SAND2007-4616P

Risk Assessment of Transportation of Radioactive Materials Using RADTRAN

KHNP Training Program
Module #5: Packaging and Transportation

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SAND 2007-

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RADTRAN

- **Copyright Sandia National Labs 2003**
- **Downloadable RADTRAN with graphical user interface (GUI) input file generator RADCAT, 2004**
  - **https://radtran.sandia.gov/radcat**

RADTRAN

- **RADTRAN 5.5**
  - Fully functional atmospheric dispersion model
  - Expanded radionuclide library (149 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

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

- Risk triplet:
  - What can happen (scenario)
  - How likely is it (probability)
  - What would the consequences be
- 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	INPUTS FOR TRANSPORTATION ACCIDENTS
Package dimensions Package external dose rate Vehicle dimensions Vehicle speeds Vehicle external dose rate Route characteristics Population densities Stop characteristics Urban building density	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

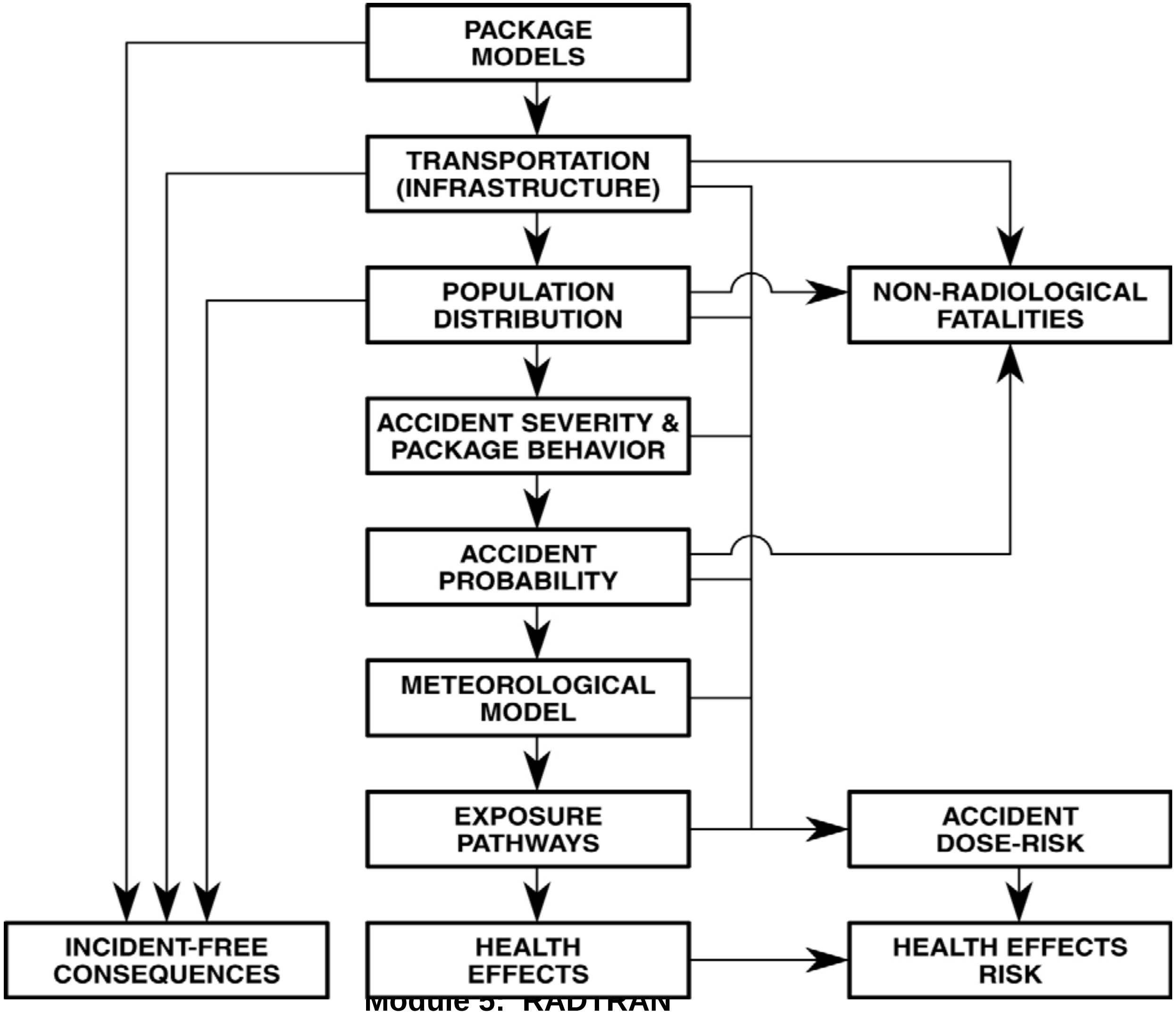
OUTPUTS FOR TRANSPORTATION ACCIDENTS

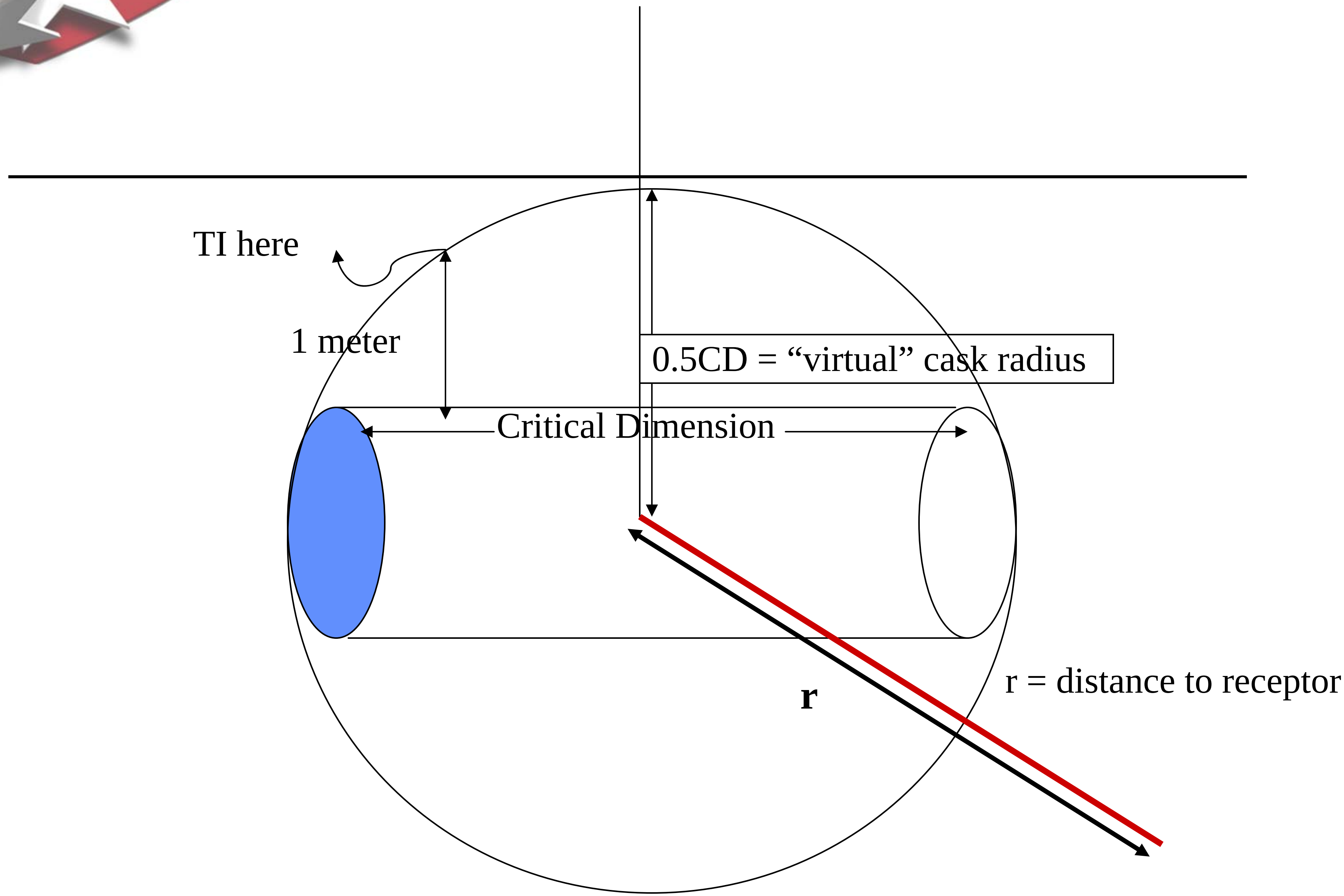
Collective “dose risks:” inhalation, resuspension, groundshine, cloudshine, ingestion
Collective doses
MEI doses and dose risks
Doses and dose risks per radionuclide
Critical group doses and dose risks
Doses and dose risks from loss of lead shielding

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
- RADTRAN reads in text files of default values:
  - RT5STD.DAT
  - RT5DAT.DAT
  - RT5ISO.DAT
  - INGEST.BIN
- 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.

RADTRAN Flow diagram





Fundamental Incident-free Model

Calculation of “Off-Link” Dose

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

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

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

$DR_N(r)$	=	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
$DR_{p\ or\ v}$	=	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

General Equation for Gamma Dose to Population Along the Route

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

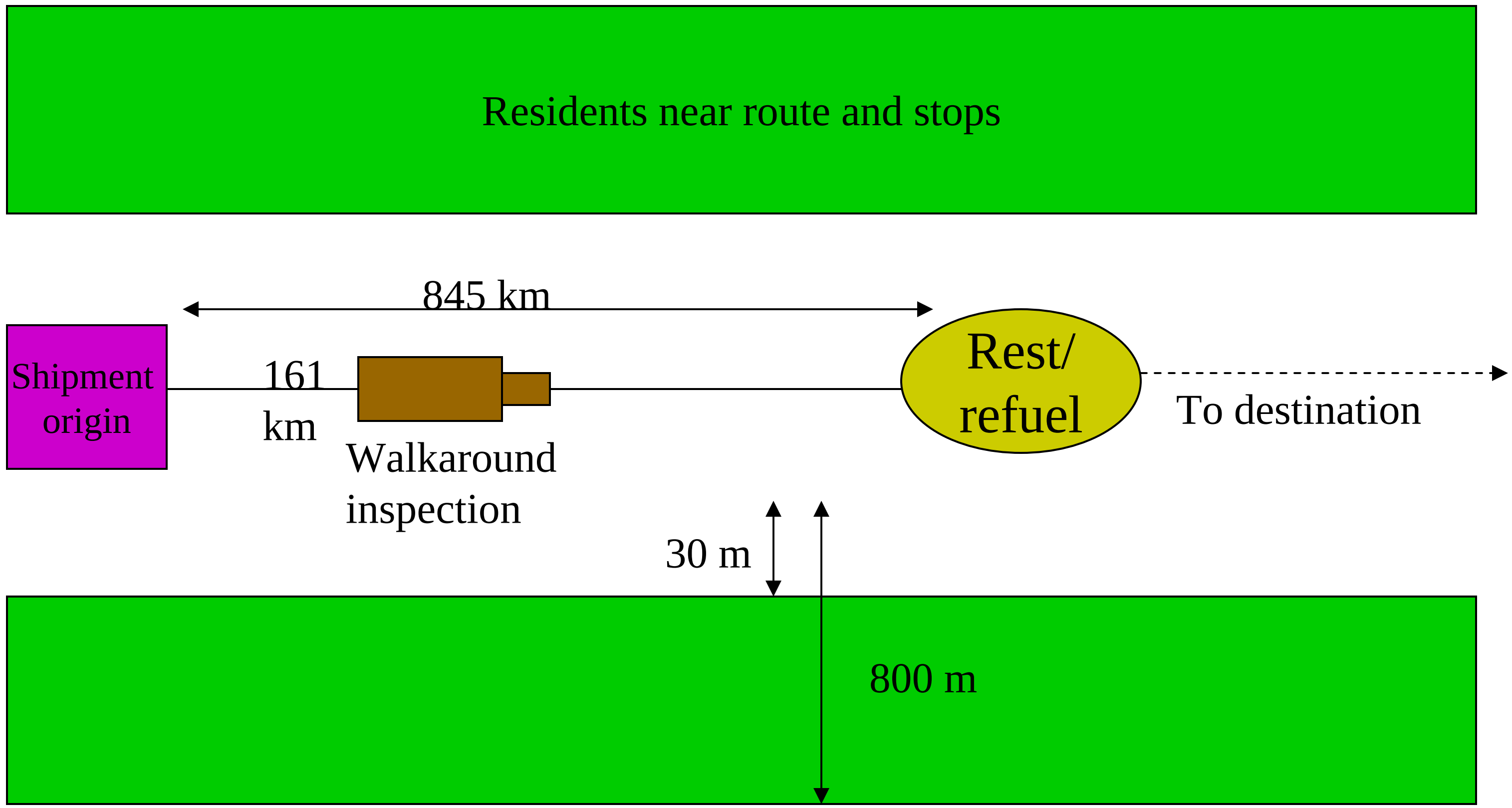
$D(x)$	=	Total integrated dose absorbed by an individual at distance x (rem)
Q_1	=	Unit conversion factor
k_0	=	Point source package shape factor (m^2)
DR_v	=	Shipment dose rate at 1 meter from surface (mrem/hr)
V	=	Shipment speed (m/s)
μ	=	Attenuation coefficient (m^{-1})
r	=	Perpendicular distance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

Final Equation for Dose to Population Along the Route

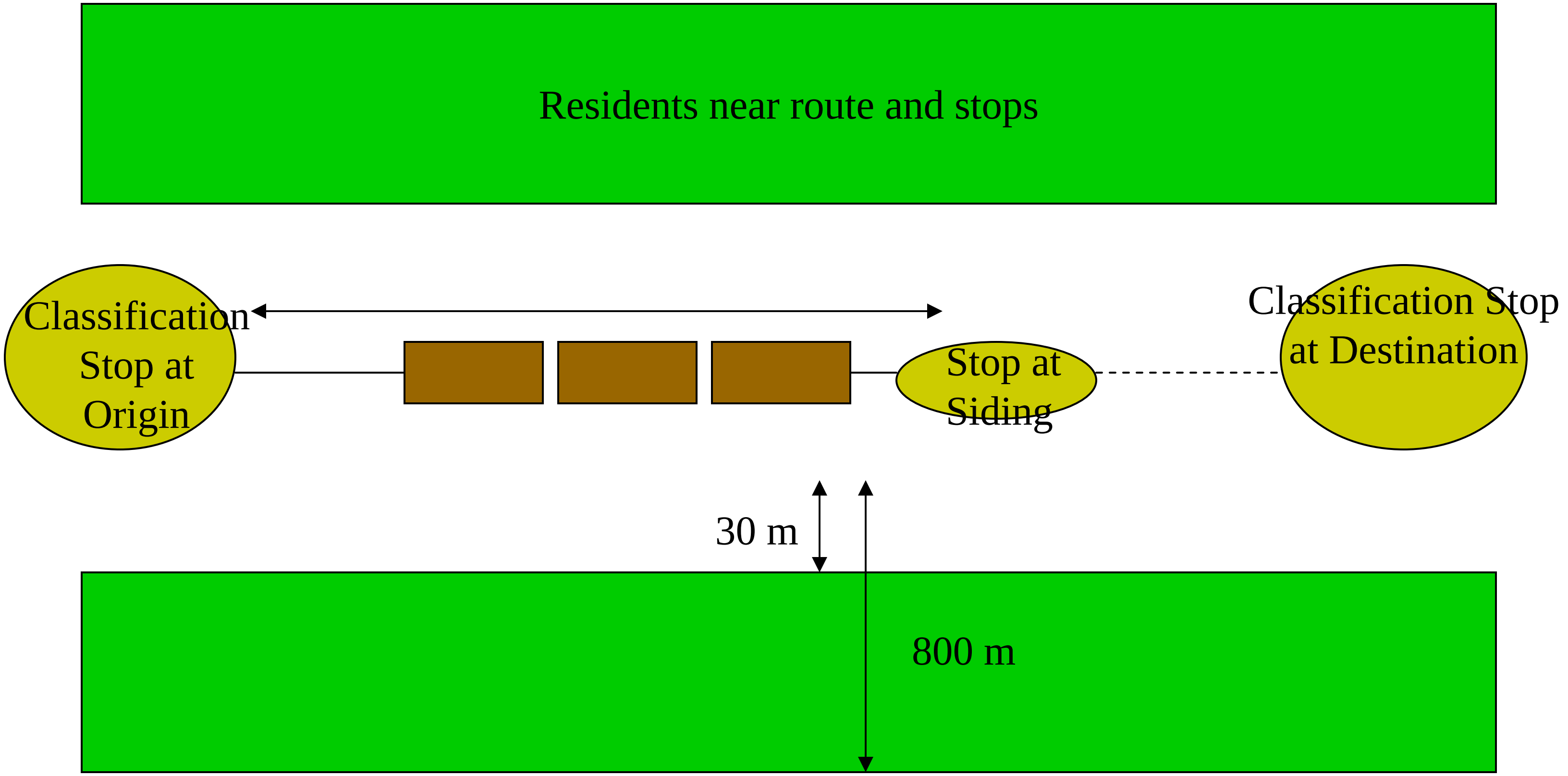
$$D_{off} = 4 \cdot Q \cdot k_0 \cdot DR_v \cdot \frac{PD_L}{V_L} \cdot NSH_L \cdot DIST_L \cdot \left[f_G \cdot (I + J) + f_N \cdot (K + L)\right]$$

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

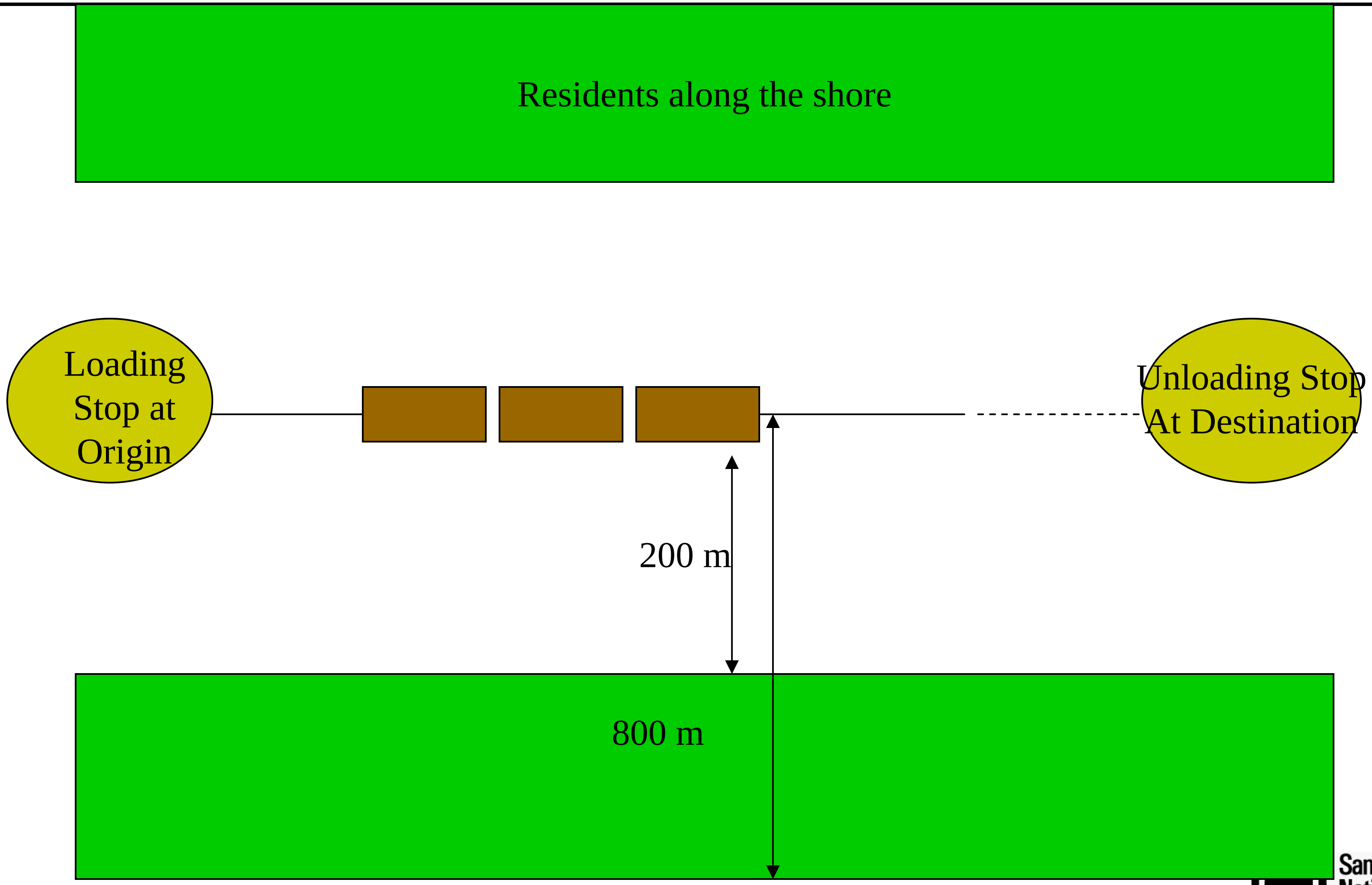
Incident-free Transportation: Legal-weight Truck Route and Stops



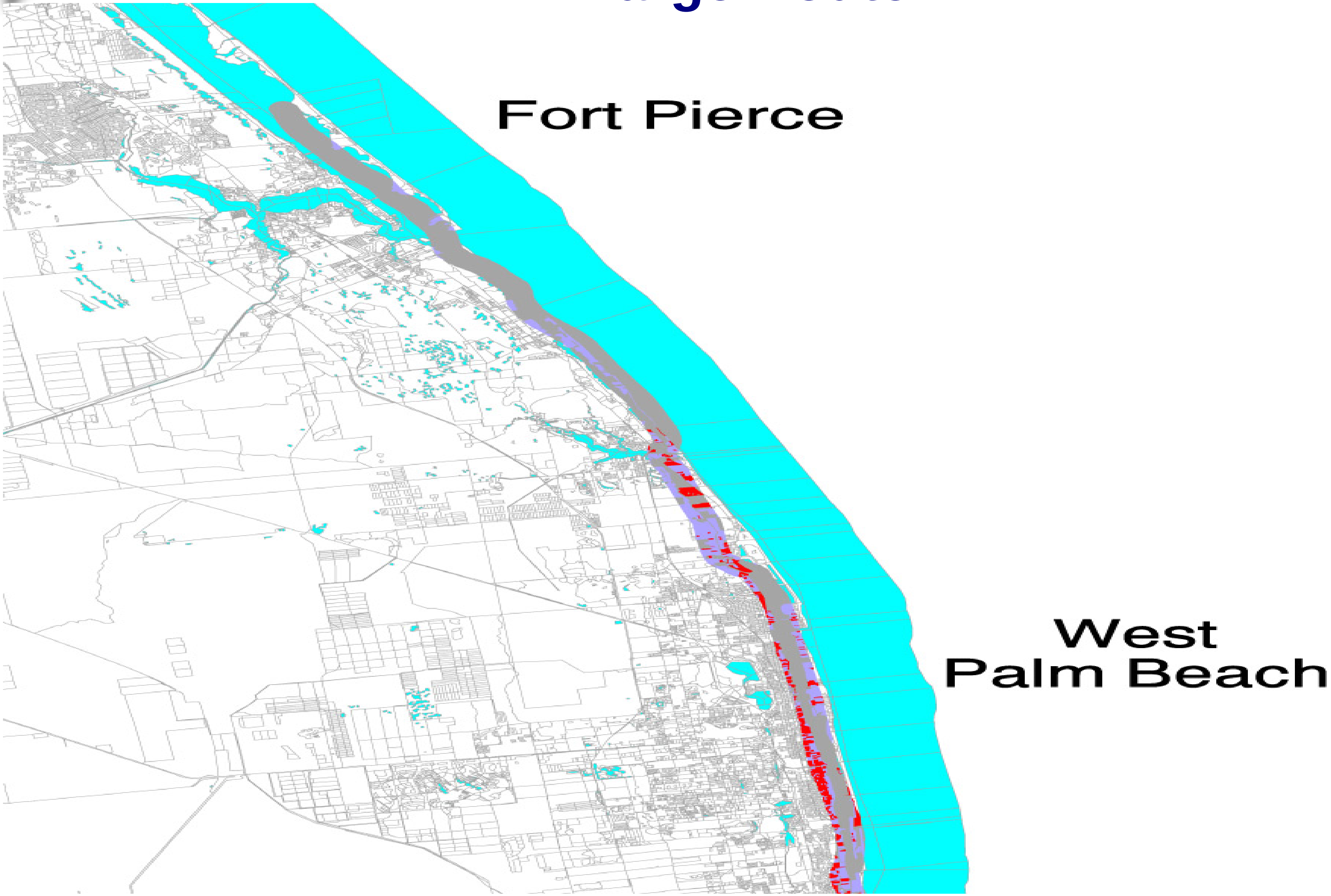
Incident-free Transportation: Rail Route and Stops



Incident-free Transportation: Barge Route and Stops



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

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

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

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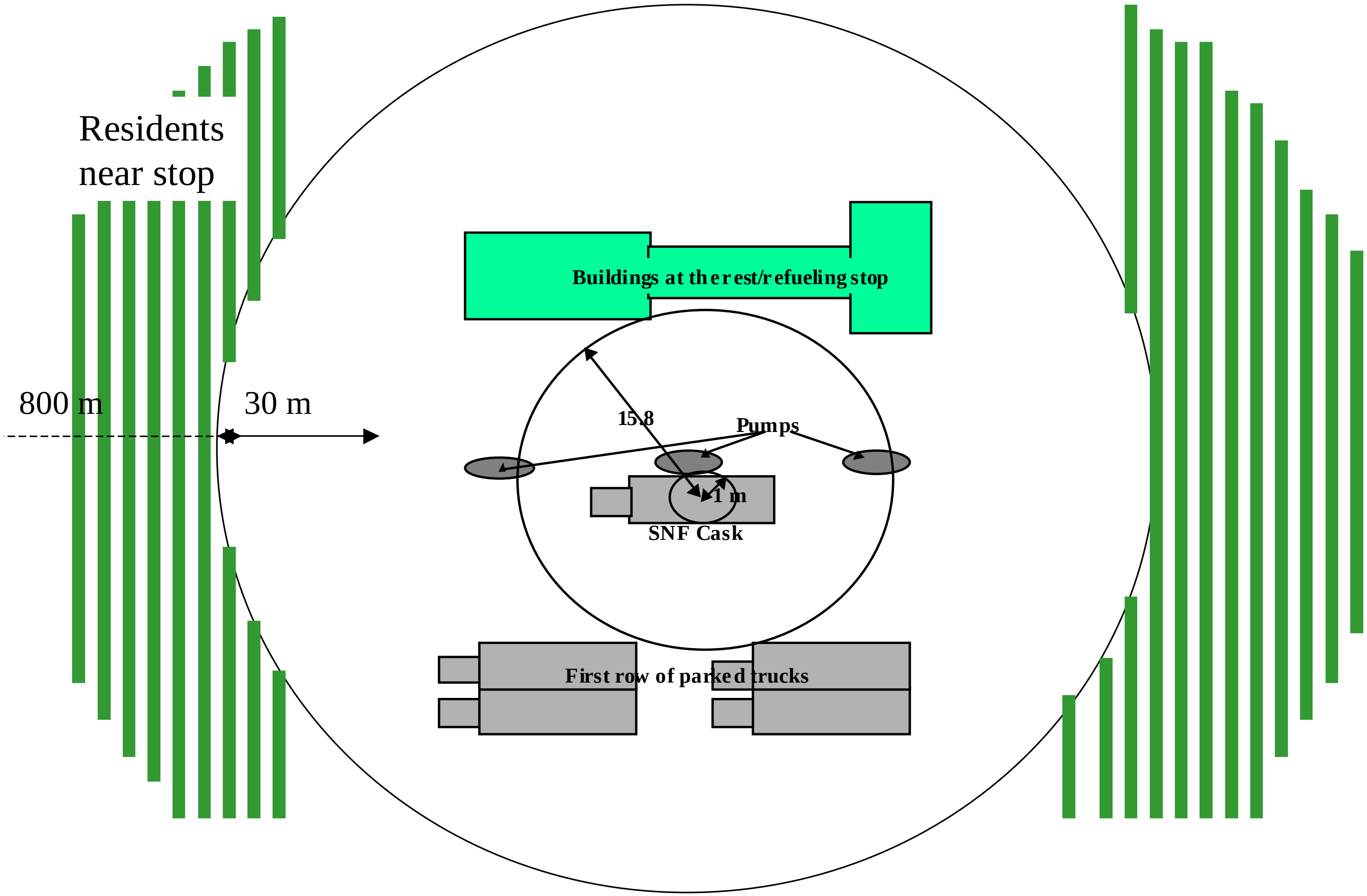


Dose to People at Stops
Number of People at an Average Distance

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

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

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

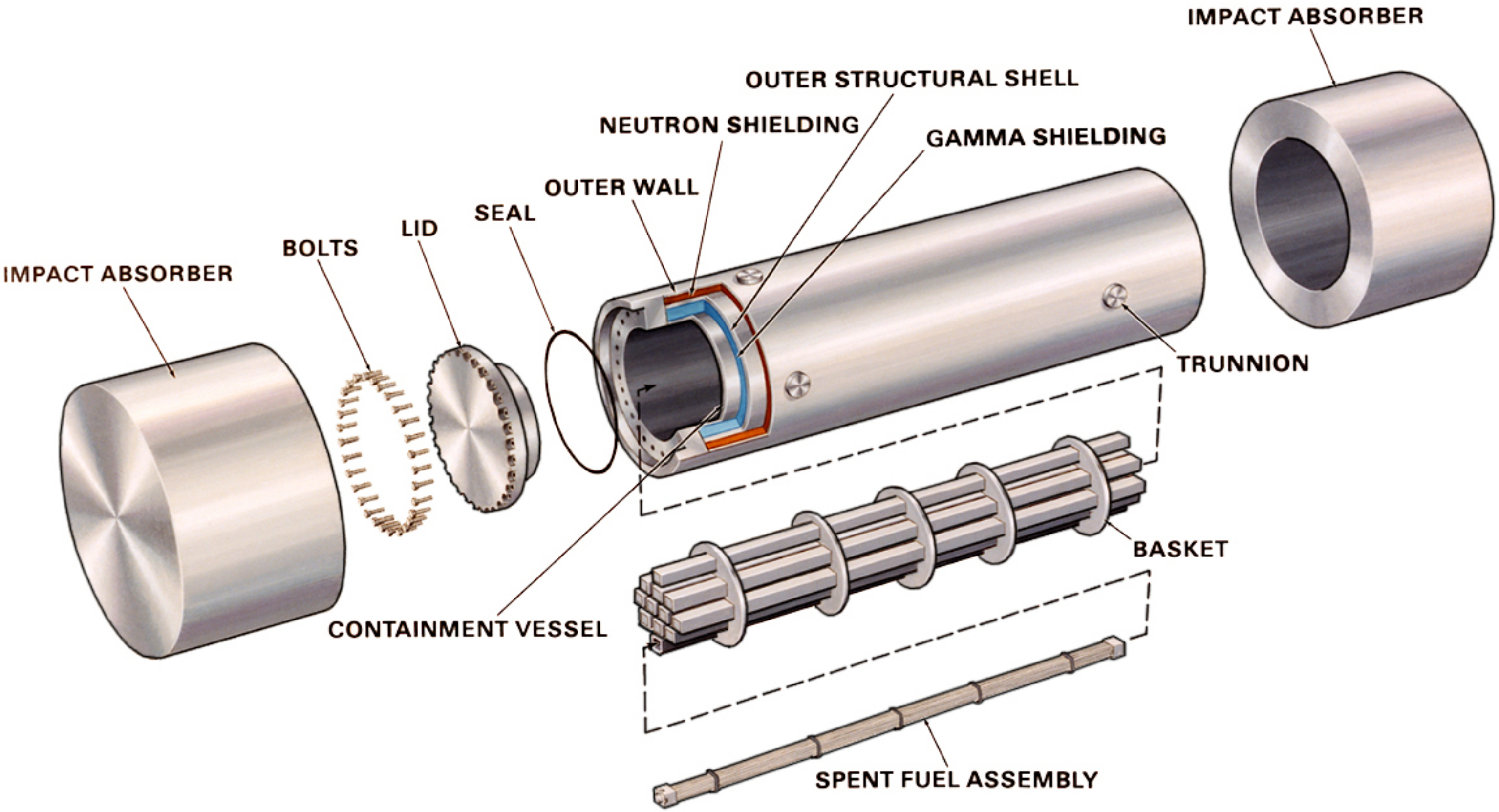
max = Maximum radial distance from source

min = Minimum radial distance from source

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



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 Se 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 Sea 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 Fi ● (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

Transportation Accidents : Matrix of NUREG/CR-6672 Cases (detail)

>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	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 Se 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
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	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
No Impact	21 No Release ✶ Prob 0.99996		20 Seal Failure by Fi ✹ (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	A $T_a – T_f$	B $T_a – T_f$

Change Severity Categories By Probability Weighting

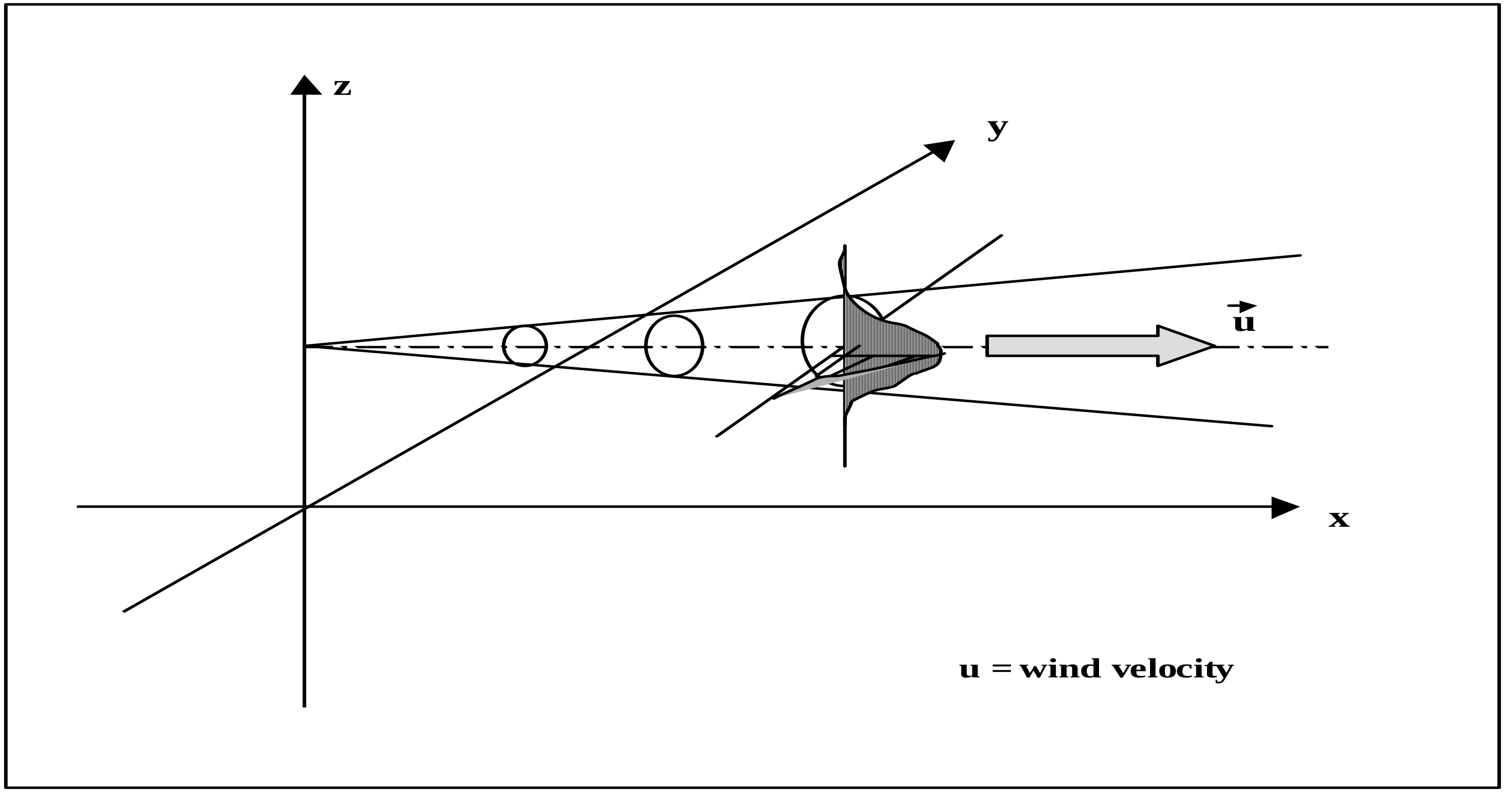
$$RF_{Sci,m} = \frac{\sum_{j,m} RF_{Cj} * P_{Cj}}{P_{Sci}}$$

$$P_{Sci} = \sum_{j} P_{Cj}$$

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

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



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

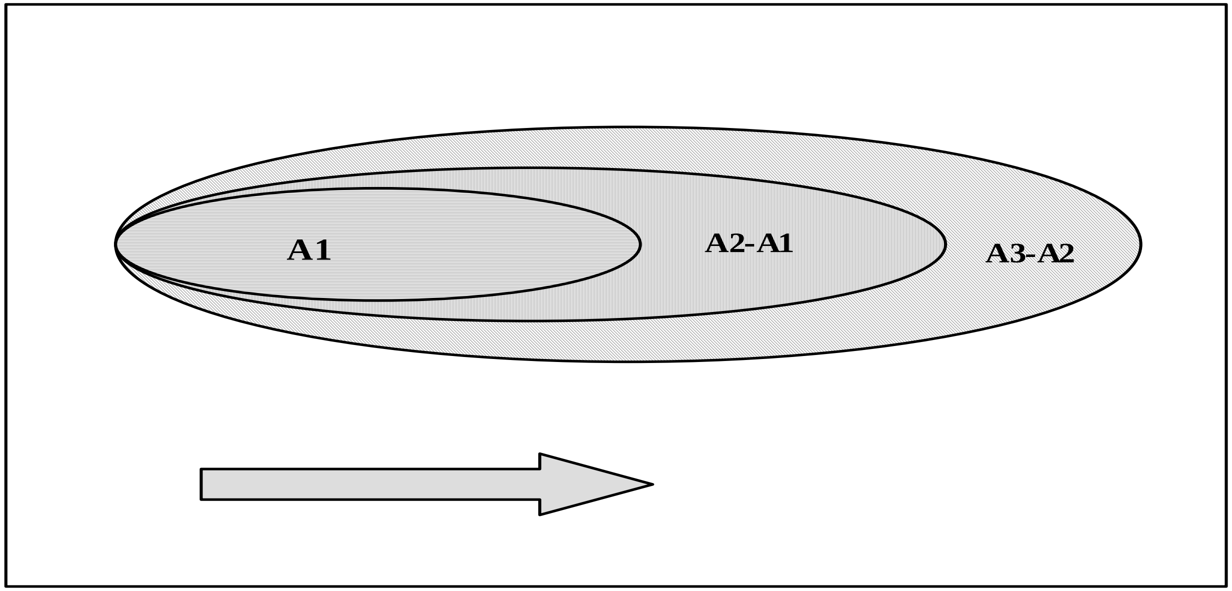
Deposition from an Elevated Source

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

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≥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:

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

A revised estimate of the material deposited is given by

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

Dose to an Individual from Inhalation of Dispersed Materials

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

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 p^{th} 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 p^{th} 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 n^{th} isopleth (m^2)

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Integrated Population Dose from Groundshine

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

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

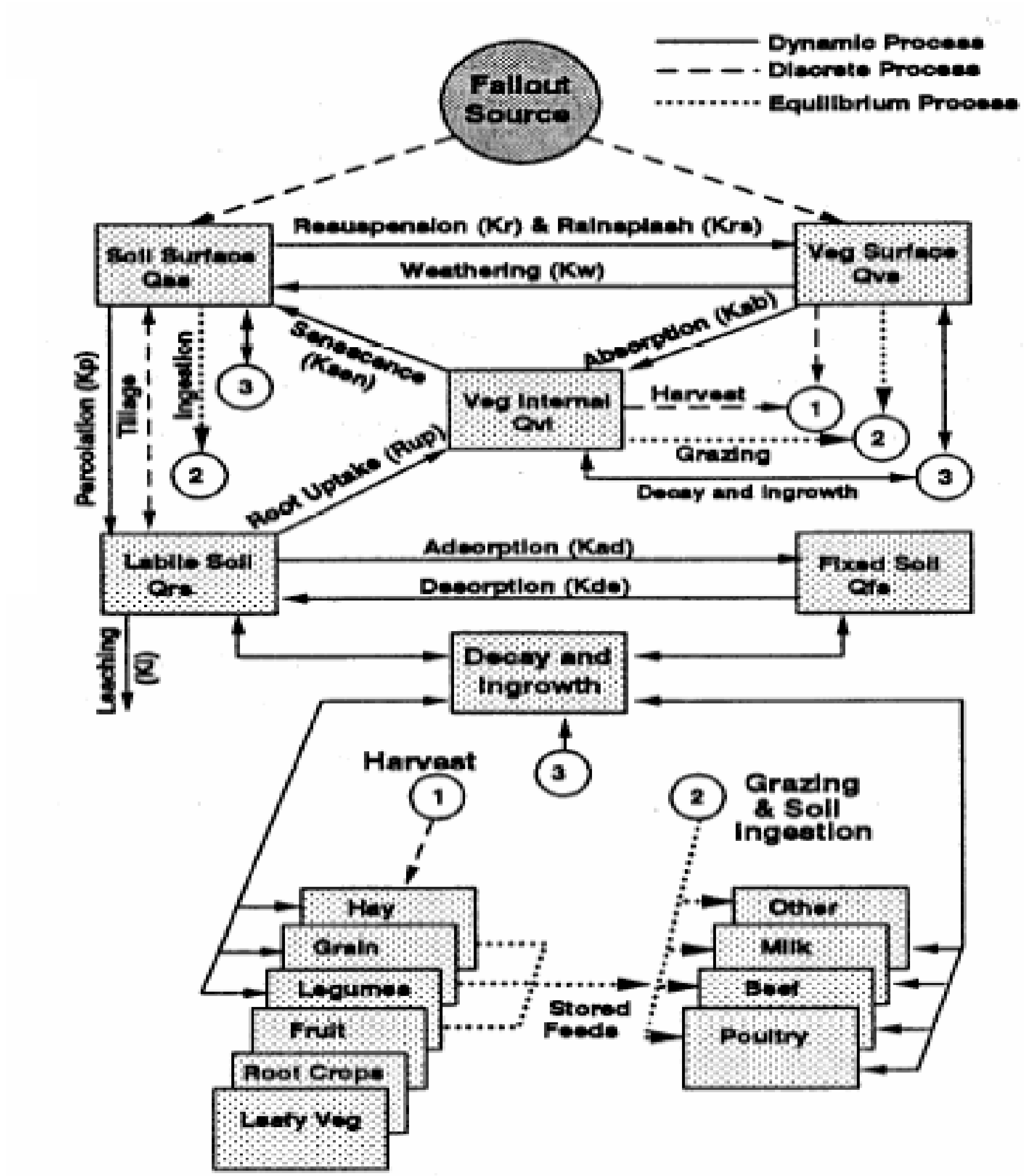
CL_p = Ground concentration (deposition) of radionuclide p (μCi/m^2)

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

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

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

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

$\gamma_{j,L}$ = 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

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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

The RADTRAN Team at SNL

Ken Sorenson, Jeff Danneels -- Managers
Ruth Weiner, Ph. D. – Principal Investigator
Douglas Osborn
Matt Dennis
Betsy Galloway – office administrative assistant
Cheryl Perea – financial analyst
Terence Heames, contractor, FORTRAN programmer
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Alex Thrower – U. S. Department of Energy

RADTRAN Equations

KHNP Training Program

Module #5: Packaging and Transportation

August 2, 2007

Ruth Weiner
Sandia National Laboratories

SAND 2007-

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

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

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

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
$DR_{p\ or\ v}$	=	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 (m^2)
μ = Linear attenuation coefficient (m^{-1})
a_1, a_2, a_3, a_4 = dimensionless coefficients; default values set

Effective Package Dimension

d_e =

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

where:

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

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Point Source Package Shape Factor

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

where:

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

Gamma Line Source

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

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
$DR_{p\ or\ v}$	=	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)

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General Equation for Gamma Dose to Population along the Route

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

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

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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 experienced from spent nuclear fuel.

Basic Equation for Dose to Population along the Route

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

where:

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)

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

Integration Factor: I

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

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

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

where:

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

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

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

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

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

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

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

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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

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

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

Point Source

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

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

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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

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

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

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

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

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)

Equation for Dose to a Rail Yard Worker

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

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)

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

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Final Equation for Dose to Cargo Inspectors for Barges

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

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)

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)

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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)

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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

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

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 p^{th} isotope and o^{th} organ (rem/Ci)
$\mathbf{X}_n$ = 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 p^{th} isotope (rem/Ci)
IF = Integral of time-integrated atmospheric dilution factors, χ, over all downwind areas
BR = Breathing rate (m^3/sec)
PD_L = Population density on line L (persons/km^2)
A_n = Area of n^{th} isopleth (m^2)

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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:

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

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

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Resuspension Dose Factor

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

where:

V_d = Deposition Velocity (m/sec)

λ_1 $= 0.693 \cdot \left(1/RT_{1/2} + 1/t_{1/2}\right)$

λ_2 $= 0.693/t_{1/2}$

$RT_{1/2}$ = Resuspension half-life = 365 days

$t_{1/2}$ = Radioactive half-life (days)

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Model for Dose to an Individual from Cloudshine

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

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
$\mathbf{X}_n$ = 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)

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Model for Integrated Population Dose from Cloudshine

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

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 p^th isotope (rem-m^3/Ci-sec)
IF = Integral of time-integrated atmospheric dilution factors, χ, 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. $[(UBF \cdot BDF) + (USWF \cdot RPD)]$

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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)

Total Decontamination Factor

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

where:

TDF = Total Decontamination Factor
CL_p = Contamination level of radionuclide p ($\mu Ci/m^2$)
CU = Contamination level after clean-up ($\mu Ci/m^2$)

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})

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Decay Factor TRM1

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

where:

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

$$\lambda_1 = \frac{0.63}{0.0031 \cdot t_{1/2} + 0.693} \qquad \lambda_3 = \frac{0.37}{0.000021 \cdot t_{1/2} + 0.693}$$

$$\lambda_2 = \frac{0.0031 \cdot t_{1/2} + 0.693}{t_{1/2}} \qquad \lambda_4 = \frac{0.000021 \cdot t_{1/2} + 0.693}{t_{1/2}}$$

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

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

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

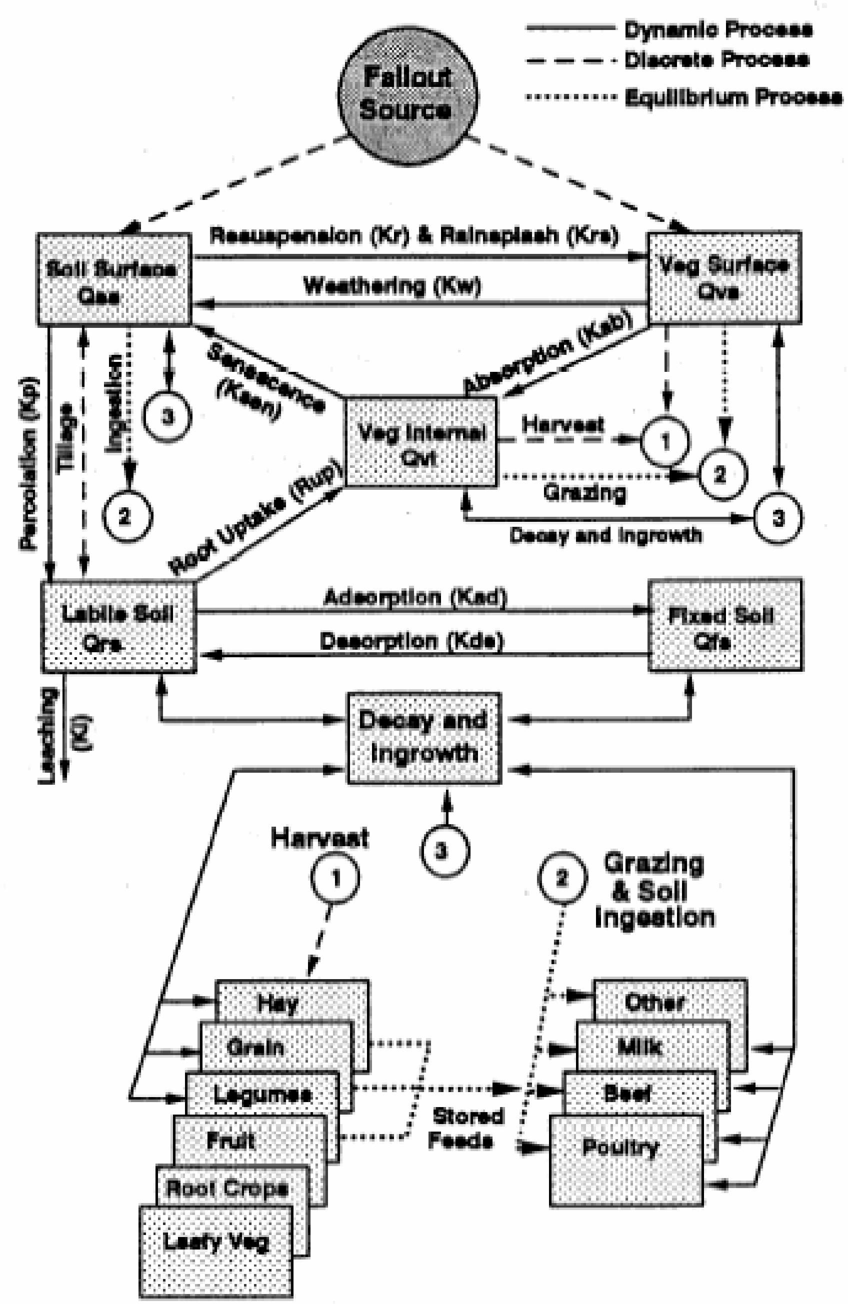
where:

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

D_{gnd} = Groundshine dose for the p^{th} radionuclide in the n^{th} isopleth in accident of severity j on link l (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

$$RISK_L^{INH} = \sum_{p=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{inh_{p,j,L}}$$

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

$$\mathrm{RISK}_{L}^{RES} = \sum_{p=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{res_{p,j,L}}$$

where:

$\gamma_{j,L}$ = 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

Cloudshine Dose-Risk

$$RISK_L^{CLD} = \sum_{p=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot Dcld_{p,j,L}$$

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

$$RISK_L^{GND} = \sum_{p=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{gnd_{p,j,L}}$$

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

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Ingestion Dose-Risk

$$RISK_L^{ING} = \sum_{p=1}^{n} \sum_{j=1}^{NSEV} \gamma_{j,L} \cdot D_{ing_{p,j,L}}$$

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

Overall Dose-Risk from Dispersion

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

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

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

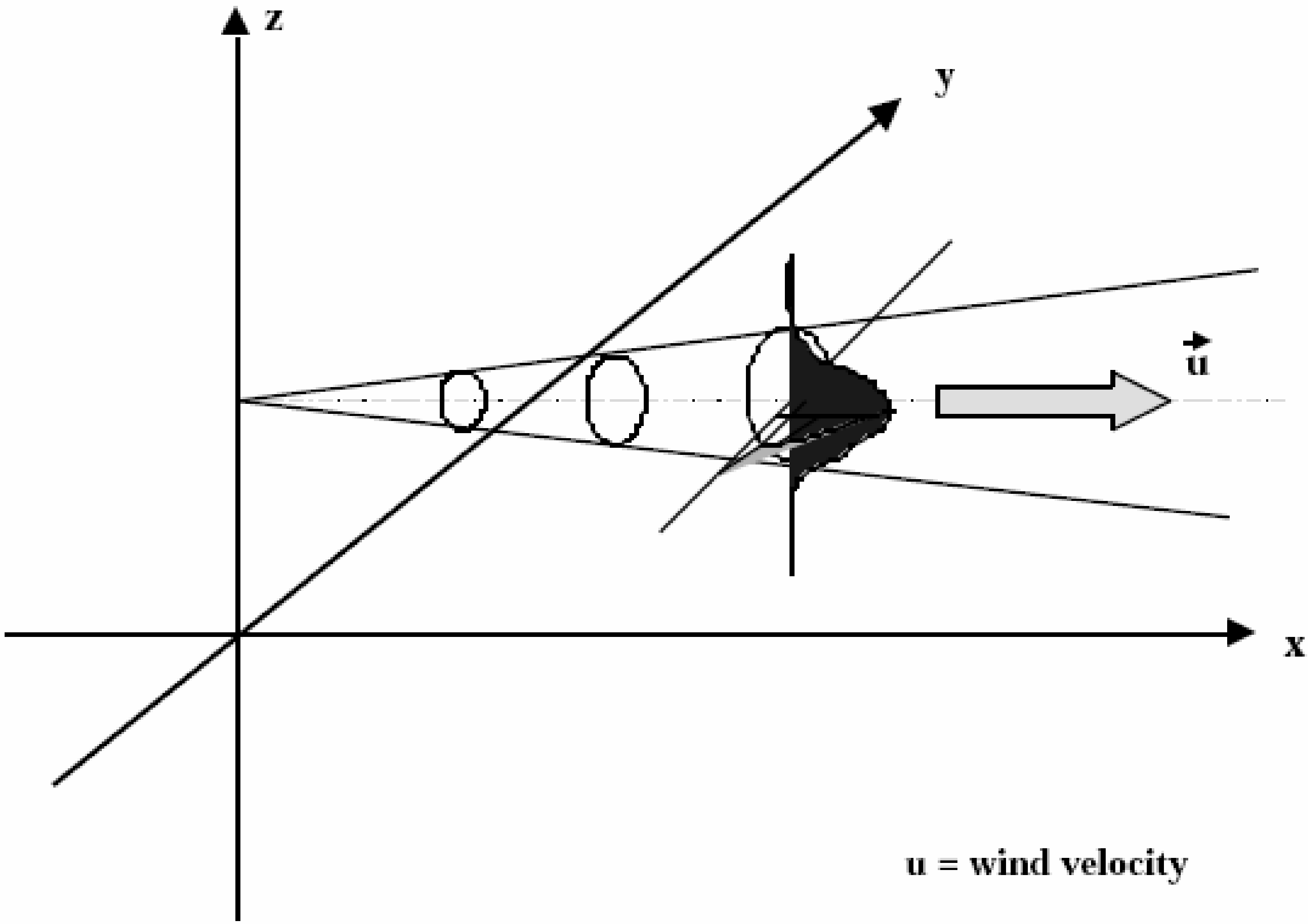
Basic Gaussian Dispersion Model for Dilution at Ground Level for an Elevated Release

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

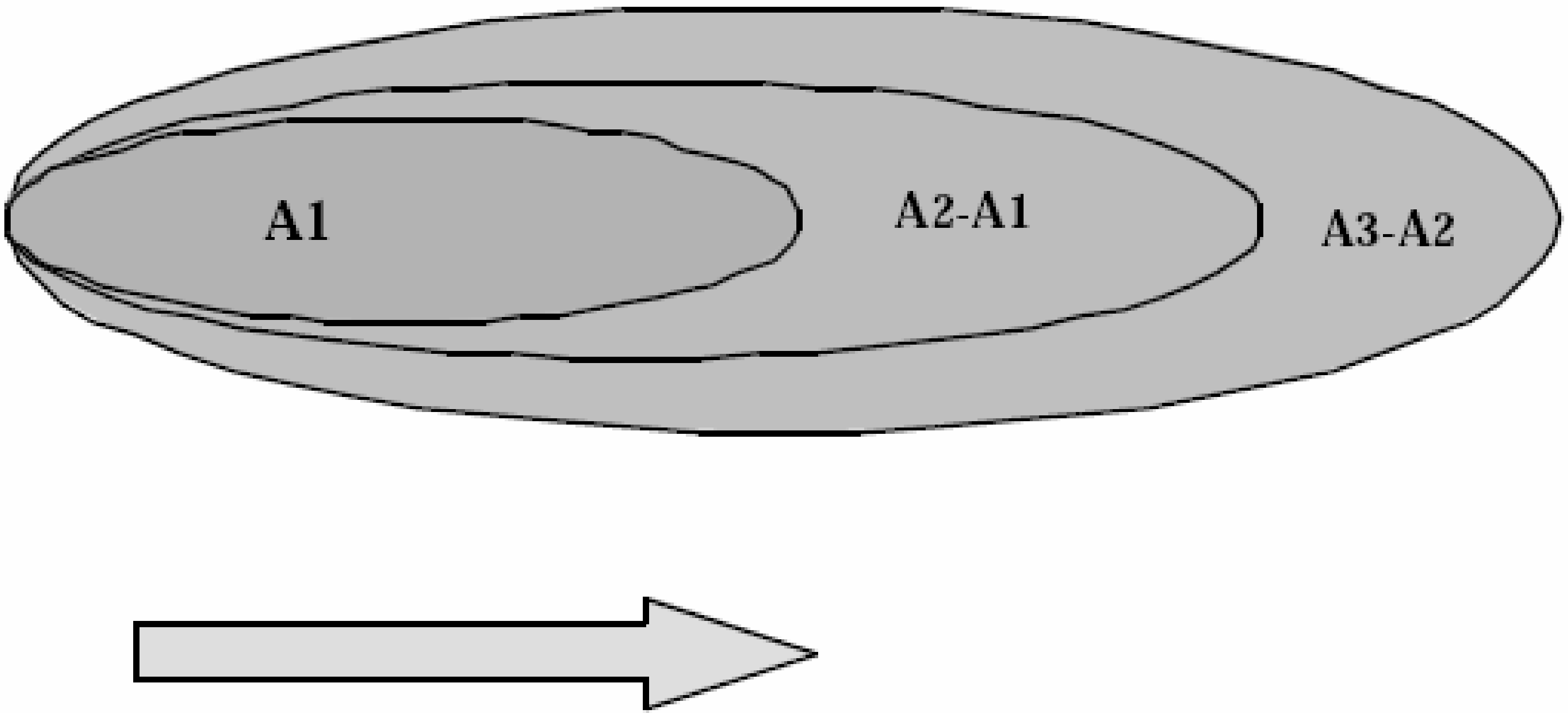
where:

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)

Diagram of Gaussian Dispersion



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)

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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)

Transportation to the Yucca Mountain Repository

KHNP Training Program
Module #5: Packaging and Transportation

July 26, 2007

Ruth Weiner
Sandia National Laboratories

SAND 2007-

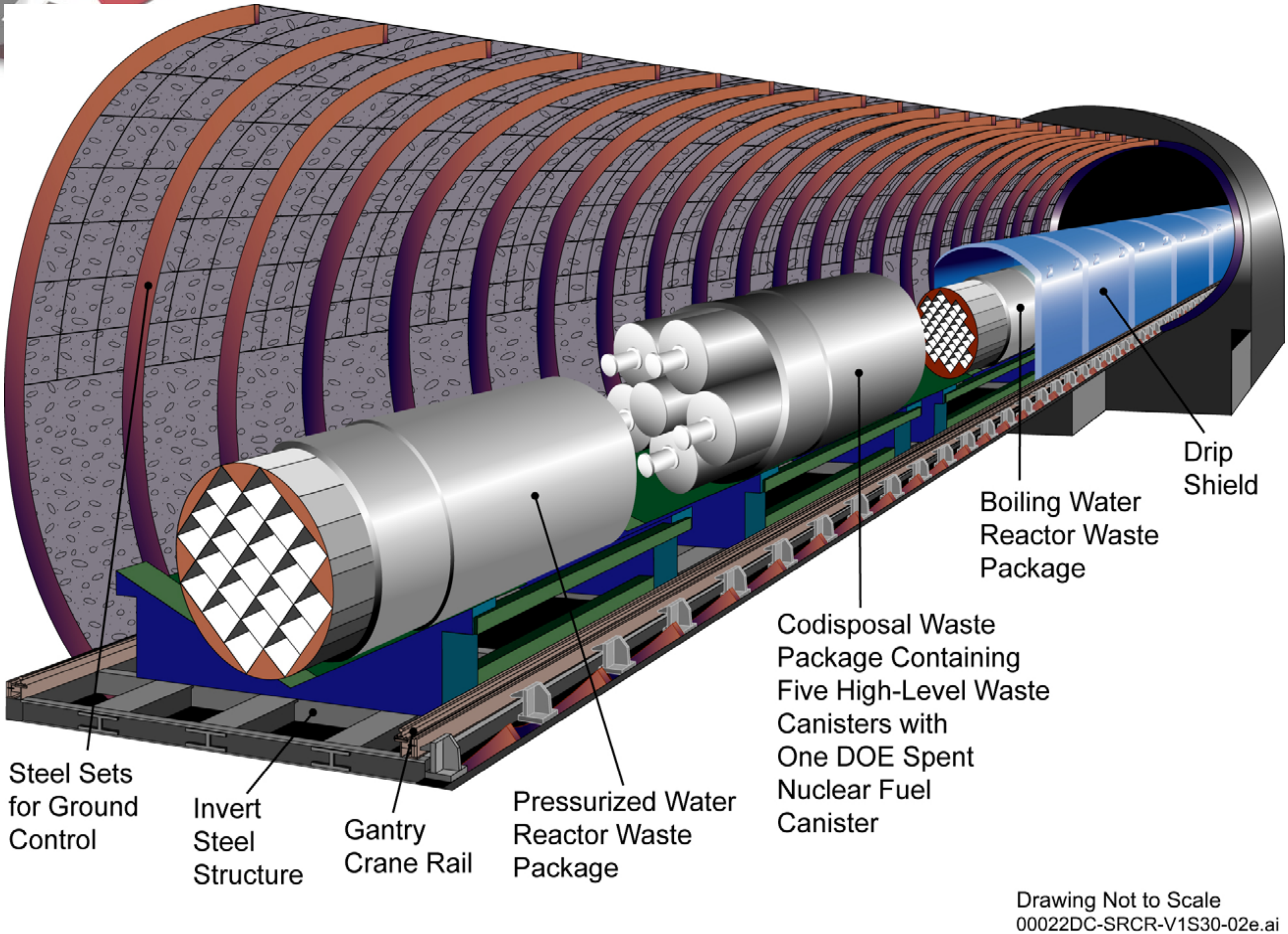
Transportation to the Yucca Mountain Repository

- Yucca Mountain selected for characterization in 1987
- On the Nevada Test Site: government-owned land
- About 160 km. NNW of Las Vegas
- No rail access
- Major U.S. highway (US95) about 20 km from the site boundary

Work Begins on the North Portal

Aerial View of the North Portal Area

TWILIGHT VIEW OF THE 25 FT. TUNNEL BORING MACHINE ENTERING THE NORTH PORTAL


Steel Sets for Ground Control
Invert Steel Structure
Gantry Crane Rail
Pressurized Water Reactor Waste Package
Codisposal Waste Package Containing Five High-Level Waste Canisters with One DOE Spent Nuclear Fuel Canister
Boiling Water Reactor Waste Package
Drip Shield
Drawing Not to Scale
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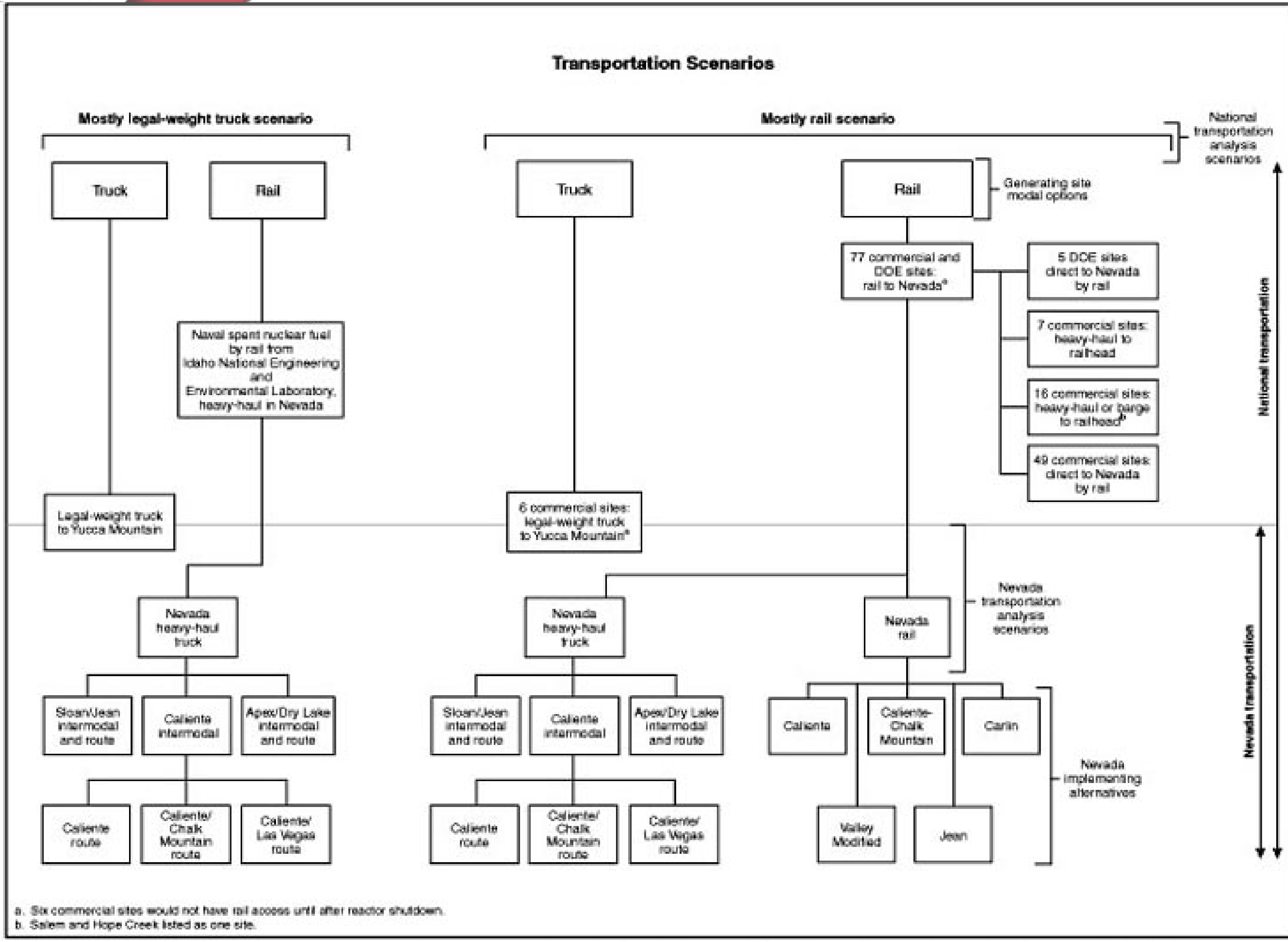
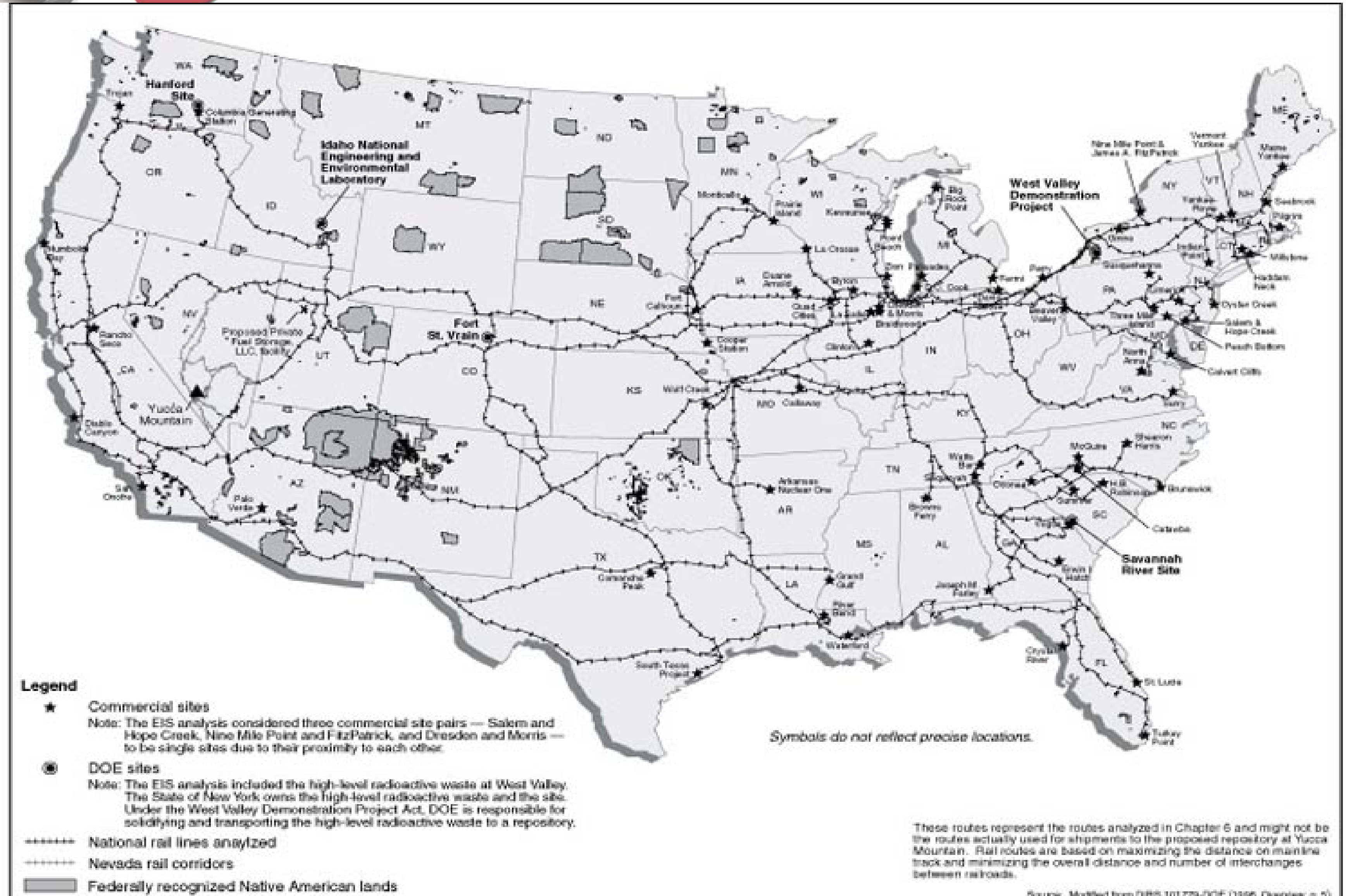
Oversize Truck on US 95

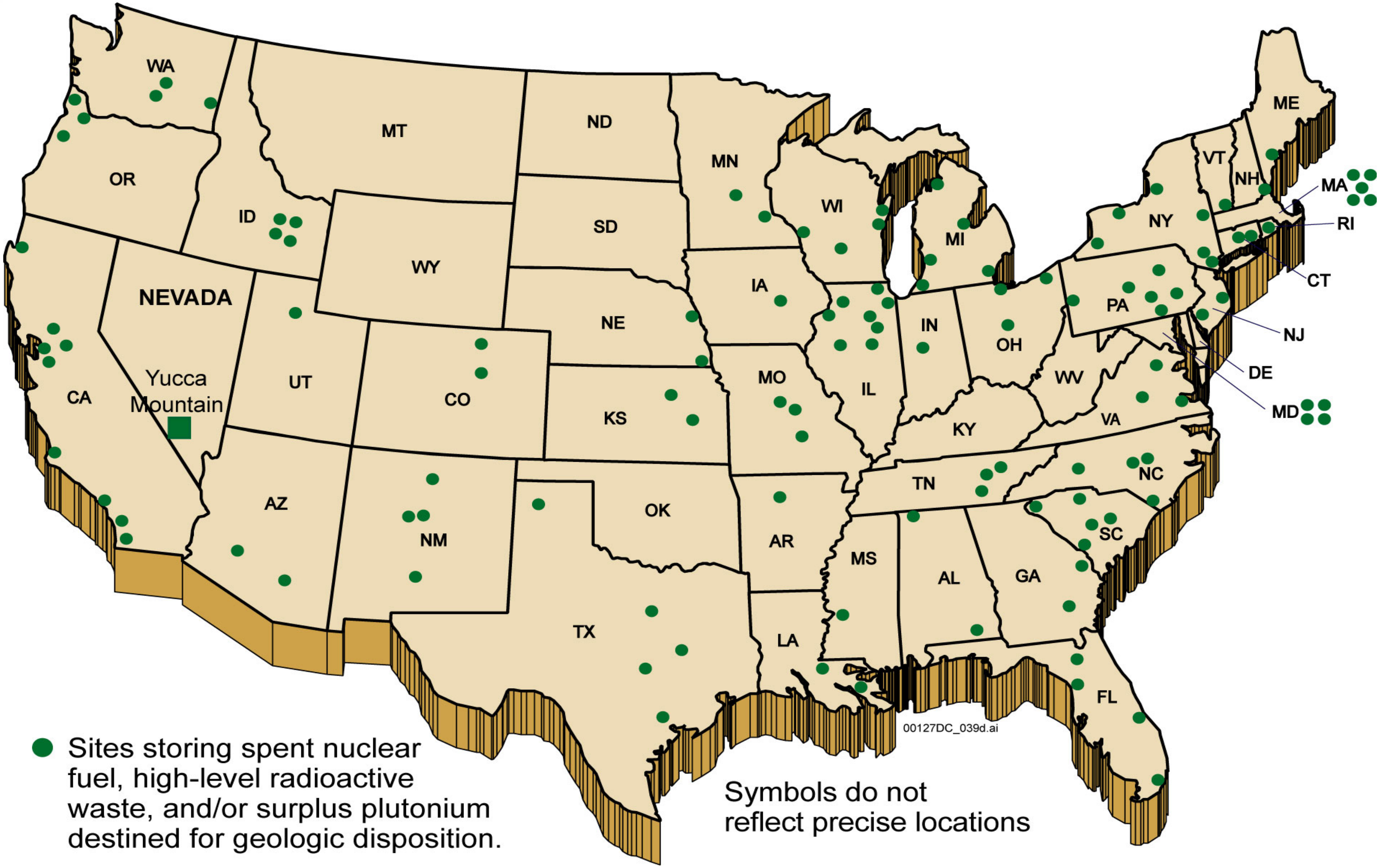
The Tunnel Boring Machine



Relationship between transportation modes, national and Nevada analytical scenarios, and Nevada transportation implementing alternatives.



Representative rail routes from commercial and DOE sites to Yucca Mountain analyzed for the Proposed Action.



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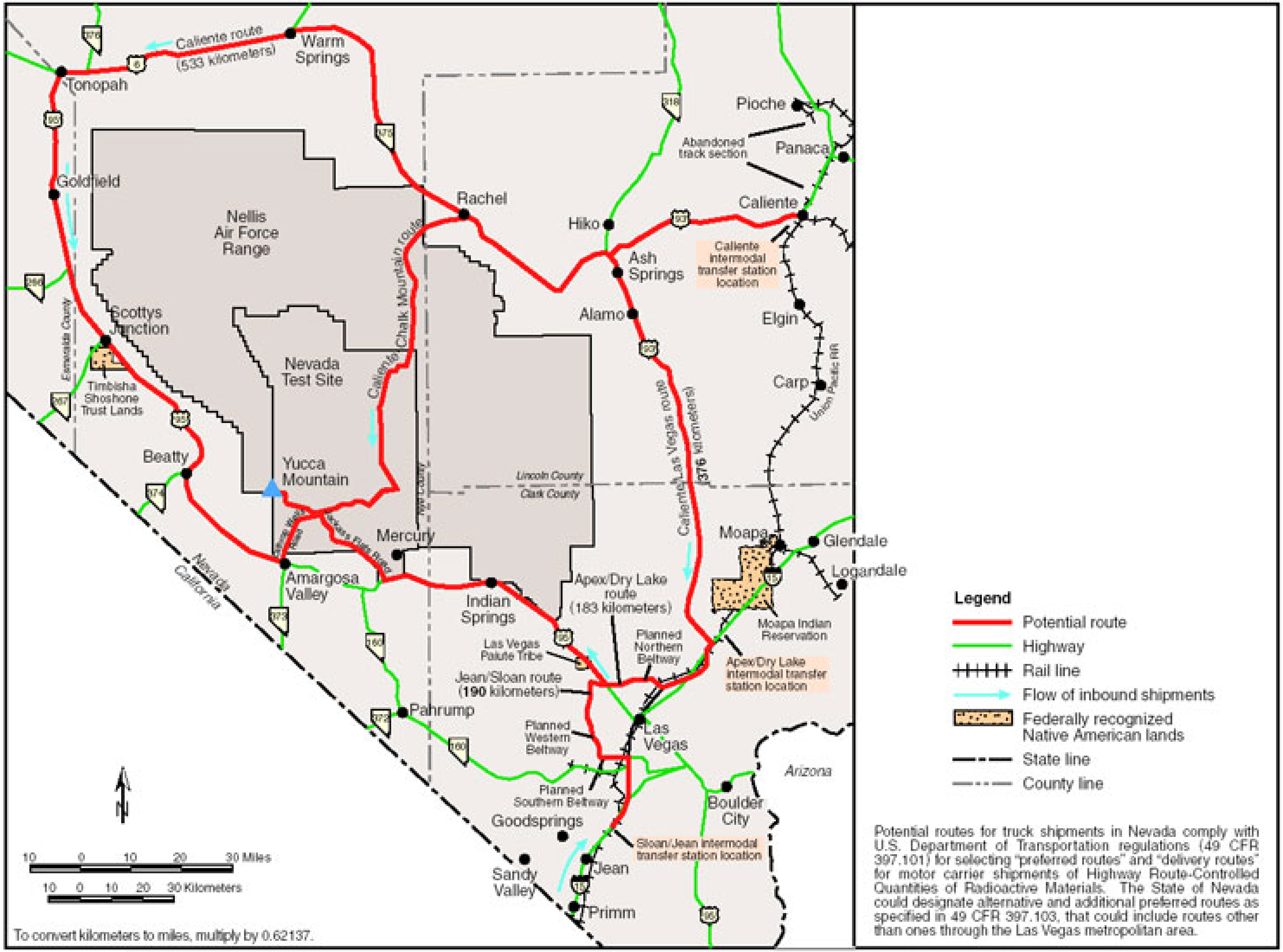

Potential intermodal transfer station locations and potential routes in Nevada for heavy-haul trucks.

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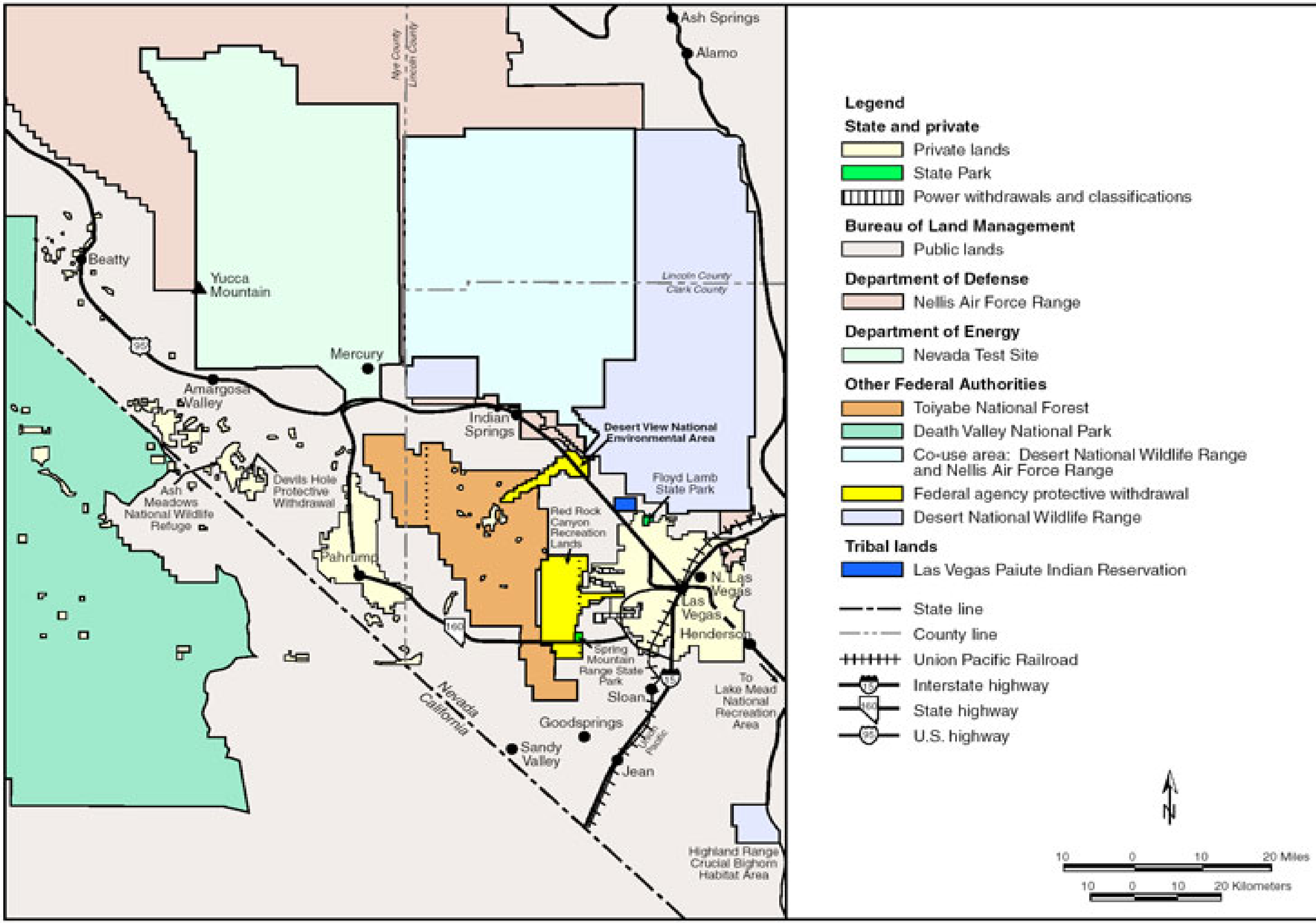


Land use and ownership in the Yucca Mountain region.

Summary of estimated number of shipments for the various inventory and national transportation analysis scenario combinations.

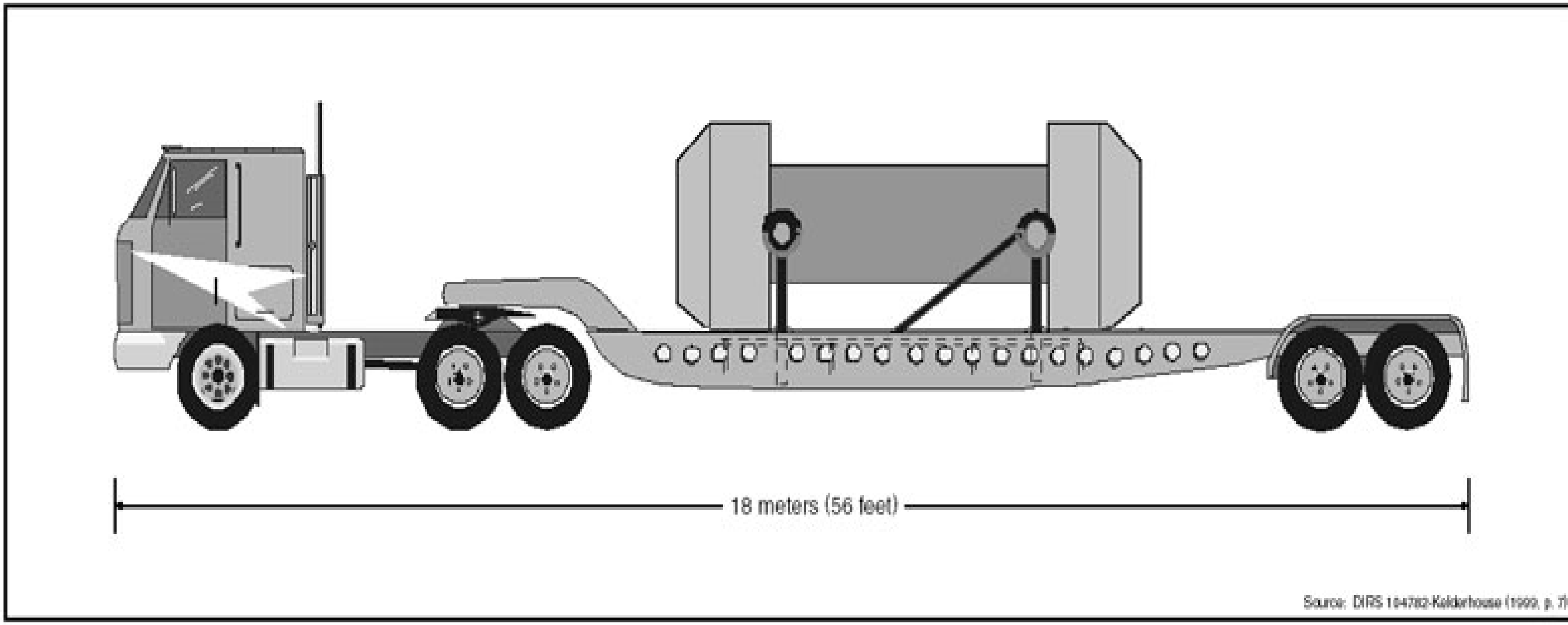
	Mostly truck		Mostly rail	
	Truck	Rail	Truck	Rail
Proposed Action				
Commercial spent nuclear fuel	41,001	0	1,079	7,218
High-level radioactive waste	8,315	0	0	1,663
DOE spent nuclear fuel	3,470	300	0	765
Greater-Than-Class-C waste	0	0	0	0
Special-Performance-Assessment-Required waste	0	0	0	0
Proposed Action totals	*52,786*	*300*	*1,079*	*9,646*
Module 1[a]				
Commercial spent nuclear fuel	79,684	0	3,122	12,989
High-level radioactive waste	22,280	0	0	4,458
DOE spent nuclear fuel	3,721	300	0	796
Greater-Than-Class-C waste	0	0	0	0
Special-Performance-Assessment-Required waste	0	0	0	0
Module 1 totals	*105,685*	*300*	*3,122*	*18,243*
Module 2[a]				
Commercial spent nuclear fuel	79,684	0	3,122	12,989
High-level radioactive waste	22,280	0	0	4,458
DOE spent nuclear fuel	3,721	300	0	796
Greater-Than-Class-C waste	1,096	0	0	282
Special-Performance-Assessment-Required waste	1,763	55	0	410
Module 2 totals	*108,544*	*355*	*3,122*	*18,935*

a. The number of shipments for Module 1 includes all shipments of spent nuclear fuel and high-level radioactive waste included in the Proposed Action and shipments of additional spent nuclear fuel and high-level radioactive waste as described in Appendix A. The number of shipments for Module 2 includes all the shipments in Module 1 and additional shipments of highly radioactive materials described in Appendix A.

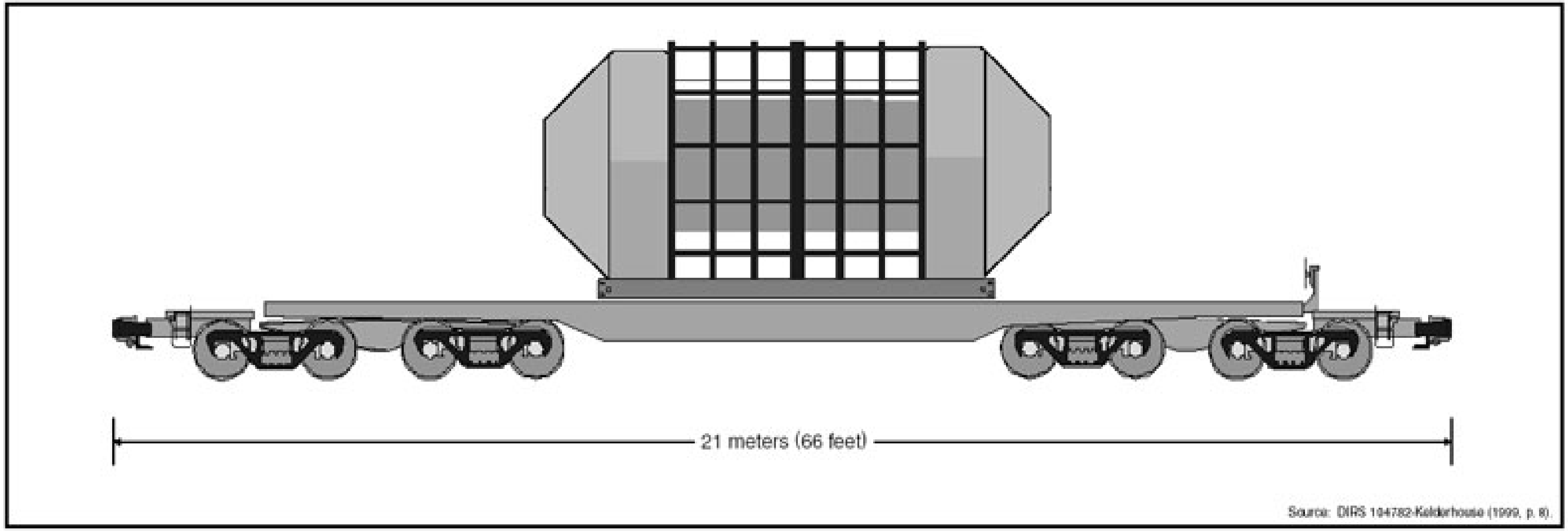
Input parameters and parameter values used for the incident-free national truck and rail transportation analysis, except stops.

Parameter	Legal-weight truck transportation	Rail transportation	Legal-weight truck and rail
Package type			Type B shipping cask
Package dimension	5.2 meters[a] long 1.0 meters diameter	5.06 meters long 2.0 meters diameter	
Dose rate			10 millirem per hour, 2 meters from side of vehicle[f]
Number of crewmen	2	5	
Distance from source to crew	3.1 meters[a]	152 meters[b]	
Speed			
Rural	88 km[c,d] per hour	64 km per hour	
Suburban	88 km/hr non-rush hour 44 km/hr rush hour	40 km per hour	
Urban	88 km/hr non-rush hour 44 km/hr rush hour	24 km per hour	
Input for stop doses: see Table J-17			
Number of people per vehicle sharing route	2	3	
Minimum and maximum distances to exposed population			30 meters to 800 meters
Population densities (persons per km²)[d]			
Rural			(e)
Suburban			(e)
Urban			(e)
One-way traffic count (vehicles per hour)			
Rural	470	1	
Suburban	780	5	
Urban	2,800	5	

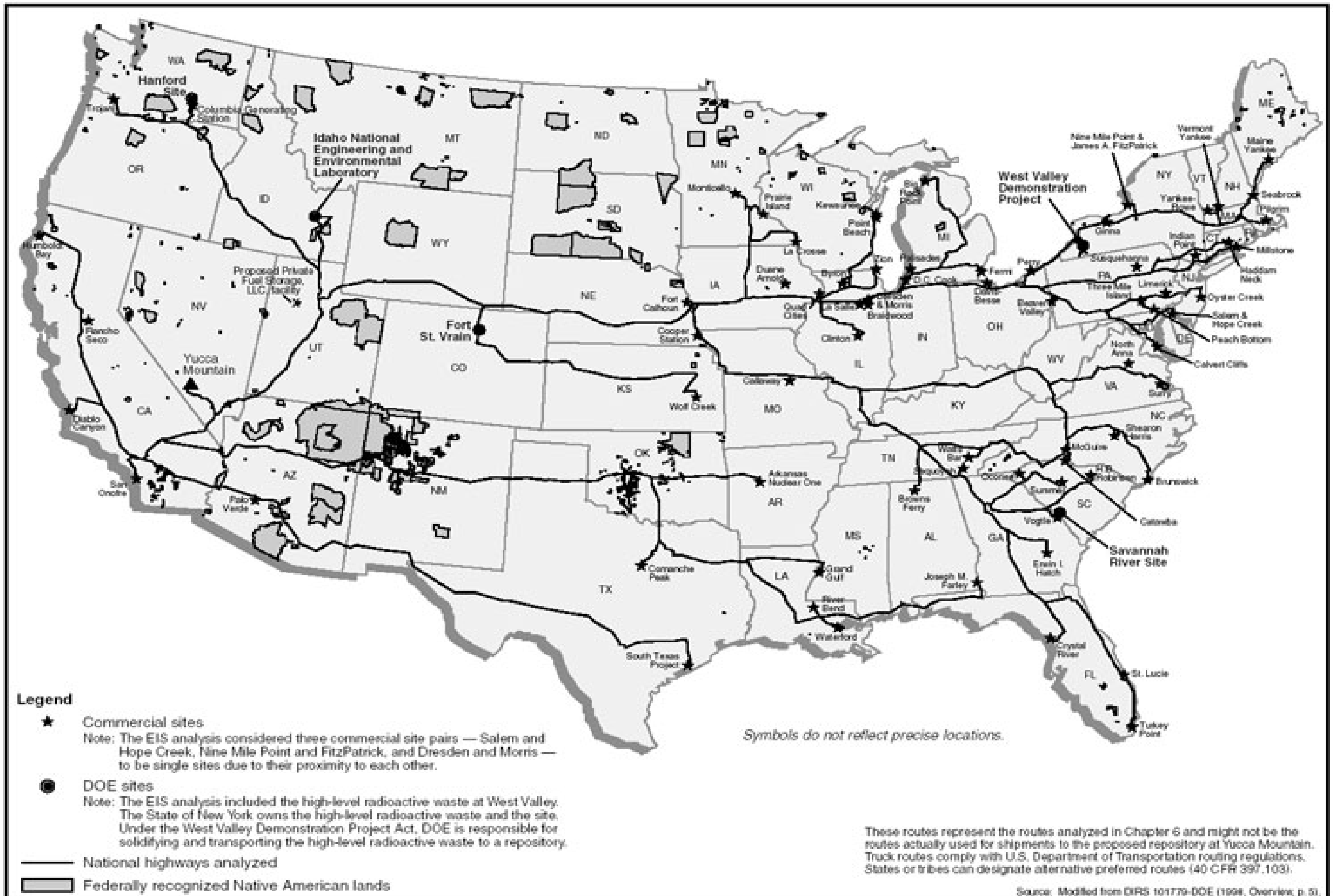
a. To convert meters to feet, multiply by 3.2808.
b. Rail crew in transit would be too far and too well shielded from the external cask radiation to receive any dose. This number is not used in the calculation and is provided for information only.
c. To convert kilometers to miles, multiply by 0.62137.
d. Assumes general freight rather than dedicated service.
e. Population densities along transportation routes were estimated using the HIGHWAY and INTERLINE computer programs, then were extrapolated to 2035.
f. The actual (equivalent) input to RADTRAN 5 is 14 millirem per hour at 1 meter (3.3 feet) from the side of the vehicle.



Artist's conception of a truck cask on a legal-weight tractor-trailer truck.



Artist's conception of a large rail cask on a railcar.



Representative truck routes from commercial and DOE sites to Yucca Mountain analyzed for the Proposed Action and Inventory Modules 1 and 2.

Summary of estimated number of shipments for the various inventory and national transportation analysis scenario combinations.

	Mostly truck		Mostly rail	
	Truck	Rail	Truck	Rail
Proposed Action				
Commercial spent nuclear fuel	41,001	0	1,079	7,218
High-level radioactive waste	8,315	0	0	1,663
DOE spent nuclear fuel	3,470	300	0	765
Greater-Than-Class-C waste	0	0	0	0
Special-Performance-Assessment-Required waste	0	0	0	0
Proposed Action totals	*52,786*	*300*	*1,079*	*9,646*
Module 1[a]				
Commercial spent nuclear fuel	79,684	0	3,122	12,989
High-level radioactive waste	22,280	0	0	4,458
DOE spent nuclear fuel	3,721	300	0	796
Greater-Than-Class-C waste	0	0	0	0
Special-Performance-Assessment-Required waste	0	0	0	0
Module 1 totals	*105,685*	*300*	*3,122*	*18,243*
Module 2[a]				
Commercial spent nuclear fuel	79,684	0	3,122	12,989
High-level radioactive waste	22,280	0	0	4,458
DOE spent nuclear fuel	3,721	300	0	796
Greater-Than-Class-C waste	1,096	0	0	282
Special-Performance-Assessment-Required waste	1,763	55	0	410
Module 2 totals	*108,544*	*355*	*3,122*	*18,935*

a. The number of shipments for Module 1 includes all shipments of spent nuclear fuel and high-level radioactive waste included in the Proposed Action and shipments of additional spent nuclear fuel and high-level radioactive waste as described in Appendix A. The number of shipments for Module 2 includes all the shipments in Module 1 and additional shipments of highly radioactive materials described in Appendix A.

National transportation impacts for the transportation of spent nuclear fuel and high-level radioactive waste for the mostly rail and mostly legal-weight truck scenarios.[a,b]

Group	Impact	Mostly legal-weight truck scenario	Mostly rail scenario
Worker	*Incident-free health impacts, radiological*		
	Maximally exposed individual (rem)	48[c]	48[c]
	Individual latent cancer fatality probability	0.02	0.02
	Collective dose (person-rem)	29,000	7,900 - 8,800
	Latent cancer fatality incidence	11.7	3.2 - 3.5[d]
	Industrial safety (fatalities)	0.9	0.29
Public	*Incident-free health impacts, radiological*		
	Average exposed individual (rem)	0.0005	0.0001
	Maximally exposed individual (rem)	2.4[e]	0.29
	Individual latent cancer fatality probability	0.0012	0.00014
	Collective dose (person-rem)	5,000	1,200 - 1,600
	Latent cancer fatality incidence	2.5	0.61 - 0.81
	Incident-free vehicle emissions impacts (fatalities)	0.95	0.55 - 0.77
	Radiological impacts from maximum reasonably foreseeable accident scenario		
	Frequency (per year)	2.3 in 10,000,000	2.8 in 10,000,000
	Maximally exposed individual (rem)	3	29
	Individual latent cancer fatality probability	0.0015	0.015
	Collective dose (person-rem)	1,100	9,900
	Latent cancer fatality incidence	0.55	5
	Accident dose risk (person-rem)	0.46	0.89
	Accident risk (latent cancer fatalities)	0.00023	0.00045
Public and transportation workers	*Fatalities from vehicular accidents*	4.9	2.3 - 3.1

a. The assumed external dose rate is 10 millirem per hour at 2 meters (6.6 feet) from the vehicle for all shipments.
b. Totals for 24 years of operation, including impacts of loading.
c. Based on 2-rem-per-year dose limit.
d. Range for the 10 rail and heavy-haul truck implementing alternatives in Nevada.
e. Based on 100-millirem-per-year dose limit.

Impacts related to repository transportation activities.

Factor	Impact
Total kilometers traveled (millions)	610 - 1,100
Total nonradiological latent fatalities[a]	0.9 - 1.6
Total nonradiological traffic fatalities[b]	6.3 - 11.4
Total nonradiological commuting worker traffic fatalities	2.4 - 4.2

a. From commuter and materials transportation.

b. From materials transportation and public fatalities from commuter transportation.

Population doses and radiological impacts from incident-free transportation for national mostly rail scenario.[a]

Category	Legal-weight truck shipments	Rail shipments[b,c]	Totals[d]
Involved workers			
Collective dose (person-rem)	360	3,300 - 4,300	3,700 - 4,600
Estimated LCFs[e]	0.14	1.3 - 1.7	1.5 - 1.9
Public			
Collective dose (person-rem)	130	1,100 - 1,500	1,200 - 1,600
Estimated LCFs	0.07	0.55 - 0.76	0.61 - 0.81

a. Impacts are totals for 24 years.

b. Barge transportation to a railhead on navigable waterways could be used for transportation from 17 commercial sites that do not have rail service but can load a rail cask. See Appendix J.

c. Includes impacts from intermodal transfer station operations.

d. Totals might differ from sums of values due to rounding.

e. LCF = latent cancer fatality.

Estimated doses and radiological impacts to maximally exposed individuals for national mostly rail scenario.[a,b]

Receptor	Dose (rem)	Probability of latent fatal cancer
Involved workers		
Crew member (rail, heavy-haul truck, or legal-weight truck)	48[c]	0.02
Escort	48[c]	0.02
Inspector (rail)	34	0.014
Railyard crew member	4.2	0.0017
Public		
Resident along route (rail)	0.0016	0.0000008
Person in traffic jam (legal-weight truck)	0.016	0.000008
Person at service station (legal-weight truck)	0.075	0.000038
Resident near rail stop	0.29	0.00014

a. The assumed external dose rate is 10 millirem per hour at 2 meters (6.6 feet) from the vehicle for all shipments.

b. Totals for 24 years.

c. Based on 2-rem-per-year administrative dose limit. If a lower dose limit, for example 500 millirem per year, was imposed for transportation workers or state inspectors, maximally exposed individual doses would be lower. See DIRS 156764-DOE (1999, Article 211) for DOE guidance on occupational dose limits.

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Estimated radiological impacts of maximum reasonably foreseeable accident scenario for national mostly legal-weight truck scenario.

Impact	Urbanized area (stable atmospheric conditions)
Accident scenario probability (annual)	0.00000023 per year (about 2.3 in 10 million)
Impacts to populations	
Population dose (person-rem)	1,100
Latent cancer fatalities	0.55
Impacts to maximally exposed individuals	
Maximally exposed individual dose (rem)	3
Probability of a latent cancer fatality	0.0015
Impacts to first responder	
Maximally exposed responder dose (rem)	0.26
Probability of latent cancer fatality	0.0000013

Estimated impacts from maximum reasonably foreseeable accident scenario for national mostly rail transportation scenario.

Impact	Urbanized area (stable atmospheric conditions)
Accident probability	0.00000028 per year (about 2.8 in 10 million)
Impacts to populations	
Population dose (person-rem)	9,900
Latent cancer fatalities	5
Impacts to maximally exposed individuals	
Maximally exposed individual dose (rem)	29
Probability of a latent cancer fatality	0.01
Impacts to first responder	
Maximally exposed responder dose (rem)	0.83
Probability of latent cancer fatality	0.0004

National transportation impacts for the transportation of spent nuclear fuel and high-level radioactive waste for the mostly rail and mostly legal-weight truck scenarios.[a,b]

Group	Impact	Mostly legal-weight truck scenario	Mostly rail scenario
Worker	*Incident-free health impacts, radiological*		
	Maximally exposed individual (rem)	48[c]	48[c]
	Individual latent cancer fatality probability	0.02	0.02
	Collective dose (person-rem)	29,000	7,900 - 8,800
	Latent cancer fatality incidence	11.7	3.2 - 3.5[d]
	Industrial safety (fatalities)	0.9	0.29
Public	*Incident-free health impacts, radiological*		
	Average exposed individual (rem)	0.0005	0.0001
	Maximally exposed individual (rem)	2.4[e]	0.29
	Individual latent cancer fatality probability	0.0012	0.00014
	Collective dose (person-rem)	5,000	1,200 - 1,600
	Latent cancer fatality incidence	2.5	0.61 - 0.81
	Incident-free vehicle emissions impacts (fatalities)	0.95	0.55 - 0.77
	Radiological impacts from maximum reasonably foreseeable accident scenario		
	Frequency (per year)	2.3 in 10,000,000	2.8 in 10,000,000
	Maximally exposed individual (rem)	3	29
	Individual latent cancer fatality probability	0.0015	0.015
	Collective dose (person-rem)	1,100	9,900
	Latent cancer fatality incidence	0.55	5
	Accident dose risk (person-rem)	0.46	0.89
	Accident risk (latent cancer fatalities)	0.00023	0.00045
Public and transportation workers	*Fatalities from vehicular accidents*	4.9	2.3 - 3.1

a. The assumed external dose rate is 10 millirem per hour at 2 meters (6.6 feet) from the vehicle for all shipments.
b. Totals for 24 years of operation, including impacts of loading.
c. Based on 2-rem-per-year dose limit.
d. Range for the 10 rail and heavy-haul truck implementing alternatives in Nevada.
e. Based on 100-millirem-per-year dose limit.