RADTRAN Workshop

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RADTRAN 6.0
Overview

RADTRAN History

- **RADTRAN I developed for NUREG-0170**
  - *EIS for the Transportation of Radioactive Materials by Air and Other Means (USNRC, 1977)*
  - Developed by Sandia National Laboratories
- **RADTRAN III, funded by DOE, made available to users outside SNL (1986)**
  - Runs on SNL server via TRANSNET gateway
  - Remote access by telnet, dial-up
- **Menu system for RADTRAN 4 (1992) allowed greatly increased user-defined input and route-specific development**
- **RADTRAN now used in essentially all DOE and most NRC environmental assessments and impact statements**

RADTRAN History - Continued

- **RADTRAN 5 (1998)**
  - **New stop model**
  - **Allowed about 85% user defined input; 15% user choices**
- **2001 security considerations required access via secure shell, making access difficult**
- **Copyright Sandia National Labs 2003**
- **Downloadable RADTRAN 5 with graphical user interface (GUI) input file generator RADCAT, 2004**

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RADTRAN Projections

- **RADTRAN 5.5**
  - Fully functional atmospheric dispersion model (from RISKIND)
  - Expanded radionuclide library (150 nuclides)
- **RADTRAN 6**
  - All of RADTRAN 5.5
  - Loss of Shielding Model
  - Economic model
  - Emphasis toward RMEI, critical group risks
  - Alternate ingestion dose calculation method

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Direction of RADTRAN Development

Earlier direction: to develop and refine a RAM transportation risk analysis protocol.

Current and future direction: to develop and maintain the transportation risk assessment tool.

SOME OBSERVATIONS

- **For historical reasons, risks from both incident-free transportation and transportation accidents have been overestimated.**

- **"Collective dose" for very low-dose chronic exposure has been questioned by NRC.**

- **Focus of risk assessments is shifting toward**

  - **Separate reporting of consequences**

  - **Doses and risks to RMEI and critical groups**

  - **Doses and risks to first responders**

RADTRAN Inputs

INPUTS FOR INCIDENT-FREE TRANSPORTATION

Package dimensions
Package external dose rate
Vehicle dimensions
Vehicle speeds
Vehicle external dose rate
Route characteristics
Population densities
Stop characteristics
Urban building density

INPUTS FOR TRANSPORTATION ACCIDENTS

Radionuclide inventory
Accident rate (route characteristic)
Conditional probability of accident severity
Release, aerosol, respirable fractions
Particle settling velocity
Meteorological parameters
Population densities
Fraction of land in agriculture

RADTRAN Output

OUTPUTS FOR INCIDENT-FREE TRANSPORTATION

Collective external dose to residents along route
Collective external dose to public at stops
Collective external dose to urban non-residents
Collective dose to occupants of vehicles sharing route
Occupational external doses
MEI external doses

**OUTPUTS FOR TRANSPORTATION ACCIDENTS**

Collective "dose risks:" inhalation, resuspension, groundshine, cloudshine, ingestion
Collective doses
MEI doses and dose risks
Doses and dose risks per radionuclide
Critical group doses and dose risks
Doses and dose risks from loss of lead shielding

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How RADTRAN Works

- **Text input file is generated by the user directly or using the generator RADCAT**
- **RADTRAN reads in input file**
- **RADTRAN reads in text files of default values:**
- **All defaults can be overwritten except collective occupational doses at rail classification stops**
- **RADTRAN reads numbers and multiplies them according to the program. It is a very forgiving code; numbers between 10^{30} and 10^{-30} can be entered.**
- **Input is echoed in the output.**

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RADTRAN Flow diagram

TI here

1 meter

0.5CD = "virtual" cask radius

Critical Dimension

r

r = distance to receptor

Fundamental Incident-free Model

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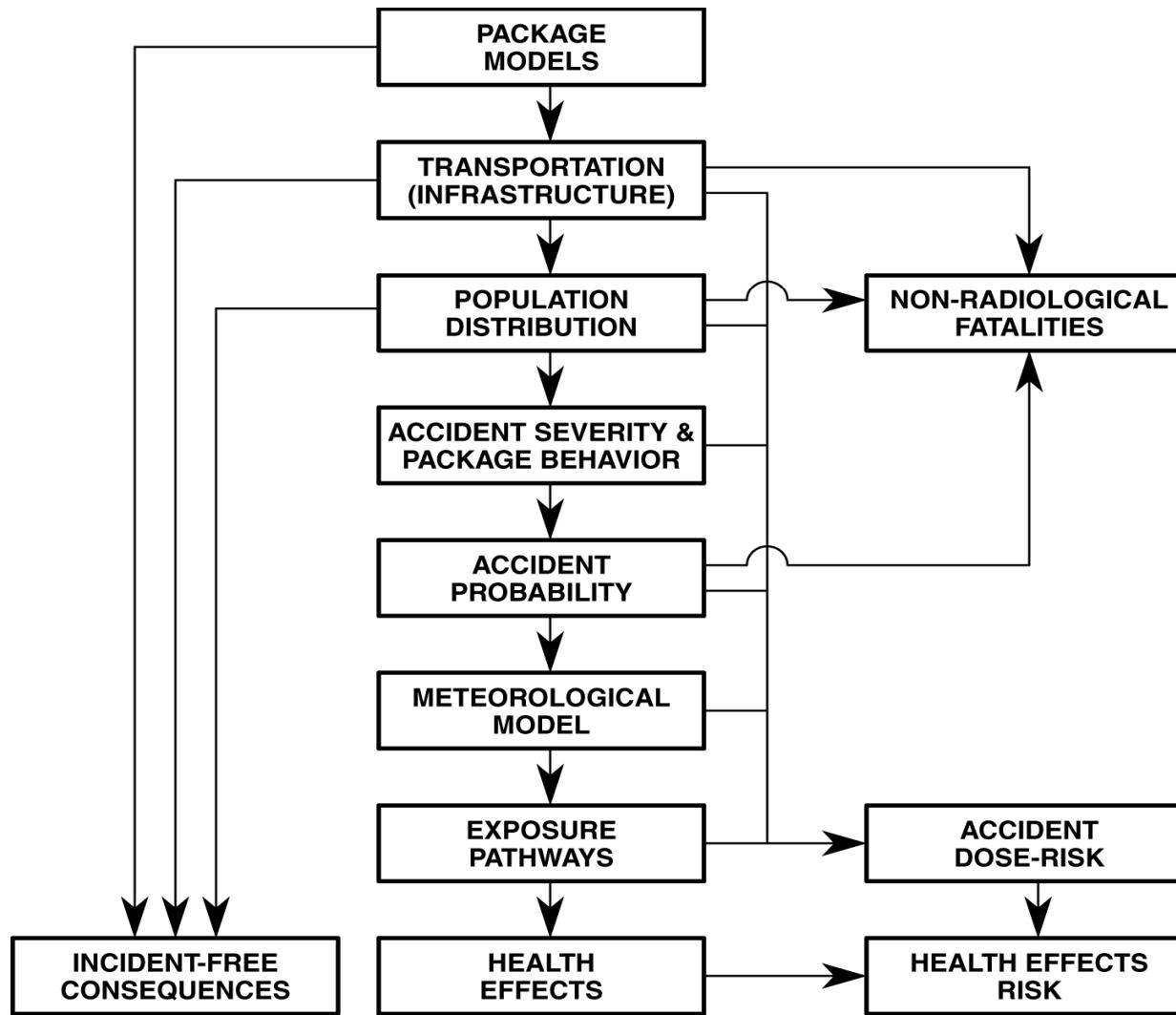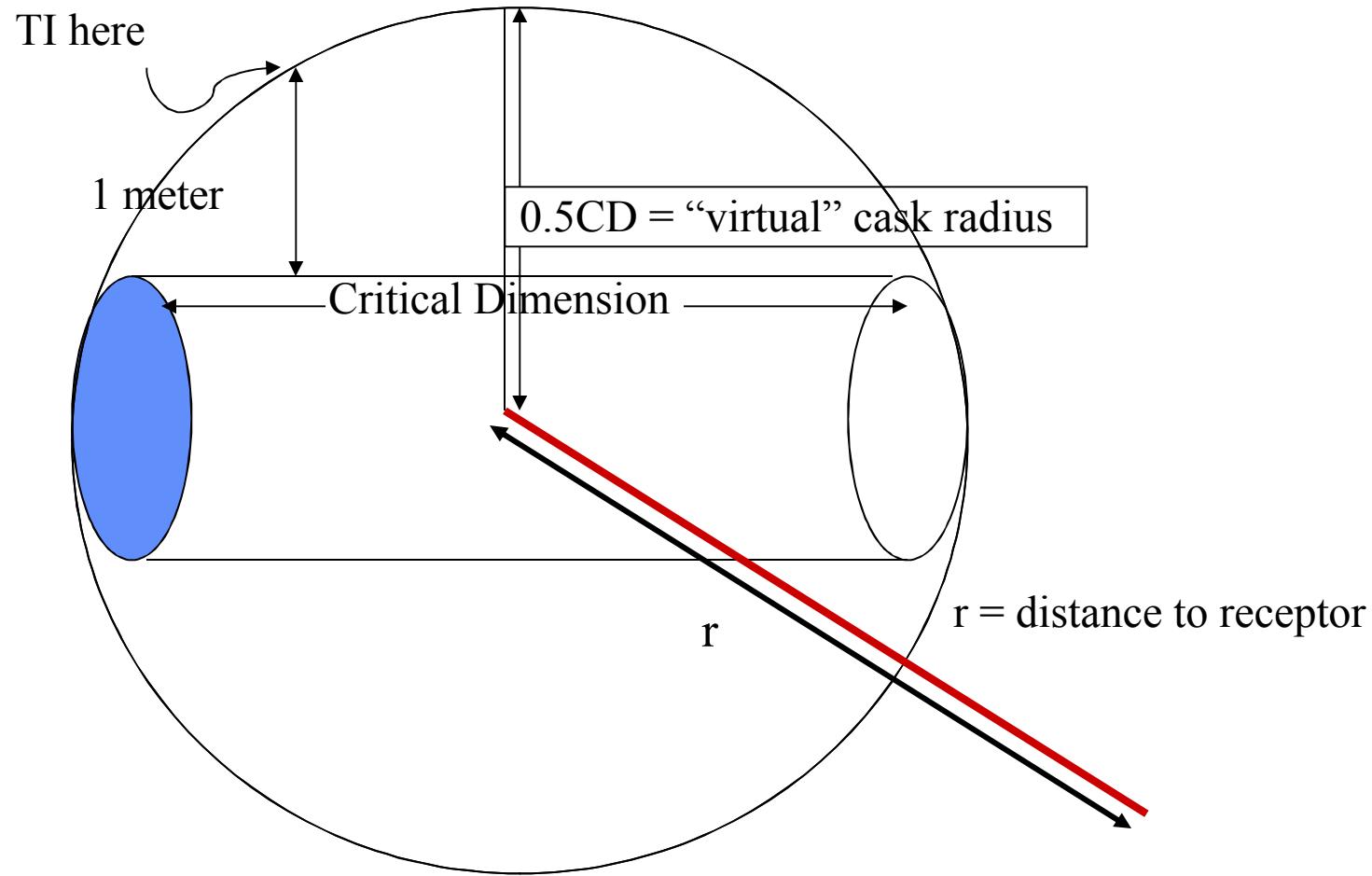
Calculation of "Off-Link" Dose

$$D = \frac{4 \cdot Q_1 \cdot DIST \cdot DRp \cdot PD}{V} \left\{ fg \cdot \int_{min}^{d} I_g(x)dx + f_n \cdot \int_{min}^{d} I_n(x)dx \right\}$$

- **PD (population density), DR_p, DIST (m), and V (velocity; mps), d and min are user-defined parameters**
- **RADTRAN 5 carries out calculation and then multiplies by # of packages per shipment and total # of shipments to calculate total population dose per link**

Neutron Dose Calculation

$$DR_N(r) = Q_1 \cdot DR_{p \text{ or } v} \cdot f_N \cdot \frac{k_0}{r^2} \cdot e^{(-\mu \cdot r)} \cdot \left(1 + a_1 \cdot r + a_2 \cdot r^2 + a_3 \cdot r^3 + a_4 \cdot r^4\right)$$

$DR_N(r)$ = Neutron dose rate at distance r (mrem/hr)

r = Radial distance from source (m)

Q_1 = Unit conversion factor

f_N = Fraction of dose rate at 1 meter from package that is neutron radiation

$DR_{p \text{ or } v}$ = Package or vehicle dose rate at 1m (mrem/hr)

k_0 = Point source shape factor (m^2)

μ = Linear attenuation coefficient (m^{-1})

a_1, a_2, a_3, a_4 = dimensionless coefficients; default values set

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General Equation for Gamma Dose to Population Along the Route

$$D(x) = \frac{2 \cdot Q_1 \cdot k_0 \cdot DR_v}{V} \cdot \int_x^\infty \left(\frac{e^{(-\mu \cdot r)} \cdot B(r)}{r \cdot (r^2 - x^2)^{0.5}} \right) dr$$

$D(x)$ = Total integrated dose absorbed by an individual at distance x (rem)

Q_1 = Unit conversion factor

k_0 = Point source package shape factor (m^2)

DR_v = Shipment dose rate at 1 meter from surface (mrem/hr)

V = Shipment speed (m/s)

μ = Attenuation coefficient (m^{-1})

r = Perpendicular distance of individual from shipment path (m)

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

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Final Equation for Dose to Population Along the Route

$$D_{off} = 4 \cdot Q \cdot k_0 \cdot DR_v \cdot \frac{PD_L}{V_L} \cdot NSH_L \cdot DIST_L \cdot \left[f_G \cdot (I + J) + f_N \cdot (K + L) \right]$$

D_{off} = Integrated population dose per km of strip (person-rem)

Q = Units conversion factor

k_0 = Point source package shape factor (m^2)

DR_v = Shipment dose rate at 1 meter from surface (mrem/hr)

PD_L = Population density for segment L (persons/km^2)

V_L = Shipment speed for segment L (m/s)

NSH_L = Number of shipments that travel on segment L

$DIST_L$ = Distance on segment L (km)

f_G = Fraction of dose rate at 1 meter from package that is gamma radiation

f_N = Fraction of dose rate at 1 meter from package that is neutron radiation

I, K = Integrals as in general equation for non-urban populations

J, L = Integrals as in general equation; factor includes pedestrian-to-resident ratio

Incident-free Transportation:
Legal-weight Truck Route and Stops
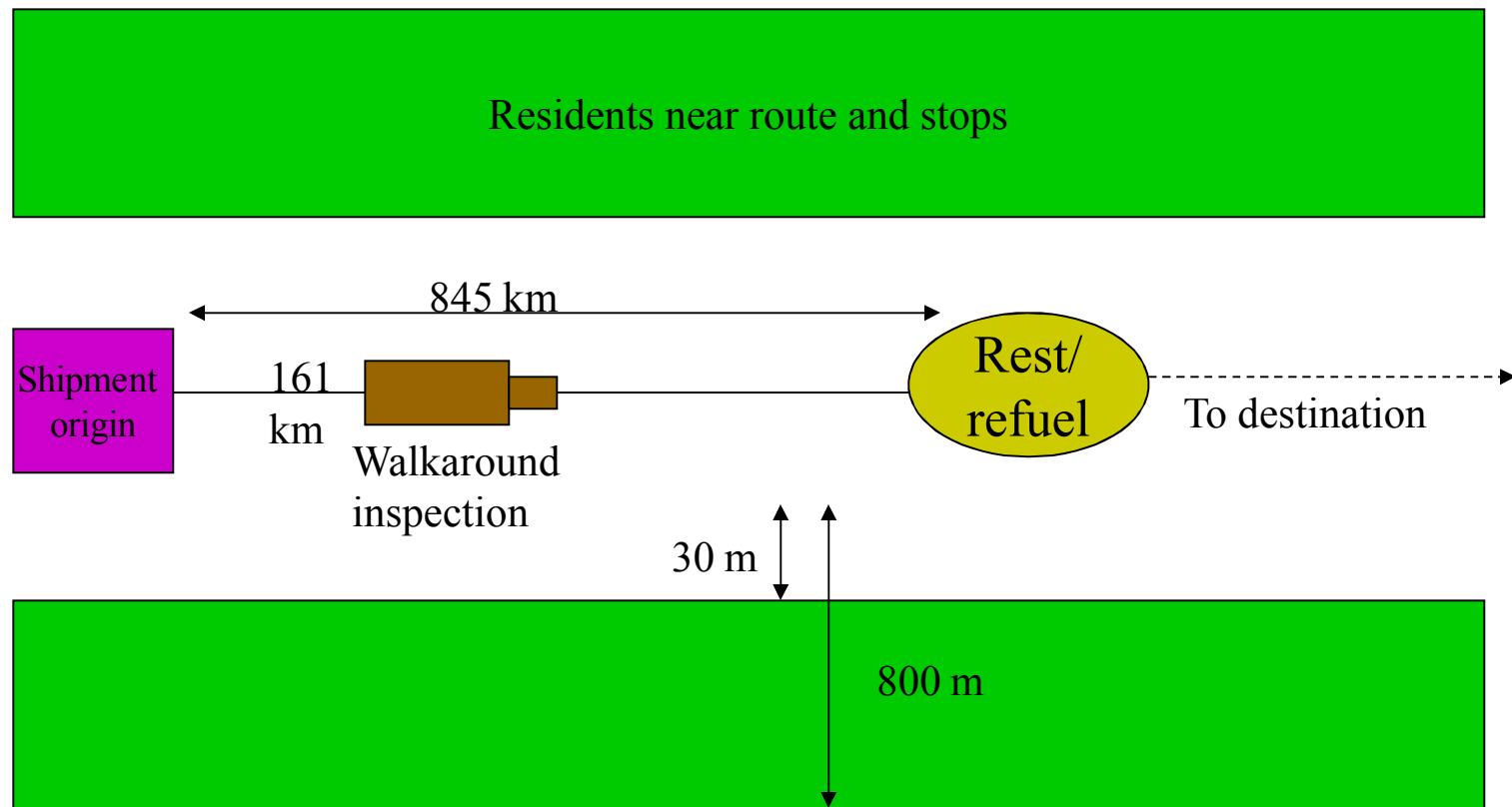
# Incident-free Transportation: Rail Route and Stops
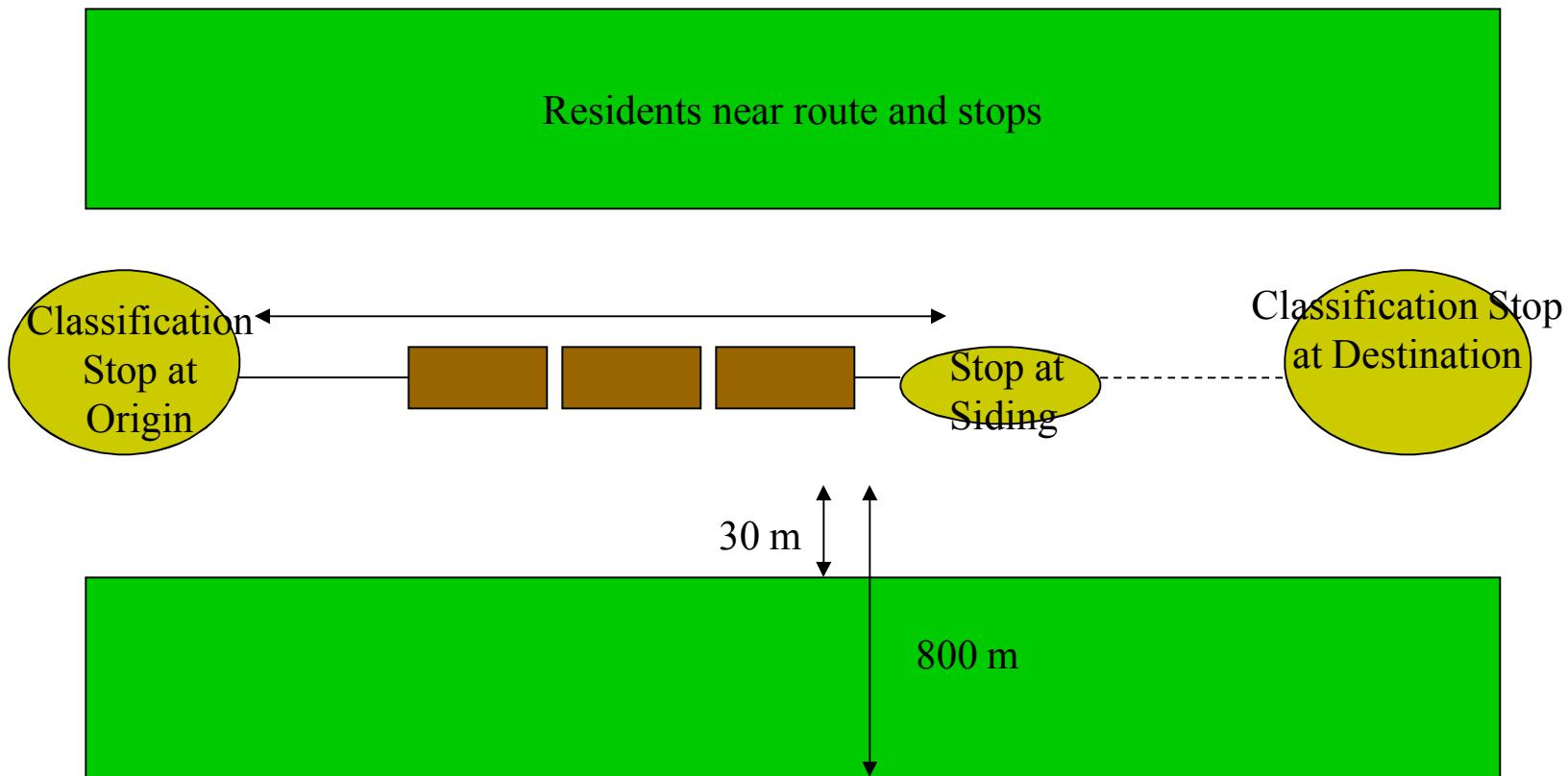
Incident-free Transportation: Barge Route and Stops
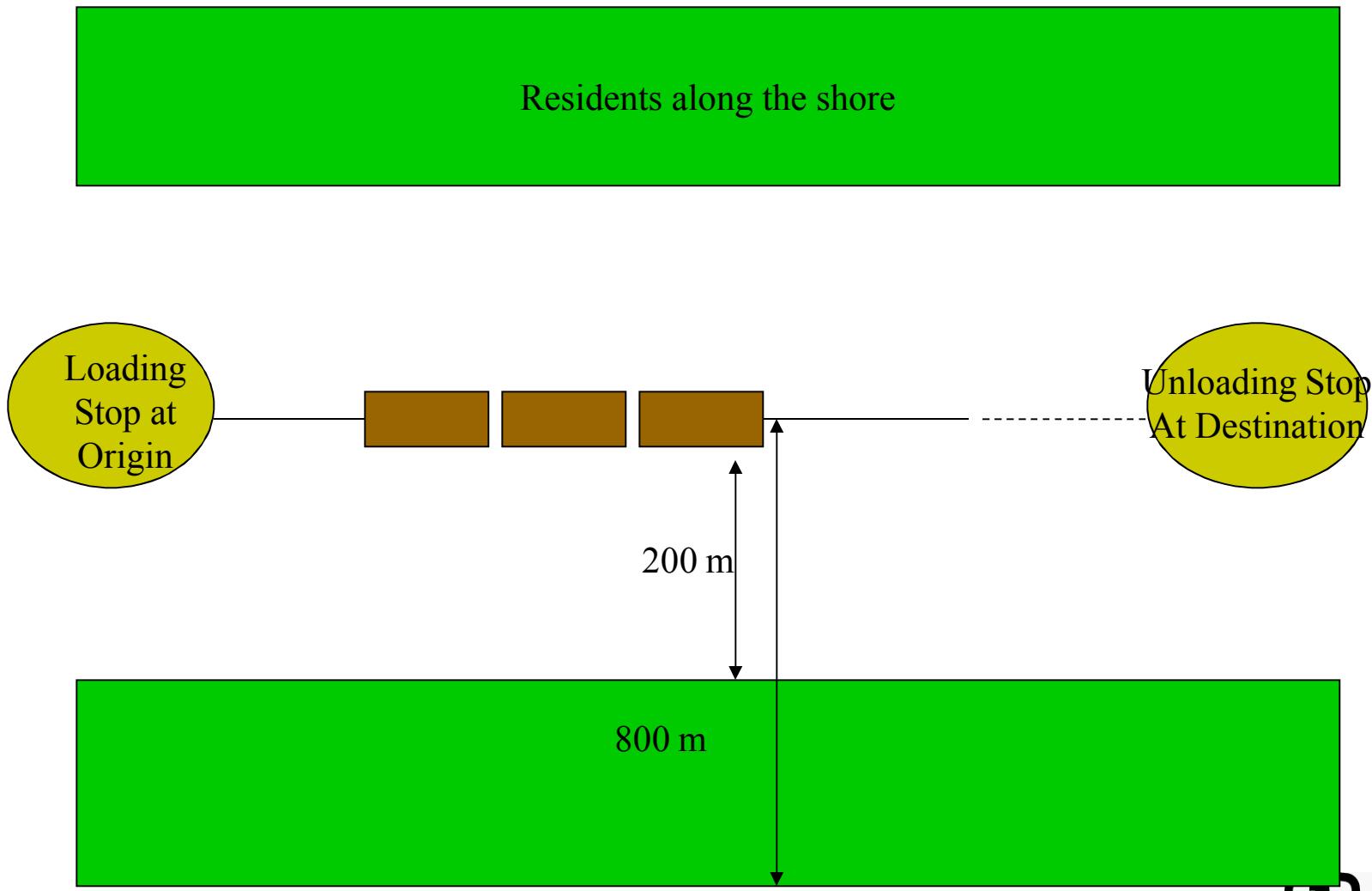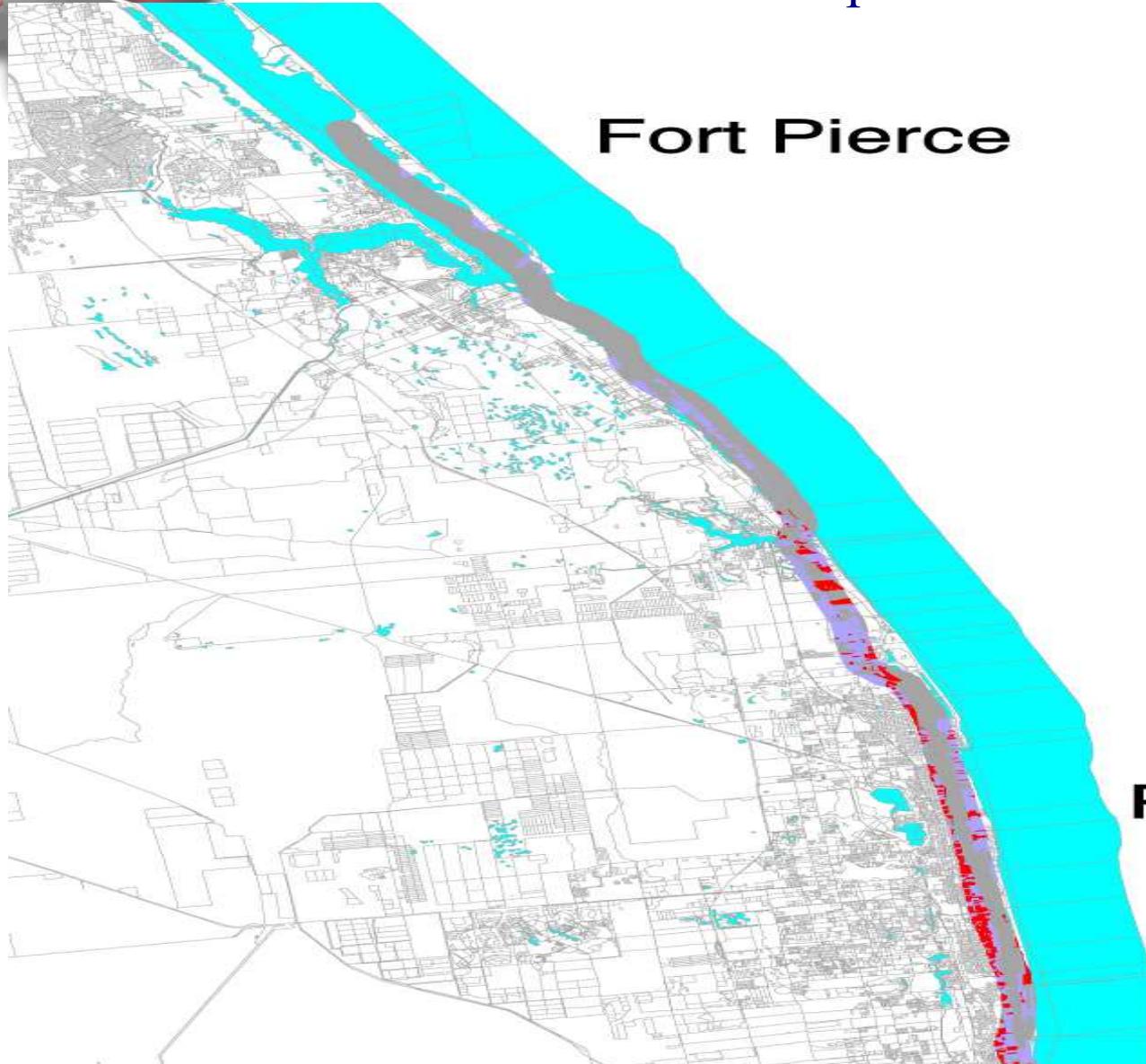
Residents along the shore

Loading Stop at Origin

Unloading Stop At Destination

200 m

800 m

Incident-free Transportation: Barge Route

Final Equation for Dose to Occupants of Vehicles Sharing the Route Moving in the Opposite Direction

$$D_{opp} = Q_2 \cdot k_0 \cdot DR_v \cdot \frac{N}{V_L{}^2} \cdot PPV \cdot DIST_L \cdot NSH \cdot \left[f_G \cdot I_G + f_N \cdot I_N \right]$$

D_{opp} = Integrated population dose per km of strip (person-rem)

Q_2 = Conversion factor

k_0 = Point source package shape factor (m^2)

DR_v = Shipment dose rate at 1 meter from surface (mrem/hr)

N = One-way traffic count (average number of vehicles that pass per hour)

V = Average velocity of all traffic (m/s)

PPV = Vehicle occupancy (average number of person per vehicle)

$DIST_L$ = Distance traveled on segment L

NSH = Number of shipments

f_G = Fraction of dose rate at 1 meter from package that is gamma radiation

f_N = Fraction of dose rate at 1 meter from package that is neutron radiation

I_G, I_N = Integrals as in the general equation

Final Equation for Dose to Occupants of Vehicles Sharing the Route Moving in the Same Direction

$$D_{sdir} = Q_2 \cdot k_0 \cdot DR_v \cdot \frac{N}{V^2} \cdot PPV \cdot DIST_L \cdot NSH \cdot [F_1 + F_2]$$

D_{sdir} = Integrated population dose per km of strip (person-rem)

Q_2 = Conversion factor

k_0 = Point source package shape factor (m^2)

DR_v = Shipment dose rate at 1 meter from surface (mrem/hr)

N = One-way traffic count (average number of vehicles that pass per hour)

V = Average velocity of all traffic (m/s)

PPV = Vehicle occupancy (average number of person per vehicle)

$DIST_L$ = Distance traveled on segment L

NSH = Number of shipments

$$F_1 = 2 \cdot V \cdot \left[\left[F_G \cdot \int_{2V}^{\infty} \left[\frac{e^{(-\mu G \cdot r)} \, B_G(\mu r)}{r^2} \right] dr \right] + \left[F_N \cdot \int_{2V}^{\infty} \left[\frac{e^{(-\mu N \cdot r)} \, B_N(\mu r)}{r^2} \right] dr \right] \right]$$

$$F_2 = \frac{V}{x} \cdot \left[\left[F_G \cdot \int_{2V}^{\infty} \left[\frac{e^{(-\mu G \cdot r)} \, B_G(\mu r)}{r^2} \right] dr \right] + \left[F_N \cdot \int_{2V}^{\infty} \left[\frac{e^{(-\mu N \cdot r)} \, B_N(\mu r)}{r^2} \right] dr \right] \right]$$

Truck Stop Model

Residents near stop

800 m

30 m

Buildings at the rest/refueling stop

15.8

Pumps

1 m

SNF Cask

First row of parked trucks
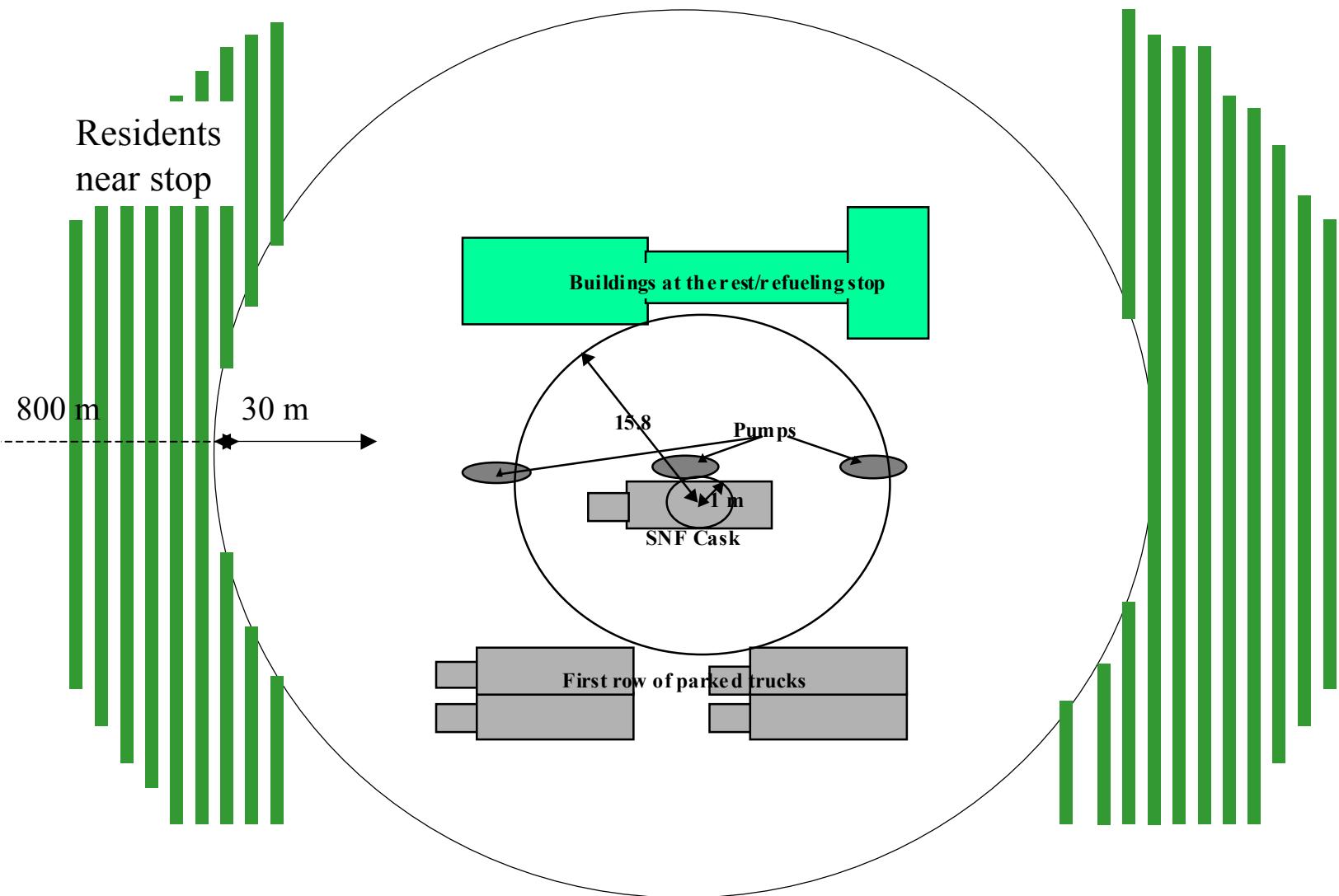
Dose to People at Stops
Number of People at an Average Distance

$$D = Q_4 \cdot DR \cdot P \cdot T \cdot NSH \cdot SF \cdot \left[\left(FG \cdot TR_G \right) + \left(FN \cdot TR_N \right) \right] \cdot \frac{k_0}{r^2}$$

D = Integrated population dose for stop (person-rem)

Q_4 = Conversion factor

k_0 = Point source shape factor for vehicle (m^2)

DR = Vehicle dose rate at 1 meter from surface (mrem/hr)

P = Average number of expected persons

T = Duration of stop (hr)

NSH = Number of shipment by vehicle

SF = Shielding factor at stops

r = Average radial source-to-receptor distance (m)

FG = Fraction of vehicle dose rate from gamma radiation

FN = Fraction of vehicle dose rate from neutron radiation

TR_G, TR_N = Term for gamma, neutron radiation source strength

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Dose to People at Stops
Population Density in an Annulus

$$D1_{stop} = 2\pi \cdot Q_4 \cdot k_0 \cdot DR \cdot PD \cdot T \cdot NSH \cdot SF \cdot \left[\ln(max) - \ln(min)\right]$$

$D1_{stop}$ = Integrated population dose for stop (person-rem)

Q_4 = Conversion factor

k_0 = Point source shape factor for vehicle (m^2)

DR = Vehicle dose rate at 1 meter from surface (mrem/hr)

PD = Population density of annular area at stop (persons/km^2)

T = Duration of stop (hr)

NSH = Number of shipment by vehicle

SF = Shielding factor at stop

max = Maximum radial distance from source

min = Minimum radial distance from source

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Default Values for Incident-free Transportation

• Residential shielding factors (rural, suburban, urban)
    •"Shielding factor" is the fraction of radiation that penetrates the shielding
•Fraction of urban residential population inside (and outside) of buildings
•Ratio of pedestrian density to urban residential population density
•Distance from route and vehicle speed for maximum exposure
•Distance of vehicle from the nearest population (shoulder, edge of right-of-way)
•LCF/person-rem for occupational and public exposure
•Genetic effects/person-rem
•Duration of shipping campaign
•Regulatory constraint flag
•Rail transport:
    •Minimum number of classification stops
    •Distance-dependent worker exposure factor
    •Dedicated rail flag

SPENT FUEL CASK

IMPACT ABSORBER

OUTER STRUCTURAL SHELL

NEUTRON SHIELDING

GAMMA SHIELDING

OUTER WALL

SEAL

BOLTS

LID

IMPACT ABSORBER

TRUNNION

CONTAINMENT VESSEL

BASKET

SPENT FUEL ASSEMBLY
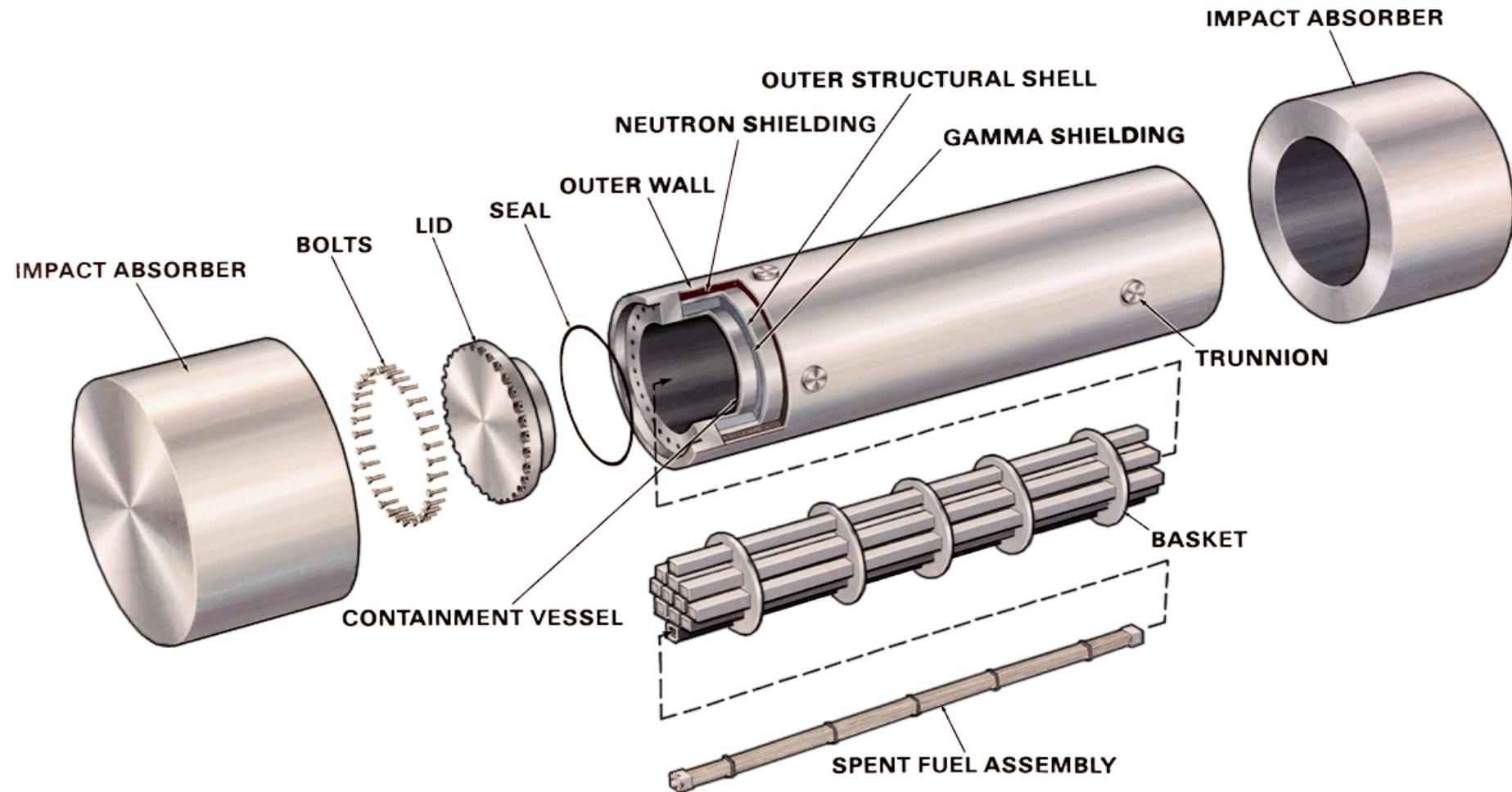
Transportation Accidents : Matrix of NUREG/CR-6672 Cases

>120	**3** Seal Failure on Impact ✳ (Part) 1.9E-05 (Ru) 1.9E-05 (Cs) 1.8E-05 (Kr) 8.0E-01 (Crud) 6.4E-02 Prob 4.49E-09	**13** Seal Failure on Impact ⊕ (Part) 2.0E-05 (Ru) 2.0E-05 (Cs) 1.8E-05 (Kr) 8.2E-01 (Crud) 6.5E-02 Prob 3.82E-11	**14** Seal Failure on Impact ⊕ (Part) 2.1E-05 (Ru) 2.1E-05 (Cs) 2.0E-05 (Kr) 8.9E-01 (Crud) 7.1E-02 Prob 1.27E-12	**15** Seal Failure on Impact (Part) 2.2E-05 (Ru) 2.2E-05 (Cs) 2.2E-05 (Kr) 9.1E-01 (Crud) 7.4E-02 Prob 1.88E-14	**19** Failure by Shear/Puncture Seal Failure from Fire ⊕ (Part) 2.2E-05 (Ru) 2.3E-05 (Cs) 2.2E-05 (Kr) 9.1E-01 (Crud) 7.4E-02 Prob 1.88E-17
90 − 120	**2** Seal Failure on Impact ✳ (Part) 1.3E-05 (Ru) 1.3E-05 (Cs) 8.6E-06 (Kr) 8.0E-01 (Crud) 4.4E-02 Prob 1.17E-07	**10** Seal Failure by Impact ✳ (Part) 1.3E-05 (Ru) 1.3E-05 (Cs) 8.8E-06 (Kr) 8.2E-01 (Crud) 4.5E-02 Prob 9.93E-10	**11** Seal Failure by Impact ⊕ (Part) 1.5E-05 (Ru) 1.5E-05 (Cs) 9.6E-06 (Kr) 8.9E-01 (Crud) 4.9E-02 Prob 3.30E-11	**12** Seal Failure by Impact ⊕ (Part) 1.5E-05 (Ru) 1.5E-05 (Cs) 1.4E-05 (Kr) 9.1E-01 (Crud) 5.1E-02 Prob 4.91E-13	**18** Failure by Shear/Puncture Seal Failure from Fire ⊕ (Part) 1.5E-05 (Ru) 1.8E-05 (Cs) 1.4E-05 (Kr) 9.1E-01 (Crud) 5.1E-02 Prob 4.91E-16
60 − 90	**1** Seal Failure on Impact ✱ (Part) 2.5E-07 (Ru) 2.5E-07 (Cs) 1.2E-08 (Kr) 4.1E-01 (Crud) 1.4E-03 Prob 8.60E-06	**7** Seal Failure by Impact ✱ (Part) 2.6E-07 (Ru) 2.6E-07 (Cs) 1.3E-08 (Kr) 4.3E-01 (Crud) 1.5E-03 Prob 7.31E-08	**8** Seal Failure by Impact ✱ (Part) 2.9E-07 (Ru) 2.9E-07 (Cs) 1.5E-08 (Kr) 4.9E-01 (Crud) 1.7E-03 Prob 2.43E-09	**9** Seal Failure by Impact ⊕ (Part) 6.8E-06 (Ru) 6.8E-06 (Cs) 2.7E-05 (Kr) 8.5E-01 (Crud) 4.5E-03 Prob 3.61E-11	**17** Failure by Shear/Puncture, Seal Failure from Fire ⊕ (Part) 8.9E-06 (Ru) 5.0E-05 (Cs) 5.5E-05 (Kr) 8.5E-01 (Crud) 5.4E-03 Prob 3.61E-14
30 − 60	Barge Only (Crud) 3.0E-05	**4** Seal Failure by Fire ✱ (Part) 1.0E-07 (Ru) 1.0E-07 (Cs) 4.1E-09 (Kr) 1.4E-01 (Crud) 1.4E-03 Prob 3.05E-05	**5** Seal Failure by Fire ✱ (Part) 1.3E-07 (Ru) 1.3E-07 (Cs) 5.4E-09 (Kr) 1.8E-01 (Crud) 1.8E-03 Prob 1.01E-06	**6** Seal Failure by Fire ⊕ (Part) 1.4E-05 (Ru) 1.4E-05 (Cs) 3.6E-05 (Kr) 8.4E-01 (Crud) 5.4E-03 Prob 1.51E-08	**16** Failure by Shear/Puncture, Seal Failure from Fire ⊕ (Part) 1.8E-05 (Ru) 8.4E-05 (Cs) 9.6E-05 (Kr) 8.4E-01 (Crud) 6.4E-03 Prob 5.69E-11
No Impact	**21** No Release ✱ Prob 0.99996			**20** Seal Failure by Fire ✱ (Part) 2.5E-07 (Ru) 2.5E-07 (Cs) 1.7E-05 (Kr) 8.4E-01 (Crud) 9.4E-03 Prob 6.32E-06	
	No Fire	$T_a - T_s$	$T_a - T_b$	**A** $T_a - T_f$	**B** $T_a - T_f$

Change Severity Categories By Probability Weighting

$$RF_{Sci,m} = \frac{\sum_{j,m} RF_{Cj} * P_{Cj}}{P_{Sci}} \qquad P_{Sci} = \sum_{j} P_{Cj}$$

j	=	the cases included in severity category I
P_{Cj}	=	the case j probability
P_{Sci}	=	the accident severity i probability

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Severity category	NUREG/CR-6672 Case	Severity fraction	PWR release fractions				
			Kr	Cs	Ru	Particulates	Crud
1	19	0.99993	0.00000	0.00000	0.00000	0.00000	0.00000
2	2, 3	6.06E-05	1.36E-01	4.09E-09	1.02E-07	1.02E-07	1.36E-03
3	18	5.86E-06	8.39E-01	1.68E-05	6.71E-08	6.71E-08	2.52E-03
4	1, 5, 6, 8	4.95E-07	4.49E-01	1.35E-08	3.37E-07	3.37E-07	1.83E-03
5	4	7.49E-08	8.35E-01	3.60E-05	3.77E-06	3.77E-06	3.16E-03
6	7, 9, 10, 11, 12, 13, 14, 15, 16, 17	3.00E-10	8.40E-01	2.40E-05	2.14E-05	5.01E-06	3.17E-03

Atmospheric Dispersion

u = wind velocity
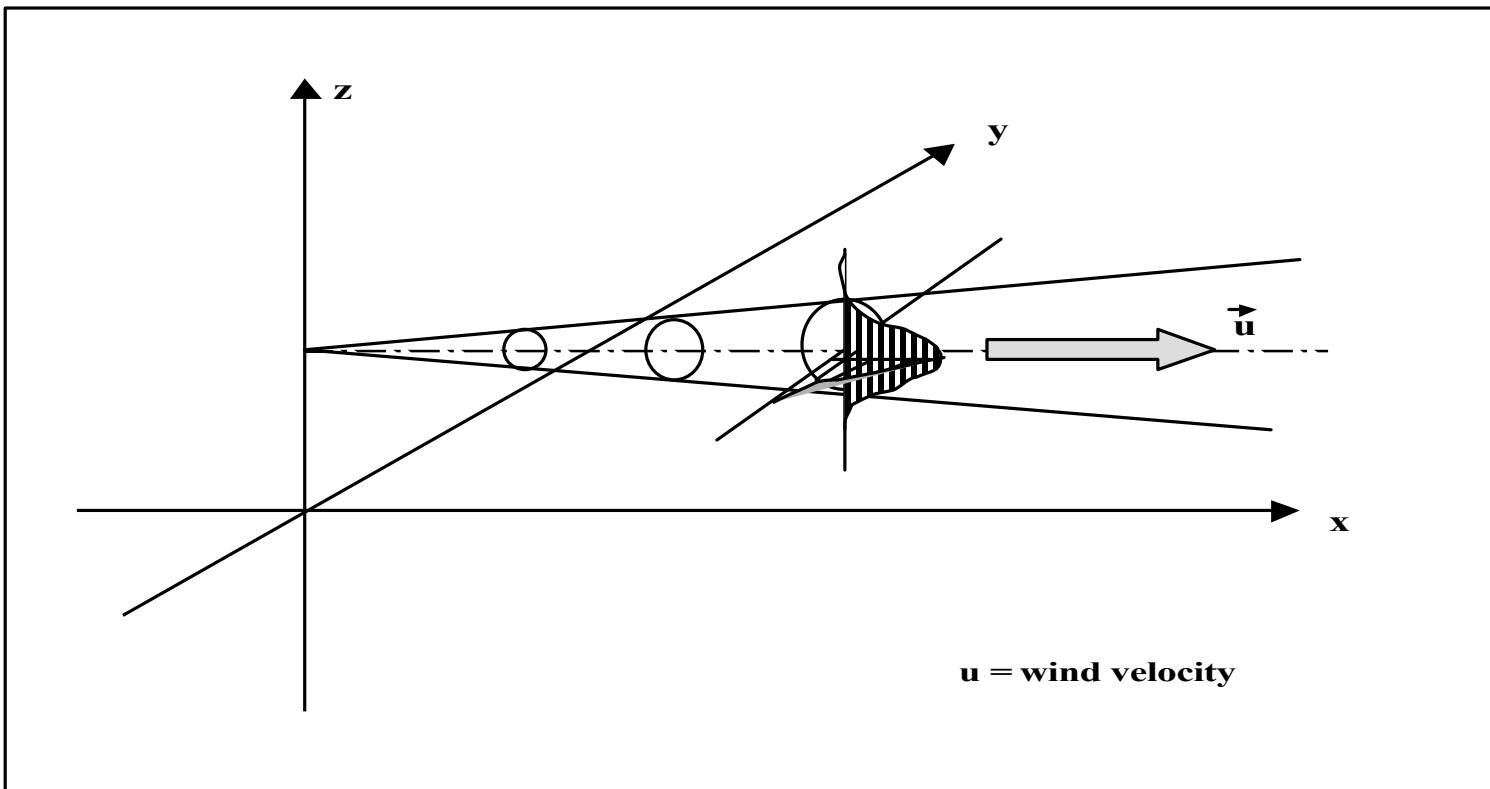
Gaussian Dispersion

Gaussian Dispersion from a Ground-Level Source

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

At y = 0 and z = 0: ground level and plume centerline

$$\frac{CHI}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z}$$

Gaussian Dispersion from an Elevated Source

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

From Turner, B. D. Workbook of Atmospheric DIspersion Estimates, 1970

Gaussian Dispersion With Deposition

Deposition from an Elevated Source

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

Deposition velocity

$$V_d = \left[\frac{gd^2\rho}{18\mu}\right]$$
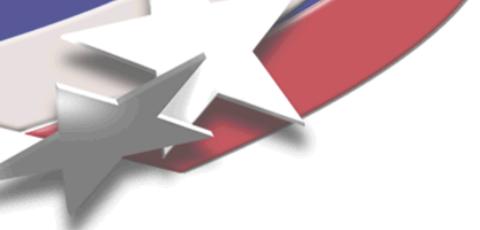
Dispersion Footprint
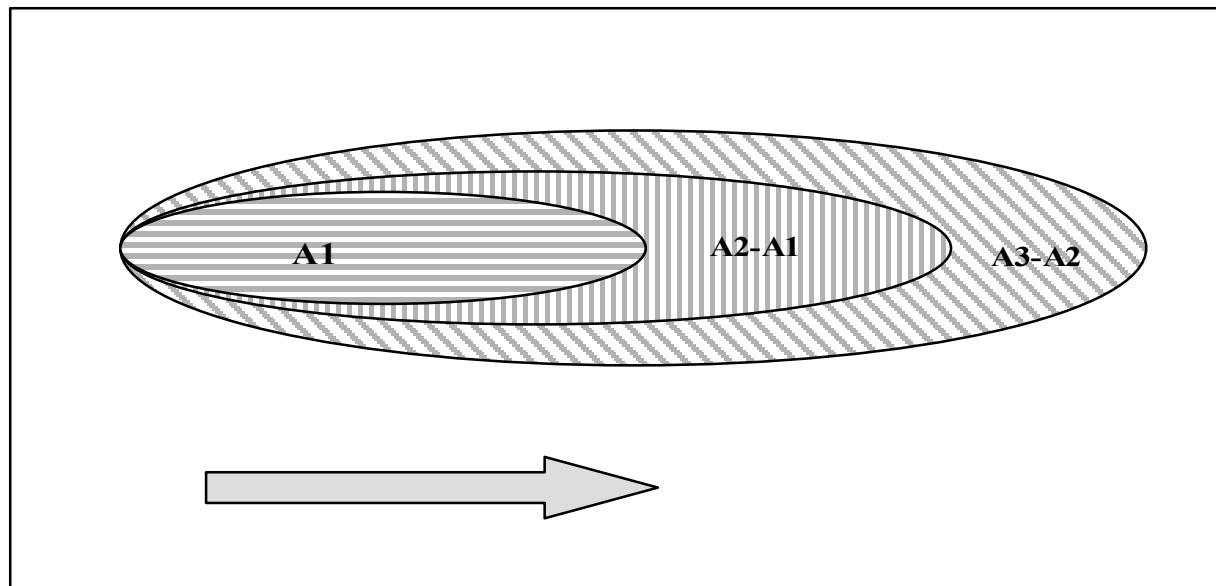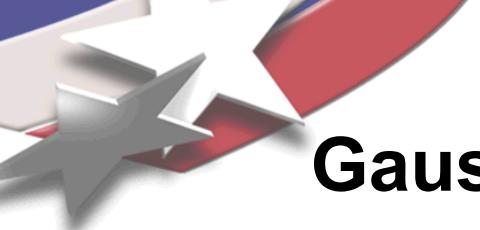
Gaussian Dispersion With Deposition In RADTRAN

The amount deposited in the first isopleth area is:

$$DEP_1^0 = \overline{CHI}_1 \cdot V_d \cdot A_1$$

The amount of material deposited in the nth area, $n \geq 2$, is

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

The total amount of material deposited out to A_n is then

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

When deposition occurs, a revised value of the airborne concentration is calculated:

$$CHI_n^1 = \sqrt{\left(CHI_n \cdot \left(1 - DEP_n^N\right) \cdot CHI_{n-1}^0 \cdot \left(1 - DEP_{n-1}^N\right)\right)}$$

A revised estimate of the material deposited is given by

$$DEP_n^1 = CHI_n^0 \cdot V_d \cdot [A_n - A_{n-1}]$$

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Dose to an Individual from Inhalation of Dispersed Materials

$$D_{inh} = \sum_{m}^{\text{all packages}} \sum_{p}^{\text{all radionuclides}} \sum_{o}^{\text{all organs}} \left(Ci_p \cdot PPS_L \cdot RF_{p,\,j} \cdot AER_{p,\,j} \cdot RESP_{p,\,j} \cdot RPC_{p,\,o} \cdot CHI_n \cdot BR \right)$$

D_{inh} = Individual inhalation dose (rem)

Ci_p = Number of curies of isotope p in package (Ci)

PPS_L = Number of packages on link L

$RF_{p,j}$ = Fraction of package contents released in accident of severity j

$AER_{p,j}$ = Fraction of released material that is aerosol in accident of severity j

$RESP_{p,j}$ = Fraction of aerosolized material that is respirable in accident of severity j

$RPC_{p,o}$ = Dose conversion factor of pth isotope and o^{th} organ (rem/Ci)

CHI_n = dilution factor in nth isopleth area (Ci-sec/m^3/Ci-released)

BR = Breathing rate (m^3/sec)

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Integrated Population Dose from Inhalation of Dispersed Materials

$$D_{inh}^{pop} = Q_7 \cdot Ci_p \cdot PPS_L \cdot RF_{p,\,j} \cdot AER_{p,j} \cdot RESP_{p,\,j} \cdot RPC_p \cdot IF \cdot BR \cdot PD_L \cdot A_n$$

D_{inh} = Population inhalation dose (rem)

Q_7 = Conversion factor

Ci_p = Number of curies of isotope p in package (Ci)

PPS_L = Number of packages on link L

$RF_{p,j}$ = Fraction of radionuclide p released in accident of severity j

$AER_{p,j}$ = Fraction of released radionuclide p that is aerosol in accident of severity j

$RESP_{p,j}$ = Fraction of aerosolized radionuclide p that is respirable in accident of severity j

RPC_p = Dose conversion factor of pth isotope (rem/Ci)

IF = Integral of time-integrated atmospheric dilution factors over downwind areas

BR = Breathing rate (m^3/sec)

PD_L = Population density on link L (persons/km^2)

A_n = Area of nth isopleth (m^2)

Integrated Population Dose from Groundshine

$$DR(T) = CL_p \cdot GDF \cdot \left[0.63 \cdot e^{-0.0031 \cdot t1/2} + 0.37 \cdot e^{-0.000021 \cdot t1/2}\right] \cdot e^{\frac{-0.693 \cdot ET}{t1/2}}$$

DR(T) = Groundshine dose rate at time T (rem/day)

CL_p = Ground concentration (deposition) of radionuclide p ($\mu Ci/m^2$)

GDF   = Groundshine dose factor for radionuclide p (rem-m^2/day-μCi)

$t_{1/2}$ = Half-life of radionuclide p (days)

Societal Ingestion Dose

COMIDA has been run and has output the ingestion dose for one curie of each radionuclide in the internal RADTRAN library. RADTRAN finds the output for each nuclide in the input file and multiplies by the activity, release fraction, etc.
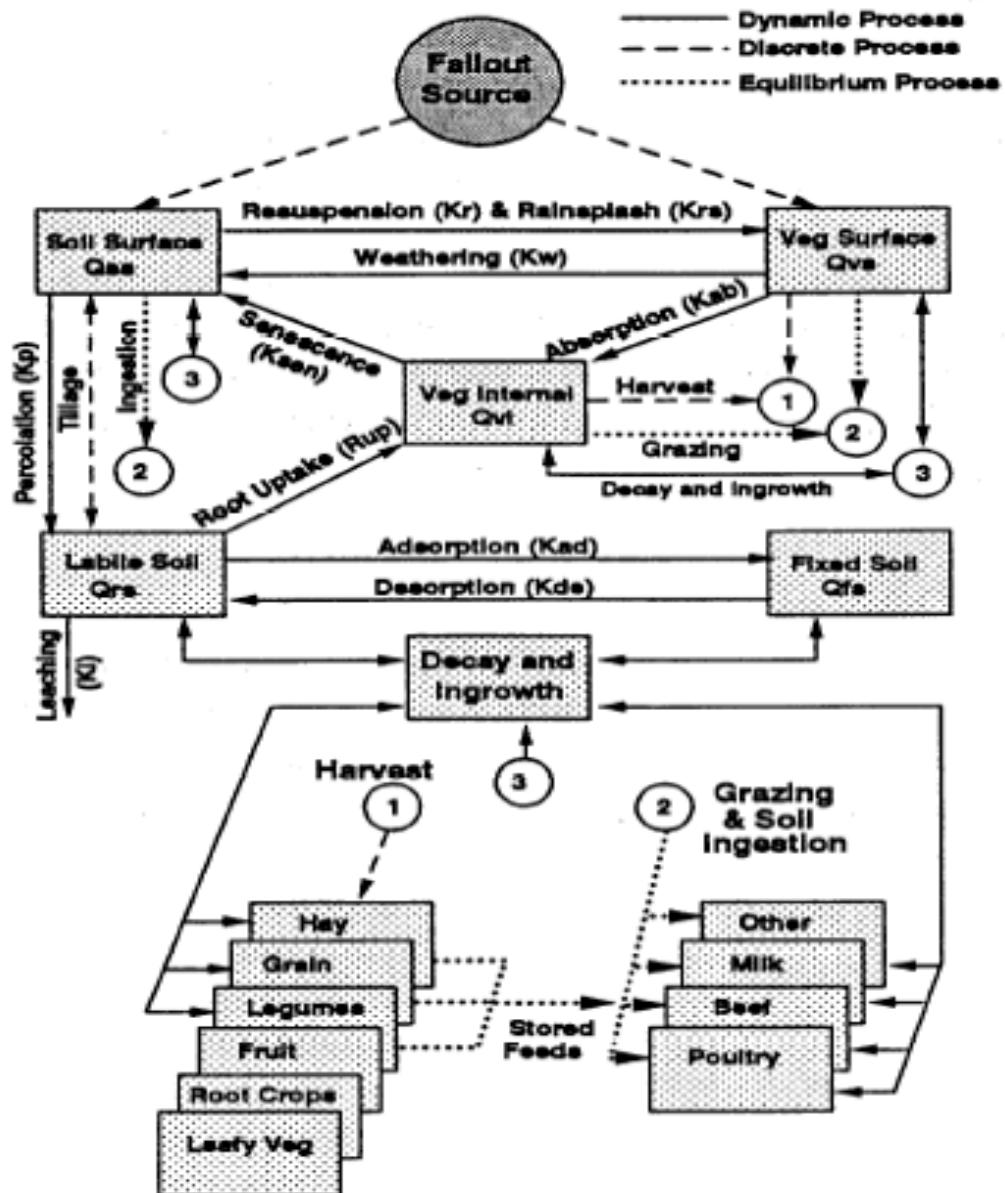
Dose Risk
Inhalation Example

$$\mathrm{RISK}_{L}^{INH} = \sum_{p=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,\,L} \cdot \mathrm{D}_{inh_{p,j,L}}$$

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

D_{inh} = Population inhalation dose from radionuclide p in an accident of severity j on link L (person-rem)

NSEV = Number of accident severity categories

n = Number of radionuclides in package

Default Values for Transportation Accidents

- Fraction of outside air in urban buildings
- Ratio of pedestrian density to urban residential population density
- Fraction of urban residential population inside (and outside) of buildings
- Average breathing rate
- Cleanup level (microcuries/sq. m.)
- Interdicton threshold
- Evacuation time
- Survey interval
- LCF/person-rem for occupational and public exposure
- Genetic effects/person-rem
- Duration of shipping campaign

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Loss-of-Shielding 3-D Model
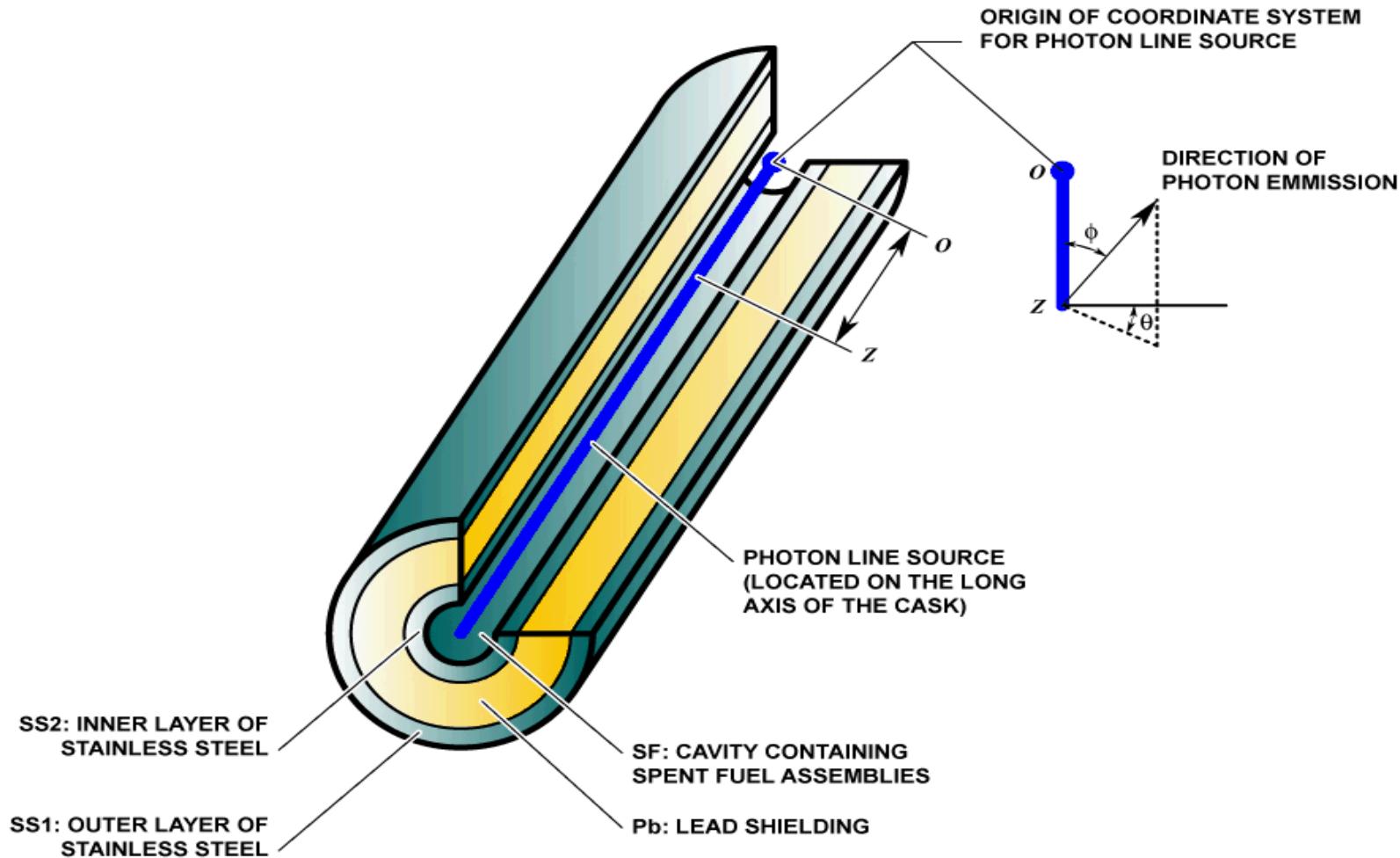
Loss-of-Shielding 2-D Model (Damaged Cask)
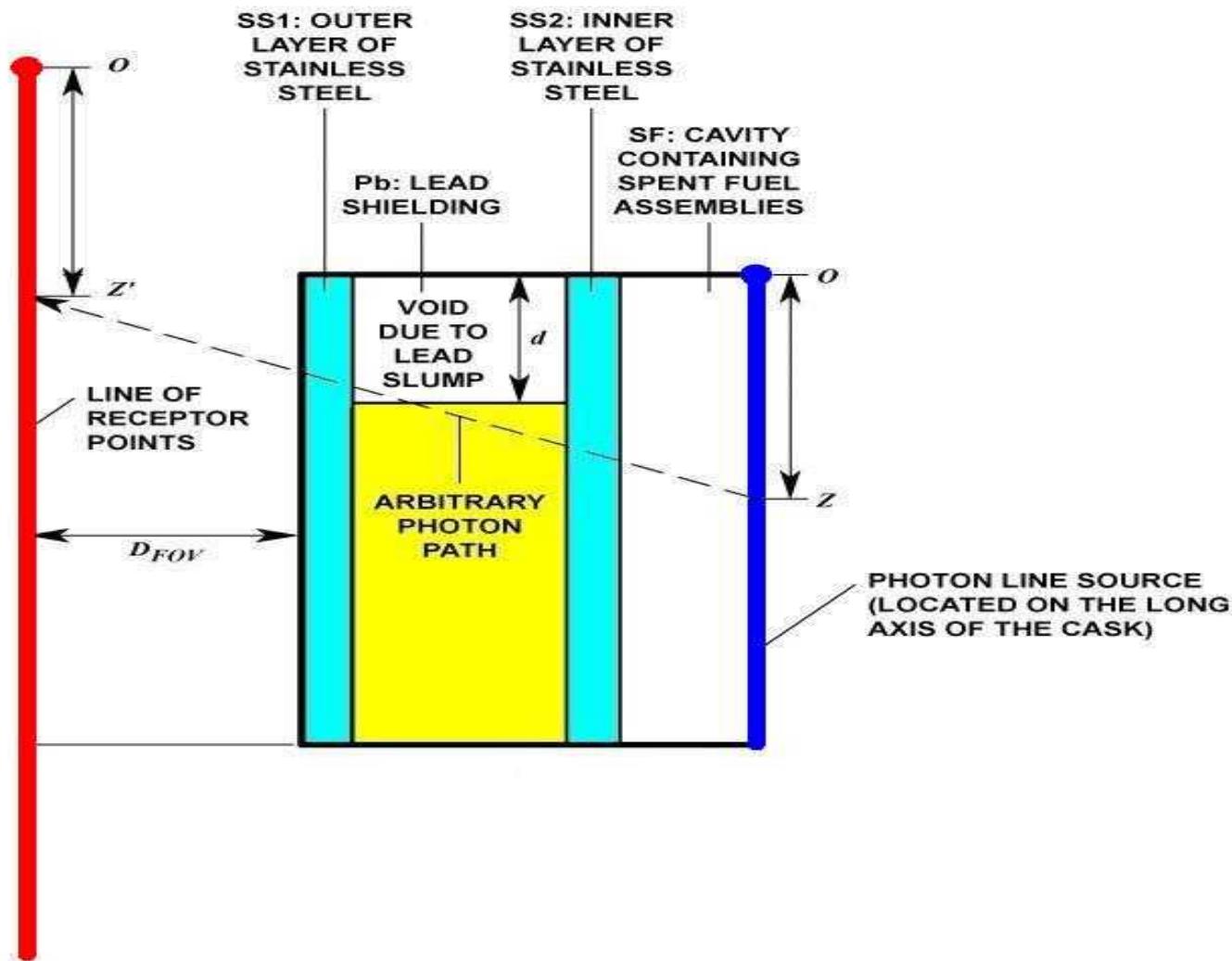
Integration With Other Systems

- RADTRAN uses a text input file that can be created with any commercial text editor or with RADCAT, or can be made from a text template.
- RADTRAN output can be either a text file or an Excel (spreadsheet) file
- RADTRAN output can be read electronically into an ACCESS database.
- RADTRAN uses routing code output (e.g., TRAGIS) for distances and population densities.

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Comparison to Similar Codes

- RISKIND:
  - Can run only one scenario at a time
  - User input of, e.g., radionuclides is difficult
  - No LOS module
- HOTSPOT
  - Designed for explosions
  - Uses much more memory
  - No incident-free module
  - No LOS module
- MACCS 2
  - Designed for reactor accidents
  - More complex than needed for transportation
  - GUI input file generator not yet available

RADTRAN 6.0
Equations

Incident Free Calculations

- Gamma Point Source
- Neutron Point Source
- Effective Package Dimension (d_e)
  - If $r > 2d_e$ then the point source equations apply
- Point Source Package Shape Factor
- Gamma Line Source
- Neutron Line Source
- Line Source Shape Factor
- General equation for Gamma Dose to Population along the Route
- General Neutron Dose Equation
- Basic Equation for Dose to Population along the Route
- Final Equation for Dose to Population along the Route
- Integration Factor: I
- Integration Factor: J
- Integration Factor: K
- Integration Factor: L
- General Equation for Dose to Persons Traveling in Opposite Direction
- Final Equation for Dose to Persons Traveling in Opposite Direction

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Incident Free Calculations

- Integration Factor: I_G
- Integration Factor: I_N
- Final Equation for Dose to Persons Traveling in the Same Direction
- Traffic Factor: F_1
- Traffic Factor: F_2
- Equation for Dose to Population for Stopped Shipments – Option 1: Point Source
- Equation for Dose to Population for Stopped Shipments – Option 1: Line Source
- Term for Gamma Radiation Source Strength: TR_G
- Term for Neutron Radiation Source Strength: TR_N
- Equation for Dose to Population for Stopped Shipments – Option 2: No Attenuation
- Equation for Dose to Population for Stopped Shipments – Option 2: Attenuation
- Final Equation for Dose to Crew Members – Highway Mode
- Equation for Dose to Rail Yard Worker
- Equation for Dose to Rail Yard Workers
- Final Equation for Dose to Cargo Inspectors for Barges
- Equation for Dose to Handlers – Small Packages
- Equation for Dose to Handlers – Large and Intermediate Packages: Point Source
- Equation for Dose to Handlers – Large and Intermediate Packages: Line Source

Gamma Point Source

$$DR_G(r) = Q_1 \cdot DR_{p \text{ or } v} \cdot f_G \cdot \frac{k_0}{r^2}$$

where:

$DR_G(r)$ = Gamma dose rate at distance r (mrem/hr)

r = Radial distance from source (m)

Q_1 = Unit conversion factor

f_G = Fraction of dose rate at 1m from package that is gamma radiation

$DR_{p \text{ or } v}$ = Package or vehicle dose rate at 1 meter (mrem/hr)

k_0 = Point source shape factor (m^2)

Neutron Point Source

$$DR_N(r) = Q_1 \cdot DR_{p\ or\ v} \cdot f_N \cdot \frac{k_0}{r^2} \cdot e^{(-\mu \cdot r)} \cdot \left(1 + a_1 \cdot r + a_2 \cdot r^2 + a_3 \cdot r^3 + a_4 \cdot r^4\right)$$

where:

$DR_N(r)$ = Neutron dose rate at distance r (mrem/hr)

r = Radial distance from source (m)

Q_1 = Unit conversion factor

f_N = Fraction of dose rate at 1 meter from package that is neutron radiation

$DR_{p\ or\ v}$ = Package or vehicle dose rate at 1m (mrem/hr)

k_0 = Point source shape factor (m²)

μ = Linear attenuation coefficient (m^{-1})

a_1, a_2, a_3, a_4 = dimensionless coefficients; default values set

Effective Package Dimension

$$d_e = \begin{cases} d_p, \text{ if } d_p < 4 \text{ meters, or} \\ d_v, \text{ if } d_v < 4 \text{ meters, or} \\ 2 \cdot (1 + 0.5 \cdot d_p)^{0.75} - 0.55, \text{ if } d_p > 4 \text{ meters and } < 9 \text{ meters, or} \\ 2 \cdot (1 + 0.5 \cdot d_v)^{0.75} - 0.55, \text{ if } dv > 4 \text{ meters and } < 9 \text{ meters} \end{cases}$$

where:

d_e = Effective package dimension (m)
d_v = Vehicle dimension (m)
d_p = Package dimension (m)

Point Source Package Shape Factor

$$k_0 = (1 + 0.5 \cdot d_e)^2$$

where:

k_0 = Point source package shape factor (m^2)
d_e = Effective package dimension (m)

Gamma Line Source

$$DR_G(r) = Q_1 \cdot DR_{p \text{ or } v} \cdot f_G \cdot \frac{k_1}{r} \cdot e^{(-\mu \cdot r)}$$

where:

$DR_G(r)$ = Gamma dose rate at distance r (mrem/hr)

r = Radial distance from source (m)

Q_1 = Unit conversion factor

f_G = Fraction of dose rate at 1meter from package that is gamma radiation

$DR_{p \text{ or } v}$ = Package or vehicle dose rate at 1m (mrem/hr)

k_1 = Line source shape factor (m)

μ = Linear attenuation coefficient (m^{-1})

Neutron Line Source

$$DR_N(r) = Q_1 \cdot DR_{p\ or\ v} \cdot f_N \cdot \frac{k_1}{r} \cdot e^{(-\mu \cdot r)} \cdot \left(1 + a_1 \cdot r + a_2 \cdot r^2 + a_3 \cdot r^3 + a_4 \cdot r^4\right)$$

where:

$DR_N(r)$ = Neutron dose rate at distance r (mrem/hr)

r = Radial distance from source (m)

Q1 = Unit conversion factor

f_N = Fraction of dose rate at 1 meter from package that is neutron radiation

$DR_{p\ or\ v}$ = Package or vehicle dose rate at 1meter (mrem/hr)

k1 = Line source shape factor (m)

m = Linear attenuation coefficient (m-1)

a_1, a_2, a_3, a_4 = dimensionless coefficients

Line Source Shape Factor

$$k_1 = 1 + 0.5 \cdot d_e$$

where:

k_1 =   Line source shape factor (m)

d_e =   Effective package dimension (m)

General Equation for Gamma Dose to Population along the Route

$$D(x) = \frac{2 \cdot Q_1 \cdot k_0 \cdot DR_v}{V} \cdot \int_{x}^{\infty} \left(\frac{e^{(-\mu \cdot r)} \cdot B(r)}{r \cdot \left(r^2 - x^2\right)^{0.5}} \right) dr$$

where:

D(x)   = Total integrated does absorbed by an individual at distance x (rem)
Q_1 = Unit conversion factor
k_0 = Point source package shape factor (m^2)
DR_v = Shipment dose rate at 1 meter from surface (mrem/hr)
V   = Shipment speed (m/s)
μ = Attenuation coefficient (m^{-1})
r   = Perpendicular distance of individual from shipment path (m)
B(r)   = Buildup factor expressed as a geometric progression
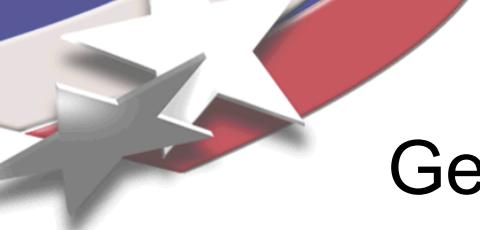
General Neutron Dose Equation?

There is no neutron dose calculated because of the neutron shielding that will be used on the shipment as well as the low neutron fluence that is experience from spent nuclear fuel.

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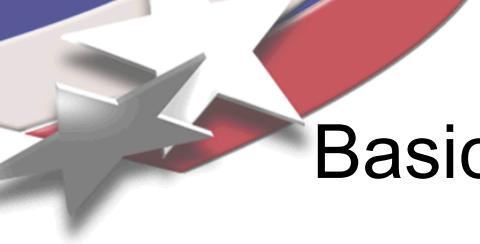
Basic Equation for Dose to Population along the Route

$$\mathrm{D_{off}} = 2 \cdot \mathrm{Q} \cdot \mathrm{PD} \cdot \int\limits_{\min}^{\max} \big(\mathrm{D(x)}\big)\, dx$$

where:

$\mathrm{D_{off}}$ = Integrated population dose per km of strip (person-rem)

Q = Units conversion factor

PD = Population density (persons/km^2)

max = Maximum distance perpendicular to shipment route over which exposure is evaluated (m)

min = Minimum distance perpendicular to shipment route over which exposure is evaluated (m)

D(x) = Total integrated dose absorbed by an individual at distance x (rem)

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Final Equation for Dose to Population along the Route

$$D_{off} = 4 \cdot Q \cdot k_0 \cdot DR_v \cdot \frac{PD_L}{V_L} \cdot NSH_L \cdot DIST_L \cdot \left[f_G \cdot (I + J) + f_N \cdot (K + L) \right]$$

where:

D_{off} = Integrated population dose per km of strip (person-rem)

Q = Units conversion factor

k_0 = Point source package shape factor (m^2)

DR_v = Shipment dose rate at 1 meter from surface (mrem/hr)

PD_L = Population density for segment L (persons/km^2)

V_L = Shipment speed for segment L (m/s)

NSH_L = Number of shipments that travel on segment L

$DIST_L$ = Distance on segment L (km)

f_G = Fraction of dose rate at 1 meter from package that is gamma radiation

f_N = Fraction of dose rate at 1 meter from package that is neutron radiation

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Integration Factor: I

$$I = \int_{min}^{0} \left[\frac{e^{(-\mu_G \cdot r)} \, B_G(r)}{r \cdot \left(r^2 + x^2\right)^{0.5}} \right] dr \cdot RPD_{S \, or \, U}$$

where:

min   = Minimum distance perpendicular to shipment route over which exposure is evaluated (m)

μ_G = Attenuation coefficient for gamma radiation (m^{-1})

$B_G(r)$ = Buildup factor expressed as a geometric progression for gamma radiation

r   = Perpendicular distance of individual from shipment path (m)

$RPD_{S \, or \, U}$ = Ratio of pedestrian density to residential population density in suburban (S) or urban (U) route segments.

Integration Factor: J

$$J = \int_{0}^{\text{max}} \left[\frac{e^{(-\mu_G \cdot r)} \, B_G(r)}{r \cdot \left(r^2 + x^2\right)^{0.5}} \right] dr \cdot \text{SF}$$

where:

max = Maximum distance perpendicular to shipment route over which exposure is evaluated (m)

μ_G = Attenuation coefficient for gamma radiation (m^{-1})

$B_G(r)$ = Buildup factor expressed as a geometric progression for gamma radiation

r = Perpendicular distance of individual from shipment path (m)

SF = Shielding factor

Integration Factor: K

$$K = \int_{min}^{0} \left[\frac{e^{(-\mu_N \cdot r)} \, B_N(r)}{r \cdot \left(r^2 + x^2 \right)^{0.5}} \right] dr \cdot RPD_{S \, or \, U}$$

where:

min = Minimum distance perpendicular to shipment route over which exposure is evaluated (m)

r = Perpendicular distance of individual from shipment path (m)

$RPD_{S \, or \, U}$ = Ratio of pedestrian density to residential population density in suburban (S) or urban (U) route segments.

μ_N = Attenuation coefficient for neutron radiation (m^{-1})

$B_N(r)$ = Buildup factor expressed as a geometric progression for neutron radiation

Integration Factor: L

$$L = \int_0^{max} \left[\frac{e^{(-\mu_N \cdot r)} \, B_N(r)}{r \cdot \left(r^2 + x^2\right)^{0.5}} \right] dr \cdot SF$$

where:

max = Maximum distance perpendicular to shipment route over which exposure is evaluated (m)

r = Perpendicular distance of individual from shipment path (m)

SF = Shielding factor

μ_N = Attenuation coefficient for neutron radiation (m^{-1})

$B_N(r)$ = Buildup factor expressed as a geometric progression for neutron radiation

General Equation for Dose to Persons Traveling in the Opposite Direction

$$D(x) = \frac{2 \cdot Q_1 \cdot k_0 \cdot DR_v}{2 \cdot V} \cdot \int_x^{\infty} \left(\frac{e^{(-\mu \cdot r)} \cdot B(r)}{r \cdot \left(r^2 + x^2\right)^{0.5}} \right) dr$$

where:

$D(x)$ = Total integrated dose absorbed by an individual at distance x (rem)

Q_1 = Unit conversion factor

k_0 = Point source package shape factor (m^2)

DR_v = Shipment dose rate at 1 meter from surface (mrem/hr)

V = Shipment speed (m/s)

μ = Attenuation coefficient (m^{-1})

r = Perpendicular distance of individual from shipment path (m)

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

Final Equation for Dose to Persons Traveling in the Opposite Direction

$$D_{opp} = Q_2 \cdot k_0 \cdot DR_v \cdot \frac{N}{V_L^2} \cdot PPV \cdot DIST_L \cdot NSH \cdot \left[f_G \cdot I_G + f_N \cdot I_N \right]$$

where:

D_{opp}	=	Integrated population dose per km of strip (person-rem)
Q_2	=	Conversion factor
k_0	=	Point source package shape factor (m^2)
DR_v	=	Shipment dose rate at 1 meter from surface (mrem/hr)
N	=	One-way traffic count (average number of vehicles that pass per hour)
V	=	Average velocity of all traffic (m/s)
PPV	=	Vehicle occupancy (average number of person per vehicle)
$DIST_L$	=	Distance traveled on segment L
NSH	=	Number of shipments
f_G	=	Fraction of dose rate at 1 meter from package that is gamma radiation
f_N	=	Fraction of dose rate at 1 meter from package that is neutron radiation

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Integration Factor: I_G

$$I_G = \int_{x}^{\infty} \left[\frac{e^{(-\mu_G \cdot r)} \, B_G(r)}{r \cdot \left(r^2 + x^2\right)^{0.5}} \right] dr$$

where;

r   =   Perpendicular distance of individual from shipment path (m)

μ_G =   Attenuation coefficient for gamma radiation (m^{-1})

$B_G(r)$ =   Buildup factor expressed as a geometric progression for gamma radiation

Integration Factor: I_N

$$I_N = \int_{x}^{\infty} \left[\frac{e^{(-\mu_N \cdot r)} \, B_N(r)}{r \cdot \left(r^2 + x^2\right)^{0.5}} \right] dr$$

where:

r = Perpendicular distance of individual from shipment path (m)

μ_N = Attenuation coefficient for neutron radiation (m^{-1})

$B_N(r)$ = Buildup factor expressed as a geometric progression for neutron radiation

Final Equation for Dose to Persons Traveling in the Same Direction

$$D_{sdir} = Q_2 \cdot k_0 \cdot DR_v \cdot \frac{N}{V^2} \cdot PPV \cdot DIST_L \cdot NSH \cdot [F_1 + F_2]$$

where:

D_{sdir}	=	Integrated population dose per km of strip (person-rem)
Q_2	=	Conversion factor
k_0	=	Point source package shape factor (m^2)
DR_v	=	Shipment dose rate at 1 meter from surface (mrem/hr)
N	=	One-way traffic count (average number of vehicles that pass per hour)
V	=	Average velocity of all traffic (m/s)
PPV	=	Vehicle occupancy (average number of person per vehicle)
$DIST_L$	=	Distance traveled on segment L
NSH	=	Number of shipments
F_1	=	Traffic factor
F_2	=	Traffic factor

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Traffic Factor: F_1

$$F_1 = 2 \cdot V \cdot \left[\left[F_G \cdot \int_{2V}^{\infty} \left[\frac{e^{(-\mu_G \cdot r)} \, B_G(\mu r)}{r^2} \right] dr \right] + \left[F_N \cdot \int_{2V}^{\infty} \left[\frac{e^{(-\mu_N \cdot r)} \, B_N(\mu r)}{r^2} \right] dr \right] \right]$$

where:

F_G = Fraction of DR_v that is gamma radiation

F_N = Fraction of DR_v that is neutron radiation

V = Average velocity (m/s)

μ_G = Attenuation coefficient for gamma radiation (m^{-1})

μ_N = Attenuation coefficient for neutron radiation (m^{-1})

$B_G(r)$ = Buildup factor expressed as a geometric progression for gamma radiation

$B_N(r)$ = Buildup factor expressed as a geometric progression for neutron radiation

Traffic Factor: F_2

$$F_2 = \frac{V}{x} \cdot \left[\left[F_G \cdot \int_{2V}^{\infty} \left[\frac{e^{(-\mu_G \cdot r)} \, B_G(\mu r)}{r^2} \right] dr \right] + \left[F_N \cdot \int_{2V}^{\infty} \left[\frac{e^{(-\mu_N \cdot r)} \, B_N(\mu r)}{r^2} \right] dr \right] \right]$$

where:

x   = Minimum perpendicular distance to adjacent vehicle (m)
F_G = Fraction of DR_v that is gamma radiation
F_N = Fraction of DR_v that is neutron radiation
V   = Average velocity (m/s)
μ_G = Attenuation coefficient for gamma radiation (m^{-1})
μ_N = Attenuation coefficient for neutron radiation (m^{-1})
$B_G(r)$ = Buildup factor expressed as a geometric progression for gamma radiation
$B_N(r)$ = Buildup factor expressed as a geometric progression for neutron radiation

Equation for Dose to Population for Stopped Shipments
Option 1: Average-Distance Method
Point Source

$$D = Q_4 \cdot DR \cdot P \cdot T \cdot NSH \cdot SF \cdot \left[(FG \cdot TR_G) + (FN \cdot TR_N) \right] \cdot \frac{k_0}{r^2}$$

where:

D = Integrated population dose for stop (person-rem)

Q_4 = Conversion factor

k_0 = Point source shape factor for vehicle (m^2)

DR = Vehicle dose rate at 1 meter from surface (mrem/hr)

P = Average number of expected persons

T = Duration of stop (hr)

NSH = Number of shipment by vehicle

SF = Shielding factor at stop

r = Average radial source-to-receptor distance (m)

FG = Fraction of vehicle dose rate from gamma radiation

FN = Fraction of vehicle dose rate from neutron radiation

TR_G = Term for gamma radiation source strength

TR_N = Term for neutron radiation source strength

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Equation for Dose to Population for Stopped Shipments
Option 1: Average-Distance Method
Line Source

$$D = Q_4 \cdot DR \cdot P \cdot T \cdot NSH \cdot SF \cdot \left[\left(FG \cdot TR_G\right) + \left(FN \cdot TR_N\right)\right] \cdot \frac{k_1}{r}$$

where:

D	=	Integrated population dose for stop (person-rem)
Q_4	=	Conversion factor
k_1	=	Line source shape factor for vehicle (m)
DR	=	Vehicle dose rate at 1 meter from surface (mrem/hr)
P	=	Average number of expected persons
T	=	Duration of stop (hr)
NSH	=	Number of shipment by vehicle
SF	=	Shielding factor at stop
r	=	Average radial source-to-receptor distance (m)
FG	=	Fraction of vehicle dose rate from gamma radiation
FN	=	Fraction of vehicle dose rate from neutron radiation
TR_G	=	Term for gamma radiation source strength
TR_N	=	Term for neutron radiation source strength

Term for Gamma Radiation Source Strength: TR_G

$$TR_G = e^{(-\mu_G \cdot r)} \cdot \left(1 + a_{1G} \cdot r + a_{2G} \cdot r^2 + a_{3G} \cdot r^3 + a_{4G} \cdot r^4\right)$$

where:

TR_G = Term for gamma radiation source strength

r = Radial distance from source (m)

μ_G = Gamma attenuation coefficient (m^{-1})

$a_{1G}, a_{2G}, a_{3G}, a_{4G}$ = dimensionless coefficients for gamma radiation

Term for Neutron Radiation Source Strength: TR_N

$$TR_N = e^{(-\mu_N \cdot r)} \cdot \left(1 + a_{1N} \cdot r + a_{2N} \cdot r^2 + a_{3N} \cdot r^3 + a_{4N} \cdot r^4\right)$$

where:

TR_N = Term for neutron radiation source strength

r = Radial distance from source (m)

μ_N = Neutron attenuation coefficient (m^{-1})

$a_{1N}, a_{2N}, a_{3N}, a_{4N}$ = dimensionless coefficients for neutron radiation

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Equation for Dose to Population for Stopped Shipments
Option 2: Annular-Area Method

Assuming attenuation coefficients for gamma and neutron radiation in air is ~0.00

$$D1_{stop} = 2\pi \cdot Q_4 \cdot k_0 \cdot DR \cdot PD \cdot T \cdot NSH \cdot SF \cdot \left[\ln(max) - \ln(min)\right]$$

where:

$D1_{stop}$	=	Integrated population dose for stop (person-rem)
Q_4	=	Conversion factor
k_0	=	Point source shape factor for vehicle (m^2)
DR	=	Vehicle dose rate at 1 meter from surface (mrem/hr)
PD	=	Population density of annular area at stop (persons/km^2)
T	=	Duration of stop (hr)
NSH	=	Number of shipment by vehicle
SF	=	Shielding factor at stop
max	=	Maximum radial distance of concern
min	=	Minimum radial distance of concern

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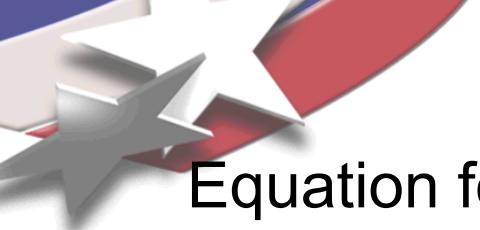
Equation for Dose to Population for Stopped Shipments
Option 2: Annular-Area Method
If prior assumption is not valid

$$D2_{stop} = D1_{stop} \cdot \left(f_G \cdot C_G + f_N \cdot C_N \right)$$

where:

$D2_{stop}$ = Integrated population dose for stop (person-rem)

$D1_{stop}$ = Integrated population dose for stop (person-rem)

f_G = Fraction of dose rate at 1 meter from package that is gamma radiation

C_G = Gamma source strength modifier defined over max/min

f_N = Fraction of dose rate at 1 meter from package that is neutron radiation

C_N = Neutron source strength modifier defined over max/min

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Final Equation for Dose to Crew Members – Highway Mode

$$D_{crew} = Q_1 \cdot DR \cdot \frac{N}{V} \cdot NSH \cdot DIST \cdot CSF \cdot \left[\left(FG \cdot TR_G \right) + \left(FN \cdot TR_N \right) \right] \cdot \frac{k_0}{r^2}$$

where:

D_{crew} = integrated dose to crew (person-rem)
Q_1 = Unit conversion factor
DR = Vehicle dose rate at 1-meter from surface (mrem/hr)
N = Number of crew members
V = Average velocity (m/s)
NSH = Number of shipments
DIST = Distance traveled (km)
CSF = Crew shielding factor
FG = Fraction of vehicle dose rate from gamma radiation
FN = Fraction of vehicle dose rate from neutron radiation
TR_G = dose-distance relationship factor for gamma radiation
TR_N = dose-distance relationship factor for neutron radiation
k_0 = "Crew-view" point-source package shape factor for de (m^2)
d_e = The characteristic dimension of package surface nearest to the crew (m)
r = Source-to-worker distance (m)

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Equation for Dose to a Rail Yard Worker

$$D_{rail} = Q_1 \cdot k_0 \cdot DR \cdot NSH \cdot \left[(FG \cdot R_G) + (FN \cdot R_N) \right]$$

where:

D_{rail} = Rail worker dose (person-rem)
Q_1 = Unit conversion factor
k_0 = Line-source rail-car shape factor (m)
DR = Dose rate at 1-meter from rail car (mrem/hr)
NSH = Number of shipments by rail car
FG = Fraction of rail-car dose rate from gamma radiation
FN = Fraction of rail-car dose rate from neutron radiation
R_G = Dose-distance relationship factor for gamma radiation (person-rem/hr)
R_N = Dose-distance relationship factor for neutron radiation (person-rem/hr)

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Final Equation for Dose to Rail Yard Workers

$$D_{CL} = D_{rail} \cdot \left(DIC + \sum^{All\ Links} \left(DDC \cdot DIST_L \right) \right)$$

where:

D_{CL} = Total dose to worker during classifications and inspections in rail yards (person-rem)

D_{rail} = Dose to worker per classification or inspection (person-rem)

DIC = Number of distance-independent classifications per trip

DDC = Number of distance-dependent classifications per km

$DIST_L$ = Length of segment

Final Equation for Dose to Cargo Inspectors for Barges

$$D_{barge} = 0.5 \cdot Q_5 \cdot k_0 \cdot \frac{DR \cdot DIST \cdot NSH}{V} \cdot CSF \cdot \left[(FG \cdot TR_G) + (FN \cdot TR_N) \right]$$

where:

D_{barge} = Cargo Inspector dose (person-rem)

Q_5 = Unit conversion factor

k_0 = "Crew-view" line-source shape factor (m)

DR = Dose rate at 1-meter from surface of shipment (mrem/hr)

DIST = Distance traveled (km)

V = Average velocity (m/s)

NSH = Number of shipments by barge

CSF = Crew shielding factor for cargo hold

FG = Fraction of rail-car dose rate from gamma radiation

FN = Fraction of rail-car dose rate from neutron radiation

TR_G = Dose-distance relationship factor at 2-meters for gamma radiation (person-rem/hr)

TR_N = Dose-distance relationship factor at 2-meters for neutron radiation (person-rem/hr)

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Equation for Dose to Handlers
Small Packages

$$D_{Hsmall} = k_H \cdot DR \cdot PPS \cdot NSH \cdot \left[\left(FG \cdot TR_{Gd} \right) + \left(FN \cdot TR_{Nd} \right) \right]$$

where:

D_{Hsmall} = Integrated dose to handlers of small packages (person-rem)

k_H = Handling-to-dose conversion factor for small packages

DR = Dose rate at 1-meter from surface (mrem/hr)

PPS = Number of packages per shipment

NSH = Number of shipments by vehicle

FG = Fraction of rail-car dose rate from gamma radiation

FN = Fraction of rail-car dose rate from neutron radiation

TR_{Gd} = Dose-distance relationship factor at distance d for gamma radiation (person-rem/hr)

TR_{Nd} = Dose-distance relationship factor at distance d for neutron radiation (person-rem/hr)

d = Average package-to-handler distance (m)

Equation for Dose to Handlers
Large and Intermediate Packages
Point Source

$$D_H = \frac{Q_4 \cdot k_0 \cdot DR \cdot PPS}{d_H^2} \cdot T_H \cdot PPH \cdot NSH \cdot \left[\left(FG \cdot TR_{Gd_H} \right) + \left(FN \cdot TR_{Nd_H} \right) \right]$$

where:

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

Q_4 = Unit conversion factor

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

DR = Dose rate at 1-meter from surface (mrem/hr)

T_H = Average exposure time of handlers (hr)

PPS = Number of packages per shipment

PPH = Number of packages per handler

NSH = Number of shipments by vehicle

FG = Fraction of rail-car dose rate from gamma radiation

FN = Fraction of rail-car dose rate from neutron radiation

TR_{Gd} = Dose-distance relationship factor at distance d_H for gamma radiation (person-rem/hr)

TR_{Nd} = Dose-distance relationship factor at distance d_H for neutron radiation (person-rem/hr)

d_H = Average package-to-handler distance (m)

Equation for Dose to Handlers
Large and Intermediate Packages
Line Source

$$D_H = \frac{Q_4 \cdot k_1 \cdot DR \cdot PPS}{d_H} \cdot T_H \cdot PPH \cdot NSH \cdot \left[\left(FG \cdot TR_{Gd_H} \right) + \left(FN \cdot TR_{Nd_H} \right) \right]$$

where:

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

Q_4 = Unit conversion factor

k_1 = Line-source shape factor (m)

DR = Dose rate at 1-meter from surface (mrem/hr)

T_H = Average exposure time of handlers (hr)

PPS = Number of packages per shipment

PPH = Number of packages per handler

NSH = Number of shipments by vehicle

FG = Fraction of rail-car dose rate from gamma radiation

FN = Fraction of rail-car dose rate from neutron radiation

TR_{Gd} = Dose-distance relationship factor at distance d_H for gamma radiation (person-rem/hr)

TR_{Nd} = Dose-distance relationship factor at distance d_H for neutron radiation (person-rem/hr)

d_H = Average package-to-handler distance (m)

Accident Dose and Dose-Risk Calculations

- Model for Dose to Individual from Inhalation of Dispersed Materials
- Model for Integrate Population Dose from Direct Inhalation of Dispersed Material
- Population Densities in Urban Areas
- Model for Integrated Population Does from Resuspension
- Resuspension Dose Factor
- Model for Dose to an Individual from Cloudshine
- Model for Integrated Population Dose from Cloudshine
- Model for Integrated Population Dose from Groundshine
- Equation for Determining Contamination Level (CL)
- Total Decontamination Factor

Accident Dose and Dose-Risk Calculations

- Calculation of Groundshine Dose for No-Action Decision – TDF < 1.00 (i.e. CL<CU)
- Decay Factor TRM1
- Decay Factor TRM2
- Calculation of Groundshine Dose for Evacuation and Clean-Up – 1.00<TDF<Interdiction
- Calculation of Groundshine Dose for Interdiction Decision – TDF > Interdiction
- Calculation of Total Groundshine Dose
- Ingestion Dose
- Probability of an Accident
- Inhalation Dose-Risk
- Resuspension Dose-Risk
- Cloudshine Dose-Risk
- Groundshine Dose-Risk
- Ingestion Dose-Risk
- Overall Does Risk from Dispersion

Model for Dose to an Individual from Inhalation of Dispersed Materials

$$D_{inh} = \sum_{m}^{all\ materials} \sum_{p}^{all\ radionuclides} \sum_{o}^{all\ organs} \left(Ci_p \cdot PPS_L \cdot RF_{p,j} \cdot AER_{p,j} \cdot RESP_{p,j} \cdot RPC_{p,o} \cdot X_n \cdot BR \right)$$

where:

D_{inh} = Individual inhalation dose (rem)

Ci_p = Number of curies of isotope p in package (Ci)

PPS_L = Number of packages on link L

$RF_{p,j}$ = Fraction of package contents released in accident of severity j

$AER_{p,j}$ = Fraction of released material that is aerosol in accident of severity j

$RESP_{p,j}$ = Fraction of aerosolized material that is respirable in accident of severity j

$RPC_{p,o}$ = Dose conversion factor of pth isotope and o^{th} organ (rem/Ci)

X_n = dilution factor (chi) in nth isopleth area (Ci-sec/m^3/Ci-released)

BR = Breathing rate (m^3/sec)

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Model for Integrated Population Dose from Direct Inhalation of Dispersed Material

$$D_{inh}^{pop} = Q_7 \cdot Ci_p \cdot PPS_L \cdot RF_{p,j} \cdot AER_{p.j} \cdot RESP_{p,j} \cdot RPC_p \cdot IF \cdot BR \cdot PD_L \cdot A_n$$

where:

D_{inh} = Population inhalation dose (rem)

Q_7 = Conversion factor

Ci_p = Number of curies of isotope p in package (Ci)

PPS_L = Number of packages on link L

$RF_{p,j}$ = Fraction of radionuclide p released in accident of severity j

$AER_{p,j}$ = Fraction of released radionuclide p that is aerosol in accident of severity j

$RESP_{p,j}$ = Fraction of aerosolized radionuclide p that is respirable in accident of severity j

RPC_p = Dose conversion factor of pth isotope (rem/Ci)

IF = Integral of time-integrated atmospheric dilution factors, $\mathbf{X}$, over all downwind areas

BR = Breathing rate (m^3/sec)

PD_L = Population density on line L (persons/km^2)

A_n = Area of nth isopleth (m^2)

Population Densities in Urban Areas

In urban areas, persons inside and persons outside of buildings may accumulate inhalations dose. To account for this, the population density term (PD_L) is multiplied by the following equation:

$$\left[\left(\mathrm{UBF} \cdot \mathrm{BDF}\right) + \left(\mathrm{USWF} \cdot \mathrm{RPD}\right)\right]$$

where:

UBF = Fraction of persons indoors (or urban building fraction)
BDF = Building Dose Factor
USWF = Fraction of persons outdoors (or urban sidewalk fraction)
RPD   = Ratio of pedestrian density to residential density
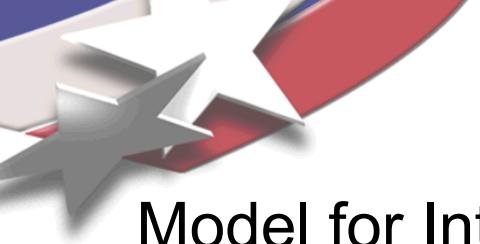
Model for Integrated Population Dose from Resuspension

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

where:

D_{inh} = Population inhalation dose (rem)
RDF = Resuspension dose factor

Resuspension Dose Factor

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

where:

V_d = Deposition Velocity (m/sec)

$\lambda_1 = 0.693 \cdot \left(1/\text{RT}_{1/2} + 1/t_{1/2}\right)$

$\lambda_2 = 0.693/t_{1/2}$

$\text{RT}_{1/2}$ = Resuspension half-life = 365 days
$t_{1/2}$ = Radioactive half-life (days)

Model for Dose to an Individual from Cloudshine

$$D_{cld}^{ind} = \sum_{m}^{materials} \sum_{p}^{radionuclides} \sum_{o}^{organs} \left(Ci_p \cdot PPS \cdot RF_{p,j} \cdot AER_{p,j} \cdot X_n \cdot CDF \right)$$

where:

D_{cld} = Individual cloudshine dose (rem)

Ci_p = Number of curies of isotope p in package (Ci)

PPS = Number of packages

$RF_{p,j}$ = Fraction of radionuclide p that is released in accident of severity j

$AER_{p,j}$ = Fraction of radionuclide p that released material that is aerosol in accident of severity j

X_n = Time-integrated concentration of radionuclide p in n_{th} isopleth (Ci-sec/m^3)

CDF = Cloudshine dose factor for radionuclide p (rem-m^3/Ci-sec)
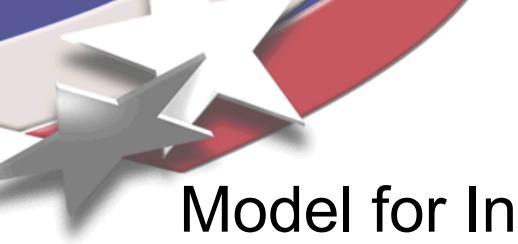
Model for Integrated Population Dose from Cloudshine

$$D^{pop}_{cld\ p,\ j,\ L,\ m} = Q_7 \cdot Ci_p \cdot PPS_{L,\ m} \cdot RF_{p,\ j} \cdot AER_{p.j} \cdot CDF_p \cdot IF \cdot PD_L$$

where:

D_{cld} = Population cloudshine dose (rem)

Q_7 = Conversion factor

Ci_p = Number of curies of isotope p in package (Ci)

$PPS_{L,m}$ = Number of packages of material m per shipment on link L

$RF_{p,j}$ = Fraction of radionuclide p released in accident of severity j

$AER_{p,j}$ = Fraction of released radionuclide p that is aerosol in accident of severity j

CDF_p = Cloudshine dose conversion factor of pth isotope (rem-m^3/Ci-sec)

IF = Integral of time-integrated atmospheric dilution factors, X, over all downwind areas

PD_L = Population density on line L (persons/km^2)

Note: This equation also uses the correction factor for population densities in urban areas. $[(UBF \cdot BDF) + (USWF \cdot RPD)]$

Model for Integrated Population Dose from Groundshine

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

where:

DR(T) = Groundshine dose rate at time T (rem/day)
CL_p = Contamination level of radionuclide p (μCi/m^2)
GDF   = Groundshine dose factor for radionuclide p (rem-m^2/day-μCi)
$t_{1/2}$ = Half-life of radionuclide p (days)
ET   = Elapsed time (days)

Equation for Determining Contamination Level (CL)

$$CL_{p,\,j} = Q_9 \cdot Ci_{p,\,j} \cdot PPS \cdot DC_{p,\,j}$$

where:

$CL_{p,j}$ = Contamination level of radionuclide p for an accident of severity j (μCi/m^2)

Q_9 = Unit conversion factor

$Ci_{p,j}$ = Number of curies of radionuclide p released from package in an accident of severity j (Ci)

PPS = Number of packages per shipment

$DC_{p,j}$ = Deposited concentration of radionuclide p from a single package in an accident of severity j (Ci/m^2/Ci-released)

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Total Decontamination Factor

$$TDF = \frac{\sum\limits^{all\,materials} \sum\limits^{all\,radionuclides} CL_p}{CU}$$

where:

TDF = Total Decontamination Factor

CL_p = Contamination level of radionuclide p (μCi/m^2)

CU = Contamination level after clean-up (μCi/m^2)

Calculation of Groundshine Dose for No-Action Decision TDF < 1.00 (i.e. CL < CU)

$$D_{gnd} = Q_7 \cdot GDF_p \cdot t_{1/2} \cdot A_n \cdot PD_L \cdot CL_{n,\,j,\,p} \cdot \left[TRM1 + TRM2 \right]$$

where:

D_{gnd} = Population groundshine dose (person-rem)

Q_7 = Unit conversion factor

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

GDF_p = Groundshine dose conversion factor (rem-m^2/day-μCi)

A_n = area of nth isopleth (km^2)

PD_L = Population density of link L (persons/km^2)

$CL_{n,j,p}$ = Contamination level of isotope p in nth area for accident of severity j (Ci/m^2)

$TRM1$ = Decay factor (day^{-1})

$TRM2$ = Decay factor (day^{-1})

Decay Factor TRM1

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

where:

TE = Elapsed time (day)

$t_{1/2}$ = half-life for radionuclide p (day)

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

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

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

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

Note: 0.0031 and 0.000021 have units of day^{-1}

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Decay Factor TRM2

$$\mathrm{TRM2} = \left[\lambda_1 \cdot \left(e^{-\lambda_2 \cdot \mathrm{TS}} \right) + \lambda_3 \cdot \left(e^{-\lambda_4 \cdot \mathrm{TS}} - e^{-\lambda_4 \cdot 1.83E+04} \right) \right]$$

where:

TS = Survey time (day)

$t_{1/2}$ = half-life for radionuclide p (day)

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

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

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

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

Note: 0.0031 and 0.000021 have units of day^{-1}

Calculation of Groundshine Dose for Evacuation and Clean-Up
1.00 < TDF < Interdiction

$$D_{gnd} = Q_7 \cdot GDF_p \cdot t_{1/2} \cdot (A_n - A_{n-1}) \cdot PPS_L \cdot PD_L \cdot [TRM1 \cdot CL_{n,j,p} + TRM2 \cdot CU]$$

where:

D_{gnd} = Population groundshine dose (person-rem)

Q_7 = Unit conversion factor

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

GDF_p = Groundshine dose conversion factor (rem-m^2/day-μCi)

A_n = area of nth isopleth (km^2)

A_{n-1} = area of n-1th isopleth (km^2)

PD_L = Population density of link L (persons/km^2)

PPS_L = Number of packages per shipment on link L

$CL_{n,j,p}$ = Contamination level of isotope p in nth area for accident of severity j (Ci/m^2)

TRM1 = Decay factor (day^{-1})

CU = Contamination level after clean-up (μCi/m^2)

TRM2 = Decay factor (day^{-1})

Calculation of Groundshine Dose for Interdiction Decision TDF > Interdiction

$$D_{gnd} = Q_7 \cdot GDF_p \cdot t_{1/2} \cdot \left(A_n - A_{n-1}\right) \cdot PPS_L \cdot PD_L \cdot TRM1 \cdot CL_{n,\,j,\,p}$$

where:

D_{gnd} = Population groundshine dose (person-rem)

Q_7 = Unit conversion factor

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

GDF_p = Groundshine dose conversion factor (rem-m^2/day-μCi)

A_n = area of nth isopleth (km^2)

A_{n-1} = area of n-1th isopleth (km^2)

PD_L = Population density of link L (persons/km^2)

PPS_L = Number of packages per shipment on link L

$CL_{n,j,p}$ = Contamination level of isotope p in nth area for accident of severity j (Ci/m^2)

$TRM1$ = Decay factor (day^{-1})

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Calculation of Total Groundshine Dose

$$D_{gnd\text{ - }total} = \sum_{n=1}^{NAREAS} D_{gnd_n}$$

where:

$D_{gnd\text{-}total}$ = Total groundshine dose (person-rem)

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

Ingestion Dose

COMIDA has been developed to estimate the ingestion dose for most isotopes in the internal RADTRAN data library.
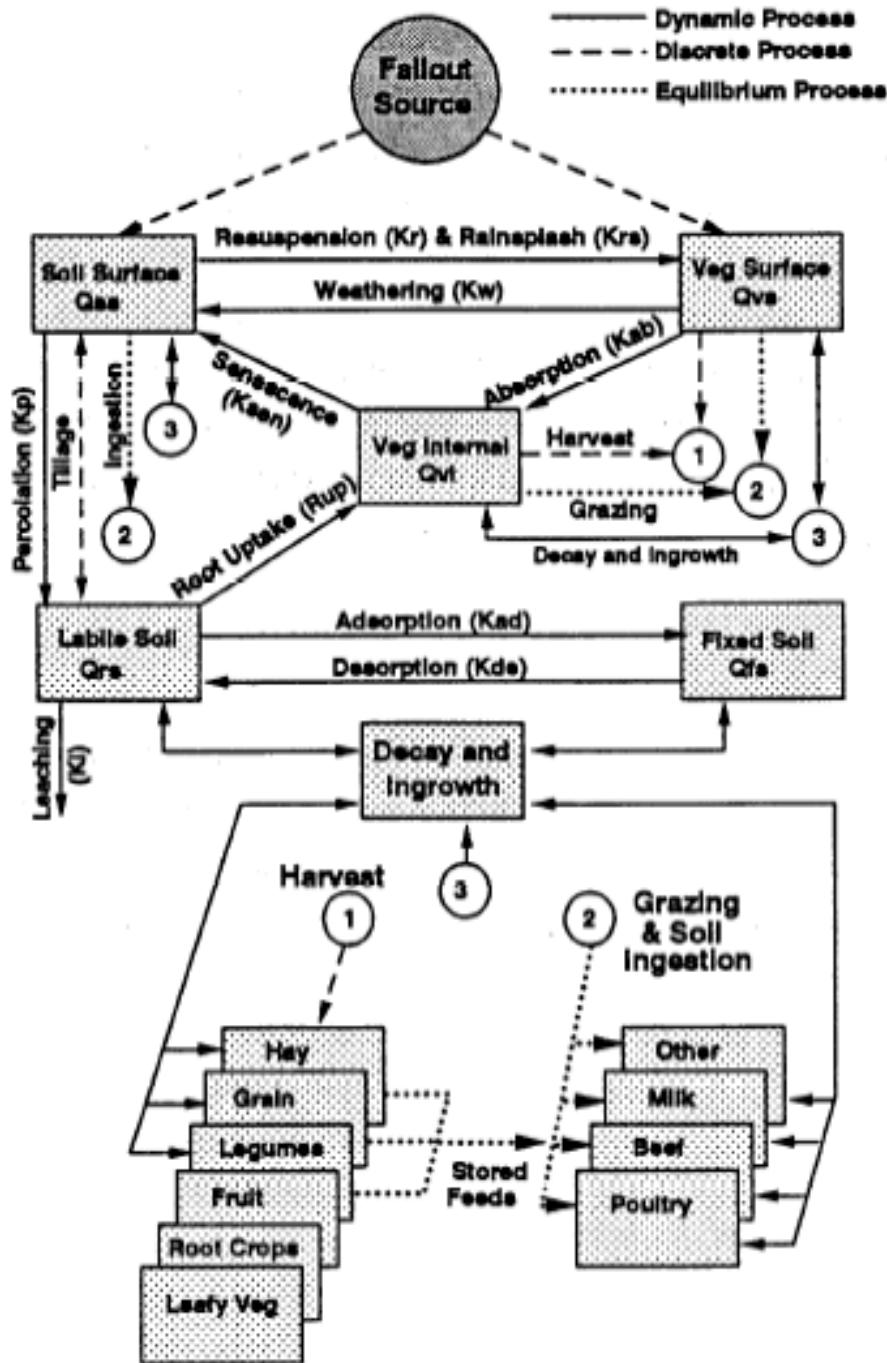
Probability of an Accident

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

where:

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

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

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

NSH_L = Number of shipments on link L

$DIST_L$ = Length of link L (km)

Inhalation Dose-Risk

$$\mathrm{RISK}_{L}^{\mathrm{INH}} = \sum_{p=1}^{n} \sum_{j=1}^{\mathrm{NSEV}} \gamma_{j,\,L} \cdot \mathrm{Dinh}_{p,j,L}$$

where:

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

D_{inh} = Dose from inhalation of isotope p in an accident of severity j on link L (person-rem)

NSEV = Number of accident-severity categories

n = Number of radionuclides in package

Resuspension Dose-Risk

$$\text{RISK}_{\text{L}}^{\text{RES}} = \sum_{\text{p}=1}^{\text{n}} \sum_{\text{j}=1}^{\text{NSEV}} \gamma_{\text{j, L}} \cdot \text{D}_{\text{res}_{\text{p,j,L}}}$$

where:

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

D_{res} = Dose from resuspension of isotope p in an accident of severity j on link L (person-rem)

NSEV = Number of accident-severity categories

n   = Number of radionuclides in package

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Cloudshine Dose-Risk

$$\mathrm{RISK}_{L}^{\mathrm{CLD}} = \sum_{p=1}^{n} \sum_{j=1}^{\mathrm{NSEV}} \gamma_{j,L} \cdot \mathrm{Dcld}_{p,j,L}$$

where:

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

D_{cld} = Dose from cloudshine of isotope p in an accident of severity j on link L (person-rem)

NSEV = Number of accident-severity categories

n = Number of radionuclides in package

Groundshine Dose-Risk

$$\text{RISK}_{\text{L}}^{\text{GND}} = \sum_{p=1}^{n} \sum_{j=1}^{\text{NSEV}} \gamma_{j,\,\text{L}} \cdot \text{Dgnd}_{p,j,L}$$

where:

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

D_{gnd} = Dose from groundshine of isotope p in an accident of severity j on link L (person-rem)

NSEV   = Number of accident-severity categories

n   = Number of radionuclides in package

Ingestion Dose-Risk

$$\text{RISK}_{\text{L}}^{\text{ING}} = \sum_{p=1}^{n} \sum_{j=1}^{\text{NSEV}} \gamma_{j,\text{L}} \cdot \text{Ding}_{p,j,L}$$

where:

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

D_{ing} = Dose from ingestion of isotope p in an accident of severity j on link L (person-rem)

NSEV   = Number of accident-severity categories

n   = Number of radionuclides in package

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Overall Dose-Risk from Dispersion

$$\mathrm{RISK}_{\mathrm{L}}^{\mathrm{TOTAL}} = \sum_{n}^{\mathrm{inh,\,res,\,cld,\,gnd}} \mathrm{RISK}^{n}$$

where:

$\mathrm{RISK}^{\mathrm{INH}}$ = Inhalation dose risk
$\mathrm{RISK}^{\mathrm{RES}}$ = Resuspension dose risk
$\mathrm{RISK}^{\mathrm{CLD}}$ = Cloudshine dose risk
$\mathrm{RISK}^{\mathrm{GND}}$ = Groundshine dose risk
n = Index for risk class

Note: Ingestion dose risk is listed separately and should not be added to the other pathways because the population exposed via this pathway is entirely different.

Gaussian Atmospheric Dispersion Models

- Basic Gaussian Dispersion Model for Dilution at Ground Level for an Elevated Release

- Diagram of Gaussian Dispersion

- Typical Plume Footprint

- Basic Gaussian Dispersion Model for Dilution at Ground Level for an Elevated Release along the Plume Centerline

- Basic Gaussian Dispersion Model for Dilution at Ground Level for an Elevated Release with Dry Deposition

- Basic Gaussian Dispersion Model for Dilution at Ground Level along the Plume Centerline with Dry Deposition

Basic Gaussian Dispersion Model for Dilution at Ground Level for an Elevated Release

$$\frac{X}{Q} = \frac{1}{\pi \cdot \sigma_y \cdot \sigma_z \cdot \mu} \cdot e^{\left(\frac{-y^2}{2 \cdot \sigma_y^2}\right)} \cdot e^{\left(\frac{-H^2}{2 \cdot \sigma_z^2}\right)}$$

where:

X = Concentration of dispersed substance at ground level (Ci/m^3)
Q = Rate of release of dispersed substance (Ci/sec)
μ = Wind speed (m/sec)
σ_y = Crosswind meteorological constant (m) [y-axis Gaussian half-width]
σ_z = Vertical meteorological constant (m) [z-axis Gaussian half-width]
y = Distance off centerline (m)
H = Release height (m)
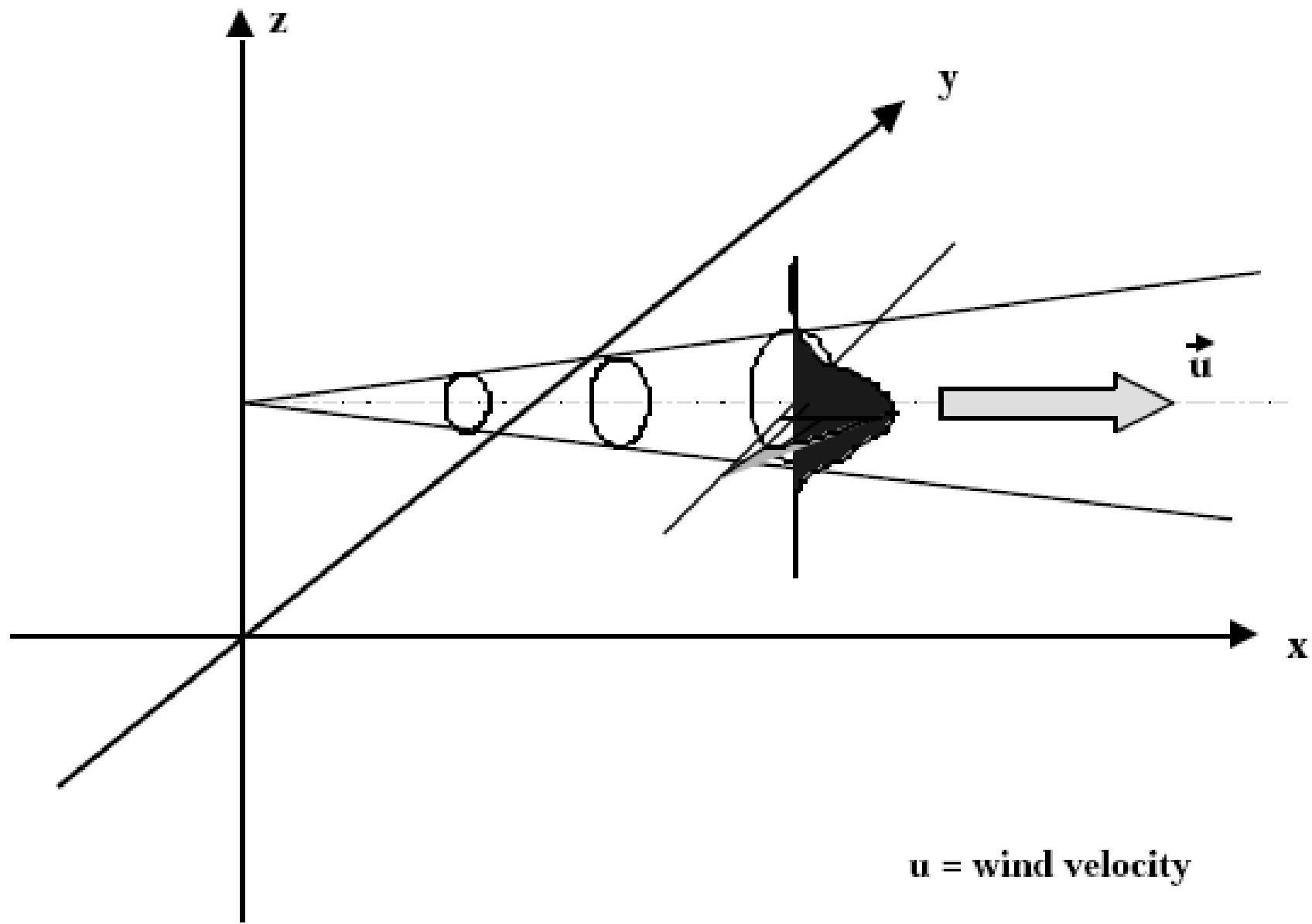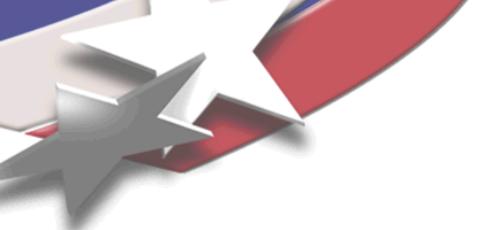
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Diagram of Gaussian Dispersion

u = wind velocity

Typical Plume Footprint

Basic Gaussian Dispersion Model for Dilution at Ground Level for an Elevated Release along the Plume Centerline

$$\frac{X}{Q} = \frac{1}{\pi \cdot \sigma_y \cdot \sigma_z \cdot \mu} \cdot e^{\left(\frac{-H^2}{2 \cdot \sigma_z^2}\right)}$$

where:

X = Concentration of dispersed substance at ground level (Ci/m^3)

Q = Rate of release of dispersed substance (Ci/sec)

μ = Wind speed (m/sec)

σ_y = Crosswind meteorological constant (m) [y-axis Gaussian half-width]

σ_z = Vertical meteorological constant (m) [z-axis Gaussian half-width]

H = Release height (m)

Basic Gaussian Dispersion Model for Dilution at Ground Level for an Elevated Release with Dry Deposition

$$\frac{X}{Q} = \frac{V_s}{\pi \cdot \sigma_y \cdot \sigma_z \cdot \mu} \cdot e^{\left(\frac{-y^2}{2\cdot\sigma_y^2}\right)} \cdot e^{\left(\frac{-\left(H-\frac{V_s \cdot x}{\mu}\right)}{2\cdot\sigma_z^2}\right)}$$

where:

X = Concentration of dispersed substance at ground level (Ci/m^3)

Q = Rate of release of dispersed substance (Ci/sec)

μ = Wind speed (m/sec)

σ_y = Crosswind meteorological constant (m) [y-axis Gaussian half-width]

σ_z = Vertical meteorological constant (m) [z-axis Gaussian half-width]

H = Release height (m)

y = Crosswind distance off centerline (m)

x = Downwind distance along the centerline (m)

V_s = Dispersed substance deposition velocity (m/sec)
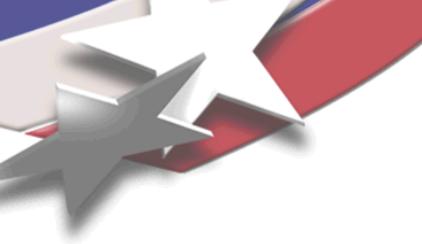
Basic Gaussian Dispersion Model for Dilution at Ground Level along the Plume Centerline with Dry Deposition

$$\frac{X}{Q} = \frac{V_s}{\pi \cdot \sigma_y \cdot \sigma_z \cdot \mu}$$

where:

X = Concentration of dispersed substance at ground level (Ci/m^3)
Q = Rate of release of dispersed substance (Ci/sec)
μ = Wind speed (m/sec)
σ_y = Crosswind meteorological constant (m) [y-axis Gaussian half-width]
σ_z = Vertical meteorological constant (m) [z-axis Gaussian half-width]
V_s = Dispersed substance deposition velocity (m/sec)

NEW
IMPROVEMENTS
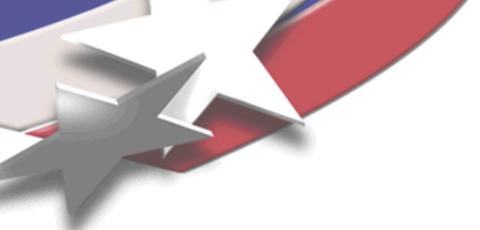
Introduction

- **Radioactive Materials Transportation Code**

- **Radiologic Risk and Dose Assessment**

- **First used in NUREG-0170 in 1977**

- **Released RadCat 3.0 with RADTRAN 6.0 in 2010**

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RADTRAN Inputs

INPUTS
ROUTINE TRANSPORTATION

- Package dimensions
- Package external dose rate
- Vehicle dimensions
- Vehicle speeds
- Vehicle external dose rate
- Route characteristics
- Population densities
- Stop characteristics
- Urban building density

INPUTS
TRANSPORTATION ACCIDENTS

- Radionuclide inventory
- Accident rate (route characteristic)
- Conditional probability of accident severity
- Release, aerosol, respirable fractions
- Particle settling velocity
- Meteorological parameters
- Population densities
- Fraction of land in agriculture

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RADTRAN Outputs

OUTPUTS
ROUTINE TRANSPORTATION

- Collective external dose to residents along route
- Collective external dose to public at stops
- Collective external dose to urban non-residents
- Collective dose to occupants of vehicles sharing route
- Occupational external doses MEI external doses

OUTPUTS
TRANSPORTATION ACCIDENTS

- Collective "dose risks:" inhalation, resuspension, groundshine, cloudshine, ingestion
- Collective doses
- MEI doses and dose risks
- Doses and dose risks per radionuclide
- Critical group doses and dose risks
- Doses and dose risks from loss of lead shielding

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How RADTRAN Works

- **Text input file is generated by the user directly or using the generator RADCAT**
- **RADTRAN reads in input file as R5IN.DAT (RadCat 2.3)**
- **RADTRAN reads in input file as RADTRAN.INPUT (RadCat 3.0)**
- **RADTRAN reads in text files of default values:**
  - **Example from RADTRAN 6.0   RT6_Isotope.INFILE**
- **All defaults can be overwritten except collective occupational doses at rail classification stops**
- **RADTRAN reads numbers and multiplies them according to the program. It is a very forgiving code; numbers between 10^{30} and 10^{-30} can be entered.**
- **Input is echoed in the output.**

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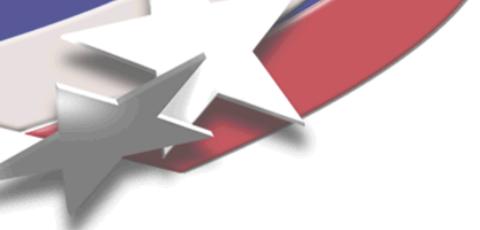
The Latest and Greatest

- **RADTRAN 6.0**
  - **All of RADTRAN 5.6 (updated code)**
  - **Full Conversion for Historic and International Units**
  - **Revised Loss of Shielding Model**
  - **New Economic Model**
  - **New Uncertainty Analysis Module**

  - **http://radtran.sandia.gov**

UNIT CONVERSION

Unit Conversion

- **RADTRAN 5.6 allowed only for historic or SI output**

- **RadCat 3.0/RADTRAN 6.0 version allows:**
  - **Input** ➡ **SI or Historical**
  - **Output** ➡ **SI or Historical**
- **Rem or Sv and Ci or Bq**

Cloudshine Dose Factor		
Nuclide	rem-m^3/Ci-s	Sv-m^3/Bq-s
Sr-90	2.79E-05	7.541E-18
Th-230	6.44E-05	1.741E-17

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Unit Conversion Logic

- **SI Output requires command "Bq_Sv"**
- **SI_INPUT 1 or 0 (0=historical; 1=SI)**

```
RADTRAN 6      March 2006
&& Truck
TITLE Truck Example
INPUT STANDARD
FORM  UNIT
DIMEN 6 0 18
PARM 3 4 2
BQ_SV
SI_INPUT 0
SEVERITY
  NPOP=1
    NMODE=1
      2.05E-01  2.00E-01  9.00E-02
      8.00E-02  7.00E-02  6.00E-02
```

LOSS
OF
SHIELDING
MODEL

SPENT FUEL CASK

IMPACT ABSORBER

OUTER STRUCTURAL SHELL

NEUTRON SHIELDING

GAMMA SHIELDING

OUTER WALL

SEAL

LID

BOLTS

IMPACT ABSORBER

TRUNNION

CONTAINMENT VESSEL

BASKET

SPENT FUEL ASSEMBLY

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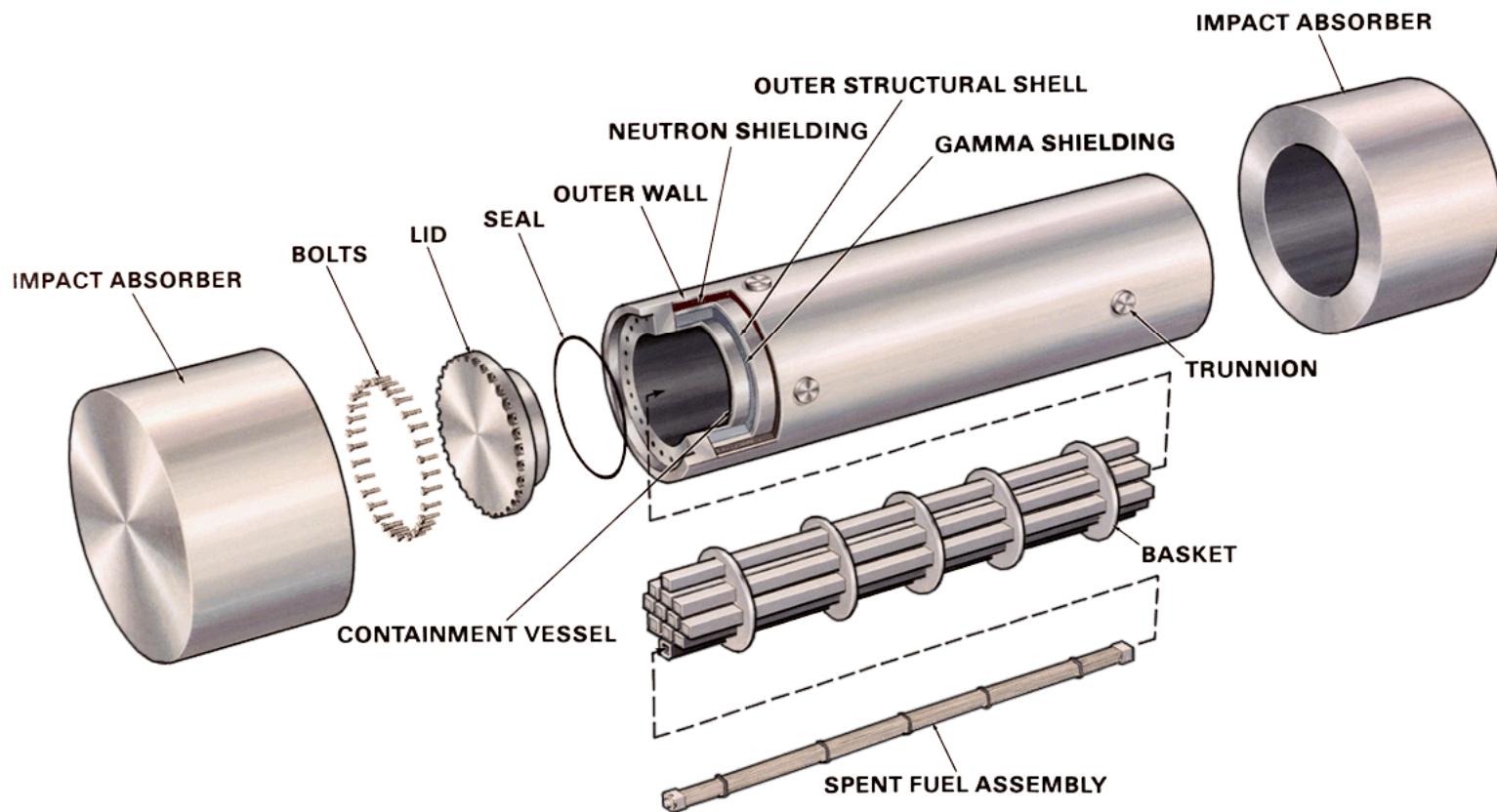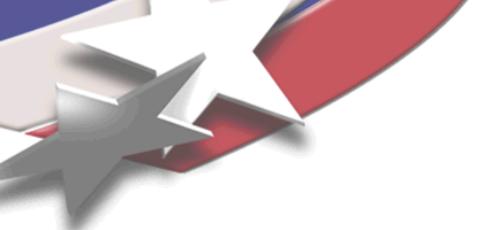
Loss of Shielding (LOS)

Air Gap

Fuel Region
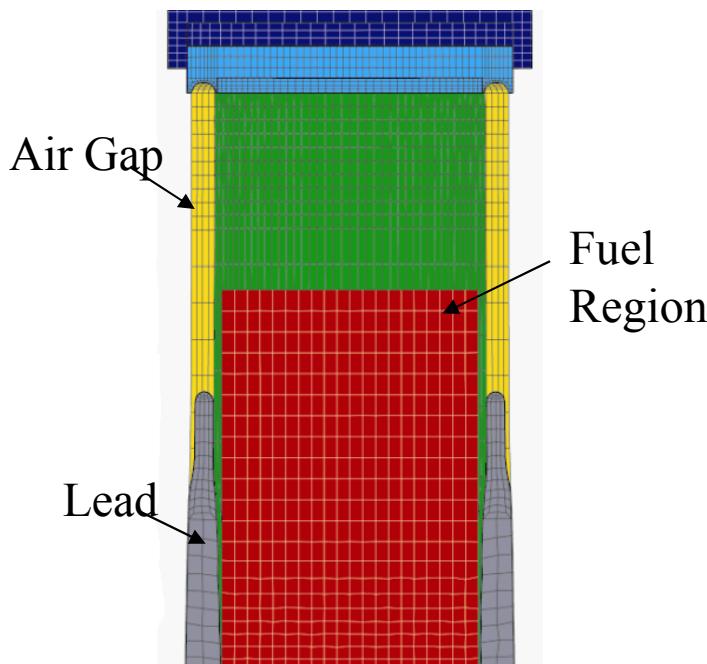
Lead

- LOS may occur during intense heating or high velocity impact and slump of the lead gamma shield.

- Without lead shielding, potential for excessive exterior dose rate.

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LOS Accident Scenarios

- **NUREG/CR-6672 describes 9 different accident scenarios w/ slump fraction.**

Loss of Shielding Case	LOS Accident Condition	Fraction of Shield Lost
1	End impact	0.052
2	End impact	0.158
3	End impact	0.264
4	End impact	0.368
5	Corner impact	0.033
6	Corner impact	0.096
7	Corner impact	0.158
8	Corner impact	0.255
9	Lead melt (T>350 C)	0.029
10	Lead melt and impact with puncture of external shield wall (T>350 C)	0.5
11	No shielding loss	0.0

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LOS Logic

```
LOS_SHIELD
   NPOP=1
   ACIDNT_PRB
      1.71E-06  4.63E-07  3.21E-08  2.53E-10  2.20E-05
      5.97E-06  4.14E-07  3.27E-09  4.90E-05  1.66E-09
   FRAC_LOST
      0.052    0.158    0.264    0.368    0.033
      0.096    0.158    0.255    0.029    0.500
   NPOP=3
   ……………..
   ………
LOSS OF SHIELDING STOP
      NAME          VEHICLE   PEOPLE   DISTANCE      SHLD FCTR  EXPOS TIME
 LOS_STOP LOSA      VEH1      2.00      3.00   3.00      1.000    4.000
 LOS_STOP LOSB      VEH10     2.00      7.50   7.50      1.000    2.000
 LOS_STOP LOSC      VEH1      1.00       3.00   3.00      0.500    2.000
```

LOS Output

• **Maximum Radiological Dose and Average Radiological Dose (person rem)**

```
LOSS OF SHIELDING CASE =    LOSA FOR LINK =   TRACK3
             AVERAGE RADIOLOGICAL DOSE (P_REM )

 SLMP FRAC        3.0m TO CASK
 2.90E-02   1.17E+00
 3.30E-02   1.35E+00
 5.20E-02   2.29E+00
 9.60E-02   4.64E+00
 1.58E-01   8.27E+00
 1.58E-01   8.27E+00
 2.55E-01   1.44E+01
 2.64E-01   1.50E+01
 3.68E-01   2.20E+01
 5.00E-01   3.14E+01
```

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Loss of Shielding Output

- **Maximum Radiological Dose and Average Radiological Dose (person-rem)**

LOS Average Radiological Dose at 3m from Cask
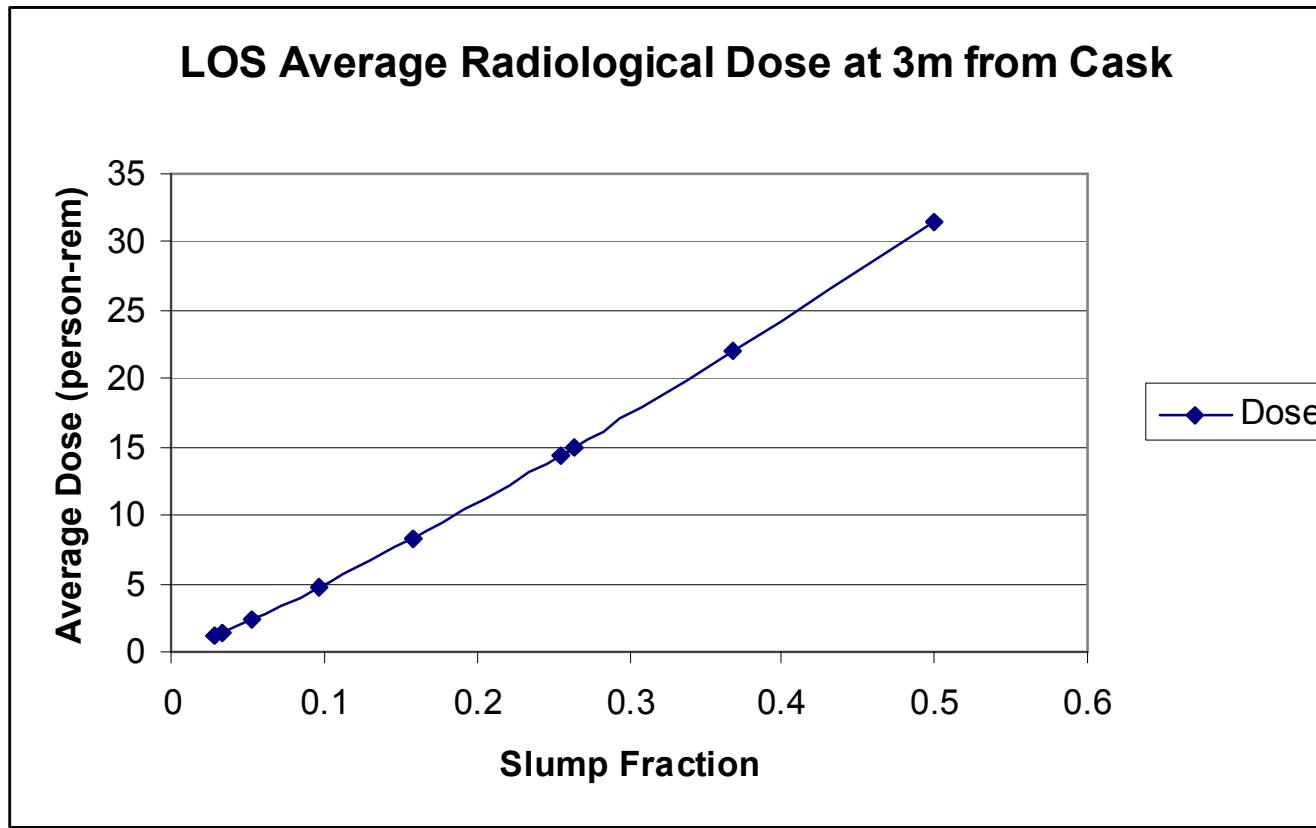
ECONOMIC MODEL

Economic Model

The economic categories are:

- **Building Cleanup**
  - Residential
  - Commercial
  - Industrial
- **Road Cleanup**
- **Soil Cleanup**
- **Agricultural Damage**
  - Crops
  - Livestock
- **Evacuation and Emergency**

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Building and Road Cleanup

- **Buildings and road surfaces pressure washed**
- **Water collected in resin and resin disposed as Low Level Radioactive Waste**

$$C_{BR} = C_{wash} + C_{\text{Resin}}$$

Where:

C_{BR} = Total building and road cleanup cost

C_{wash} = Total wash down and water collection cost

C_{Resin} = Resin disposal cost

Soil Cleanup

- Soil removed to user-defined depth
- Area a function of both the population zone being examined (rural, suburban, or urban) and the land use category (residential, commercial, or industrial).
- The area around buildings is either paved parking areas or soil.

$$C_S = C_R * \left(A_{Soil} \cdot d_{soil} \right)$$

Where:
C_R = soil removal cost ($/m^3)
A_{soil} = area of soil to be removed
d_{soil} = depth of soil to be removed

Agriculture Damage

- **Agricultural damage classified as crop (cropland) damage and livestock (rangeland/pastureland) damage.**
- **One year crop and two year livestock sequestration**
- **Costs for only rural zones**

$$C_A = A_n \cdot \left(\left(C_{area} \cdot F_{RC} \right) + \left(L_{area} \cdot F_{RL} \right) \right)$$

Where:

C_{area} = Annual crop profit per m^2 of rural land

L_{area} = Bi-annual livestock profit per m^2 of rural land

A_n = Area under the nth isopleth, which is summed over all isopleths

F_{RC} = Crop fraction

F_{RL} = Livestock fraction

Isopleths for Cleanup and Evacuation

- CULVL = 0.2 μCi/m^2

- Total area contaminated > CULVL = 10.3 km^2

- Downwind distance = 11.1 km

- Isopleths
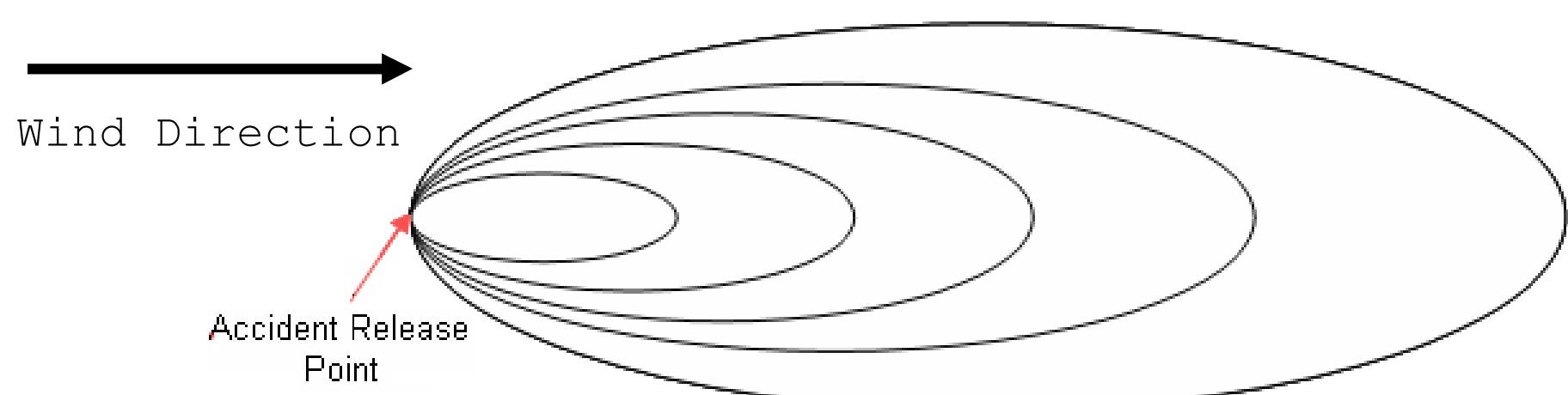
Evacuation Costs

- **Modeled using FEMA-generated costs similar to natural disaster**

- **Both natural and radiological disasters could require human evacuation, temporary shelter, emergency workers, and government-subsidized loans**

$$C_E = \sum_n \left(P_n \cdot \frac{A_n}{1000^2} \cdot C_{PA} \right)$$

Where:

P_n = Population in the nth isopleth area

A_n = Area within the nth isopleth (km^2)

C_{PA} = Evacuation and emergency cost per person-m^2
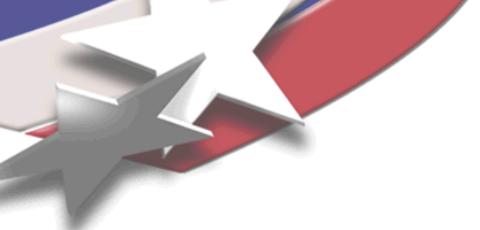
RADTRAN Output Example

Isopleth	AREA_USED (m^2)	AREA_SOIL (m^2)	RESIN (m^3)	REMOVED (Ci)
1	2.17E+01	2.33E+02	7.94E+00	1.13E+01
2	5.07E+01	5.44E+02	9.31E+00	1.33E+01
...	...	...	...	...
12	2.77E+05	2.97E+06	1.38E-01	1.98E-01
13	5.35E+05	5.74E+06	1.00E-15	0.00E+00

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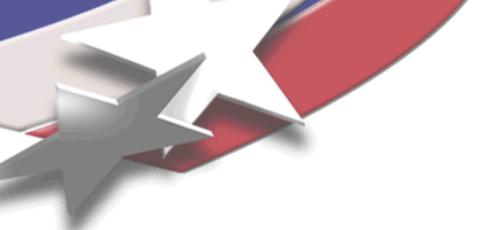
RADTRAN Output Example

Isopleth	Co-60 (μCi/m^2)	Sr-90 (μCi/m^2)	Pu-244 (μCi/m^2)
1	**9.40E+03**	**9.40E+03**	**2.57E+04**
2	**4.73E+03**	**4.73E+03**	**1.29E+04**
...	**...**	**...**	**...**
12	5.52E-02	5.52E-02	1.50E-01
13	**1.24E-02**	**1.24E-02**	**3.37E-02**
CULVL	2.00E-01		

RADTRAN Output Example (Rural)

Isopleth	RESIN ($)	WASH ALL ($)	SOIL ($)	CROP_STOCK ($)	EVACUATION ($)
1	1.28E+05	7.02E+02	8.75E+03	4.19E+00	9.96E-06
2	1.49E+05	1.64E+03	2.04E+04	9.77E+00	5.42E-05
...	...	...	...	...	...
12	3.46E+03	8.94E+06	1.11E+08	5.34E+04	1.62E+03
13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Totals (million $)	$1.1	$15.7	$195.8	$0.09	$0.002

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UNCERTAINTY ANALYSIS MODULE

RADTRAN Uncertainty Analysis Module

- **Interface between RADTRAN and a Monte Carlo Sampling (MCS) program**

- **Default beta distributions for the selected input parameters are developed as a guide to the user who does not have data specific to his or her scenario**

- **Module allows for flexible input over a range of realistic values**

- **Future will incorporate coupled parameters and RadCat GUI**

RADTRAN Uncertainty Analysis Module Graphical User Interface

- **A Sandia developed GUI for MCS is used with RADTRAN**

- **User can view CDF and PDF**

- **User-determined:**
 - **Range and Shape**

  - **Type**

  - **# Sample Points**
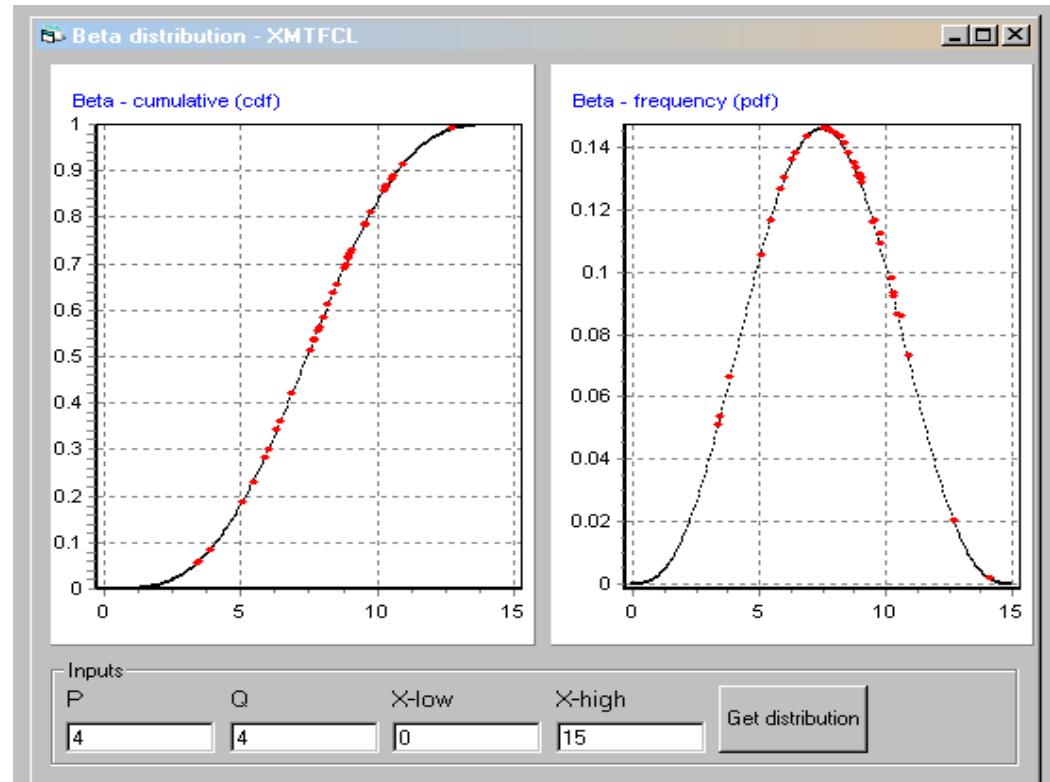
Input Parameter
Distributions

RADTRAN Input Files

Each of the N
input files are
run
sequentially.

RADTRAN Output Files
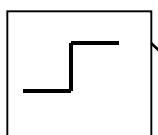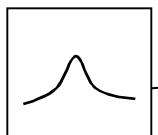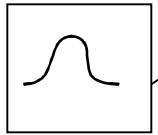
PARAM. 1

PARAM. 2

PARAM. 3

PARAM. 34

Monte Carlo
Uncertainty
Software

Case1.DAT

Case2.DAT

Case3.DAT

Case4.DAT

Case5.DAT

CaseN.DAT

RADTRAN

out1.DAT
out_monte1.svf

out2.DAT
out_monte2.svf

out3.DAT
out_monte3.svf

out4.DAT
out_monte4.svf

out5.DAT
out_monte5.svf

outN.DAT
out_monteN.svf

User designates number of
samples, N, from each
distribution. This should
equal the number of
RADTRAN input files.

All.txt
Outputs reported in
tabular form, from which
a histogram may easily
be constructed.

Total Expected Population Risk
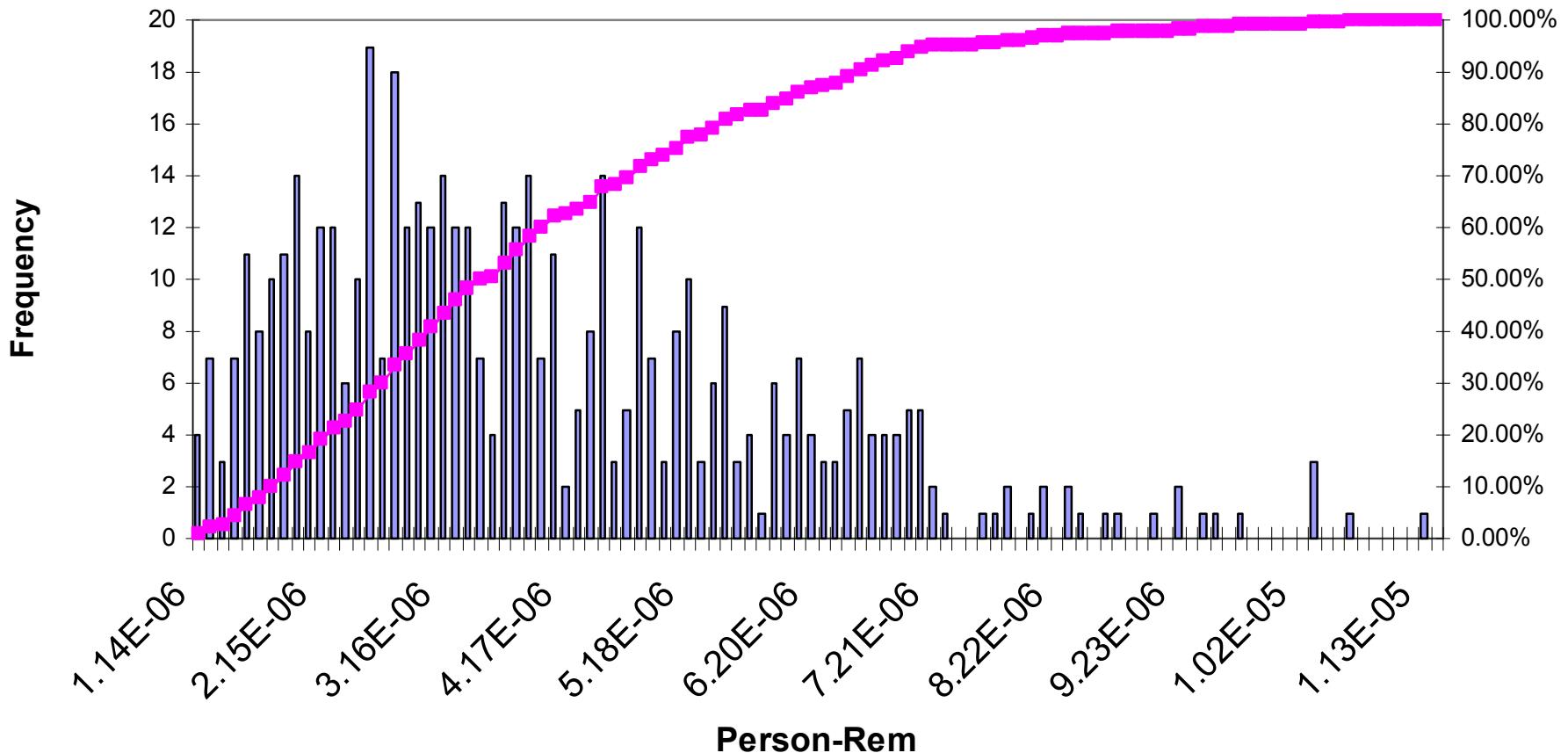
Greatest frequency at 2.55 E -06 person-rem

Questions?

https://radtran.sandia.gov

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Matt Dennis   **mldenni@sandia.gov**

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Fundamental Incident-free Model

TI here

1 meter

0.5CD = "virtual" cask radius

Critical Dimension

r

r = distance to receptor

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Loss-of-Shielding 3-D Model

ORIGIN OF COORDINATE SYSTEM
FOR PHOTON LINE SOURCE

DIRECTION OF
PHOTON EMMISSION

PHOTON LINE SOURCE
(LOCATED ON THE LONG
AXIS OF THE CASK)

SS2: INNER LAYER OF
STAINLESS STEEL

SS1: OUTER LAYER OF
STAINLESS STEEL

SF: CAVITY CONTAINING
SPENT FUEL ASSEMBLIES

Pb: LEAD SHIELDING

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Loss-of-Shielding 2-D Model (Damaged Cask)