E-05	2.92E+03
Nb-95	3.52E+01	7.66E-01	1.38E-01	2.39E-04	5.55E+03
Mo-99	2.75E+00	2.60E-01	4.60E-02	8.09E-05	3.36E+03

Nuclide Name	Gonad Inhalation (rem-Ci)	Lung Inhalation (rem/Ci)	Marrow Inhalation (rem-Ci)	COMIDA Name	A1 Limit (Ci)	A2 Limit (Ci)
H-3 (WTR)	6.66E+01	6.66E+01	6.66E+01	NONE	1080	1080
H-3 (GAS)	6.66E-03	6.66E-03	6.66E-03	NONE	1080	1080
Be-10	1.78E+03	2.00E+05	5.92E+03	Be-10	541	13.5
C-14 (ORG)	2.15E+03	2.15E+03	2.11E+03	NONE	1080	54.1
C-14 (GAS)	2.29E+01	2.29E+01	2.29E+01	NONE	1080	54.1
Na-22	3.00E+03	3.29E+03	5.55E+03	Na-22	13.5	13.5
P-32	6.29E+02	8.88E+04	7.77E+03	P-32	8.11	8.11
S-35	2.85E+01	4.44E+04	2.74E+01	S-35	1080	54.1
Cl-36	9.99E+02	2.04E+05	9.62E+02	Cl-36	541	13.5
Ca-41	3.48E+00	5.18E+02	1.96E+02	Ca-41	1080	1080
Ca-45	4.44E+01	7.77E+04	2.66E+03	Ca-45	1080	24.3
Sc-46	3.26E+02	1.63E+05	5.92E+03	Sc-46	13.5	13.5
Cr-51	1.18E+01	5.18E+02	4.81E+01	Cr-51	811	811
Mn-54	5.55E+02	2.22E+04	4.07E+03	Mn-54	27	27
Fe-55	3.52E+02	1.11E+03	6.66E+02	Fe-55	1080	1080
Co-57	1.85E+02	1.18E+04	4.81E+02	Co-57	216	216
Co-58	4.44E+02	3.29E+04	2.07E+03	Co-58	27	27
Fe-59	1.37E+03	8.51E+04	4.81E+03	Fe-59	21.6	21.6
Ni-59	2.89E+02	1.33E+03	4.07E+01	Ni-59	1080	1080
Co-60	7.03E+03	1.78E+05	1.07E+04	Co-60	10.8	10.8
Ni-63	7.03E+02	8.14E+03	1.04E+02	Ni-63	1080	811
Zn-65	2.29E+03	1.78E+04	4.07E+03	Zn-65	54.1	54.1
Ga-67	1.41E+01	5.92E+03	6.29E+01	Ga-67	162	162
Kr-85	0.00E+00	0.00E+00	0.00E+00	NONE	541	270
Rb-86	2.74E+03	2.81E+03	5.18E+03	Rb-86	8.11	8.11
Rb-87	1.44E+03	1.52E+03	2.85E+03	Rb-87	100000	100000
Sr-89	1.70E+02	1.67E+05	4.07E+03	Sr-89	16.2	13.5
Sr-90	1.04E+03	7.03E+05	4.07E+04	Sr-90	5.41	2.7
Y-90	1.33E+01	2.59E+04	3.70E+02	Y-90	5.41	5.41
Y-91	2.22E+02	1.85E+05	1.07E+04	Y-91	8.11	8.11
Zr-93	8.51E+00	9.99E+03	2.15E+03	Zr-93	1080	5.41
Zr-95	5.92E+02	1.15E+05	8.51E+03	Zr-95	27	24.3
Nb-94	4.44E+03	2.07E+05	1.26E+04	Nb-94	16.2	16.2
Nb-95m	3.03E+01	2.00E+04	2.37E+02	Nb-95m	27	24.3
Nb-95	2.22E+02	3.52E+04	1.52E+03	Nb-95	27	27
Mo-99	5.66E+01	1.99E+04	1.72E+02	Mo-99	16.2	13.5

Nuclide Name	Half Life (days)	Photon Energy (MeV)	Cloudshine (rem-m^3/Ci-sec)	Groundshine (rem-m^2/μCi-day)	Effective Inhalation (rem/Ci)
Tc-99	7.77E+07	0.00E+00	5.99E-06	2.49E-08	1.48E+04
Rh-102	1.06E+03	2.13E+00	3.85E-01	6.65E-04	2.55E+04
Ru-103	3.93E+01	4.70E-01	8.33E-02	1.48E-04	8.89E+03
Ru-106	3.68E+02	2.01E-01	3.85E-02	6.78E-05	1.04E+05
Pd-107	2.37E+09	0.00E+00	0.00E+00	0.00E+00	3.15E+02
Cd-109	4.64E+02	2.64E-02	1.09E-03	7.19E-06	2.44E+04
Ag-111	7.45E+00	2.63E-02	4.77E-03	8.54E-06	5.55E+03
In-111	2.83E+00	4.05E-01	6.88E-02	1.25E-04	8.51E+02
Cd-113m	4.96E+03	0.00E+00	2.57E-05	8.41E-08	1.92E+05
Sn-113	1.15E+02	2.28E-02	1.41E-03	6.81E-06	9.99E+03
In-114m	4.95E+01	9.42E-02	1.55E-02	2.93E-05	2.26E+04
Cd-115m	4.46E+01	2.19E-02	4.33E-03	7.48E-06	3.63E+03
Sn-119m	2.93E+02	1.15E-02	3.74E-04	3.32E-06	8.14E+03
Sn-121m	2.01E+04	4.94E-03	2.23E-04	1.56E-06	1.67E+04
Sn-123	1.29E+02	6.88E-03	1.49E-03	2.68E-06	3.00E+04
Te-123m	1.20E+02	1.48E-01	2.41E-02	4.57E-05	1.48E+04
Sb-124	6.02E+01	1.80E+00	3.39E-01	5.47E-04	2.37E+04
I-125	6.01E+01	4.20E-02	1.93E-03	1.37E-05	5.18E+03
Te-125m	5.80E+01	3.55E-02	1.68E-03	1.15E-05	1.26E+04
Sb-125	1.01E+03	4.30E-01	7.47E-02	1.36E-04	1.78E+04
Sn-125	9.64E+00	3.11E-01	5.85E-02	9.62E-05	1.15E+04
Sb-126	1.24E+01	2.83E+00	5.07E-01	8.89E-04	1.04E+04
Sn-126	3.65E+07	5.65E-02	7.81E-03	1.75E-05	1.04E+05
Sb-127	3.85E+00	6.85E-01	1.23E-01	2.16E-04	6.29E+03
Te-127m	1.09E+02	1.12E-02	5.44E-04	3.61E-06	2.74E+04
Te-127	3.90E-01	4.86E-03	8.95E-04	1.66E-06	4.81E+02
I-129	5.73E+09	2.46E-02	1.41E-03	8.25E-06	5.55E+04
Te-129m	3.36E+01	3.75E-02	5.74E-03	1.21E-05	2.44E+04
I-131	8.04E+00	3.80E-01	6.73E-02	1.20E-04	8.88E+03
Te-132	3.26E+00	2.33E-01	3.81E-02	7.29E-05	7.40E+03
Xe-133m	2.19E+00	4.07E-02	5.07E-03	1.30E-05	0.00E+00
Xe-133	5.25E+00	4.60E-02	5.77E-03	1.47E-05	0.00E+00
Cs-134	7.52E+02	1.55E+00	2.80E-01	4.86E-04	3.37E+04
Cs-135	8.40E+08	0.00E+00	2.09E-06	1.06E-08	1.15E+04
Cs-137	1.10E+04	5.69E-02	1.07E-01	1.77E-04	3.59E+04
Ba-140	1.27E+01	1.82E-01	3.17E-02	5.75E-05	1.89E+04

Nuclide Name	Gonad Inhalation (rem-Ci)	Lung Inhalation (rem/Ci)	Marrow Inhalation (rem-Ci)	COMIDA Name	A1 Limit (Ci)	A2 Limit (Ci)
Tc-99	3.40E+01	1.15E+05	3.15E+01	Tc-99	1080	24.3
Rh-102	9.62E+03	7.40E+04	1.11E+04	Rh-102	13.5	13.5
Ru-103	3.07E+02	6.67E+04	9.25E+02	Ru-103	54.1	24.3
Ru-106	9.62E+03	7.03E+05	6.29E+03	Ru-106	5.41	5.41
Pd-107	7.03E-01	1.96E+03	3.59E+00	Pd-107	100000	100000
Cd-109	1.89E+03	1.04E+05	7.03E+02	Cd-109	1080	27
Ag-111	5.18E+01	3.70E+04	6.66E+01	Ag-111	16.2	13.5
In-111	3.07E+01	3.55E+03	1.74E+02	In-111	54.1	54.1
Cd-113m	2.74E+04	1.63E+05	1.59E+03	Cd-113m	541	2.43
Sn-113	2.55E+02	7.03E+04	1.70E+03	Sn-113	108	108
In-114m	1.18E+03	1.15E+05	3.37E+04	In-114m	8.11	8.11
Cd-115m	4.44E+01	2.15E+04	1.18E+02	Cd-115m	8.11	8.11
Sn-119m	1.33E+02	5.92E+04	7.03E+02	Sn-119m	1080	1080
Sn-121m	5.18E+02	1.22E+05	1.55E+03	Sn-121m	1080	24.3
Sn-123	4.07E+02	2.26E+05	2.78E+03	Sn-123	16.2	13.5
Te-123m	1.26E+02	1.11E+05	3.37E+03	Te-123m	189	189
Sb-124	5.18E+02	1.63E+05	4.44E+03	Sb-124	16.2	13.5
I-125	7.77E+00	5.92E+03	6.29E+01	I-125	541	54.1
Te-125m	4.44E+01	9.62E+04	1.52E+03	Te-125m	811	243
Sb-125	7.77E+02	1.17E+05	3.15E+03	Sb-125	54.1	24.3
Sn-125	8.88E+01	7.40E+04	1.22E+03	Sn-125	5.41	5.41
Sb-126	3.66E+02	6.29E+04	2.37E+03	Sb-126	10.8	10.8
Sn-126	9.25E+03	6.29E+05	2.41E+04	Sn-126	8.11	8.11
Sb-127	7.40E+01	4.07E+04	4.44E+02	Sb-127	541	13.5
Te-127m	1.30E+02	2.07E+05	7.40E+03	Te-127m	541	13.5
Te-127	2.70E+00	2.78E+03	6.29E+00	NONE	541	13.5
I-129	5.18E+01	6.66E+04	1.26E+02	I-129	10000	100000
Te-129m	1.70E+02	1.78E+05	4.44E+03	Te-129m	16.2	13.5
I-131	3.44E+01	3.55E+04	2.07E+02	I-131	81.1	13.5
Te-132	2.52E+02	3.70E+04	8.14E+02	Te-132	10.8	10.8
Xe-133m	0.00E+00	0.00E+00	0.00E+00	NONE	16.2	13.5
Xe-133	0.00E+00	0.00E+00	0.00E+00	NONE	541	541
Cs-134	7.40E+03	1.78E+05	1.15E+04	Cs-134	16.2	13.5
Cs-135	8.51E+02	8.51E+04	6.66E+02	Cs-135	1080	24.3
Cs-137	5.55E+03	2.18E+05	6.29E+03	Cs-137	54.1	13.5
Ba-140	1.89E+02	1.30E+05	2.37E+03	Ba-140	10.8	10.8

Nuclide Name	Half Life (days)	Photon Energy (MeV)	Cloudshine (rem-m^3/Ci-sec)	Groundshine (rem-m^2/μCi-day)	Effective Inhalation (rem/Ci)
Ce-141	3.25E+01	7.61E-02	1.27E-02	2.36E-05	1.18E+04
Pr-143	1.36E+01	8.90E-09	7.77E-05	2.24E-07	8.14E+03
Ce-144	2.84E+02	5.27E-02	1.04E-02	1.88E-05	1.33E+05
Pm-146	2.02E+03	7.53E-01	1.33E-01	2.37E-04	7.77E+04
Nd-147	1.10E+01	1.40E-01	2.29E-02	4.44E-05	7.77E+03
Pm-147	9.58E+02	4.37E-06	2.56E-06	1.09E-08	1.85E+04
Sm-147	3.87E+13	0.00E+00	0.00E+00	0.00E+00	3.55E+07
Pm-148m	4.13E+01	1.99E+00	3.58E-01	6.27E-04	1.89E+04
Sm-151	3.29E+04	1.34E-05	1.34E-07	1.61E-09	1.48E+04
Eu-152	4.87E+03	1.14E+00	2.09E-01	3.52E-04	1.55E+05
Gd-153	2.42E+02	1.05E-01	1.37E-02	3.39E-05	7.77E+03
Eu-154	3.21E+03	1.22E+00	2.27E-01	3.80E-04	1.96E+05
Eu-155	1.81E+03	6.05E-02	9.21E-03	1.89E-05	2.55E+04
Eu-156	1.52E+01	1.31E+00	2.50E-01	3.93E-04	1.26E+04
Tb-160	7.23E+01	1.12E+00	2.05E-01	3.45E-04	2.59E+04
Ho-166m	4.38E+05	1.74E+00	3.13E-01	5.43E-04	4.44E+05
Tm-170	1.29E+02	5.46E-03	8.25E-04	1.89E-06	2.59E+04
Hf-175	7.00E+01	3.68E-01	6.25E-02	1.16E-04	4.44E+03
Hf-181	4.24E+01	5.55E-01	9.69E-02	1.75E-04	1.85E+04
W-181	1.21E+02	4.04E-02	5.18E-03	1.26E-05	2.81E+04
Ta-182	1.15E+02	1.29E+00	2.37E-01	3.93E-04	2.81E+04
W-185	7.51E+01	5.67E-05	1.99E-05	5.88E-08	4.44E+02
W-188	6.94E+01	1.90E-03	3.34E-04	6.14E-07	2.11E+03
Ir-192	7.40E+01	8.11E-01	1.45E-01	2.57E-04	1.92E+04
Tl-202	1.22E+01	4.67E-01	8.07E-02	1.47E-04	7.03E+02
Tl-204	1.38E+03	1.13E-03	2.07E-04	4.73E-07	1.44E+03
Bi-210	5.01E+00	0.00E+00	1.22E-04	3.36E-07	3.44E+05
Pb-210	8.14E+03	4.81E-03	2.09E-04	7.93E-07	4.07E+06
Po-210	1.38E+02	8.50E-06	1.54E-06	2.65E-09	1.22E+07
Pb-212	4.43E-01	1.48E-01	2.54E-02	4.57E-05	6.25E+05
Ra-223	1.14E+01	1.33E-01	2.25E-02	4.09E-05	2.74E+07
Ra-224	3.66E+00	9.89E-03	1.74E-03	3.06E-06	1.11E+07
Ac-225	1.00E+01	1.79E-02	2.67E-03	5.05E-06	2.74E+07
Ra-225	1.48E+01	1.37E-02	1.03E-03	4.25E-06	2.33E+07
Ra-226	5.84E+05	6.74E-03	1.17E-03	2.06E-06	1.30E+07
Ac-227	7.95E+03	2.31E-04	2.15E-05	5.02E-08	8.14E+08

Nuclide Name	Gonad Inhalation (rem-Ci)	Lung Inhalation (rem/Ci)	Marrow Inhalation (rem-Ci)	COMIDA Name	A1 Limit (Ci)	A2 Limit (Ci)
Ce-141	7.77E+01	8.88E+04	1.07E+03	Ce-141	270	13.5
Pr-143	2.78E+00	5.55E+04	4.44E+02	Pr-143	108	13.5
Ce-144	6.29E+03	6.66E+05	5.18E+04	Ce-144	5.41	5.41
Pm-146	6.29E+03	9.99E+04	1.92E+04	Pm-146	5	0.5
Nd-147	1.70E+01	5.55E+04	7.03E+02	Nd-147	108	13.5
Pm-147	1.48E+00	7.03E+04	4.81E+03	Pm-147	1080	24.3
Sm-147	1.18E+03	1.70E+07	4.07E+06	Sm-147	100000	100000
Pm-148m	4.81E+02	1.15E+05	7.40E+03	Pm-148m	13.5	13.5
Sm-151	5.18E-01	1.11E+04	1.81E+03	Sm-151	1080	108
Eu-152	1.37E+04	1.44E+05	2.59E+05	Eu-152	24.3	24.3
Gd-153	8.51E+01	4.07E+04	3.44E+03	Gd-153	270	135
Eu-154	1.22E+04	2.92E+05	3.70E+04	Eu-154	21.6	13.5
Eu-155	3.11E+02	6.66E+04	5.55E+03	Eu-155	541	54.1
Eu-156	1.59E+02	8.14E+04	2.33E+03	Eu-156	16.2	13.5
Tb-160	4.44E+02	1.67E+05	1.04E+04	Tb-160	24.3	13.5
Ho-166m	3.59E+04	2.07E+05	3.55E+04	Ho-166m	16.2	8.11
Tm-170	3.22E+02	1.78E+05	1.70E+04	Tm-170	108	13.5
Hf-175	1.70E+02	2.52E+04	2.59E+03	Hf-175	81.1	81.1
Hf-181	2.04E+02	1.37E+05	4.07E+03	Hf-181	54.1	24.3
W-181	1.18E+03	1.96E+05	5.18E+03	W-181	811	811
Ta-182	1.18E+03	1.96E+05	5.18E+03	Ta-182	21.6	13.5
W-185	9.25E+00	7.77E+01	1.63E+02	W-185	1080	24.3
W-188	2.96E+01	9.62E+01	1.07E+03	W-188	5.41	5.41
Ir-192	8.51E+02	1.33E+05	2.55E+03	Ir-192	27	13.5
Tl-202	3.70E+02	4.07E+02	4.44E+02	Tl-202	54.1	54.1
Tl-204	8.51E+02	9.25E+02	8.51E+02	Tl-204	108	13.5
Bi-210	1.74E+02	2.85E+06	1.70E+02	Bi-210	16.2	13.5
Pb-210	2.41E+05	1.81E+07	1.22E+06	Pb-210	16.2	0.243
Po-210	1.81E+05	9.62E+07	1.67E+06	Po-210	1080	0.541
Pb-212	1.92E+03	5.18E+06	6.29E+03	Pb-212	8.11	8.11
Ra-223	1.22E+04	2.29E+08	2.78E+05	Ra-223	16.2	0.811
Ra-224	9.25E+03	9.25E+07	1.48E+05	Ra-224	8.11	1.62
Ac-225	1.33E+05	2.26E+08	9.25E+05	Ac-225	16.2	0.27
Ra-225	5.55E+04	1.92E+08	7.40E+05	Ra-225	16.2	0.541
Ra-226	8.88E+04	9.99E+07	3.70E+05	Ra-226	8.11	0.541
Ac-227	2.89E+08	3.66E+08	5.55E+07	Ac-227	1080	0.000541

Nuclide Name	Half Life (days)	Photon Energy (MeV)	Cloudshine (rem-m^3/Ci-sec)	Groundshine (rem-m^2/μCi-day)	Effective Inhalation (rem/Ci)
Th-227	1.87E+01	1.06E-01	1.81E-02	3.32E-05	3.15E+07
Ra-228	2.10E+03	4.14E-09	0.00E+00	0.00E+00	9.62E+06
Th-228	6.98E+02	3.30E-03	3.40E-04	7.51E-07	1.18E+08
Th-229	2.68E+06	9.54E-02	1.42E-02	2.73E-05	4.07E+08
Th-230	2.81E+07	1.55E-03	6.44E-05	2.40E-07	1.59E+08
Pa-231	1.20E+07	4.76E-02	6.36E-03	1.30E-05	5.18E+08
Th-232	5.13E+12	1.33E-03	3.23E-05	1.76E-07	1.67E+08
U-232	2.63E+04	2.19E-03	5.25E-05	3.23E-07	2.89E+07
Pa-233	2.70E+01	2.03E-01	3.46E-02	6.23E-05	1.22E+04
U-233	5.79E+07	1.31E-03	6.03E-05	2.29E-07	1.33E+07
Th-234	2.41E+01	9.34E-03	1.25E-03	2.66E-06	2.44E+04
U-234	8.92E+07	1.73E-03	2.82E-05	2.39E-07	1.30E+07
Np-235	3.96E+02	7.09E-03	1.89E-04	1.17E-06	1.55E+03
U-235	2.57E+11	1.54E-01	2.66E-02	4.73E-05	1.15E+07
Np-236a	4.20E+07	1.36E-01	1.98E-02	3.84E-05	1.18E+07
Pu-236	1.04E+03	2.09E-03	2.35E-05	3.14E-07	7.40E+07
U-236	8.55E+09	1.57E-03	1.85E-05	2.08E-07	1.18E+07
Np-237	7.82E+08	3.43E-02	3.81E-03	9.17E-06	8.51E+07
Pu-237	4.53E+01	5.23E-02	7.47E-03	1.49E-05	1.30E+03
U-237	6.75E+00	1.42E-01	2.21E-02	4.25E-05	6.29E+03
Np-238	2.12E+00	5.50E-01	1.01E-01	1.69E-04	7.77E+03
Pu-238	3.20E+04	1.81E-03	1.81E-05	2.68E-07	1.70E+08
U-238	1.63E+12	1.36E-03	1.26E-05	1.76E-07	1.07E+07
Np-239	2.36E+00	1.72E-01	2.85E-02	5.21E-05	3.44E+03
Pu-239	8.78E+06	7.96E-04	1.57E-05	1.17E-07	1.85E+08
Pu-240	2.39E+06	1.73E-03	1.76E-05	2.57E-07	1.85E+08
Am-241	1.58E+05	3.24E-02	3.03E-03	8.79E-06	1.55E+08
Pu-241	5.26E+03	2.54E-06	2.68E-07	6.17E-10	3.33E+06
Am-242m	5.55E+04	5.11E-03	1.17E-04	9.65E-07	1.37E+08
Cm-242	1.63E+02	1.83E-03	2.11E-05	3.06E-07	1.92E+07
Pu-242	1.37E+08	1.44E-03	1.48E-05	2.13E-07	1.78E+08
Am-243	2.69E+06	5.59E-02	8.07E-03	1.71E-05	1.52E+08
Cm-243	1.04E+04	1.34E-01	2.18E-02	4.00E-05	1.15E+08
Cm-244	6.61E+03	1.70E-03	1.82E-05	2.81E-07	9.99E+07
Pu-244	3.01E+10	1.22E-03	1.10E-05	1.78E-07	1.74E+08
Cm-245	3.10E+06	9.55E-03	1.47E-02	2.78E-05	1.55E+08

Nuclide Name	Gonad Inhalation (rem-Ci)	Lung Inhalation (rem/Ci)	Marrow Inhalation (rem-Ci)	COMIDA Name	A1 Limit (Ci)	A2 Limit (Ci)
Th-227	1.04E+05	2.59E+08	1.22E+06	Th-227	243	0.27
Ra-228	1.85E+06	2.92E+07	1.92E+06	Ra-228	16.2	1.08
Th-228	1.30E+07	6.66E+08	3.29E+07	Th-228	8.11	0.0108
Th-229	1.22E+08	4.44E+08	2.78E+07	Th-229	8.11	0.000811
Th-230	7.03E+07	2.60E-05	1.41E+07	Th-230	54.1	0.00541
Pa-231	1.52E+04	1.07E+08	9.25E+06	Pa-231	16.2	0.00162
Th-232	7.77E+07	7.40E+07	1.18E+07	Th-232	100000	100000
U-232	4.81E+06	1.44E+08	2.29E+06	U-232	81.1	0.00811
Pa-233	3.40E+01	9.25E+04	1.37E+03	Pa-233	135	24.3
U-233	5.18E+05	9.99E+07	3.18E+05	U-233	270	0.027
Th-234	5.92E+02	1.70E+05	7.03E+03	Th-234	5.41	5.41
U-234	5.18E+05	9.62E+07	3.15E+05	U-234	270	0.027
Np-235	4.07E+02	5.92E+03	1.04E+03	Np-235	1080	1080
U-235	4.81E+05	8.51E+07	2.92E+05	U-235	100000	100000
Np-236a	8.88E+06	5.92E+05	1.67E+05	Np-236a	189	0.027
Pu-236	2.37E+07	1.33E+08	1.26E+07	Pu-236	189	0.0189
U-236	4.81E+05	8.88E+07	2.96E+05	U-236	270	0.027
Np-237	5.18E+07	9.99E+07	1.04E+07	Np-237	54.1	0.00541
Pu-237	6.29E+01	8.51E+03	4.81E+02	Pu-237	541	541
U-237	1.44E+01	4.44E+04	1.33E+02	U-237	5	0.5
Np-238	3.44E+03	1.96E+04	9.99E+02	Np-238	5	0.5
Pu-238	7.03E+07	1.26E+08	1.37E+07	Pu-238	54.1	0.00541
U-238	4.44E+05	8.14E+07	2.92E+05	U-238	100000	100000
Np-239	3.70E+01	2.33E+04	1.30E+02	Np-239	162	13.5
Pu-239	7.77E+07	1.11E+08	1.30E+07	Pu-239	54.1	0.00541
Pu-240	7.77E+07	1.11E+08	1.30E+07	Pu-240	54.1	0.00541
Am-241	1.22E+08	1.22E+08	8.14E+06	Am-241	54.1	0.00541
Pu-241	1.55E+06	2.85E+04	1.33E+04	Pu-241	1080	0.27
Am-242m	1.18E+08	1.96E+07	4.07E+06	Am-242m	54.1	0.00541
Cm-242	1.78E+06	1.30E+08	4.07E+06	Cm-242	1080	0.27
Pu-242	7.40E+07	1.04E+08	1.22E+07	Pu-242	54.1	0.00541
Am-243	1.22E+08	1.15E+08	7.77E+06	Am-243	54.1	0.00541
Cm-243	8.51E+07	1.37E+08	8.51E+06	Cm-243	81.1	0.00811
Cm-244	6.66E+07	1.37E+08	8.51E+06	Cm-244	108	0.0108
Pu-244	7.40E+07	9.62E+07	1.22E+07	Pu-244	8.11	0.00541
Cm-245	1.26E+08	1.18E+08	8.14E+06	Cm-245	54.1	0.00541

Nuclide Name	Half Life (days)	Photon Energy (MeV)	Cloudshine (rem-m^3/Ci-sec)	Groundshine (rem-m^2/μCi-day)	Effective Inhalation (rem/Ci)
Cm-246	1.73E+06	1.51E-03	1.65E-05	2.51E-07	1.55E+08
Cm-247	5.69E+09	3.14E-01	5.55E-02	9.91E-05	1.44E+08
Cm-248	1.24E+08	1.16E-03	1.25E-05	1.92E-07	5.55E+08
Cf-252	9.63E+02	1.20E-03	1.87E-05	2.31E-07	7.40E+07

Nuclide Name	Gonad Inhalation (rem-Ci)	Lung Inhalation (rem/Ci)	Marrow Inhalation (rem-Ci)	COMIDA Name	A1 Limit (Ci)	A2 Limit (Ci)
Cm-246	1.22E+08	1.18E+08	8.14E+06	Cm-246	54.1	0.00541
Cm-247	1.15E+08	1.04E+08	7.40E+06	Cm-247	54.1	0.00541
Cm-248	4.44E+08	2.33E+08	3.00E+07	Cm-248	1.08	0.00135
Cf-252	1.48E+07	1.92E+08	2.81E+07	Cf-252	2.7	0.027

APPENDIX D. HIGHWAY VEHICLE DENSITIES

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History

While the data contained in this report can be utilized to provide traffic density figures for any application where such values would be appropriate, they were gathered to aid users of RADTRAN. Historically, standard inputs for the vehicle densities on highways in the United States were the values shown in Table 1 below. The population density zone divisions are those employed by the routing software TRAGIS, which was developed by Oak Ridge National Laboratories (Johnson and Michelhaugh, 2000), and provide the mileage of each route that falls within each of these three zones. A 1975 traffic study (NRC, 1977) resulted in the traffic density values shown in the Table D-1; these values have been used in the RADTRAN program since 1977. Recognition that traffic densities have changed during the past 30 years warranted reinvestigation of those traffic density figures, resulting in this report.

Table D-1: Historical Values Used for Traffic Density in RADTRAN Calculations

Population Density Zone	Traffic Density
0 persons/km^2 – 54 persons/km^2: *Rural*	470 vehicles/hr
54 persons/km^2 – 1284 persons/km^2: *Suburban*	780 vehicles/hr
1284 persons/km^2 and up: *Urban*	2800 vehicles/hr

Approach

The present study was conducted by combining state traffic data (which provided average traffic counts) and U.S. Census 2000 data (which allowed the geographic correlation of the traffic counts with the three familiar population density zones). This process also allowed the division of traffic counts into those for two highway categories: U.S. highways and interstate highways. An additional benefit of this approach is that it provides the ability to define traffic densities for each state individually, or to combine the values for several states along a shipment route to determine an average traffic density along that route.

2000 U.S. Census Data

The U. S. Census (http://www.census.gov) divides the entire population of the country by state, subdivides it by county, further subdivides it into tracts, and finally includes individual census blocks as its smallest subdivision. The size of census blocks is roughly of inverse proportion to the number of inhabitants in each block; therefore, census blocks in less populated areas of the United States, such as the Mojave Desert, will often be several thousand times larger than census blocks in the middle of Manhattan where population is abundant. Within each census block the ethnicities, ages, and other identifying characteristics of inhabitants are compiled. A digital version of this census data for the 2000 Census was imported into the software program ArcView GIS, the geographic information system used in this analysis. Also used in the GIS program was a digital map of all of the U.S. and Interstate highways in the continental U.S.

The GIS program was configured to divide each highway into 1.6-kilometer-long pieces, and to calculate the number of persons within each 1.6-km-by-1.6-km square centered on the highway. Each of these numbers was compared to the limits of the three population density zones, and assigned a corresponding letter ("R" for rural zones, "S" for suburban zones, and "U" for urban zones).

Traffic Count Data

Most states, through their local departments of transportation, compile annual reports containing average traffic counts for their U.S., interstate, and state highways. The only highways considered for this analysis were U.S. and interstate highways, because these are the highways most frequented by radioactive material shipments. These counts are typically carried out using one of two types of equipment: a permanent collector, which is permanently located at the counting site, or a temporary counter, which can be moved frequently among several locations; most use optical or pressure sensing technology to obtain counts of passing vehicles.

This raw data is refined to obtain Average Annual Daily Traffic Counts (AADTs) for each considered public road. In the case of permanent counters, a yearly count total is simply divided by the number of days in the counting year to produce this value; for temporary counters, however, the process is more complicated. Because this type of counter is only present at the count location for a few hours or days during the count year, the raw count data that they produce are extrapolated using a variety of weighting algorithms, the contents of which are outside the scope of this report. The AADT for each considered road is then integrated into an annual report. This analysis used reports from the most recent count year, 2003.

While most states have a system in place similar to the one described above, some states do not currently have such a count report. These states have necessarily been unable to provide data for this traffic study and will not be included in this report. This is discussed in more detail in the next bolded section.

Data Synthesis

Once each highway is divided into rural, suburban, and urban portions via the GIS program, the traffic count data is similarly divided into 1.6-km-long portions and the average traffic density is calculated for each section. Every portion of the traffic data is then matched up with its corresponding population density zone designation. Finally, the traffic densities of all of the sections of the road that fall into each designation are averaged; thus, traffic densities divided into population density categories are calculated for each highway. These are compiled for each state, and then all of the traffic densities for each highway type within the state are distance averaged using Equation D-1. This is done to determine an average state-wide value for each highway type and population density zone.

$$TD_{i,j} = \frac{\sum_{k=1}^{N} TD_{i,j,k} \cdot L_{i,j,k}}{\sum_{k=1}^{N} L_{i,j,k}} \qquad \text{Equation D-1}$$

Where:

$TD_{i,j}$ ≡ State-Wide Average Traffic Density for the Current i,j Set
i ≡ Highway Type (U.S. or Interstate)
j ≡ Population Density Zone (Rural, Suburban, or Urban)
k ≡ Highway Index
N ≡ Number of Highways in the Current i,j Set
$TD_{i,j,k}$ ≡ Average Traffic Density for the Current i,j,k Set
$L_{i,j,k}$ ≡ Length for the Current i,j,k Set

This process was completed for each state included in the analysis, and the results are included in this report. Also included are the average traffic density values for each highway type divided into ten U.S. Environmental Protection Agency (EPA) regions, shown in Table 2. Finally, the data is also combined into a national average.

Limitations of Study

The U.S. Census only counts people where they reside; therefore, the data does not take into account the day-time influx of population into commercial and industrial centers. Also, only states whose traffic count data were readily available were considered for reporting. States that do not have the capability of developing or maintaining electronic traffic counts were automatically discounted, in addition to Hawaii and Alaska, which were considered to be relatively free of radiological shipments. In all, 21 states were included in this analysis; these states are shown in dark gray in Figure D-1. The figure also shows, in light gray, states whose data are available, but for which an analysis was not completed.

Table D-2: United States Divided into 10 EPA Regions

Region	States Included in Region
1	Connecticut, Massachusetts, Maine, New Hampshire, Rhode Island, Vermont
2	New Jersey, New York
3	Delaware. Maryland, Pennsylvania, Virginia, West Virginia
4	Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee
5	Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin
6	Arkansas, Louisiana, New Mexico, Oklahoma, Texas
7	Iowa, Kansas, Missouri, Nebraska
8	Colorado, Montana, North Dakota, South Dakota, Utah
9	Arizona, California, Nevada
10	Idaho, Oregon , Washington

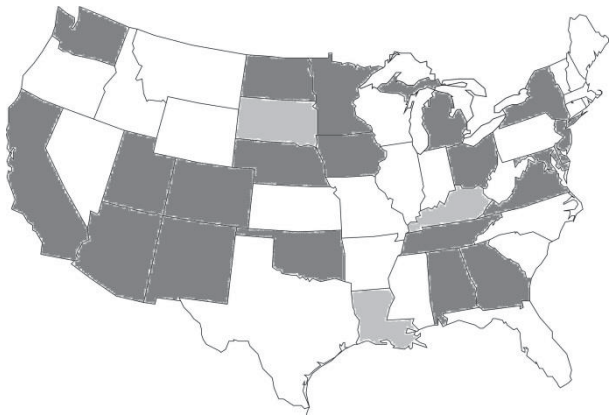

Figure D-1: States currently considered in this report (dark gray), and states whose data are available, but for which an analysis was not completed (light gray)

State-by-State Average Traffic Densities

Tables D-3 and D-4 on the following two pages list a state-by-state summary of the vehicle densities in each of the three population density zones. Each traffic density is compared to the historical values from Table D-1, and the total length of all of the sections of highway with each zone designation is given as the final column under each zone type.

Table D-3: State-by-State Traffic Densities Divided into Population Density Zones—Interstate Highways

Interstate Highways									
	Rural Zone			Suburban Zone			Urban Zone		
State	Traffic Density (vehicles/hr)	Departure from Historic Value (470 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (780 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (2800 vehicles/hr)	Length (km)
Alabama	1161	1477%	813	2138	174%	541	3784	35%	90
Arizona	825	76%	1401	2144	175%	288	4208	50%	145
California	1924	309%	1660	4509	478%	589	7914	183%	1205
Colorado	1248	166%	1036	2342	200%	338	4051	45%	127
Delaware	7187	1429%	3	3651	368%	19	3350	20%	34
Georgia	1537	227%	956	3286	321%	730	7340	162%	208
Iowa	992	111%	956	1588	104%	171	2157	-23%	80
Maryland	1953	315%	159	3656	369%	294	6100	118%	230
Michigan	1219	159%	827	2309	196%	792	4648	66%	360
Minnesota	738	57%	895	2296	194%	383	4376	56%	196
Nebraska	833	77%	677	1685	116%	50	3075	10%	40
New Jersey	2609	455%	105	3322	326%	277	4527	62%	225
New Mexico	654	39%	1195	1208	55%	349	3347	20%	58
New York	835	78%	927	1818	133%	1236	4002	43%	508
North Dakota	293	-38%	793	575	-26%	95	1063	-62%	29
Ohio	1824	288%	637	2655	240%	1002	4241	51%	476
Oklahoma	1175	150%	1046	1786	129%	352	2778	-1%	88
Tennessee	1570	234%	780	2735	251%	674	4121	47%	130
Utah	731	56%	1113	1958	151%	256	3940	41%	142
Vermont	439	-7%	259	726	-7%	230	2129	-24%	5
Washington	1123	139%	616	2670	242%	362	5624	101	206

Table D-4: State-by-State Traffic Densities Divided into Population Density Zones—U.S. Highways

U.S Highways									
	Rural Zone			Suburban Zone			Urban Zone		
State	Traffic Density (vehicles/hr)	Departure from Historic Value (470 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (780 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (2800 vehicles/hr)	Length (km)
Alabama	313	-33%	2888	607	-22%	2650	1077	-62%	230
Arizona	169	-64%	2296	364	-53%	348	2718	-3%	109
California	628	34%	1401	2231	186%	483	5771	106%	455
Colorado	320	-32%	4953	665	-15%	1250	1069	-62%	389
Delaware	800	70%	69	1134	45%	217	1712	-39%	63
Georgia*									
Iowa	280	-40%	3627	306	-61%	1073	481	-83%	262
Maryland	915	95%	302	1156	48%	365	1634	-42%	161
Michigan	471	0%	1911	786	1%	1268	1771	-37%	237
Minnesota	249	-47%	3768	523	-33%	1393	1323	-53%	296
Nebraska	161	-66%	4827	289	-63%	1014	857	-69%	177
New Jersey	916	95%	124	948	21%	656	1521	-46%	478
New Mexico	175	-63%	4693	450	-42%	759	563	-80%	93
New York	290	-38%	829	453	-42%	1022	887	-68%	296
North Dakota	129	-73%	2233	182	-77%	348	666	-76%	21
Ohio	363	-23%	2225	551	-29%	2029	816	-71%	774
Oklahoma	279	-41%	3911	354	-55%	1234	716	-74%	132
Tennessee*									
Utah	386	-18%	1585	509	-35%	328	1147	-59%	135
Vermont	288	-39%	467	377	-52%	451	422	-85%	66
Washington	322	-31%	1883	482	-38%	763	718	-74%	140

* These states only provided interstate highway data; U.S. highway data was not available.

Average Regional Traffic Densities

Tables D-5 and D-6 were constructed by taking existing data for all of the states within each region and distance-averaging them into the three familiar zone types. It is important to note that these values should be seen only as an approximation of the final traffic density values for each region; in Region 6, for example, Texas will eventually play a major role in defining the traffic densities of the region.

National Average Traffic Densities

Tables D-7 and D-8 display the results obtained when the state-wide data are distance-averaged over the entire country. These are the results that directly compare with the historical values found in Table D-1.

Table D-5: Average Regional Traffic Densities Divided into Population Density Zones—Interstate Highways

Interstate Highways									
	Rural Zone			Suburban Zone			Urban Zone		
Region	Traffic Density (vehicles/hr)	Departure from Historic Value (470 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (780 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (2800 vehicles/hr)	Length (km)
1	439	-7%	259	726	-7%	230	2129	-24%	5
2	1015	116%	1031	2094	168%	1512	4163	49%	734
3	2056	338%	163	3655	369%	314	5748	105%	264
4	1427	204%	2549	2776	256%	1945	5611	100%	428
5	1200	155%	2359	2466	216%	2177	4408	57%	1033
6	897	91%	2241	1498	92%	702	3003	7%	146
7	926	97%	1633	1610	106%	220	2463	-12%	121
8	795	69%	2943	1956	151%	689	3708	32%	298
9	1421	202%	3062	3732	379%	877	7517	168%	1350
10	1123	139%	616	2670	242%	362	5624	101%	206

Table D-6: Average Regional Traffic Densities Divided into Population Density Zones—U.S. Highways

U.S. Highways									
	Rural Zone			Suburban Zone			Urban Zone		
Region	Traffic Density (vehicles/hr)	Departure from Historic Value (470 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (780 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (2800 vehicles/hr)	Length (km)
1	288	-39%	467	377	-52%	451	422	-85%	66
2	371	-21%	953	647	-17%	1678	1278	-54%	774
3	894	90%	372	1148	47%	582	1656	-41%	224
4	313	-34%	2888	607	-22%	2650	1077	-62%	230
5	335	-29%	7905	606	-22%	4690	1104	-61%	1307
6	222	-53%	8605	391	-50%	1994	653	-77%	225
7	212	-55%	8454	298	-62%	2087	632	-77%	439
8	283	-40%	8771	551	-29%	1926	1072	-62%	545
9	343	-27%	3697	1449	86%	830	5180	85%	565
10	322	-31%	1883	482	-38%	763	718	-74%	140

Table D-7: National Average Traffic Densities Divided into Population Density Zones—Interstate Highways

Interstate Highways								
Rural Zone			Suburban Zone			Urban Zone		
Traffic Density (vehicles/hr)	Departure from Historic Value (470 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (780 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (2800 vehicles/hr)	Length (km)
1119	*138%*	16856	2463	*26%*	9028	5385	*93%*	4584

Table D-8: National Average Traffic Densities Divided into Population Density Zones—U.S. Highways

U.S. Highways								
Rural Zone			Suburban Zone			Urban Zone		
Traffic Density (vehicles/hr)	Departure from Historic Value (470 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (780 vehicles/hr)	Length (km)	Traffic Density (vehicles/hr)	Departure from Historic Value (2800 vehicles/hr)	Length (km)
283	*-40%*	43993	590	*-24%*	28400	1575	*-44%*	4515

Results

This study reveals the importance of distinguishing between road types, which is captured in Figure D-2. The figure displays the departure of each traffic density in Tables D-7 and D-8 from the historical values found in Table D-1 (NRC, 1977). While traffic density on U.S. highways shows a decrease from the historically used values, interstate highways show a dramatic increase over those values.

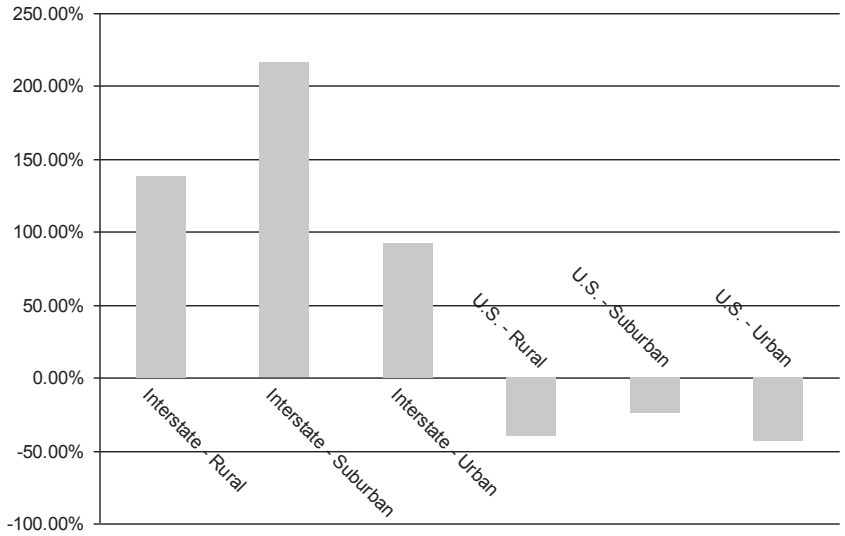

Figure D-2: Departure of National Average Traffic Densities from Historical Values

APPENDIX E. RADTRAN OUTPUT

```
 RRRR  AAA  DDDD TTTTT RRRR AAA N  N  6    000 000
 R  R A A D  D  T  R  R A A NN N 6  0  0 0  0
 R  R A  A D  D  T  R  R A  A N N N 6  0  0 0  0
 RRRR A  A D  D  T  RRRR A  A N N N 6666  0  0 0  0
 R R  AAAAA D  D  T  R R  AAAAA N  N 6  6  0 0 0  0
 R R A   A D  D  T  R R A  A N  N 6  6 0  0 0  0
 R  R A   A DDDD  T  R  R A  A N  N 6 6 6 * 0 0 0 000

      RADTRAN 6.00 September 28, 2007

     Copyright 2007 Sandia Corporation

RADTRAN 6.02 February 01, 2013

      INPUT ECHO
RADTRAN 6  July 2008
 && DEFAULT PARAMETERS IN TABLE 1 APPENDIX B The text following the ampersands are
remarks (Fig. 3)
 && NEUTRAL STABILITY AND WORST CASE
 && 45GWD FUEL
 && TI=14 MREM@1 M.
 && INCLUDES NAC
 && LOS ALSO
 && REMARK
 TITLE NACSTCCRUD_7_2011 Title in Fig, 4
 INPUT STANDARD This standard input includes many default values in RADTRAN. It is no longer
used but is retained for RADTRAN TO RUN.
  STD: 0 18         && DIMEN=NSEV NAREAS
  STD: 3 3 0        && PARM=IANA ISEN IPSQSB
  STD: .TRUE. .FALSE. .FALSE.    && FORM = UNIT, SI-OUTPUT, SI-INPUT
  STD: 2.3E12       && NEVAL FOR CF252
  STD: 9.25E5 5.77E6 1.27E6     && RPCTHY FOR I125, I129, I131
  STD: 0.0 0.0 0.0 0.0 0.0     && TRANSFER GAMMA [COEF(1,0-4]
  STD: 7.42E-3 2.02E-2 6.17E-5 3.17E-8 0.0 && TRANSFER NEUTRON [COEF(2,0-4]
  STD: 30 24        && MITDDIST MITDVEL
  STD: 1 2 .0018       && ITRAIN FMINCL DDRWEF

           ▪

OUTPUT CI_REM Units are controlled by the "preference" choice (Fig. 5)
 FORM UNIT Output is in dose units ("NON-UNIT" = LCF output) (Fig. 4)
 DIMEN 2 3 18 2 conditional probabilities (Fig. 19), 3 LOS conditional probabilities (Fig. 32), 18
isopleths (Fig. 26)
 PARM 0 3 3 0 0=economic model disabled (1= economic model enabled) (Fig. 4); 3=both incident-
free and accident analyses (Fig. 4); 3=longest output (Fig. 4); 0 = national average weather
(1=Pasquill classes; 2= user-defined)(Fig. 26)
 SEVERITY "Severities" are conditional probabilities (Fig. 19)
 NPOP=1 rural population density (Fig. 14)
  NMODE=1 highway (2=rail; 3=waterway) (Fig. 3)
  0.00282 conditional probability of release accident (Fig. 19)
 9.94E-4 conditional probability of release accident (Fig. 19)
 NPOP=2 suburban population density (Fig. 14)
  NMODE=1
  0.00282
 9.94E-4
 NPOP=3 urban population density (Fig. 14)
```

NMODE=1
0.00282
9.94E-4

RELEASE **accident release fractions listed by physical/chemical group (Fig. 21)**
GROUP=CRUD
RFRAC **release fractions (Fig. 21)**
0.001 **release fraction associated with conditional probability 0.00282**
0.001 **release fraction associated with conditional probability 9.94E-04**
AERSOL **aerosol fractions (Fig. 22)**
1.0 **aerosol fraction associated with release fraction 0.001 and conditional probability 0.00282**
0.0 **aerosol fraction associated with release fraction 0.0 and conditional probability 9.94E-04**
RESP **fraction of aerosol that is inhaled into the lung (Fig. 22)**
0.01 **respirable fraction associated with aerosol fraction 1.0, release fraction 0.001 and conditional probability 0.00282**
0.01 **respirable fraction associated with aerosol fraction 0.0, release fraction 0.001 and conditional probability 9.94E-04**
DEPVEL 0.0323 **deposition velocity of CRUD particles (Fig. 20)**

LOS_SHIELD **Loss of shielding (LOS) conditional probabilities (Fig. 32)**
NPOP=1
ACIDNT_PRB **accident probability (Fig. 32)**
0.99 **conditional probability of LOS accident 1** 0.005 **conditional probability of LOS accident 2** 0.005 **conditional probability of LOS accident 2**
FRAC_LOST **fraction lost (Fig. 33)**
0.0 **shielding fraction lost in LOS accident 1** 0.1 **shielding fraction lost in LOS accident 2** 0.9 **shielding fraction lost in LOS accident 3**
NPOP=2
ACIDNT_PRB
0.99 0.005 0.005
FRAC_LOST
0.0 0.1 0.9
NPOP=3
ACIDNT_PRB
0.99 0.005 0.005
FRAC_LOST
0.0 0.1 0.9

PACKAGE **(Fig.6)** NACSTC **package name** 14.0 **package external dose rate** 0.77 **gamma fraction** 0.23 **neutron fraction** 4.9 **package longest dimension**
CO60 **radionuclide in package (Figs 7,8)** 225.42 **curies of radionuclide** CRUD **physical/chemical group of radionuclide**
END

VEHICLE -1 **minus sign indicates exclusive use (Fig. 11)** NACSTC **vehicle name (Fig. 10)** 1.400000E01 **vehicle external dose rate (Fig. 10)** 0.77 **gamma fraction (Fig.11)** 0.23 **neutron fraction (Fig.11)** 4.9 **vehicle longest dimension (Fig. 10)** 1.0 **number of shipments (Fig. 10)** 2.0 **crew size (Fig. 11)** 3.5 **crew distance (m) (Fig. 11)** 0.38 **crew shielding (Fig. 11)** 2.5 **crew view (vehicle short dimension) (Fig.11)**
NACSTC 1.0 **number of packages on vehicle (Fig. 11)**

FLAGS
IACC 2 **not used**
IUOPT 2 **default residential shielding factors: R: 0% shielding (factor =1); S:13% shielding (factor = 0.87); U: 98.8% shielding (factor = 0.012) (Fig. 29)**
REGCHECK 0 **no regulatory constraints (1= crew dose and external dose regulatory constraints imposed) (Fig. 29)**

MODSTD **list of default parameter values (Fig. 29)**
DISTOFF FREEWAY 3.000000E01 3.000000E01 8.000000E02 **shoulder, minimum, and maximum distances from moving vehicle on a freeway**
DISTOFF SECONDARY 2.700000E01 3.000000E01 8.000000E02 **shoulder, minimum, and maximum distances from moving vehicle on a freeway**

DISTOFF STREET 5.000000E00 8.000000E00 8.000000E02 **pavement , minimum, and maximum distances from moving vehicle on a city street**
DISTON **perpendicular distances between vehicles on route (m)**
FREEWAY 1.500000E01
SECONDARY 3.000000E00
STREET 3.000000E00
ADJACENT 4.000000E00
BDF 5.000000E-02 **fraction of outside air in urban buildings**
BRATE 3.300000E-04 **breathing rate (m^3/sec)**
CULVL 2.000000E-01 **cleanup level (μCi/m^2)**
EVACUATION 1.000000E00 **evacuation time (days)**
GECON 1.000000E-04 **not used**
INTERDICT 4.000000E01 **interdiction level (multiplier on CULVL)**
LCFCON 6.000000E-04 **LCF/rem (public)** 6.000000E-04 **LCF/rem (occupational)**
SURVEY 1.000000E01 **survey interval (days)**
UBF 5.200000E-01 **fraction of urban population in buildings**
USWF 4.800000E-01 **fraction of urban population on the sidewalk**
CAMPAIGN 8.330000E-02 **length of shipping campaign (year)**
MITDDIST 3.000000E01 **distance from vehicle to MEI (m)**
MITDVEL 2.400000E01 **minimum speed of vehicle passing MEI (km/hr)**
RPD 6.000000E00 **ratio of pedestrians (on sidewalk along route) to urban residential population**
RR 1.000000E00 **rural shielding factor (0% shielding)**
RU 1.800000E-02 **urban shielding factor (98.8% shielding)**
RS 8.700000E-01 **suburban shielding factor (13% shielding)**
SMALLPKG 5.000000E-01 **minimum package dimension (m)**
RPCTHYROID **I-131 dose conversion factor**
EOF

LINK **(Figs. 14 and 15)** R **link name** NACSTC **vehicle name** 1.0 **link length (km)** 102 **speed on link (km/hr)** 795 **vehicles/hour** 1.0 **persons/vehicle** 17.0 **population density (persons/km^2)** 2.89E-7 **accidents/km** 0.0363 **fatalities/accident** R **population designator** 1 **primary highway (interstate)** 0.5 **fraction of land in agriculture**
LINK S NACSTC 1.0 102 1956 1.0 300.0 2.89E-7 0.0363 S 1 0.0
LINK U NACSTC 1.0 85 3708 1.0 2400.0 2.89E-7 0.0363 U 1 0.0

STOP **(Fig. 16)** RURAL_1 **stop name** NACSTC **vehicle name** 10.0 **minimum distance (m)** 20.0 **maximum distance (m)** 17.0 **exposed persons/km^2** 1.0 **residential shielding** 1.0 **time at stop (hours)**
STOP RURAL_2 NACSTC 10.0 50.0 17.0 1.0 1.0

LOS_STOP STOP_LOSS1 NACSTC 10.0 **minimum distance (m)** 20.0 **maximum distance (m)** 17.0 **exposed persons/km^2** 1.0 **residential shielding** 1.0 **time at stop (hours)**
LOS_STOP STOP_LOSS2 NACSTC 10.0 50.0 17.0 1.0 1.0

EOF
END OF INPUT ECHO.I

****
Repeat of input file with some additions

NUMBER OF ACCIDENT SEVERITY CATEGORIES = 2
NUMBER OF LOSS OF SHIELDING PROBABILITIES = 3
These seven items are a repeat of PARM and DIMEN jn the input file,
NUMBER OF DEPOSITION AREAS (ISOPLETHS) = 18
INCIDENT FREE AND ACCIDENT ANALYSES INVOKED
DETAILED INPUT, FULL OUTPUT, SENSITIVITY ANALYIS EDIT & POPULATION RISK BY LINK & FULL ECONOMIC OUTPUT
USER SUPPLIED OR NATIONAL AVERAGE WEATHER DILUTION INPUT
HISTORICAL UNITS ON INPUT
HISTORICAL UNITS ON OUTPUT
DOSE UNITS ON OUTPUT

INGESTION FILE = RT6_Ingestion.BIN **From Title screen.**

PACKAGE AND MATERIAL CHARACTERISTICS INPUT DATA

MATERIAL	DIMENSION (METERS)	EFFECTIVE DIMENSION	K(0) METERS SQ.	FRACTION GAMMA	FRACTION NEUTRON	DOSE RATE (mrem/hr)
NACSTC	4.900E+00	4.513E+00	1.060E+01	7.700E-01	2.300E-01	1.400E+01

K(0) IS DOSE RATE CONVERSION FACT

VEHICLE CHARACTERISTICS INPUT DATA
****

VEHICLE NAME NACSTC
MODE TYPE HIGHWAY
EXCLUSIVE USE YES
DOSE RATE (mrem/hr) 1.40E+01
FRACTION OF GAMMA FOR VEH 7.70E-01
FRACTION OF NEUTRON FOR V 2.30E-01
K(0) (SQ. METERS) 1.06E+01
VEHICLE SIZE (M) 4.90E+00
EFFECTIVE SIZE (M) 4.51E+00
NUMBER OF SHIPMENTS 1.00E+00
NUMBER OF CREW 2.00E+00
CREW DISTANCE (M) 3.50E+00
CREW DOSE ADJUSTMENT FACT 3.80E-01
CREW EXPOSER WIDTH (M) 2.50E+00
EFFECTIVE EXPOSER WIDTH 2.50E+00
K(0) (SQ M) CREW EXPOSURE 5.06E+00

VEHICLE	MATERIAL	NO.PACKAGES
NACSTC	NACSTC	1.00E+00

TRANSFER COEFFICIENTS: MU A(1) A(2) A(3) A(4)

GAMMA	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
NEUTRON	7.420E-03	2.020E-02	6.170E-05	3.170E-08	0.000E+00

The "transfer coefficients" are the coefficients of the Taylor expansion of the basic equation for dose from the spherical virtual source (Section 4(?)) to a receptor at some distance from the source.

The values below are from the Parameters screen,

DISTANCES (METERS)	FREEWAY	SECONDARY STREET	RAIL	WATER	ADJACENT
OFFLINK:					
MINIMUM DISTANCE	3.00E+01	2.70E+01	5.00E+00	3.00E+01	2.00E+02
SIDEWALK + MINIMUM	3.00E+01	3.00E+01	8.00E+00	3.00E+01	2.00E+02
MAXIMUM DISTANCE	8.00E+02	8.00E+02	8.00E+02	8.00E+02	1.00E+03
ONLINK:					
OPPOSITE DIRECTION	1.50E+01	3.00E+00	3.00E+00	3.00E+00	4.00E+00
ADJACENT VEHICLE		4.00E+00			

STOP RELATED INPUT DATA
****

STOP	RURAL1	RURAL2
VEHICLE	NACSTC	NACSTC
PERSONS	1.70E+01	1.70E+01
MINIMUM DISTANCE(M)	1.00E+01	1.00E+01
MAXIMUM DISTANCE(M)	2.00E+01	5.00E+01
SHIELDING FACTOR	1.00E+00	1.00E+00

TIME (HR) 1.00E+00 1.00E+00

LINK RELATED INPUT DATA
****
LINK LINK_R LINK_S LINK_U
VEHICLE NACSTC NACSTC NACSTC
DISTANCE (KM) 1.00E+00 1.00E+00 1.00E+00
PERSONS PER VEHICLE 1.00E+00 1.00E+00 1.00E+00
SPEED (KM/HR) 1.02E+02 1.02E+02 8.50E+01
POPULATION DENSITY (#/KM^2) 1.70E+01 3.00E+02 2.40E+03
VEHICLE DENSITY (#/HR) 7.95E+02 1.96E+03 3.71E+03
ACCIDENT RATE/KM 2.89E-07 2.89E-07 2.89E-07
FATALITIES/ACCIDENT 3.63E-02 3.63E-02 3.63E-02
ZONE RURAL SUBURBAN URBAN
ROAD TYPE FREEWAY FREEWAY FREEWAY
FARMING FRACTION 5.00E-01 0.00E+00 0.00E+00

LOSS OF SHIELDING STOP RELATED INPUT DATA
****
LOSS SHIELDING STOPSTOP_LOSS1 STOP_LOSS2
VEHICLE NACSTC NACSTC
ZONE RURAL RURAL
NUMB PEOLPE EXPOSED 1.70E+01 1.70E+01
MINIMUM DISTANCE(M) 1.00E+01 1.00E+01
MAXIMUM DISTANCE(M) 2.00E+01 5.00E+01
SHIELDING FACTOR 1.00E+00 1.00E+00
EXPOSURE TIME (HR) 1.00E+00 1.00E+00

Chart of fractions of lead shielding lost v. conditional probability of loss.
RURAL SUBURBAN URBAN
FAIL FRAC PROB FAIL FRAC PROB FAIL FRAC PROB
0.00E+00 9.90E-01 0.00E+00 9.90E-01 0.00E+00 9.90E-01
1.00E-01 5.00E-03 1.00E-01 5.00E-03 1.00E-01 5.00E-03
9.00E-01 5.00E-03 9.00E-01 5.00E-03 9.00E-01 5.00E-03

ISOTOPE RELATED INPUT DATA
****

NUCLIDE CURIES WASTE RELEASE RESUSPENSION
PER PKG LIMIT GROUP FACTOR
NACSTC **pkg name** (CI/M^3)
CO60 **nuclide** 2.25E+02 **Ci/pkg** 7.00E+02 **LLW Class C limit – not used** CRUD **group** 1.03E+00
The package name, radionuclide(s), physical/chemical group, and Ci/pkg are on the Radionuclides screen.
All nuclides for each package will be listed.

The dose conversion factors for all radionuclides loaded into packages, including the half-life in days are shown below (from the internal radionuclide library
NUCLIDE HALF GAMMA AIR IMMERISON (SHINE) DCF INGESTION NEUTRON
LIFE ENERGY CLOUD GROUND NUCLIDE EMISSION
NACSTC (Days) (MeV/nt) (rem-m^3/Ci-s)(rem-m^2/uCi-d) neu/sec/CI
CO60 1.92E+03 2.50E+00 4.66E-01 7.51E-04 Co-60 0.00E+00

NUCLIDE INHALATION DOSE CONVERSION FACTORS
LUNG MARROW THYROID EFFECTIVE
NACSTC (REM/CI) (REM/CI) (REM/CI) (REM/CI)
CO60 1.78E+05 1.07E+04 0.00E+00 3.70E+04

RELEASE RELATED INPUT DATA

****

RELEASE FRACTIONS

GROUP SEVER: 1 SEVER: 2
CRUD 1.00E-03 1.00E-03

DEPOSITION VELOCITIES
GROUP M/SEC
CRUD 3.23E-02

ACCIDENT SEVERITY FRACTIONS
FOR HIGHWAY

ZONE SEVER: 1 SEVER: 2
RURAL 2.82E-03 9.94E-04
SUBURBAN 2.82E-03 9.94E-04
URBAN 2.82E-03 9.94E-04

AEROSOLIZED FRACTION OF RELEASED MATERIAL

GROUP SEVER: 1 SEVER: 2
CRUD 1.00E+00 0.00E+00

RESPIRABLE FRACTION OF AEROSOLS (BELOW 10 MICRONS AED)

GROUP SEVER: 1 SEVER: 2
CRUD 1.00E-02 1.00E-02

HEALTH RELATED INPUT DATA
****

These threshold values are taken from various literature sources. When RADTRAN is run, the appropriate RADTRAN output is compared with these values. If that ouput (e.g. the accident output for marrow dose) is larger that any of the listed values, an early morbidity and/or early mortality will be reported in the output.

EARLY MORBIDITY THRESHOLD VALUE FOR LUNG 5.000E+02 REM
EARLY MORBIDITY THRESHOLD VALUE FOR MARROW/WHOLE BODY 5.000E+01 REM
EARLY MORBIDITY THRESHOLD VALUE FOR THYROID 2.000E+02 REM

EARLY FATALITY PROBABILITIES (EF)

DOSE(REM) EF MARROW DOSE(REM) EF LUNG "**EF" - effective**
680.00 1.00000 1525.00 1.00000
670.00 0.99999 1500.00 0.99999
660.00 0.99998 1475.00 0.99997
650.00 0.99996 1450.00 0.99991
640.00 0.99992 1425.00 0.99974
630.00 0.99983 1400.00 0.99933
620.00 0.99967 1375.00 0.99840
610.00 0.99938 1350.00 0.99653
600.00 0.99889 1325.00 0.99306
590.00 0.99808 1300.00 0.98709
580.00 0.99679 1275.00 0.97755
570.00 0.99482 1250.00 0.96331
560.00 0.99192 1225.00 0.94326

550.00 0.98776 1200.00 0.91656
540.00 0.98199 1175.00 0.88274
530.00 0.97423 1150.00 0.84178
520.00 0.96406 1125.00 0.79420
510.00 0.95111 1100.00 0.74095
500.00 0.93502 1075.00 0.68335
490.00 0.91551 1050.00 0.62293
480.00 0.89237 1025.00 0.56130
470.00 0.86552 1000.00 0.50000
460.00 0.83499 975.00 0.44042
450.00 0.80096 950.00 0.38372
440.00 0.76371 925.00 0.33077
430.00 0.72363 900.00 0.28218
420.00 0.68123 875.00 0.23830
410.00 0.63706 850.00 0.19925
400.00 0.59172 825.00 0.16498
390.00 0.54583 800.00 0.13529
380.00 0.50000 775.00 0.10988
370.00 0.45481 750.00 0.08837
360.00 0.41078 725.00 0.07038
350.00 0.36838 700.00 0.05548
340.00 0.32798 675.00 0.04329
330.00 0.28990 650.00 0.03341
320.00 0.25438 625.00 0.02549
310.00 0.22155 600.00 0.01922
300.00 0.19150 575.00 0.01430
290.00 0.16425 550.00 0.01050
280.00 0.13977 525.00 0.00759
270.00 0.11797 500.00 0.00000
260.00 0.09872
250.00 0.08188
240.00 0.06729
230.00 0.05475
220.00 0.04408
210.00 0.03510
200.00 0.02761
190.00 0.02143
180.00 0.01639
170.00 0.01234
160.00 0.00913
150.00 0.00000

DISPERSAL ACCIDENT INPUT DATA
****

AREADA (M SQ)	CENTER LINE(M)	DILUTION FACTOR*
4.590E+02	3.300E+01	3.420E-03
1.530E+03	6.800E+01	1.720E-03
3.940E+03	1.050E+02	8.580E-04
1.250E+04	2.440E+02	3.420E-04
3.040E+04	3.690E+02	1.720E-04
6.850E+04	5.610E+02	8.580E-05
1.760E+05	1.018E+03	3.420E-05
4.450E+05	1.628E+03	1.720E-05
8.590E+05	2.308E+03	8.580E-06
2.550E+06	4.269E+03	3.420E-06
4.450E+06	5.468E+03	1.720E-06
1.030E+07	1.114E+04	8.580E-07
2.160E+07	1.310E+04	3.420E-07
5.520E+07	2.133E+04	1.720E-07
1.770E+08	4.050E+04	8.580E-08

```
   4.890E+08  6.999E+04  5.420E-08
   8.120E+08  8.986E+04  4.300E-08
   1.350E+09  1.209E+05  3.420E-08

* DILUTION FACTOR UNITS ARE (CI-SEC/M**3/CI-RELEASED)


   OTHER DISPERSAL ACCIDENT INPUT PARAMETERS
   ****************************************

BUILDING DOSE FACTOR      (BDF) = 5.000E-02
CONTAMINATION CLEAN UP LEVEL(micro-CI/M^2)(CULVL) = 2.000E-01
BREATHING RATE (M**3/SEC)     (BRATE) = 3.300E-04
INTERDICTION THRESHOLD (Ci/micro-Ci) (INTERDICT) = 4.000E+01
EVACUATION TIME (DAYS)    (EVACUATION) = 1.000E+00
SURVEY INTERVAL (DAYS)     (SURVEY) = 1.000E+01
CAMPAIGN LENGTH (YEARS)     (TIMEYR) = 8.330E-02
FRACTION OF URBAN AREAS WITH BUILDINGS  (UBF) = 5.200E-01
FRACTION OF URBAN AREAS WITH SIDEWALKS  (USWF) = 4.800E-01
RATIO OF SIDEWALK PEDESTRIAN DENSITY  (RPD) = 6.000E+00
MAXIMUM IN-TRANSIT DOSE DISTANCE (M)  (DMDIST) = 3.000E+01
MAXIMUM IN-TRANSIT DOSE VELOCITY (KM/H) (DMVEL) = 2.400E+01
IACC VALUE: 1=NON-DISPERSAL, 2=DISPERSAL   = 2
REGULATORY CHECK, 1=DO CHECKS, 0=NO CHECKS  = 0
BUILDING SHIELDING OPTION     (IUOPT) = 2
 RURAL SHIELDING FACTOR      = 1.000E+00
 SUBURBAN SHIELDING FACTOR      = 8.700E-01
URBAN SHIELDING FACTOR      = 1.800E-02

     INGESTION RELATED INPUT DATA
     ****************************


    COMIDA INGESTION FILE USED: RT6_Ingestion.BIN

      COMIDA FILE HEADER
COMIDA2 07/22/03 08:58:40 Ver. 1.11a, 1/28/96: avoiding use of UNIT 6 for HP

    DOSE CONVERSION FILE USED IN COMIDA
FGRDCF 07/10/03 21:45:47 Version 1.10
Implicit daughter halflives (m) less than 90 and less than 0.100 of parent

  BACKYARD FARMER INGESTION DOSE (REM/CI DEPOSITED)

    PACKAGE NUCLIDE EFFECTIVE THYROID
    NACSTC Co-60  1.328E+04 3.779E+03


 SOCIETAL INGESTION DOSE (PERSON-REM/CI DEPOSITED)

NUCLIDE GONADS BREAST LUNGS RED MAR BONE SU THYROID REMAIND EFFECTI
Co-60 1.6E+00 5.7E-01 4.5E-01 6.8E-01 4.8E-01 4.1E-01 2.6E+00 1.4E+00
      END OF INPUT EDIT


   OOO U  U TTTTT PPPP U  U TTTTT
  O  O U  U  T  P  P U  U  T
  O  O U  U  T  P  P U  U  T
  O  O U  U  T  PPPP U  U  T
  O  O U  U  T  P   U  U  T
  O  O U  U  T  P   U  U  T
   OOO UUUUU  T  P   UUUUU  T
```

RADTRAN 6.00 September 28, 2007

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NON-RADIOLOGICAL DATA (ACCIDENTS and FATALITIES)
****

HIGHWAY
NACSTC **Calculated from LINKS input**

LINK	ACCIDENT RATE	ACCIDENTS	FATALITIES
LINK_R	2.89E-07	2.89E-07	1.05E-08
LINK_S	2.89E-07	2.89E-07	1.05E-08
LINK_U	2.89E-07	2.89E-07	1.05E-08

TOTALS: 8.67E-07 3.15E-08

REGULATORY CHECKS HAVE BEEN DISABLED
********** ****** **** **** ********

CALCULATIONAL INFORMATION

IN CALCULATING THE DEPLETION FOR THE FOLLOWING GROUPS,
THE CONCENTRATIONS IN THE LISTED AREA HAVE BECOME NEGATIVE.
THE CONTAMINATION AND CONCENTRATIONS IN THE LISTED AREA AND
LARGER HAVE BEEN SET TO ZERO.

GROUP CRUD AREA 15

FOR NACSTC AREAS WITH TOTAL CONTAMINATION RATIO GREATER THAN 40.0000
(THE AREAS MARKED WITH AN 'X' ARE INTERDICTED

AREA/SEVERITY **P_C 1**	**P_C 2**	**SEVERITY, P_C = conditional probability**
1	X	-
2	X	-
3	-	-
4	-	-
5	-	-
6	-	-
7	-	-
8	-	-
9	-	-
10	-	-
11	-	-
12	-	-
13	-	-
14	-	-
15	-	-
16	-	-
17	-	-
18	-	-

The areas marked with "x" are interdicted because the Ci/m^2 exceeds the cleanup standard (Parameters screen). This does not impact the dose calculation or any other calculation.

RELEASE FRACTIONS

GROUP SEVER: 1 SEVER: 2
CRUD 1.00E-03 1.00E-03

DEPOSITION VELOCITIES
GROUP M/SEC
CRUD 3.23E-02

DILUTION FACTORS
CHI VALUES AFTER DEPLETION (CI-SEC/M**3/CI-RELEASED)

DISTANCE	CRUD
3.30E+01	3.42E-03
6.80E+01	1.72E-03
1.05E+02	7.85E-04
2.44E+02	2.82E-04
3.69E+02	1.19E-04
5.61E+02	5.05E-05
1.02E+03	1.69E-05
1.63E+03	6.74E-06
2.31E+03	2.57E-06
4.27E+03	8.34E-07
5.47E+03	2.82E-07
1.11E+04	1.15E-07
1.31E+04	3.43E-08
2.13E+04	1.33E-08
4.05E+04	4.65E-09
7.00E+04	0.00E+00
8.99E+04	0.00E+00
1.21E+05	0.00E+00

"CHI" (the Greek letter X) is concentration. The source of the downwind distance (left-hand column).is the Accident-Average Weather screen.

DEPOSITION FACTORS
CHI DEPOSITED (CI/M**2/CI-RELEASED)

DISTANCE	CRUD **Distance is downwind distance in meters.**
3.30E+01	1.10E-04
6.80E+01	5.55E-05
1.05E+02	2.54E-05
2.44E+02	9.11E-06
3.69E+02	3.86E-06
5.61E+02	1.63E-06
1.02E+03	5.45E-07
1.63E+03	2.18E-07
2.31E+03	8.30E-08
4.27E+03	2.69E-08
5.47E+03	9.11E-09
1.11E+04	3.72E-09
1.31E+04	1.11E-09
2.13E+04	4.30E-10
4.05E+04	1.50E-10
7.00E+04	0.00E+00
8.99E+04	0.00E+00
1.21E+05	0.00E+00

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1

AIR CONCENTRATION GROUND CONTAMINATION
INHALATION ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP
PATHWAY BONE
CNTR LINE LUNG MARROW THYROID (CI-S/M**3) (MICRO CI/M**2)
3.30E+01 4.53E-04 1.91E-02 9.41E-05 7.71E-04 2.49E+01
6.80E+01 2.27E-04 9.58E-03 4.73E-05 3.87E-04 1.25E+01
1.05E+02 1.04E-04 4.38E-03 2.16E-05 1.77E-04 5.72E+00
2.44E+02 3.73E-05 1.57E-03 7.76E-06 6.36E-05 2.05E+00
3.69E+02 1.58E-05 6.66E-04 3.29E-06 2.69E-05 8.70E-01
5.61E+02 6.68E-06 2.81E-04 1.39E-06 1.14E-05 3.68E-01
1.02E+03 2.23E-06 9.41E-05 4.64E-07 3.80E-06 1.23E-01
1.63E+03 8.93E-07 3.76E-05 1.86E-07 1.52E-06 4.91E-02
2.31E+03 3.40E-07 1.43E-05 7.07E-08 5.79E-07 1.87E-02
4.27E+03 1.10E-07 4.65E-06 2.30E-08 1.88E-07 6.07E-03
5.47E+03 3.74E-08 1.57E-06 7.77E-09 6.36E-08 2.05E-03
1.11E+04 1.53E-08 6.42E-07 3.17E-09 2.60E-08 8.39E-04
1.31E+04 4.54E-09 1.91E-07 9.44E-10 7.73E-09 2.50E-04
2.13E+04 1.76E-09 7.42E-08 3.66E-10 3.00E-09 9.69E-05
4.05E+04 6.16E-10 2.59E-08 1.28E-10 1.05E-09 3.39E-05
7.00E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 **Zeros occur when the**
8.99E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 **calculated dose is**
1.21E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 **negative**

PASQUILL CATEGORY A
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
3.30E+01 9.41E-05 1.36E-06 3.59E-04 1.87E-02 1.91E-02 3.31E-01 9.41E-02
6.80E+01 4.73E-05 3.42E-07 1.80E-04 9.38E-03 9.61E-03 1.66E-01 4.73E-02
1.05E+02 2.16E-05 7.15E-08 8.25E-05 4.29E-03 4.39E-03 7.59E-02 2.16E-02
2.44E+02 7.76E-06 9.23E-09 2.96E-05 1.54E-03 1.58E-03 2.73E-02 7.76E-03
3.69E+02 3.29E-06 1.65E-09 1.25E-05 6.52E-04 6.68E-04 1.16E-02 3.29E-03
5.61E+02 1.39E-06 2.95E-10 5.30E-06 2.76E-04 2.82E-04 4.88E-03 1.39E-03
1.02E+03 4.64E-07 3.30E-11 1.77E-06 9.22E-05 9.44E-05 1.63E-03 4.64E-04
1.63E+03 1.86E-07 5.27E-12 7.08E-07 3.68E-05 3.77E-05 6.52E-04 1.86E-04
2.31E+03 7.07E-08 7.66E-13 2.70E-07 1.40E-05 1.44E-05 2.49E-04 7.07E-05
4.27E+03 2.30E-08 8.07E-14 8.76E-08 4.56E-06 4.67E-06 8.07E-05 2.30E-05
5.47E+03 7.77E-09 9.23E-15 2.96E-08 1.54E-06 1.58E-06 2.73E-05 7.76E-06
1.11E+04 3.17E-09 1.54E-15 1.21E-08 6.29E-07 6.45E-07 1.11E-05 3.17E-06
1.31E+04 9.44E-10 1.36E-16 3.60E-09 1.87E-07 1.92E-07 3.32E-06 9.44E-07
2.13E+04 3.66E-10 2.05E-17 1.40E-09 7.27E-08 7.45E-08 1.29E-06 3.66E-07
4.05E+04 1.28E-10 2.51E-18 4.89E-10 2.54E-08 2.60E-08 4.50E-07 1.28E-07
7.00E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
8.99E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.21E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

RUN DATE: [07-24-2013 AT 08:05] PAGE 21

NACSTD_SAMPLEREPEAT_01_03_14

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2 **All zero because the aerosolized fraction for this conditional probability (severity) is zero.**
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP
CNTR LINE LUNG BONE MARROW THYROID (CI-S/M**3) (MICRO CI/M**2)
3.30E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

6.80E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.05E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.44E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
3.69E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
5.61E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.02E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.63E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.31E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
4.27E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
5.47E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.11E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.31E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.13E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
4.05E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
7.00E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
8.99E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.21E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

PASQUILL CATEGORY A
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
ALL VALUES WERE 0.0

INCIDENT-FREE SUMMARY
******** **** *******

IN-TRANSIT POPULATION EXPOSURE IN PERSON-REM
From Link and Vehicle screens

CREW OFF LINK ON LINK **Off-link = residents along the route**
LINK_R 4.39E-05 4.65E-07 5.55E-06 **On-link = occupants of heicles sharing the route**
LINK_S 4.39E-05 7.13E-06 1.37E-05
LINK_U 5.27E-05 1.42E-06 3.76E-05

ZONE
RURAL 4.39E-05 4.65E-07 5.55E-06
SUBURB 4.39E-05 7.13E-06 1.37E-05
URBAN 5.27E-05 1.42E-06 3.76E-05

TOTALS: 1.40E-04 9.01E-06 5.68E-05

MAXIMUM INDIVIDUAL IN-TRANSIT DOSE f**om incident-free transportation**
NACSTC 5.67E-07 REM

STOP EXPOSURE IN PERSON-REM

ANNULAR AREA RURAL1 1.14E-05
ANNULAR AREA RURAL2 2.71E-05

TOTAL: 3.86E-05

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

LINK PARAMETER IMPORTANCE CHANGE
LINK_R ----------
DISTANCE FROM PACKAGE TO CREW -8.736E-07 -1.7502 %
VELOCITY -5.547E-07 -1.1113 %
NUMBER OF SHIPMENTS 4.991E-07 1.0000 %
DISTANCE TRAVELED 4.991E-07 1.0000 %
DOSE RATE FOR VEHICLE (TI) 4.991E-07 1.0000 %
CREW DOSE ADJUSTMENT FACTOR 4.389E-07 0.8794 %
NUMBER OF CREW MEMBERS 4.389E-07 0.8794 %
NUMBER OF PEOPLE PER VEHICLE 5.554E-08 0.1113 %
TRAFFIC COUNT 5.554E-08 0.1113 %
SHIELDING FACTOR (RR,RS,RU) 4.645E-09 0.0093 %
POPULATION DENSITY 4.645E-09 0.0093 %

Same for all links.
INCIDENT-FREE IMPORTANCE ANALYSIS SUMMARY
ESTIMATES THE PERSON-REM INFLUENCE OF A ONE PERCENT INCREASE IN THE PARAMETER

STOP PARAMETER IMPORTANCE CHANGE
RURAL1 ----------
MAXIMUM DISTANCE AT STOP -3.047E-07 -2.6667 %
STOP TIME 1.143E-07 1.0000 %
POPULATION/POPULATION DENSITY 1.143E-07 1.0000 %
NUMBER OF SHIPMENTS 1.143E-07 1.0000 %
DOSE RATE FOR VEHICLE 1.143E-07 1.0000 %
MINIMUM DISTANCE AT STOP 7.617E-08 0.6667 %

Same for all stops.

NUMBER OF EXPECTED ACCIDENTS

The products of the number of accidents on each link and the conditional probability (severity)
LINK SEVER: 1 SEVER: 2
LINK_R 8.15E-10 2.87E-10
LINK_S 8.15E-10 2.87E-10
LINK_U 8.15E-10 2.87E-10

NUMBER OF EARLY FATALITIES FROM INHALATION

ALL VALUES ARE 0.0

NUMBER OF EARLY MORBIDITY CASES FROM INHALATION

ALL VALUES ARE 0.0

MAXIMUM RISK FOR INDIVIDUAL IN NEAREST ISOPLETH (DOSE IN REM)
FROM INHALATION, CLOUDSHINE, AND GROUNDSHINE EXPOSURE DURING EVACUATION

LINK SEVER: 1 SEVER: 2
LINK_R 1.59E-11 0.00E+00
LINK_S 1.59E-11 0.00E+00
LINK_U 1.59E-11 0.00E+00

LOSS OF SHIELDING STOP = STOP_LOSS1 FOR LINK = LINK_R
AVERAGE RADIOLOGICAL DOSE (P_REM)

10.0 20.0
SLMP FRAC m TO CASK m TO CASK
0.00E+00 1.37E-02 3.43E-03

1.00E-01 4.34E-01 9.95E-02
9.00E-01 4.53E+01 1.04E+01

LOSS OF SHIELDING STOP = STOP_LOSS1 FOR LINK = LINK_S
AVERAGE RADIOLOGICAL DOSE (P_REM)

10.0 20.0
SLMP FRAC m TO CASK m TO CASK
0.00E+00 1.37E-02 3.43E-03
1.00E-01 4.34E-01 9.95E-02
9.00E-01 4.53E+01 1.04E+01

LOSS OF SHIELDING STOP = STOP_LOSS1 FOR LINK = LINK_U
AVERAGE RADIOLOGICAL DOSE (P_REM)

10.0 20.0
SLMP FRAC m TO CASK m TO CASK
0.00E+00 1.37E-02 3.43E-03
1.00E-01 4.34E-01 9.95E-02
9.00E-01 4.53E+01 1.04E+01

LOSS OF SHIELDING STOP = STOP_LOSS2 FOR LINK = LINK_R
AVERAGE RADIOLOGICAL DOSE (P_REM)

10.0 20.0 50.0
SLMP FRAC m TO CASK m TO CASK m TO CASK
0.00E+00 1.37E-02 3.43E-03 5.48E-04
1.00E-01 4.34E-01 9.95E-02 1.42E-02
9.00E-01 4.53E+01 1.04E+01 1.47E+00

LOSS OF SHIELDING STOP = STOP_LOSS2 FOR LINK = LINK_S
AVERAGE RADIOLOGICAL DOSE (P_REM)

10.0 20.0 50.0
SLMP FRAC m TO CASK m TO CASK m TO CASK
0.00E+00 1.37E-02 3.43E-03 5.48E-04
1.00E-01 4.34E-01 9.95E-02 1.42E-02
9.00E-01 4.53E+01 1.04E+01 1.47E+00

LOSS OF SHIELDING STOP = STOP_LOSS2 FOR LINK = LINK_U
AVERAGE RADIOLOGICAL DOSE (P_REM)

10.0 20.0 50.0
SLMP FRAC m TO CASK m TO CASK m TO CASK
0.00E+00 1.37E-02 3.43E-03 5.48E-04
1.00E-01 4.34E-01 9.95E-02 1.42E-02
9.00E-01 4.53E+01 1.04E+01 1.47E+00

LOSS OF SHIELDING STOP ON LINK = LINK_R
MAXIMUM RADIOLOGICAL DOSE (P_REM) AT 2 M FROM CASK
STOP STOP
SLMP FRACSTOP_LOSS1STOP_LOSS2
0.00E+00 1.46E-01 1.46E-01
1.00E-01 1.81E+02 1.81E+02
9.00E-01 1.15E+03 1.15E+03

LOSS OF SHIELDING STOP ON LINK = LINK_S
MAXIMUM RADIOLOGICAL DOSE (P_REM) AT 2 M FROM CASK
STOP STOP
SLMP FRACSTOP_LOSS1STOP_LOSS2
0.00E+00 1.46E-01 1.46E-01
1.00E-01 1.81E+02 1.81E+02
9.00E-01 1.15E+03 1.15E+03

LOSS OF SHIELDING STOP ON LINK = LINK_U
MAXIMUM RADIOLOGICAL DOSE (P_REM) AT 2 M FROM CASK
STOP STOP
SLMP FRACSTOP_LOSS1STOP_LOSS2
0.00E+00 1.46E-01 1.46E-01
1.00E-01 1.81E+02 1.81E+02
9.00E-01 1.15E+03 1.15E+03

EXPECTED VALUES OF POPULATION RISK IN PERSON-REM

LINK INHALED RESUSPD CLOUDSH GROUNDSH TOTAL
LINK_R 1.15E-14 3.11E-16 4.40E-14 1.55E-12 1.61E-12
LINK_S 2.03E-13 5.49E-15 7.77E-13 2.74E-11 2.83E-11
LINK_U 4.73E-12 1.28E-13 1.81E-11 6.36E-10 6.59E-10

ZONE
RURAL 1.15E-14 3.11E-16 4.40E-14 1.55E-12 1.61E-12
SUBURB 2.03E-13 5.49E-15 7.77E-13 2.74E-11 2.83E-11
URBAN 4.73E-12 1.28E-13 1.81E-11 6.36E-10 6.59E-10

TOTALS: 4.95E-12 1.33E-13 1.89E-11 6.65E-10 6.89E-10

SOCIETAL INGESTION RISK - PERSON-REM

LINK GONADS EFFECTIVE
LINK_R 5.16E-11 4.48E-11

TOTAL 5.16E-11 4.48E-11

SOCIETAL INGESTION RISK BY ORGAN - PERSON-REM

LINK BREAST LUNGS RED MARR BONE SUR THYROID REMAINDER
LINK_R 1.78E-11 1.42E-11 2.13E-11 1.52E-11 1.27E-11 8.04E-11

TOTAL 1.78E-11 1.42E-11 2.13E-11 1.52E-11 1.27E-11 8.04E-11

EXPECTED RISK VALUES - OTHER

LINK EARLY EARLY
FATALITY MORBIDITY
LINK_R 0.00E+00 0.00E+00
LINK_S 0.00E+00 0.00E+00
LINK_U 0.00E+00 0.00E+00

TOTAL 0.00E+00 0.00E+00

LOSS OF SHIELDING RISK VALUES P_REM BY CASE

LOSS OF SHIELDING STOP STOP_LOSS1

DISTANCE 10.0 20.0
LINK =LINK_R 2.42E-01 5.57E-02
DISTANCE 10.0 20.0
LINK =LINK_S 2.42E-01 5.57E-02
DISTANCE 10.0 20.0
LINK =LINK_U 2.42E-01 5.57E-02

LOSS OF SHIELDING STOP STOP_LOSS2

DISTANCE 10.0 20.0 50.0
LINK =LINK_R 2.42E-01 5.57E-02 7.97E-03
DISTANCE 10.0 20.0 50.0
LINK =LINK_S 2.42E-01 5.57E-02 7.97E-03
DISTANCE 10.0 20.0 50.0
LINK =LINK_U 2.42E-01 5.57E-02 7.97E-03

LOSS OF SHIELDING TOTAL RISK VALUES

LINK =LINK_U
DISTANCE FROM CASK (M) = 1.00 2.00 3.00 4.00 5.00 10.00
RISK P_REM = 4.62E-06 2.08E-06 1.30E-06 9.32E-07 7.21E-07 1.40E-07

LINK =LINK_U
DISTANCE FROM CASK (M) = 1.00 2.00 3.00 4.00 5.00 10.00
RISK P_REM = 4.62E-06 2.08E-06 1.30E-06 9.32E-07 7.21E-07 1.40E-07

LINK =LINK_U
DISTANCE FROM CASK (M) = 1.00 2.00 3.00 4.00 5.00 10.00
RISK P_REM = 4.62E-06 2.08E-06 1.30E-06 9.32E-07 7.21E-07 1.40E-07

ACCIDENT RESULTS USING THE PASQUILL OPTION
Only results different from Average Weather are reported

METEOROLOGICAL INPUT DATA BASED ON PASQUILL CATEGORIES
****
PROB. A PROB. B PROB. C PROB. D PROB. E PROB. F
0.0000 0.1000 0.2000 0.5000 0.2000 0.0000

AREA (M SQ)	*PASQUILL CATEGORY A	B	C	D	E	F
4.60E+02	6.00E-03	4.00E-03	4.00E-03	4.30E-03	9.60E-03	6.20E-02
1.50E+03	1.70E-03	1.30E-03	1.10E-03	1.30E-03	3.20E-03	1.80E-02
3.90E+03	8.40E-04	5.50E-04	5.70E-04	6.50E-04	1.60E-03	8.40E-03
1.30E+04	1.70E-04	1.30E-04	1.30E-04	1.80E-04	4.00E-04	2.00E-03
3.00E+04	7.80E-05	6.00E-05	6.70E-05	9.50E-05	2.10E-04	9.20E-04
6.90E+04	2.80E-05	2.70E-05	3.00E-05	4.30E-05	1.40E-04	4.40E-04
1.80E+05	8.00E-06	1.00E-05	1.00E-05	1.80E-05	4.40E-05	2.00E-04
4.50E+05	2.20E-06	3.50E-06	5.00E-06	8.50E-06	2.10E-05	1.00E-04
8.60E+05	9.00E-07	1.60E-06	2.80E-06	5.00E-06	1.20E-05	6.20E-05
2.60E+06	1.40E-07	4.10E-07	1.00E-06	1.90E-06	4.80E-06	2.60E-05
4.50E+06	7.00E-08	2.20E-07	6.00E-07	1.30E-06	3.60E-06	1.90E-05
1.70E+07	1.10E-08	5.00E-08	1.70E-07	4.00E-07	1.40E-06	8.40E-06
2.20E+07	7.76E-09	3.20E-08	1.30E-07	3.00E-07	1.20E-06	7.00E-06
5.50E+07	2.24E-09	1.10E-08	5.70E-08	1.50E-07	6.00E-07	4.00E-06
1.80E+08	4.50E-10	2.50E-09	1.70E-08	5.50E-08	2.80E-07	2.00E-06
5.00E+08	1.13E-10	7.24E-10	6.32E-09	2.41E-08	1.38E-07	1.09E-06
8.00E+08	5.96E-11	4.09E-10	4.01E-09	1.65E-08	9.97E-08	8.22E-07

1.40E+09 2.76E-11 2.08E-10 2.33E-09 1.05E-08 6.77E-08 5.89E-07

* DILUTION FACTOR UNITS ARE (CI-SEC/M**3/CI-RELEASED)

AREA CENTER LINE DISTANCES (M)
(M SQ) A B C D E F
4.60E+02 2.40E+01 3.00E+01 3.30E+01 3.60E+01 4.20E+01 2.50E+01
1.50E+03 4.50E+01 5.40E+01 6.80E+01 7.70E+01 8.40E+01 6.00E+01
3.90E+03 6.50E+01 8.50E+01 9.80E+01 1.18E+02 1.30E+02 1.04E+02
1.30E+04 1.48E+02 1.82E+02 2.23E+02 2.61E+02 3.12E+02 2.90E+02
3.00E+04 2.21E+02 2.74E+02 3.22E+02 3.87E+02 4.68E+02 5.05E+02
6.90E+04 3.74E+02 4.17E+02 5.03E+02 6.33E+02 6.05E+02 8.57E+02
1.80E+05 5.89E+02 7.04E+02 9.25E+02 1.08E+03 1.26E+03 1.51E+03
4.50E+05 8.99E+02 1.22E+03 1.36E+03 1.73E+03 2.00E+03 2.48E+03
8.60E+05 1.20E+03 1.85E+03 1.87E+03 2.40E+03 2.85E+03 3.49E+03
2.60E+06 2.22E+03 3.80E+03 3.31E+03 4.37E+03 5.09E+03 6.51E+03
4.50E+06 2.78E+03 5.27E+03 4.40E+03 5.53E+03 6.10E+03 8.16E+03
1.70E+07 5.11E+03 1.15E+04 8.85E+03 1.15E+04 1.19E+04 1.46E+04
2.20E+07 5.72E+03 1.46E+04 1.03E+04 1.37E+04 1.35E+04 1.67E+04
5.50E+07 8.65E+03 2.56E+04 1.62E+04 2.11E+04 2.37E+04 2.49E+04
1.80E+08 1.46E+04 5.59E+04 3.17E+04 3.92E+04 4.39E+04 4.09E+04
5.00E+08 2.31E+04 1.08E+05 5.50E+04 6.56E+04 7.70E+04 6.29E+04
8.00E+08 2.82E+04 1.45E+05 7.07E+04 8.12E+04 1.01E+05 7.76E+04
1.40E+09 3.62E+04 2.06E+05 9.61E+04 1.06E+05 1.38E+05 9.71E+04

BACKYARD FARMER INGESTION DOSE (REM/CI DEPOSITED)

PACKAGE NUCLIDE EFFECTIVE THYROID
NACSTC Co-60 1.328E+04 3.779E+03

SOCIETAL INGESTION DOSE (PERSON-REM/CI DEPOSITED)

NUCLIDE GONADS BREAST LUNGS RED MAR BONE SU THYROID REMAIND EFFECTI
Co-60 1.6E+00 5.7E-01 4.5E-01 6.8E-01 4.8E-01 4.1E-01 2.6E+00 1.4E+00

OOO U U TTTTT PPPP U U TTTTT
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DEPOSITION VELOCITIES
GROUP M/SEC
CRUD 3.23E-02

DILUTION FACTORS FOR PASQUILL CATEGORY B
CHI VALUES AFTER DEPLETION (CI-SEC/M**3/CI-RELEASED)

DISTANCE CRUD
3.00E+01 4.00E-03
5.40E+01 1.30E-03
8.50E+01 5.07E-04
1.82E+02 1.12E-04
2.74E+02 4.73E-05
4.17E+02 2.02E-05
7.04E+02 7.11E-06

1.22E+03 2.34E-06
1.85E+03 1.01E-06
3.80E+03 2.51E-07
5.27E+03 1.28E-07
1.15E+04 2.86E-08
1.46E+04 1.75E-08
2.56E+04 5.99E-09
5.59E+04 1.33E-09
1.08E+05 3.78E-10
1.45E+05 2.11E-10
2.06E+05 1.06E-10

DEPOSITION FACTORS
CHI DEPOSITED (CI/M**2/CI-RELEASED)

DISTANCE CRUD
3.00E+01 1.29E-04
5.40E+01 4.19E-05
8.50E+01 1.64E-05
1.82E+02 3.61E-06
2.74E+02 1.53E-06
4.17E+02 6.54E-07
7.04E+02 2.30E-07
1.22E+03 7.55E-08
1.85E+03 3.27E-08
3.80E+03 8.10E-09
5.27E+03 4.15E-09
1.15E+04 9.24E-10
1.46E+04 5.66E-10
2.56E+04 1.93E-10
5.59E+04 4.31E-11
1.08E+05 1.22E-11
1.45E+05 6.80E-12
2.06E+05 3.44E-12

PASQUILL CATEGORY B
VEHICLE NACSTC

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP

CNTR LINE	LUNG	BONE MARROW	THYROID	(CI-S/M**3)	(MICRO CI/M**2)
3.00E+01	5.30E-04	2.23E-02	1.10E-04	9.02E-04	2.91E+01
5.40E+01	1.72E-04	7.24E-03	3.57E-05	2.93E-04	9.45E+00
8.50E+01	6.72E-05	2.83E-03	1.40E-05	1.14E-04	3.69E+00
1.82E+02	1.48E-05	6.23E-04	3.07E-06	2.52E-05	8.13E-01
2.74E+02	6.27E-06	2.64E-04	1.30E-06	1.07E-05	3.45E-01
4.17E+02	2.68E-06	1.13E-04	5.57E-07	4.56E-06	1.47E-01
7.04E+02	9.41E-07	3.96E-05	1.96E-07	1.60E-06	5.17E-02
1.22E+03	3.09E-07	1.30E-05	6.43E-08	5.27E-07	1.70E-02
1.85E+03	1.34E-07	5.64E-06	2.78E-08	2.28E-07	7.36E-03
3.80E+03	3.32E-08	1.40E-06	6.90E-09	5.65E-08	1.83E-03
5.27E+03	1.70E-08	7.16E-07	3.53E-09	2.89E-08	9.35E-04
1.15E+04	3.79E-09	1.60E-07	7.88E-10	6.45E-09	2.08E-04
1.46E+04	2.32E-09	9.78E-08	4.83E-10	3.95E-09	1.28E-04
2.56E+04	7.93E-10	3.34E-08	1.65E-10	1.35E-09	4.36E-05
5.59E+04	1.77E-10	7.43E-09	3.67E-11	3.01E-10	9.71E-06
1.08E+05	5.00E-11	2.11E-09	1.04E-11	8.52E-11	2.75E-06
1.45E+05	2.79E-11	1.17E-09	5.79E-12	4.75E-11	1.53E-06

PASQUILL CATEGORY B
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
3.00E+01 1.10E-04 1.98E-06 4.20E-04 2.18E-02 2.24E-02 3.87E-01 1.10E-01
5.40E+01 3.57E-05 2.09E-07 1.36E-04 7.09E-03 7.26E-03 1.26E-01 3.57E-02
8.50E+01 1.40E-05 3.19E-08 5.33E-05 2.77E-03 2.84E-03 4.91E-02 1.40E-02
1.82E+02 3.07E-06 1.54E-09 1.17E-05 6.10E-04 6.25E-04 1.08E-02 3.07E-03
2.74E+02 1.30E-06 2.77E-10 4.97E-06 2.59E-04 2.65E-04 4.58E-03 1.30E-03
4.17E+02 5.57E-07 5.07E-11 2.13E-06 1.11E-04 1.13E-04 1.96E-03 5.57E-04
7.04E+02 1.96E-07 6.25E-12 7.47E-07 3.88E-05 3.98E-05 6.87E-04 1.96E-04
1.22E+03 6.43E-08 6.76E-13 2.45E-07 1.28E-05 1.31E-05 2.26E-04 6.43E-05
1.85E+03 2.78E-08 1.27E-13 1.06E-07 5.52E-06 5.66E-06 9.78E-05 2.78E-05
3.80E+03 6.90E-09 7.79E-15 2.63E-08 1.37E-06 1.40E-06 2.43E-05 6.90E-06
5.27E+03 3.53E-09 2.04E-15 1.35E-08 7.01E-07 7.18E-07 1.24E-05 3.53E-06
1.15E+04 7.88E-10 1.01E-16 3.01E-09 1.56E-07 1.60E-07 2.77E-06 7.88E-07
1.46E+04 4.83E-10 3.81E-17 1.84E-09 9.58E-08 9.81E-08 1.70E-06 4.83E-07
2.56E+04 1.65E-10 4.44E-18 6.29E-10 3.27E-08 3.35E-08 5.79E-07 1.65E-07
5.59E+04 3.67E-11 2.20E-19 1.40E-10 7.28E-09 7.46E-09 1.29E-07 3.67E-08
1.08E+05 1.04E-11 1.77E-20 3.97E-11 2.06E-09 2.11E-09 3.66E-08 1.04E-08
1.45E+05 5.79E-12 5.49E-21 2.21E-11 1.15E-09 1.18E-09 2.04E-08 5.79E-09

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP
CNTR LINE LUNG BONE MARROW THYROID (CI-S/M**3) (MICRO CI/M**2)
3.00E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
5.40E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
8.50E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.82E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.74E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
4.17E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
7.04E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.22E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.85E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
3.80E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
5.27E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.15E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.46E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.56E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
5.59E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.08E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.45E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

PASQUILL CATEGORY B
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
ALL VALUES WERE 0.0

DILUTION FACTORS FOR PASQUILL CATEGORY C

CHI VALUES AFTER DEPLETION (CI-SEC/M**3/CI-RELEASED)

DISTANCE CRUD
3.30E+01 4.00E-03
6.80E+01 1.10E-03
9.80E+01 5.29E-04
2.23E+02 1.13E-04
3.22E+02 5.34E-05
5.03E+02 2.27E-05
9.25E+02 7.11E-06
1.36E+03 3.33E-06
1.87E+03 1.74E-06
3.31E+03 5.91E-07
4.40E+03 3.20E-07
8.85E+03 8.63E-08
1.03E+04 5.73E-08
1.62E+04 2.45E-08
3.17E+04 6.62E-09
5.50E+04 2.14E-09
7.07E+04 1.20E-09
9.61E+04 6.61E-10

DEPOSITION FACTORS
CHI DEPOSITED (CI/M**2/CI-RELEASED)

DISTANCE CRUD
3.30E+01 1.29E-04
6.80E+01 3.55E-05
9.80E+01 1.71E-05
2.23E+02 3.65E-06
3.22E+02 1.72E-06
5.03E+02 7.32E-07
9.25E+02 2.30E-07
1.36E+03 1.07E-07
1.87E+03 5.64E-08
3.31E+03 1.91E-08
4.40E+03 1.04E-08
8.85E+03 2.79E-09
1.03E+04 1.85E-09
1.62E+04 7.91E-10
3.17E+04 2.14E-10
5.50E+04 6.90E-11
7.07E+04 3.88E-11
9.61E+04 2.14E-11

PASQUILL CATEGORY C
VEHICLE NACSTC

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP
CNTR LINE LUNG BONE MARROW THYROID (CI-S/M**3) (MICRO CI/M**2)
3.30E+01 5.30E-04 2.23E-02 1.10E-04 9.02E-04 2.91E+01
6.80E+01 1.45E-04 6.13E-03 3.02E-05 2.48E-04 8.00E+00
9.80E+01 7.01E-05 2.95E-03 1.46E-05 1.19E-04 3.85E+00
2.23E+02 1.50E-05 6.30E-04 3.11E-06 2.55E-05 8.23E-01
3.22E+02 7.07E-06 2.98E-04 1.47E-06 1.20E-05 3.89E-01
5.03E+02 3.00E-06 1.26E-04 6.23E-07 5.11E-06 1.65E-01
9.25E+02 9.42E-07 3.96E-05 1.96E-07 1.60E-06 5.18E-02
1.36E+03 4.41E-07 1.86E-05 9.16E-08 7.50E-07 2.42E-02

1.87E+03 2.31E-07 9.73E-06 4.80E-08 3.93E-07   1.27E-02
3.31E+03 7.83E-08 3.30E-06 1.63E-08 1.33E-07   4.30E-03
4.40E+03 4.24E-08 1.79E-06 8.82E-09 7.22E-08   2.33E-03
8.85E+03 1.14E-08 4.81E-07 2.38E-09 1.95E-08   6.29E-04
1.03E+04 7.59E-09 3.19E-07 1.58E-09 1.29E-08   4.17E-04
1.62E+04 3.24E-09 1.36E-07 6.74E-10 5.52E-09   1.78E-04
3.17E+04 8.77E-10 3.69E-08 1.82E-10 1.49E-09   4.82E-05
5.50E+04 2.83E-10 1.19E-08 5.88E-11 4.82E-10   1.56E-05
7.07E+04 1.59E-10 6.69E-09 3.30E-11 2.71E-10   8.74E-06
9.61E+04 8.76E-11 3.69E-09 1.82E-11 1.49E-10   4.81E-06

PASQUILL CATEGORY C
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
3.30E+01 1.10E-04 2.04E-06 4.20E-04 2.18E-02 2.24E-02 3.87E-01 1.10E-01
6.80E+01 3.02E-05 1.54E-07 1.15E-04 6.00E-03 6.15E-03 1.06E-01 3.02E-02
9.80E+01 1.46E-05 3.57E-08 5.56E-05 2.89E-03 2.96E-03 5.12E-02 1.46E-02
2.23E+02 3.11E-06 1.63E-09 1.19E-05 6.17E-04 6.32E-04 1.09E-02 3.11E-03
3.22E+02 1.47E-06 3.63E-10 5.61E-06 2.92E-04 2.99E-04 5.17E-03 1.47E-03
5.03E+02 6.23E-07 6.53E-11 2.38E-06 1.24E-04 1.27E-04 2.19E-03 6.23E-04
9.25E+02 1.96E-07 6.44E-12 7.47E-07 3.88E-05 3.98E-05 6.88E-04 1.96E-04
1.36E+03 9.16E-08 1.41E-12 3.50E-07 1.82E-05 1.86E-05 3.22E-04 9.16E-05
1.87E+03 4.80E-08 3.88E-13 1.83E-07 9.53E-06 9.76E-06 1.69E-04 4.80E-05
3.31E+03 1.63E-08 4.45E-14 6.21E-08 3.23E-06 3.31E-06 5.72E-05 1.63E-05
4.40E+03 8.82E-09 1.31E-14 3.37E-08 1.75E-06 1.79E-06 3.10E-05 8.82E-06
8.85E+03 2.38E-09 9.49E-16 9.07E-09 4.72E-07 4.83E-07 8.35E-06 2.38E-06
1.03E+04 1.58E-09 4.18E-16 6.02E-09 3.13E-07 3.21E-07 5.54E-06 1.58E-06
1.62E+04 6.74E-10 7.63E-17 2.57E-09 1.34E-07 1.37E-07 2.37E-06 6.74E-07
3.17E+04 1.82E-10 5.58E-18 6.96E-10 3.62E-08 3.70E-08 6.41E-07 1.82E-07
5.50E+04 5.88E-11 5.82E-19 2.24E-10 1.17E-08 1.20E-08 2.07E-07 5.88E-08
7.07E+04 3.30E-11 1.83E-19 1.26E-10 6.56E-09 6.71E-09 1.16E-07 3.30E-08
9.61E+04 1.82E-11 5.57E-20 6.95E-11 3.61E-09 3.70E-09 6.40E-08 1.82E-08

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP
CNTR LINE LUNG BONE MARROW THYROID (CI-S/M**3) (MICRO CI/M**2)
3.30E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
6.80E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
9.80E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
2.23E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
3.22E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
5.03E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
9.25E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
1.36E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
1.87E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
3.31E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
4.40E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
8.85E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
1.03E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
1.62E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
3.17E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
5.50E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
7.07E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00
9.61E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00   0.00E+00

PASQUILL CATEGORY C
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
ALL VALUES WERE 0.0

DILUTION FACTORS FOR PASQUILL CATEGORY D
CHI VALUES AFTER DEPLETION (CI-SEC/M**3/CI-RELEASED)

DISTANCE	CRUD
3.60E+01	4.30E-03
7.70E+01	1.30E-03
1.18E+02	5.98E-04
2.61E+02	1.53E-04
3.87E+02	7.24E-05
6.33E+02	3.03E-05
1.08E+03	1.16E-05
1.73E+03	4.91E-06
2.40E+03	2.56E-06
4.37E+03	8.85E-07
5.53E+03	4.96E-07
1.15E+04	1.36E-07
1.37E+04	7.07E-08
2.11E+04	3.30E-08
3.92E+04	9.27E-09
6.56E+04	2.36E-09
8.12E+04	8.21E-10
1.06E+05	3.81E-10

DEPOSITION FACTORS
CHI DEPOSITED (CI/M**2/CI-RELEASED)

DISTANCE	CRUD
3.60E+01	1.39E-04
7.70E+01	4.19E-05
1.18E+02	1.93E-05
2.61E+02	4.95E-06
3.87E+02	2.34E-06
6.33E+02	9.79E-07
1.08E+03	3.75E-07
1.73E+03	1.59E-07
2.40E+03	8.28E-08
4.37E+03	2.86E-08
5.53E+03	1.60E-08
1.15E+04	4.40E-09
1.37E+04	2.28E-09
2.11E+04	1.07E-09
3.92E+04	2.99E-10
6.56E+04	7.63E-11
8.12E+04	2.65E-11
1.06E+05	1.23E-11

PASQUILL CATEGORY D
VEHICLE NACSTC

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION

SEVERITY= 1
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP

CNTR LINE	LUNG	BONE MARROW	THYROID	(CI-S/M**3)	(MICRO CI/M**2)
3.60E+01	5.69E-04	2.40E-02	1.18E-04	9.69E-04	3.13E+01
7.70E+01	1.72E-04	7.24E-03	3.57E-05	2.93E-04	9.45E+00
1.18E+02	7.91E-05	3.33E-03	1.65E-05	1.35E-04	4.35E+00
2.61E+02	2.03E-05	8.54E-04	4.21E-06	3.45E-05	1.11E+00
3.87E+02	9.59E-06	4.04E-04	1.99E-06	1.63E-05	5.27E-01
6.33E+02	4.01E-06	1.69E-04	8.34E-07	6.83E-06	2.21E-01
1.08E+03	1.54E-06	6.48E-05	3.20E-07	2.62E-06	8.46E-02
1.73E+03	6.51E-07	2.74E-05	1.35E-07	1.11E-06	3.58E-02
2.40E+03	3.40E-07	1.43E-05	7.06E-08	5.78E-07	1.87E-02
4.37E+03	1.17E-07	4.93E-06	2.44E-08	2.00E-07	6.44E-03
5.53E+03	6.56E-08	2.76E-06	1.36E-08	1.12E-07	3.61E-03
1.15E+04	1.80E-08	7.59E-07	3.75E-09	3.07E-08	9.92E-04
1.37E+04	9.37E-09	3.94E-07	1.95E-09	1.59E-08	5.15E-04
2.11E+04	4.37E-09	1.84E-07	9.08E-10	7.44E-09	2.40E-04
3.92E+04	1.23E-09	5.17E-08	2.55E-10	2.09E-09	6.75E-05
6.56E+04	3.13E-10	1.32E-08	6.50E-11	5.33E-10	1.72E-05
8.12E+04	1.09E-10	4.58E-09	2.26E-11	1.85E-10	5.98E-06
1.06E+05	5.04E-11	2.12E-09	1.05E-11	8.59E-11	2.77E-06

PASQUILL CATEGORY D
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1

	INHALED	SHINE	BACKYARD FARMER				
CNTR LINE	EFFECTIVE	RESUSPEND	CLOUD	GROUND	TOTAL EFFECTIVE	THYROID	
3.60E+01	1.18E-04	2.12E-06	4.52E-04	2.35E-02	2.41E-02	4.16E-01	1.18E-01
7.70E+01	3.57E-05	1.93E-07	1.36E-04	7.09E-03	7.26E-03	1.26E-01	3.57E-02
1.18E+02	1.65E-05	4.10E-08	6.28E-05	3.26E-03	3.34E-03	5.78E-02	1.64E-02
2.61E+02	4.21E-06	2.69E-09	1.61E-05	8.36E-04	8.57E-04	1.48E-02	4.21E-03
3.87E+02	1.99E-06	6.02E-10	7.61E-06	3.96E-04	4.05E-04	7.01E-03	1.99E-03
6.33E+02	8.34E-07	1.05E-10	3.18E-06	1.65E-04	1.69E-04	2.93E-03	8.34E-04
1.08E+03	3.20E-07	1.55E-11	1.22E-06	6.35E-05	6.50E-05	1.12E-03	3.20E-04
1.73E+03	1.35E-07	2.77E-12	5.16E-07	2.68E-05	2.75E-05	4.75E-04	1.35E-04
2.40E+03	7.06E-08	7.54E-13	2.69E-07	1.40E-05	1.43E-05	2.48E-04	7.06E-05
4.37E+03	2.44E-08	8.98E-14	9.30E-08	4.83E-06	4.95E-06	8.56E-05	2.44E-05
5.53E+03	1.36E-08	2.82E-14	5.21E-08	2.71E-06	2.77E-06	4.79E-05	1.36E-05
1.15E+04	3.75E-09	2.13E-15	1.43E-08	7.44E-07	7.62E-07	1.32E-05	3.75E-06
1.37E+04	1.95E-09	5.74E-16	7.43E-09	3.86E-07	3.96E-07	6.84E-06	1.95E-06
2.11E+04	9.08E-10	1.25E-16	3.47E-09	1.80E-07	1.85E-07	3.19E-06	9.08E-07
3.92E+04	2.55E-10	9.85E-18	9.74E-10	5.06E-08	5.19E-08	8.97E-07	2.55E-07
6.56E+04	6.50E-11	6.40E-19	2.48E-10	1.29E-08	1.32E-08	2.29E-07	6.50E-08
8.12E+04	2.26E-11	7.73E-20	8.62E-11	4.48E-09	4.59E-09	7.94E-08	2.26E-08
1.06E+05	1.05E-11	1.66E-20	4.00E-11	2.08E-09	2.13E-09	3.68E-08	1.05E-08

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP

CNTR LINE	LUNG	BONE MARROW	THYROID	(CI-S/M**3)	(MICRO CI/M**2)
3.60E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7.70E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.18E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.61E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.87E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

6.33E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.08E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.73E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.40E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
4.37E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
5.53E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.15E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.37E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.11E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
3.92E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
6.56E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
8.12E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.06E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

PASQUILL CATEGORY D
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
ALL VALUES WERE 0.0

CALCULATIONAL INFORMATION FOR PASQUILL CATEGORY E

IN CALCULATING THE DEPLETION FOR THE FOLLOWING GROUPS,
THE CONCENTRATIONS IN THE LISTED AREA HAVE BECOME NEGATIVE.
THE CONTAMINATION AND CONCENTRATIONS IN THE LISTED AREA AND
LARGER HAVE BEEN SET TO ZERO.

GROUP CRUD AREA 11

FOR NACSTC AREAS WITH TOTAL CONTAMINATION RATIO GREATER THAN 40.0000
(THE AREAS MARKED WITH AN 'X' ARE INTERDICTED

AREA/SEVERITY 1 2
1 X -
2 X -
3 X -
4 - -
5 - -
6 - -
7 - -
8 - -
9 - -
10 - -
11 - -
12 - -
13 - -
14 - -
15 - -
16 - -
17 - -
18 - -
DILUTION FACTORS FOR PASQUILL CATEGORY E
CHI VALUES AFTER DEPLETION (CI-SEC/M**3/CI-RELEASED)

DISTANCE CRUD
4.20E+01 9.60E-03

8.40E+01 3.20E-03
1.30E+02 1.30E-03
3.12E+02 2.62E-04
4.68E+02 1.02E-04
6.05E+02 5.52E-05
1.26E+03 1.32E-05
2.00E+03 4.27E-06
2.85E+03 1.66E-06
5.09E+03 4.93E-07
6.10E+03 1.88E-07
1.19E+04 0.00E+00
1.35E+04 0.00E+00
2.37E+04 0.00E+00
4.39E+04 0.00E+00
7.70E+04 0.00E+00
1.01E+05 0.00E+00
1.38E+05 0.00E+00

DEPOSITION FACTORS
CHI DEPOSITED (CI/M**2/CI-RELEASED)

DISTANCE CRUD
4.20E+01 3.10E-04
8.40E+01 1.03E-04
1.30E+02 4.20E-05
3.12E+02 8.47E-06
4.68E+02 3.28E-06
6.05E+02 1.78E-06
1.26E+03 4.26E-07
2.00E+03 1.38E-07
2.85E+03 5.35E-08
5.09E+03 1.59E-08
6.10E+03 6.06E-09
1.19E+04 0.00E+00
1.35E+04 0.00E+00
2.37E+04 0.00E+00
4.39E+04 0.00E+00
7.70E+04 0.00E+00
1.01E+05 0.00E+00
1.38E+05 0.00E+00
PASQUILL CATEGORY E
VEHICLE NACSTC

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP
CNTR LINE LUNG BONE MARROW THYROID (CI-S/M**3) (MICRO CI/M**2)
4.20E+01 1.27E-03 5.35E-02 2.64E-04 2.16E-03 6.99E+01
8.40E+01 4.23E-04 1.78E-02 8.79E-05 7.20E-04 2.33E+01
1.30E+02 1.72E-04 7.25E-03 3.58E-05 2.93E-04 9.47E+00
3.12E+02 3.47E-05 1.46E-03 7.21E-06 5.91E-05 1.91E+00
4.68E+02 1.35E-05 5.66E-04 2.80E-06 2.29E-05 7.40E-01
6.05E+02 7.31E-06 3.08E-04 1.52E-06 1.24E-05 4.02E-01
1.26E+03 1.75E-06 7.36E-05 3.63E-07 2.97E-06 9.61E-02
2.00E+03 5.65E-07 2.38E-05 1.18E-07 9.62E-07 3.11E-02
2.85E+03 2.19E-07 9.23E-06 4.56E-08 3.73E-07 1.21E-02
5.09E+03 6.53E-08 2.75E-06 1.36E-08 1.11E-07 3.59E-03
6.10E+03 2.48E-08 1.05E-06 5.16E-09 4.23E-08 1.37E-03
1.19E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

1.35E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.37E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
4.39E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
7.70E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.01E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.38E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

PASQUILL CATEGORY E
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
4.20E+01 2.64E-04 4.71E-06 1.01E-03 5.24E-02 5.37E-02 9.29E-01 2.64E-01
8.40E+01 8.79E-05 5.22E-07 3.36E-04 1.75E-02 1.79E-02 3.09E-01 8.79E-02
1.30E+02 3.58E-05 8.64E-08 1.37E-04 7.10E-03 7.28E-03 1.26E-01 3.58E-02
3.12E+02 7.21E-06 3.51E-09 2.75E-05 1.43E-03 1.47E-03 2.54E-02 7.21E-03
4.68E+02 2.80E-06 5.27E-10 1.07E-05 5.55E-04 5.68E-04 9.83E-03 2.80E-03
6.05E+02 1.52E-06 1.56E-10 5.80E-06 3.01E-04 3.09E-04 5.34E-03 1.52E-03
1.26E+03 3.63E-07 8.90E-12 1.39E-06 7.21E-05 7.38E-05 1.28E-03 3.63E-04
2.00E+03 1.18E-07 9.31E-13 4.48E-07 2.33E-05 2.39E-05 4.13E-04 1.17E-04
2.85E+03 4.56E-08 1.40E-13 1.74E-07 9.04E-06 9.26E-06 1.60E-04 4.55E-05
5.09E+03 1.36E-08 1.24E-14 5.18E-08 2.69E-06 2.76E-06 4.77E-05 1.36E-05
6.10E+03 5.16E-09 1.80E-15 1.97E-08 1.02E-06 1.05E-06 1.81E-05 5.16E-06
1.19E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.35E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.37E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
4.39E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
7.70E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.01E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.38E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP
CNTR LINE LUNG BONE MARROW THYROID (CI-S/M**3) (MICRO CI/M**2)
4.20E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
8.40E+01 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.30E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
3.12E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
4.68E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
6.05E+02 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.26E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.00E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.85E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
5.09E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
6.10E+03 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.19E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.35E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
2.37E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
4.39E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
7.70E+04 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.01E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00
1.38E+05 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00

PASQUILL CATEGORY E
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)

FROM EXPOSURE DURING EVACUATION
SEVERITY= 2

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
ALL VALUES WERE 0.0

MAXIMUM RISK FOR INDIVIDUAL IN NEAREST ISOPLETH (DOSE IN REM)
FROM INHALATION, CLOUDSHINE, AND GROUNDSHINE EXPOSURE DURING EVACUATION

LINK SEVER: 1 SEVER: 2
LINK_R 2.45E-11 0.00E+00
LINK_S 2.45E-11 0.00E+00
LINK_U 2.45E-11 0.00E+00

EXPECTED VALUES OF POPULATION RISK IN PERSON-REM

LINK INHALED RESUSPD CLOUDSH GROUNDSH TOTAL
LINK_R 1.03E-14 2.79E-16 3.95E-14 1.41E-12 1.46E-12
LINK_S 1.83E-13 4.92E-15 6.97E-13 2.49E-11 2.58E-11
LINK_U 4.24E-12 1.14E-13 1.62E-11 5.78E-10 5.99E-10

ZONE
RURAL 1.03E-14 2.79E-16 3.95E-14 1.41E-12 1.46E-12
SUBURB 1.83E-13 4.92E-15 6.97E-13 2.49E-11 2.58E-11
URBAN 4.24E-12 1.14E-13 1.62E-11 5.78E-10 5.99E-10

TOTALS: 4.44E-12 1.20E-13 1.69E-11 6.04E-10 6.26E-10

SOCIETAL INGESTION RISK - PERSON-REM

LINK GONADS EFFECTIVE
LINK_R 5.17E-11 4.49E-11

TOTAL 5.17E-11 4.49E-11

SOCIETAL INGESTION RISK BY ORGAN - PERSON-REM

LINK BREAST LUNGS RED MARR BONE SUR THYROID REMAINDER
LINK_R 1.78E-11 1.42E-11 2.14E-11 1.52E-11 1.28E-11 8.06E-11

TOTAL 1.78E-11 1.42E-11 2.14E-11 1.52E-11 1.28E-11 8.06E-11

EXPECTED RISK VALUES - OTHER

LINK EARLY EARLY
FATALITY MORBIDITY
LINK_R 0.00E+00 0.00E+00
LINK_S 0.00E+00 0.00E+00
LINK_U 0.00E+00 0.00E+00

TOTAL 0.00E+00 0.00E+00

LINK: LINK_R EXPECTED VALUES OF POPULATION RISK IN PERSON-REM
MATERIAL ISOTOPE INHALATN RESUSP CLOUDSH GROUND TOTAL
NACSTC CO60 1.15E-14 3.11E-16 4.40E-14 1.55E-12 1.61E-12
TOTAL: 1.61E-12

LINK: LINK_S EXPECTED VALUES OF POPULATION RISK IN PERSON-REM
MATERIAL ISOTOPE INHALATN RESUSP CLOUDSH GROUND TOTAL

```
 NACSTC  CO60 2.03E-13 5.49E-15 7.77E-13 2.74E-11 2.83E-11
          TOTAL: 2.83E-11

LINK: LINK_U   EXPECTED VALUES OF POPULATION RISK IN PERSON-REM
MATERIAL ISOTOPE INHALATN RESUSP CLOUDSH GROUND  TOTAL
 NACSTC  CO60 4.73E-12 1.28E-13 1.81E-11 6.36E-10 6.59E-10
          TOTAL: 6.59E-10
EOI
END OF RUN
SUCCESSFUL COMPLETION
```

ACCIDENT RESULTS USING THE USER-DEFINED OPTION
Only results different from Average Weather are reported

```
 DISPERSAL MODEL RELATED INPUT DATA
    **********************************
 CENTER LINE DISTANCES FROM FRACTION OF PEAK:
  0.9, 0.7, 0.5,  0.3, 0.2, 0.1,
  0.05, 0.02, 0.01, 0.005, 0.002, 0.001,
  5.0e-4, 2.0e-4, 1.0e-4, 5.0e-5, 2.0e-5, 1.0e-5,
  5.0e-6, 2.0e-6, 1.0e-6, 5.0e-7, 2.0e-7, 1.0e-7

 RELEASE HEIGHT (M)     0.00000E+00
 HEAT FLUX (CAL/S)     0.00000E+00
 SOURCE WIDTH (M)     1.25000E+00
 SOURCE HEIGHT(M)     1.90000E+00
 WIND SPEED (M/S)     4.00000E+00
 ANEMOMETER HEIGHT (M)    1.00000E+01
 AMBIENT TEMPERATURE (K)   2.93000E+02
 ATMOSPHERIC MIXING HEIGHT (M)  1.00000E+03
 RAINFALL RATE (MM/HR)    0.00000E+00

 BRIGGS DISPERSION COEFFICIENTS USED
 STABILITY CATEGORY     D
 RURAL POPULATION ZONE


OOO U  U TTTTT PPPP U  U TTTTT
O O U  U   T P  P U  U T
O O U  U   T P  P U  U T
O O U  U   T PPPP U  U T
O O U  U   T P   U  U T
O O U  U   T P   U  U T
OOO UUUUU   T P   UUUUU T

AREA/SEVERITY 1 2
1   X -
2   X -
3   X -
4   X -
5   X -
6   X -
7   - -
8   - -
9   - -
10   - -
11   - -
12   - -
13   - -
14   - -
15   - -
16   - -
```

17 - -
18 - -
19 - -
20 - -
21 - -
22 - -
23 - -
24 - -
25 - -

DEPOSITION VELOCITY = 0.32E-01 (M/SEC)
DILUTION FACTORS
AT DOWNWIND LOCATION = 2.0382E+01 (M)
MAXIMUM AIR CONCENTRATION = 1.1284E-02 (CI-SEC/M^3/CI-released)
AT DOWNWIND LOCATION = 2.0382E+01 (M)
MAXIMUM GROUND DEPOSITION = 3.6447E-04 (CI/M^2/CI-released)

DOWNWIND (M)	AREA (M^2)	DILUTION (CI-S/M^3/CI-rlse)	DILUTION FRACTION	DEPOSITED (CI/M^2/CI-rlse)
2.23E+01	3.41E+00	1.02E-02	9.00E-01	3.28E-04
2.74E+01	1.99E+01	7.90E-03	7.00E-01	2.55E-04
3.54E+01	6.14E+01	5.64E-03	5.00E-01	1.82E-04
5.04E+01	1.82E+02	3.39E-03	3.00E-01	1.09E-04
6.54E+01	3.51E+02	2.26E-03	2.00E-01	7.29E-05
9.93E+01	9.06E+02	1.13E-03	1.00E-01	3.64E-05
1.47E+02	2.09E+03	5.64E-04	5.00E-02	1.82E-05
2.44E+02	5.85E+03	2.26E-04	2.00E-02	7.29E-06
3.56E+02	1.24E+04	1.13E-04	1.00E-02	3.64E-06
5.20E+02	2.62E+04	5.64E-05	5.00E-03	1.82E-06
8.60E+02	7.02E+04	2.26E-05	2.00E-03	7.29E-07
1.27E+03	1.49E+05	1.13E-05	1.00E-03	3.64E-07
1.88E+03	3.20E+05	5.64E-06	5.00E-04	1.82E-07
3.20E+03	8.82E+05	2.26E-06	2.00E-04	7.29E-08
4.79E+03	1.91E+06	1.13E-06	1.00E-04	3.64E-08
7.21E+03	4.08E+06	5.64E-07	5.00E-05	1.82E-08
1.23E+04	1.10E+07	2.26E-07	2.00E-05	7.29E-09
1.83E+04	2.24E+07	1.13E-07	1.00E-05	3.64E-09
2.69E+04	4.47E+07	5.64E-08	5.00E-06	1.82E-09
4.29E+04	1.03E+08	2.26E-08	2.00E-06	7.29E-10
6.10E+04	1.87E+08	1.13E-08	1.00E-06	3.64E-10
8.31E+04	3.22E+08	5.64E-09	5.00E-07	1.82E-10
1.20E+05	6.09E+08	2.28E-09	2.02E-07	7.36E-11

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP

CNTR LINE	LUNG	BONE MARROW	THYROID	(CI-S/M**3)	(MICRO CI/M**2)
2.23E+01	1.34E-03	5.66E-02	2.80E-04	2.29E-03	7.39E+01
2.74E+01	1.05E-03	4.40E-02	2.17E-04	1.78E-03	5.75E+01
3.54E+01	7.47E-04	3.15E-02	1.55E-04	1.27E-03	4.11E+01
5.04E+01	4.48E-04	1.89E-02	9.32E-05	7.63E-04	2.46E+01
6.54E+01	2.99E-04	1.26E-02	6.21E-05	5.09E-04	1.64E+01
9.93E+01	1.49E-04	6.29E-03	3.11E-05	2.54E-04	8.22E+00
1.47E+02	7.47E-05	3.15E-03	1.55E-05	1.27E-04	4.11E+00
2.44E+02	2.99E-05	1.26E-03	6.21E-06	5.09E-05	1.64E+00
3.56E+02	1.49E-05	6.29E-04	3.11E-06	2.54E-05	8.22E-01
5.20E+02	7.47E-06	3.15E-04	1.55E-06	1.27E-05	4.11E-01
8.60E+02	2.99E-06	1.26E-04	6.21E-07	5.09E-06	1.64E-01
1.27E+03	1.49E-06	6.29E-05	3.11E-07	2.54E-06	8.22E-02

1.88E+03 7.47E-07 3.15E-05 1.55E-07 1.27E-06 4.11E-02
3.20E+03 2.99E-07 1.26E-05 6.21E-08 5.09E-07 1.64E-02
4.79E+03 1.49E-07 6.29E-06 3.11E-08 2.54E-07 8.22E-03
7.21E+03 7.47E-08 3.15E-06 1.55E-08 1.27E-07 4.11E-03
1.23E+04 2.99E-08 1.26E-06 6.21E-09 5.09E-08 1.64E-03
1.83E+04 1.49E-08 6.29E-07 3.11E-09 2.54E-08 8.22E-04
2.69E+04 7.47E-09 3.15E-07 1.55E-09 1.27E-08 4.11E-04
4.29E+04 2.99E-09 1.26E-07 6.21E-10 5.09E-09 1.64E-04
6.10E+04 1.49E-09 6.29E-08 3.11E-10 2.54E-09 8.22E-05
8.31E+04 7.47E-10 3.15E-08 1.55E-10 1.27E-09 4.11E-05
1.20E+05 3.02E-10 1.27E-08 6.27E-11 5.13E-10 1.66E-05

PASQUILL CATEGORY D
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 1

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
2.23E+01 2.80E-04 2.43E-06 1.07E-03 5.55E-02 5.68E-02 9.82E-01 2.79E-01
2.74E+01 2.17E-04 1.47E-06 8.30E-04 4.31E-02 4.42E-02 7.64E-01 2.17E-01
3.54E+01 1.55E-04 7.51E-07 5.93E-04 3.08E-02 3.16E-02 5.46E-01 1.55E-01
5.04E+01 9.32E-05 2.70E-07 3.56E-04 1.85E-02 1.89E-02 3.27E-01 9.31E-02
6.54E+01 6.21E-05 1.20E-07 2.37E-04 1.23E-02 1.26E-02 2.18E-01 6.21E-02
9.93E+01 3.11E-05 3.00E-08 1.19E-04 6.16E-03 6.31E-03 1.09E-01 3.10E-02
1.47E+02 1.55E-05 7.51E-09 5.93E-05 3.08E-03 3.16E-03 5.46E-02 1.55E-02
2.44E+02 6.21E-06 1.20E-09 2.37E-05 1.23E-03 1.26E-03 2.18E-02 6.21E-03
3.56E+02 3.11E-06 3.00E-10 1.19E-05 6.16E-04 6.31E-04 1.09E-02 3.10E-03
5.20E+02 1.55E-06 7.51E-11 5.93E-06 3.08E-04 3.16E-04 5.46E-03 1.55E-03
8.60E+02 6.21E-07 1.20E-11 2.37E-06 1.23E-04 1.26E-04 2.18E-03 6.21E-04
1.27E+03 3.11E-07 3.00E-12 1.19E-06 6.16E-05 6.31E-05 1.09E-03 3.10E-04
1.88E+03 1.55E-07 7.51E-13 5.93E-07 3.08E-05 3.16E-05 5.46E-04 1.55E-04
3.20E+03 6.21E-08 1.20E-13 2.37E-07 1.23E-05 1.26E-05 2.18E-04 6.21E-05
4.79E+03 3.11E-08 3.00E-14 1.19E-07 6.16E-06 6.31E-06 1.09E-04 3.10E-05
7.21E+03 1.55E-08 7.51E-15 5.93E-08 3.08E-06 3.16E-06 5.46E-05 1.55E-05
1.23E+04 6.21E-09 1.20E-15 2.37E-08 1.23E-06 1.26E-06 2.18E-05 6.21E-06
1.83E+04 3.11E-09 3.00E-16 1.19E-08 6.16E-07 6.31E-07 1.09E-05 3.10E-06
2.69E+04 1.55E-09 7.51E-17 5.93E-09 3.08E-07 3.16E-07 5.46E-06 1.55E-06
4.29E+04 6.21E-10 1.20E-17 2.37E-09 1.23E-07 1.26E-07 2.18E-06 6.21E-07
6.10E+04 3.11E-10 3.00E-18 1.19E-09 6.16E-08 6.31E-08 1.09E-06 3.10E-07
8.31E+04 1.55E-10 7.51E-19 5.93E-10 3.08E-08 3.16E-08 5.46E-07 1.55E-07
1.20E+05 6.27E-11 1.22E-19 2.39E-10 1.24E-08 1.27E-08 2.20E-07 6.27E-08

NACSTD_SAMPLEREPEAT_01_03_14

MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2
AIR CONCENTRATION GROUND CONTAMINATION
INHALATION PATHWAY ORGAN DOSE AFTER DEPOSITION BEFORE CLEANUP

CNTR LINE	LUNG	BONE MARROW	THYROID	(CI-S/M**3)	(MICRO CI/M**2)
2.23E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.74E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.54E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.04E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.54E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9.93E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.47E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.44E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.56E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.20E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.60E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.27E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.88E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.20E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.79E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7.21E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.23E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.83E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.69E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.29E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.10E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.31E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.20E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

PASQUILL CATEGORY D
VEHICLE NACSTC
MAXIMUM INDIVIDUAL CONSEQUENCE (DOSE IN REM)
FROM EXPOSURE DURING EVACUATION
SEVERITY= 2

INHALED SHINE BACKYARD FARMER
CNTR LINE EFFECTIVE RESUSPEND CLOUD GROUND TOTAL EFFECTIVE THYROID
ALL VALUES WERE 0.

MAXIMUM RISK FOR INDIVIDUAL IN NEAREST ISOPLETH (DOSE IN REM)
FROM INHALATION, CLOUDSHINE, AND GROUNDSHINE EXPOSURE DURING EVACUATION

LINK	SEVER: 1	SEVER: 2
LINK_R	4.72E-11	0.00E+00
LINK_S	4.72E-11	0.00E+00
LINK_U	4.72E-11	0.00E+00

EXPECTED VALUES OF POPULATION RISK IN PERSON-REM

LINK	INHALED	RESUSPD	CLOUDSH	GROUNDSH	TOTAL
LINK_R	1.08E-14	2.91E-16	4.12E-14	1.47E-12	1.52E-12
LINK_S	1.90E-13	5.14E-15	7.27E-13	2.59E-11	2.69E-11
LINK_U	4.43E-12	1.19E-13	1.69E-11	6.03E-10	6.24E-10

ZONE					
RURAL	1.08E-14	2.91E-16	4.12E-14	1.47E-12	1.52E-12

SUBURB 1.90E-13 5.14E-15 7.27E-13 2.59E-11 2.69E-11
URBAN 4.43E-12 1.19E-13 1.69E-11 6.03E-10 6.24E-10

TOTALS: 4.63E-12 1.25E-13 1.77E-11 6.30E-10 6.53E-10

LINK GONADS EFFECTIVE
LINK_R 7.45E-11 6.46E-11

TOTAL 7.45E-11 6.46E-11

SOCIETAL INGESTION RISK BY ORGAN - PERSON-REM

LINK BREAST LUNGS RED MARR BONE SUR THYROID REMAINDER
LINK_R 2.57E-11 2.05E-11 3.08E-11 2.19E-11 1.84E-11 1.16E-10

TOTAL 2.57E-11 2.05E-11 3.08E-11 2.19E-11 1.84E-11 1.16E-10

EXPECTED RISK VALUES - OTHER

LINK EARLY EARLY
FATALITY MORBIDITY
LINK_R 0.00E+00 0.00E+00
LINK_S 0.00E+00 0.00E+00
LINK_U 0.00E+00 0.00E+00

TOTAL 0.00E+00 0.00E+00

LINK GONADS EFFECTIVE
LINK_R 7.45E-11 6.46E-11

TOTAL 7.45E-11 6.46E-11

SOCIETAL INGESTION RISK BY ORGAN - PERSON-REM

LINK BREAST LUNGS RED MARR BONE SUR THYROID REMAINDER
LINK_R 2.57E-11 2.05E-11 3.08E-11 2.19E-11 1.84E-11 1.16E-10

TOTAL 2.57E-11 2.05E-11 3.08E-11 2.19E-11 1.84E-11 1.16E-10

EXPECTED RISK VALUES - OTHER

LINK EARLY EARLY
FATALITY MORBIDITY
LINK_R 0.00E+00 0.00E+00
LINK_S 0.00E+00 0.00E+00
LINK_U 0.00E+00 0.00E+00

TOTAL 0.00E+00 0.00E+00

PASQUILL CATEGORY D
TOTAL EXPOSED POPULATION: ACCIDENT
(PERSONS UNDER PLUME FOOTPRINT FOR A SINGLE ACCIDENT)

LINK_R 1.59E+04 PERSONS
LINK_S 2.81E+05 PERSONS
LINK_U 2.25E+06 PERSONS

LINK: LINK_R EXPECTED VALUES OF POPULATION RISK IN PERSON-REM
MATERIAL ISOTOPE INHALATN RESUSP CLOUDSH GROUND TOTAL
 NACSTC CO60 1.08E-14 2.91E-16 4.12E-14 1.47E-12 1.52E-12
          TOTAL: 1.52E-12

LINK: LINK_S EXPECTED VALUES OF POPULATION RISK IN PERSON-REM
MATERIAL ISOTOPE INHALATN RESUSP CLOUDSH GROUND TOTAL
 NACSTC CO60 1.90E-13 5.14E-15 7.27E-13 2.59E-11 2.69E-11
          TOTAL: 2.69E-11

LINK: LINK_U EXPECTED VALUES OF POPULATION RISK IN PERSON-REM
MATERIAL ISOTOPE INHALATN RESUSP CLOUDSH GROUND TOTAL
 NACSTC CO60 4.43E-12 1.19E-13 1.69E-11 6.03E-10 6.24E-10
          TOTAL: 6.24E-10
EOI
END OF RUN
SUCCESSFUL COMPLETION

END OF OUTPUT

DISTRIBUTION

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