4 METEOROLOGICAL PARAMETER DISTRIBUTIONS

4.1 Precipitation Rate

Applicable Code: RESRAD

Description: The precipitation rate is defined as the average volume of water in the form of rain, snow, hail, or sleet that falls per unit of area and per unit of time at the site.

Units: meters per year (m/yr)

Probabilistic Input:

Distribution: none recommended.

Discussion: The precipitation rate, P_r, is used in the RESRAD code along with other input parameters, such as runoff coefficient, irrigation rate, and evapotranspiration coefficient, to determine the deep water percolation rate according to mass balance. The deep water percolation rate is ultimately used to calculate the radionuclide leaching rate of the contaminated zone and the subsequent contamination of the underlying groundwater system.

For a given site, the precipitation rate varies with time because the annual precipitation changes from year to year. Spatial variation within a site will be insignificant unless the area of the site is very large. Table 4.1-1 gives the annual average precipitation (in inches) for the major observing stations in all 50 states, Puerto Rico, and Pacific Islands (http:www4.ncdc.noaa.gov). The annual average precipitation is the sum of the arithmetic means for each month over the 30-year period and includes the liquid water equivalent of snowfall. The average annual precipitation for the major cities in the 48 conterminous U.S. states listed in Table 4.1-1 is 34.12 in./yr (0.867 m/yr).

A national average precipitation rate distribution is not recommended because of the large variations in precipitation that occur across the United States. Even state precipitation rate distributions may not properly represent all relevant locations because of differences in climate caused by local topography. A deterministic value for a nearby location from Table 4.1-1 may be used as a starting point for risk analysis, but the precipitation rate is a site-specific parameter that should be characterized at a contaminated site before the appropriate remedial action(s) can be selected.

Table 4.1-1 Precipitation Data for 273 U.S. Weather Recording Stations (average inches per year for the period 1961-1990)

Station	Annual Average Precipitation (Inches)	Station	Annual Average Precipitation (Inches)	Station	Annual Average Precipitation (Inches)
Birmingham AP, AL	54.58	Jacksonville, FL	51.32	Muskegon, MI	32.56
Huntsville, AL	57.18	Key West, FL	39.59	Sault Ste. Marie, MI	34.23
Mobile, AL	63.96	Miami, FL	55.91	Duluth, MN	30
Montgomery, AL	53.43	Orlando, FL	48.11	International Falls, MN	24.36
Anchorage, AK	15.91	Pensacola, FL	62.25	Minneapolis-St. Paul, MN	28.32
Annette, AK	103.28	Tallahassee, FL	65.71	Rochester, MN	29.66
Barrow, AK	4.49	Tampa, FL	43.92	Saint Cloud, MN	27.43
Bethel, AK	14.99	Vero Beach, FL	51.16	Jackson, MS	55.37
Bettles, AK	13.74	West Palm Beach, FL	60.75	Meridian, MS	56.71
Big Delta, AK	11.96	Athens, GA	49.74	Tupelo, MS	55.87
Cold Bay, AK	36	Atlanta, GA	50.77	Columbia, MO	39.05
Fairbanks, AK	10.87	Augusta, GA	44.66	Kansas City, MO	37.62
Gulkana, AK	10.87	Columbus, GA	51	St. Louis, MO	37.51
Homer, AK	25.39	Macon, GA	44.63	Springfield, MO	43.04
Juneau, AK	54.31	Savannah, GA	49.22	Billings, MT	15.08
King Salmon, AK	19.82	Hilo, HI	129.19	Glasgow, MT	10.96
Kodiak, AK	67.58	Honolulu, HI	22.02	Great Falls, MT	15.21
Kotzebue, AK	8.98	Kahului, HI	20.92	Helena, MT	11.6
Mcgrath, AK	15.96	Lihue, HI	43	Kalispell, MT	16.51
Nome, AK	14.88	Boise, ID	12.11	Missoula, MT	13.46
St. Paul Island, AK	23.32	Lewiston, ID	12.43	Grand Island, NE	24.9
Talkeetna, AK	29.21	Pocatello, ID	12.14	Lincoln, NE	28.26
Unalakleet, AK	15.59	Chicago, IL	35.82	Norfolk, NE	25.15
Valdez, AK	64.04	Moline, IL	39.08	North Platte, NE	19.3
Yakutat, AK	151.25	Peoria, IL	36.25	Omaha Eppley AP, NE	29.86
Flagstaff, AZ	22.8	Rockford, IL	36.28	Omaha (North), NE	29.39
Phoenix, AZ	7.66	Springfield, IL	35.25	Scottsbluff, NE	15.27
Tucson, AZ	12	Evansville, IN	43.14	Valentine, NE	18.23
Winslow, AZ	8.04	Fort Wayne, IN	34.75	Elko, NV	9.93
Yuma, AZ	3.17	Indianapolis, IN	39.94	Ely, NV	10.13
Fort Smith, AR	40.9	South Bend, IN	39.14	Las Vegas, NV	4.13
Little Rock, AR	50.86	Des Moines, IA	33.12	Reno, NV	7.53
North Little Rock, AR	49.25	Dubuque, IA	38.36	Winnemucca, NV	8.23
Bakersfield, CA	5.72	Sioux City, IA	25.86	Concord, NH	36.37
Bishop, CA	5.37	Waterloo, IA	33.7	Mt. Washington, NH	98.96
Eureka, CA	37.53	Concordia, KS	28.78	Atlantic City AP, NJ	40.29
Fresno, CA	10.6	Dodge City, KS	21.49	Atlantic City C.O., NJ	37.1
Long Beach, CA	11.8	Goodland, KS	18.2	Newark, NJ	43.97
Los Angeles AP, CA	12.01	Topeka, KS	35.23	Albuquerque, NM	8.88
Los Angeles C.O., CA	14.77	Wichita, KS	29.33	Clayton, NM	15.09
Redding, CA	33.3	Greater Cincinnati AP	41.33	Roswell, NM	12.58
Sacramento, CA	17.52	Jackson, KY	49.67	Albany, NY	36.17
San Diego, CA	9.9	Lexington, KY	44.55	Binghamton, NY	36.99
San Francisco AP, CA	19.7	Louisville, KY	44.39	Buffalo, NY	38.58
San Francisco C.O., CA	19.71	Paducah KY	49.31	Islip, NY	46.07
Santa Barbara, CA	16.25	Baton Rouge, LA	60.89	New York C.park, NY	47.25
Santa Maria, CA	12.36	Lake Charles, LA	54.84	New York (JFK AP), NY	41.59
Stockton, CA	13.95	New Orleans, LA	61.88	New York (Laguardia AP), NY	42.12
Alamosa, CO	7.57	Shreveport, LA	46.11	Rochester, NY	31.96
Colorado Springs, CO	16.24	Caribou, ME	36.6	Syracuse, NY	38.93
Denver, CO	15.4	Portland, ME	44.34	Asheville, NC	47.59
Grand Junction, CO	8.64	Baltimore, MD	40.76	Cape Hatteras, NC	56.09
Pueblo, CO	11.19	Blue Hill, MA	48.95	Charlotte, NC	43.09
Bridgeport, CT	41.66	Boston, MA	41.51	Greensboro-Wnstn-Salm-Hghpt, NC	42.62
Hartford, CT	44.14	Worcester, MA	47.75	Raleigh, NC	41.43
Wilmington, DE	40.84	Alpena, MI	28.83	Wilmington, NC	54.27
Washington Dulles AP, D.C.	40.24	Detroit, MI	32.62	Bismarck, ND	15.47
Washington Nat'l AP, D.C.	38.63	Flint, MI	30.28	Fargo, ND	19.45
Apalachicola, FL	54.95	Grand Rapids, MI	36.04	Williston, ND	13.67
Daytona Beach, FL	47.89	Houghton Lake, MI	28.25	Akron, OH	36.82
Fort Myers, FL	53.37	Lansing, MI	30.62	Cleveland, OH	36.63
Gainesville, FL	51.81	Marquette, MI	35.3	Columbus, OH	38.09
Dayton, OH	36.64	Providence, RI	45.53	Victoria, TX	37.41
Mansfield, OH	39.66	Charleston AP, SC	51.53	Waco, TX	31.96
Toledo, OH	32.97	Charleston C.O.,SC	48.52	Wichita Falls, TX	28.9
Youngstown, OH	37.32	Columbia, SC	49.91	Salt Lake City, UT	16.18
Oklahoma City, OK	33.36	Greenville-Spartanburg AP, SC	51.27	Burlington, VT	34.47
Tulsa, OK	40.59	Aberdeen, SD	18.55	Lynchburg, VA	40.88

Table 4.1-2 (Cont.)

Station	Annual Average Precipitation (Inches)	Station	Annual Average Precipitation (Inches)	Station	Annual Average Precipitation (Inches)
Astoria, OR	66.4	Huron, SD	20.08	Norfolk, VA	44.64
Burns, OR	9.96	Rapid City, SD	16.64	Richmond, VA	43.16
Eugene, OR	49.37	Sioux Falls, SD	23.86	Roanoke, VA	41.13
Medford, OR	18.86	Bristol-Jhnsn Cty-Kngsprt, TN	40.72	Wallops Island, VA	39.93
Pendleton, OR	12.02	Chattanooga, TN	53.46	Olympia, WA	50.59
Portland, OR	36.3	Knoxville, TN	47.14	Quillayute, WA	105.18
Salem, OR	39.16	Memphis, TN	52.1	Seattle C.o., WA	38
Guam, PC	103.04	Nashville, TN	47.3	Seattle Sea-Tac AP, WA	37.19
Koror, PC	147.97	Oak Ridge, TN	53.77	Spokane, WA	16.49
Kwajalein, Marshall IS.	102.09	Abilene, TX	24.4	Yakima, WA	7.97
Majuro, Marshall IS, PC	131.34	Amarillo, TX	19.56	San Juan, PR	52.34
Pago Pago, Amer Samoa, PC	121.8	Austin, TX	31.88	Beckley, WV	41.03
Pohnpei, Caroline Is., PC	187.76	Brownsville, TX	26.61	Charleston, WV	42.53
Chuuk, E. Caroline Is., P	138.78	Corpus Christi, TX	30.13	Elkins, WV	44.84
Wake Island, PC	35.68	Dallas-Fort Worth, TX	33.7	Huntington, WV	41.49
Yap, W Caroline IS., PC	120.06	Del Rio, TX	18.24	Green Bay, WI	28.83
Allentown, PA	43.52	El Paso, TX	8.81	La Crosse, WI	30.55
Erie, PA	41.53	Houston, TX	46.07	Madison, WI	30.88
Middletown/Harrisburg Int	40.5	Lubbock, TX	18.65	Milwaukee, WI	32.93
Philadelphia, PA	41.41	Midland-Odessa, TX	14.96	Casper, WY	12.52
Pittsburgh, PA	36.85	Port Arthur, TX	57.18	Cheyenne, WY	14.4
Avoca, PA	36.18	San Angelo, TX	20.45	Lander, WY	13.01
Williamsport, PA	40.72	San Antonio, TX	30.98	Sheridan, WY	14.48

a   To convert from inches to meters, multiply by 0.0254.

Source: Wood (1995); National Oceanic and Atmospheric Administration (1999).

4.2 Runoff Coefficient

Applicable Code: RESRAD

Description: The average annual runoff coefficient is the fraction of the average annual precipitation that does not infiltrate into the soil and is not transferred back to the atmosphere through evapotranspiration. The runoff coefficient represents the fraction of the precipitation, in excess of the deep percolation and evapotranspiration, that becomes surface flow and ends up in either perennial or intermittent surface water bodies.

Units: unitless

Probabilistic Input:

Distribution: uniform

Defining Values for Distribution:

Minimum: 0.1   Maximum: 0.8

Discussion: The runoff coefficient (C_r) is one of the input parameters used in the RESRAD code to determine the deep water percolation rate according to mass balance. The water deep percolation rate is ultimately used to calculate the radionuclide leaching rate of the contaminated zone and the subsequent contamination of the underlying groundwater system.

The runoff rate at any specific location is influenced by the morphology of the region, the degree of the slopes, the type of soil material, and the type of soil utilization. The runoff coefficient varies with the frequency, the duration, and the magnitude of precipitation events. If the precipitation rate exceeds the hydraulic conductivity of the cover or contaminated zone, the excess will be removed by runoff, and the runoff coefficient will be increased. Thus, in addition to the factors considered in Table 4.2-1, the average annual precipitation rate, the land coverage of urban environment, and the hydraulic conductivity of the unsaturated stratum exert an influence on the runoff coefficient.

Runoff curve numbers (CNs) can be used to estimate the runoff coefficient for a particular site. The Soil Conservation Service (SCS) runoff curve number indicates runoff potential for a particular area on the basis of land use and hydrologic soil groups. In the past, SCS runoff curve numbers were produced by manually relating land uses and hydrologic soil types within particular areas and performing calculations. Now, by using the ARC/INFO UNION command, engineers can compute the SCS runoff curve number for

Table 4.2-1 Runoff Coefficient Values

Type of Area	Coefficient	Value
Agricultural environment[a]		
Flat land with average slopes of 0.3-0.9 m/mi	c_1	0.3
Rolling land with average slopes of 4.6-6.1 m/mi	c_1	0.2
Hilly land with average slopes of 46-76 m/mi	c_1	0.1
Open sandy loam	c_2	0.4
Intermediate combinations of clay and loam	c_2	0.2
Tight, impervious clay	c_2	0.1
Woodlands	c_3	0.2
Cultivated lands	c_3	0.1
Urban environment		
Flat, residential area C about 30% impervious	C_r	0.4
Moderately steep, residential area C about 50% impervious	C_r	0.65
Moderately steep, built-up area C about 70% impervious	C_r	0.8

[a] The runoff coefficient for an agricultural environment is given by $C_r = 1 - c_1 - c_2 - c_3$.

Source: Gilbert et al. (1989).

the entire subbasin based on the land use and hydrologic soil type (Robbins and Phipps, 1996).

The following equation gives the SCS relationship for estimating Q (depth of runoff) from P (rainfall) and S (Maidment, 1992).

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S},$$ (4.2-1)

where:

S = (1000/CN) - 10 and

CN = runoff curve number.

The value of CN depends on the soil, cover, and hydrologic condition of the land surface. These conditions are described by Maidment (1992). The value of CN also depends on the antecedent moisture condition, which represents the degree of saturation of the soil prior to a rainfall event. Table 4.2-2 provides the SCS runoff curve numbers for average antecedent moisture conditions. These values need to be modified for very dry

Table 4.2-2 SCS Runoff Curve Numbers for Average Antecedent Moisture Condition

Land Use or Cover	Hydrologic Condition[a]	Runoff Curve No. by Hydrologic Soil Group			
		A	B	C	D
Fallow		77	86	91	94
Pasture or range	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Contoured pasture or range	Poor	47	67	81	88
	Fair	25	59	75	83
	Good	6	35	70	79
Meadow		30	58	71	78
Woods	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	25	55	70	77
Brush-brushwood grass mixture with brush the major element	Poor	48	67	77	88
	Fair	35	56	70	77
	Good	30	48	65	73
Woods-grass combination (orchard or tree farm)	Poor	57	70	82	86
	Fair	48	65	76	82
	Good	32	58	72	79
Roads (dirt)		72	82	87	89
Roads (hard surface)		74	84	90	92

[a] Poor = less than 50% ground cover, fair = 50-75% ground cover, good = greater than 75% ground cover.

Source: Meyer et al. (1997).

and very wet conditions (Meyer et al., 1997). Standard values of CN for various land uses and soil types are given by Maidment (1992).

According to the SCS, if the soil has been disturbed but no significant compaction has occurred, the hydrologic soil group can be assigned based on soil texture as follows:

- Group A: Sand, loamy sand, or sandy loam,

- Group B: Silt loam or loam,

- Group C: Silt, Sandy clay loam, and

- Group D: Clay loam, silty clay loam, sandy clay, silty clay, or clay.

A uniform distribution has been assigned as input to RESRAD for the runoff coefficient with minimum and maximum values of 0.1 and 0.8, respectively, as suggested by the data in Table 4.2-1. These input data should be changed to reflect local site conditions when performing site-specific analyses. Figure 4.2-1 displays the probability density function for the runoff coefficient.
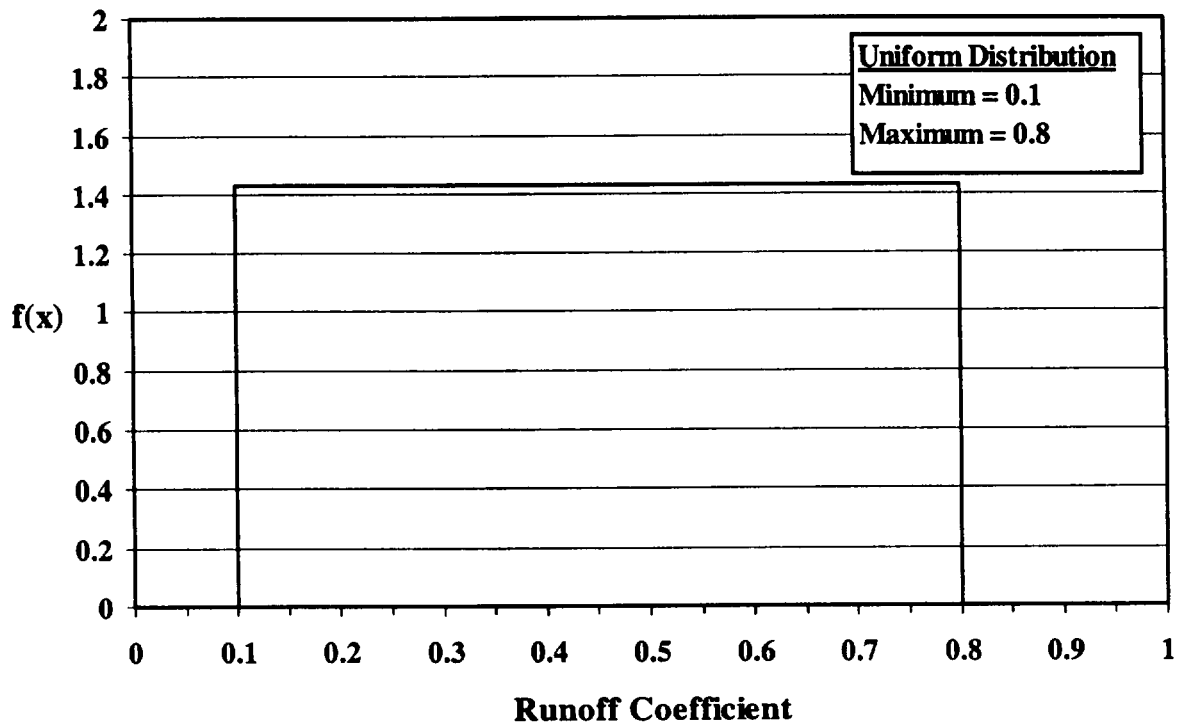
Figure 4.2-1 Runoff Coefficient Probability Density Function

4.3 Evapotranspiration Coefficient

Applicable Code: RESRAD

Description: The evapotranspiration coefficient is the ratio of the total volume of water vapor that is transferred to the atmosphere through evapotranspiration to the total volume of water available within the root zone of the soil.

Units: unitless

Probabilistic Input:

Distribution: uniform

Defining Values for the Distribution:

Minimum: 0.5   Maximum: 0.75

Discussion: The evapotranspiration coefficient, C_e, can be expressed as:

$$C_e = \frac{ET_r}{(1 - C_r)P_r + IR_r},$$ (4.3-1)

where

ET_r = the evapotranspiration rate (m/yr),

P_r = the precipitation rate (m/yr),

IR_r = the irrigation rate (m/yr), and

C_r = the runoff coefficient.

This parameter and certain other input parameters, such as precipitation, irrigation rate, and the runoff coefficient, are used in RESRAD to determine the water deep percolation rate according to mass balance. The deep water percolation rate is ultimately used to calculate the radionuclide leaching rate of the contaminated zone and the subsequent contamination of the underlying groundwater system.

Evapotranspiration is the combination of evaporation from the soil surface and transpiration from vegetation. Evaporation is defined as the process by which water is changed into vapors from liquid or solid state through heat energy and carried into the

atmosphere. The rate of evaporation depends on solar radiation, temperature, vapor pressure, humidity of air, and wind. Because of variation in climatic conditions, evaporation rates vary from one location to another. The basins in arid parts of Nevada and southeastern California have virtually zero runoff because most precipitation that falls is evaporated almost immediately.

Water used for transpiration enters the roots of plants from the surrounding soil water and moves upward through the plant tissues and into the surrounding air. The evapotranspiration coefficient depends on the method, frequency, and rate of irrigation; the texture and condition of the soil; the plant species; the age of the plant; and the climate of the region. Palmer (1993) gives a range of 0.6 to 0.75 for irrigation efficiency. The farm-irrigation efficiency is the percentage of water delivered that is utilized in crop evapotranspiration, which is equivalent to evapotranspiration for an irrigated site. The efficiency is influenced by the size of the farm because of the effect of conveyance losses between the point of delivery to the farm and the several fields. A range of 0.5 to 0.75 is suggested because a small family farm may not be well managed. Under certain conditions, a value of 0.5 is more likely if water-dependent pathways dominate. That value is consistent with a poorly managed irrigation system and leads to a higher leaching rate and a higher concentration of contaminants in the well water as a result of a lower dilution. A value of 0.75 is more likely if water-independent pathways dominate. Figure 4.3-1 displays the probability function used in RESRAD for the evapotranspiration coefficient.
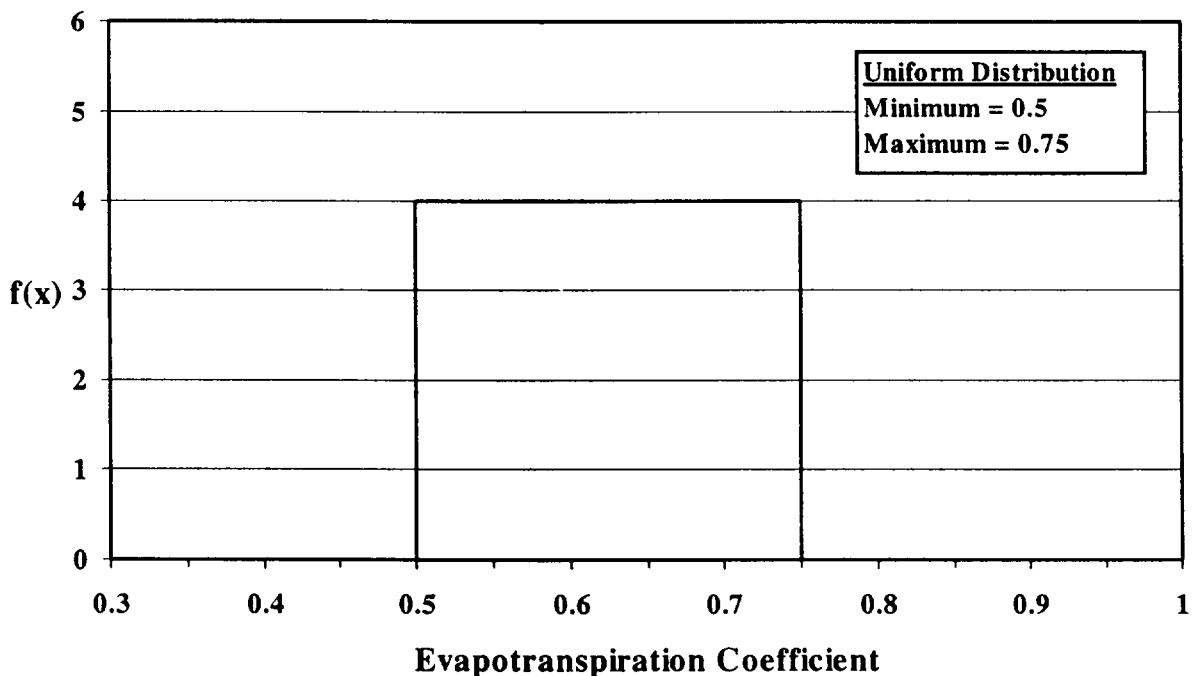

Figure 4.3-1 Evapotranspiration Coefficient Probability Density Function

4.4 Humidity

Applicable Code: RESRAD, RESRAD-BUILD

Description: In RESRAD, this parameter represents the average absolute humidity outdoors. The absolute humidity is an input used only for the computation of tritium concentration in air if tritium is present in the soil. In RESRAD-BUILD, this parameter represents the average absolute humidity in the building. The absolute humidity is an input used only for the tritium volume source model.

Units: grams per cubic meter (g/m^3)

Probabilistic Input:

RESRAD
Distribution: truncated lognormal-n

Defining values for distribution:

Underlying mean value: 1.98   Lower quantile value: 0.001
Underlying standard deviation: 0.334   Upper quantile value: 0.999

RESRAD-BUILD
Distribution: uniform

Defining values for distribution:

Minimum: 6.5   Maximum: 13.1

Discussion: RESRAD and RESRAD-BUILD require input for the absolute humidity, the actual concentration of water vapor in air. The relevant data available are given in terms of the relative humidity. The relative humidity of a water vapor-air mixture is defined as 100 times the partial pressure of water divided by the saturation vapor pressure of water at the same temperature. For this section, relative humidity was converted to absolute humidity by assuming a total pressure of 1 atmosphere in conjunction with a given temperature and partial pressure of water at that temperature. Tabulated values for the partial pressure of water over a range of temperatures were obtained from Dean (1999).

For RESRAD-BUILD, the average humidity in a building depends on the functioning of heating, ventilation, and air conditioning (HVAC) systems of the building. At normal room temperatures, the relative humidity (RH) in occupied buildings should be

maintained between approximately 30% and 60% to help maintain human health and comfort (Sterling et al., 1985). With respect to health, this range in RH minimizes allergic reactions and bacterial and viral growth. Human discomfort is noted at low and high humidities. Discomfort at low RH results from the drying of skin, hair, and respiratory membranes.

Because HVAC systems are designed to maintain a healthy environment for building occupants (the 30% to 60% RH range), a uniform distribution for the corresponding absolute humidity range is used in RESRAD-BUILD. The range of 30% to 60% relative humidity corresponds to an absolute humidity range of 6.5 to 13.1 g of water per cubic meter at 1 atmosphere pressure and 24°C (75°F). The probability density function is shown in Figure 4.4-1. However, RH values lower than 30% may occur in buildings that do not have a humidification system, especially during the winter in colder climates. Also, RH values higher than 60% may occur in buildings using natural ventilation in more temperate climates. In more temperate climates where natural ventilation may be employed, the humidity inside the building will be more representative of the outside levels.

For RESRAD, data from 231 weather stations across the conterminous 48 U.S. states, most with data for more than 30 years of record, were analyzed to obtain a perspective on ambient outdoor humidity levels. Annual average morning and afternoon RH levels were used in conjunction with annual average temperature readings at these weather stations (National Climatic Data Center [NCDC] 1999) to estimate absolute humidity levels. The morning and afternoon RH levels were averaged for each station to obtain one value for the annual average relative humidity for use in estimating the absolute humidity.

The resulting absolute humidity probability density function was fit reasonably well to a lognormal distribution by using Bayesian estimation, as shown in Figure 4.4-2. This distribution is only indicative of what might be expected, because the sampling is not representative of a uniform grid across the United States, although it is indicative of the larger population centers. Site-specific data should be used when available.
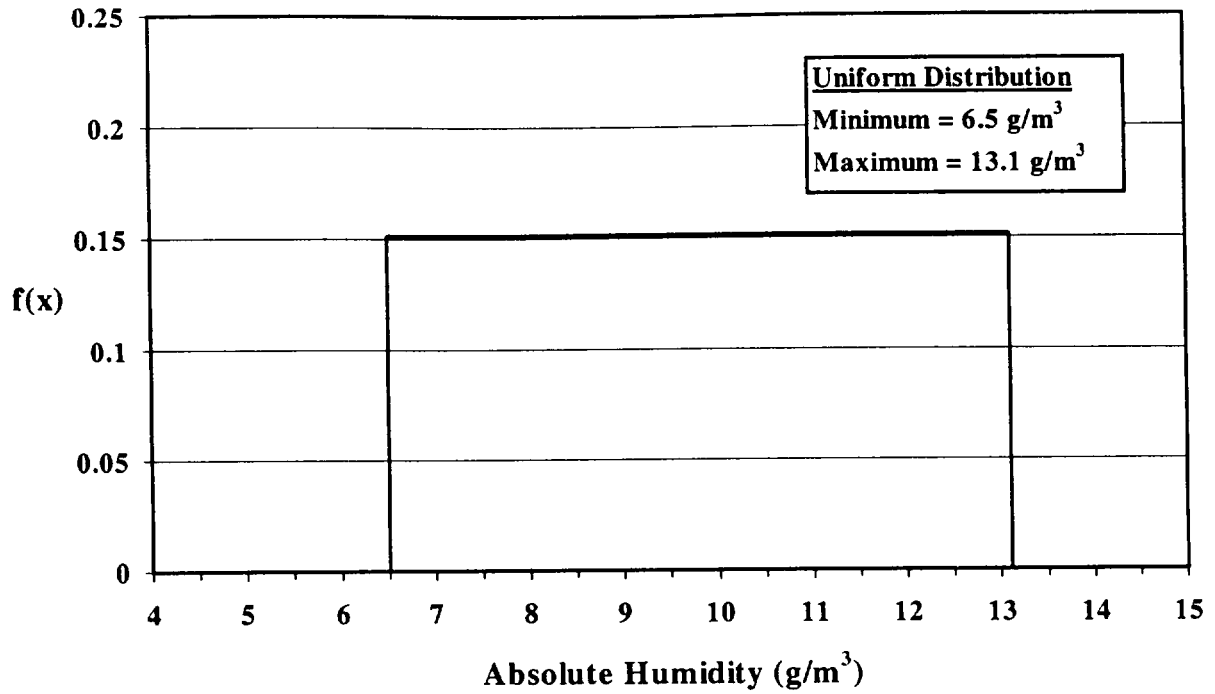
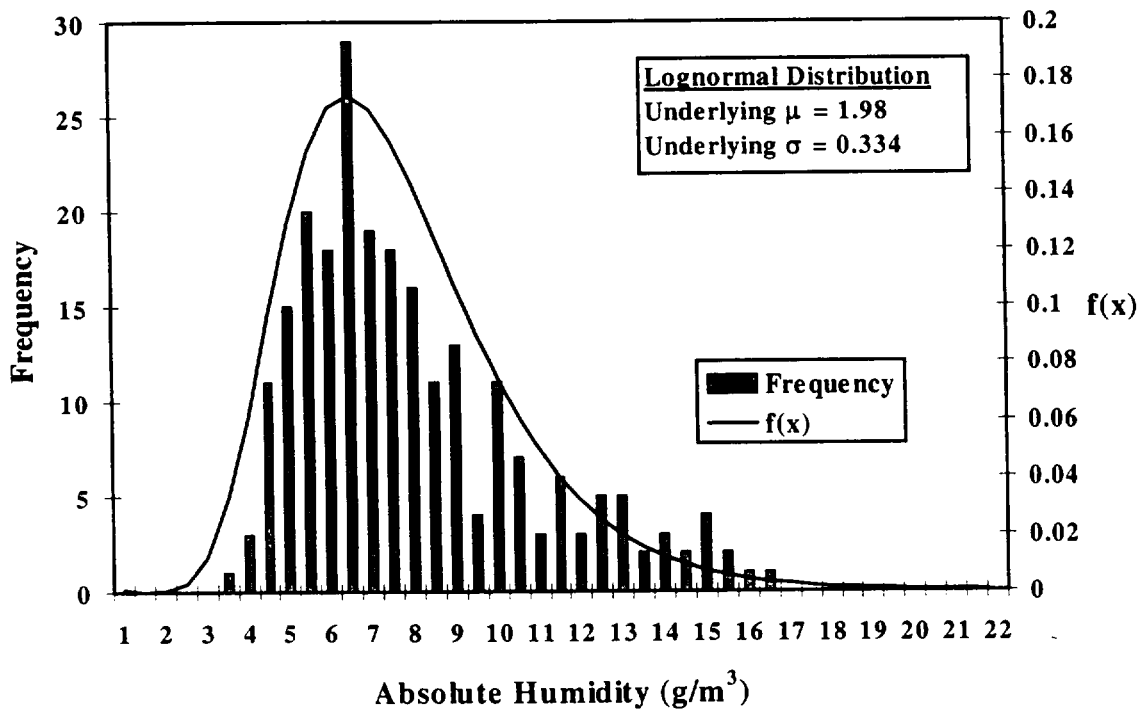**Figure 4.4-1 Absolute Humidity Probability Density Function for RESRAD-BUILD**

Figure 4.4-2 Absolute Humidity Probability Density Function for RESRAD

4.5 Wind Speed

Applicable Code: RESRAD

Description: The wind speed represents the annual average wind speed at a site.

Units: meters per second (m/s)

**Probabilistic Input:**

Distribution: bounded lognormal-n

Defining Values for Distribution:

Underlying mean value :	1.445	Lower limit:	1.4
Underlying standard deviation:	0.2419	Upper limit:	13

Discussion: The wind speed at a given location varies by time of day and by season. Wind speed distribution at a given site has been characterized by both lognormal (Luna and Church, 1974; Justus et al., 1976) and Weibull distributions (Justus et al., 1976). Annual average wind speed varies by location across the United States. To obtain a reasonable estimate for a nationwide distribution for the United States, annual average wind speed data from 271 U.S. weather stations were analyzed (NCDC, 1999). The average number of years of recorded data available for each station was 43 years.

The nationwide distribution was shown to be fit well by a lognormal distribution. Bayesian estimation was used to fit the probability density function shown in Figure 4.5-1 to a lognormal distribution. The maximum likelihood mean and standard deviation for the wind speed distribution were estimated to be 1.445 and 0.2419, respectively. Thus, the median (50th percentile) of the distribution corresponds to 4.2 m/s ($e^{1.445}$), near the national average wind speed of 4.1 m/s as determined by taking the arithmetic average of the 271 station annual averages. Lower and upper limits of 1.4 and 13 m/s imposed on the distribution correspond to the 0.000001 and 0.999999 quantiles, respectively.

This distribution is only indicative of what might be expected, because the sampling is only of limited size (271 data points) and is not representative of a uniform grid across the United States. Also, monitor sites are not always representative of all nearby areas because of differences in terrain over relatively short distances.
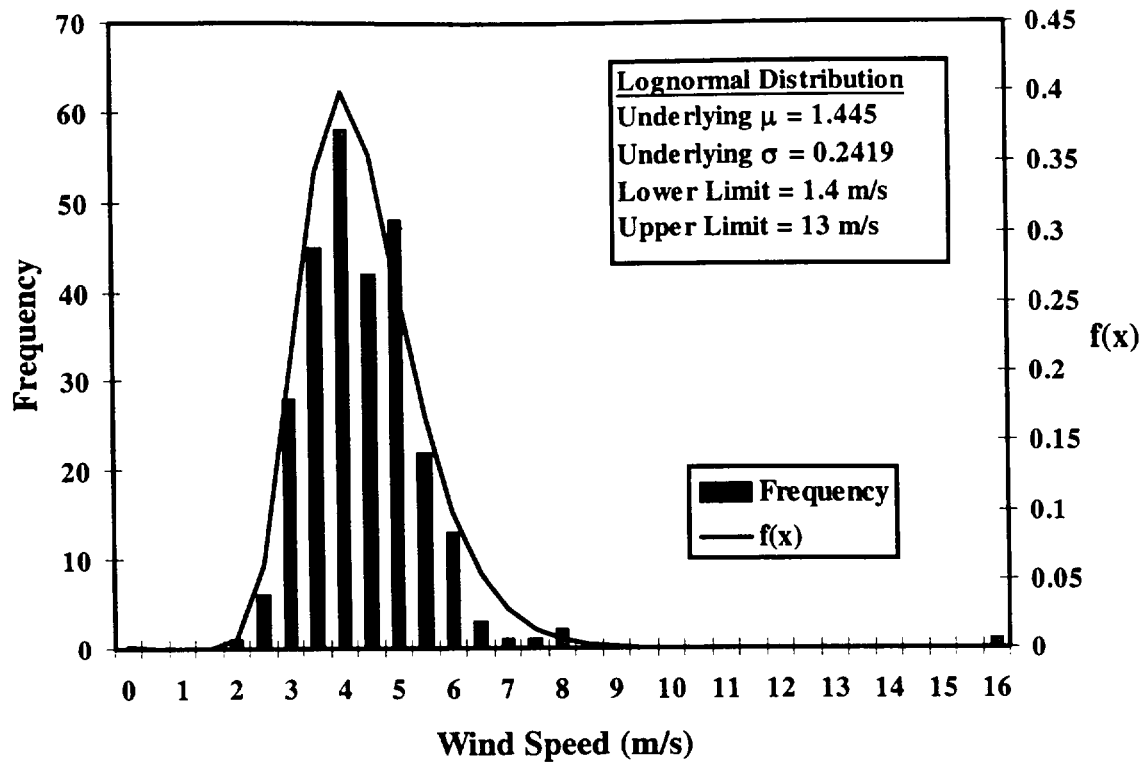
Figure 4.5-1 Wind Speed Histogram and the Fitted Probability
Density Function

4.6 Mass Loading for Inhalation

Applicable Code: RESRAD

Description: This parameter represents the concentration of contaminated airborne particulate matter (e.g., soil) that is respirable.

Units: micrograms per cubic meter ($\mu g/m^3$)

Probabilistic Input:

Distribution: user-defined continuous with linear interpolation

Defining Values for Distribution: See Table 4.6-1 for the input values.

Discussion: Resuspended contaminated soil and dust pose a radiological inhalation risk. The mass loading input to RESRAD provides the time-averaged respirable concentration of contaminated soil and dust. The respirable portion of resuspended material can be represented by the PM-10 fraction of airborne particulate matter (particulates $\leq 10\ \mu m$ in diameter). The PM-10 fraction represents particles that are capable of being deposited in thoracic (tracheobronchial and alveolar) portions of the lower respiratory tract (EPA, 1999c). Ambient PM-10 air concentrations were obtained from the EPA's Aerometric Information Retrieval System (AIRS) (EPA, 1999d).

Five years (1994-1998) of annual average ambient PM-10 air concentration measurements and the average for 1999 through November 27 for approximately 1,790 air monitoring stations across the United States and its territories were analyzed. The data are only indicative of what might be expected because the set of monitoring stations included is not representative of a uniform grid across the United States. Furthermore, the monitor sites are not always representative of all nearby areas because of differences in local weather patterns. Figure 4.6-1 presents a histogram of the data in conjunction with the cumulative distribution function (CDF) for the PM-10 data. Table 4.6-1 lists the values used for the CDF.

The RESRAD code uses the mass loading factor to estimate the annual inhalation dose. Therefore, use of a high, short-term loading will result in an overestimate of the annual dose. A time average mass loading factor should be used in RESRAD for a more realistic dose estimate.

Table 4.6-1 Cumulative Distribution Function for Mass Loading for Inhalation

Mass Loading (μg/m^3)	Cumulative Probability	Mass Loading (μg/m^3)	Cumulative Probability	Mass Loading (μg/m^3)	Cumulative Probability
0	0	36	0.9151	72	0.9974
2	0.0001	38	0.9349	74	0.9977
4	0.0015	40	0.9495	76	0.9983
6	0.0040	42	0.9592	78	0.9984
8	0.0151	44	0.9675	80	0.9984
10	0.0315	46	0.9736	82	0.9985
12	0.0558	48	0.9799	84	0.9986
14	0.0904	50	0.9844	86	0.9986
16	0.1365	52	0.9882	88	0.9988
18	0.2061	54	0.9905	90	0.9988
20	0.3020	56	0.9919	92	0.9990
22	0.4213	58	0.9928	94	0.9990
24	0.5433	60	0.9937	96	0.9990
26	0.6542	62	0.9948	98	0.9991
28	0.7448	64	0.9957	100	0.9992
30	0.8119	66	0.9962	>100	1.0000
32	0.8579	68	0.9965		
34	0.8897	70	0.9970		
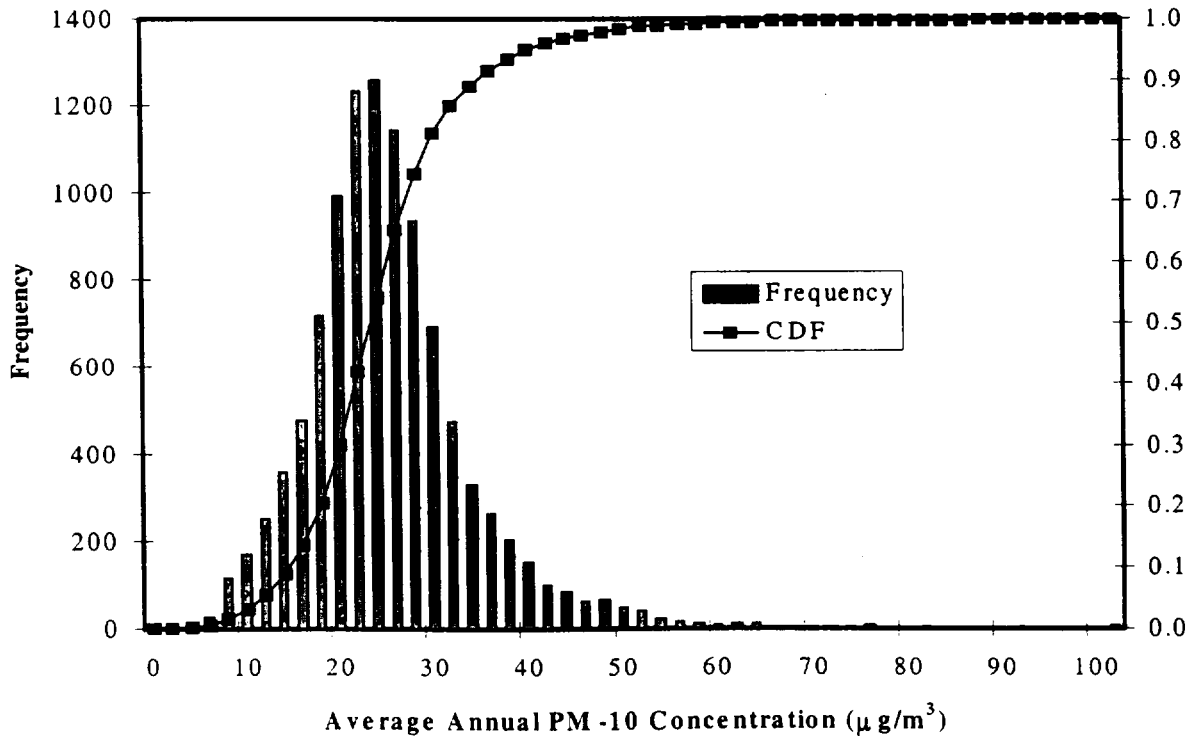
Figure 4.6-1 Mass Loading Histogram and Cumulative Distribution Function

5 HUMAN INTAKE PARAMETER DISTRIBUTIONS

5.1 Inhalation Rate

Applicable Code: RESRAD, RESRAD-BUILD

Description: This parameter reflects the rate at which a human receptor inhales air contaminated with resuspended airborne material.

Units: cubic meters per year (m^3/yr) (RESRAD)
cubic meters per day (m^3/d) (RESRAD-BUILD)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

RESRAD
Minimum: 4,380   Maximum: 13,100   Most likely: 8,400

RESRAD-BUILD
Minimum: 12   Maximum: 46   Most likely: 33.6

Discussion: The range of estimates of inhalation rate (Table 5.1-1) reflects the differences in patterns of time and activity levels, as well as age, sex, and weight of the individual. Until recently, inhalation rates for the "reference man and woman," as described by the International Commission on Radiological Protection (ICRP, 1975), were often used as default values. The ICRP best estimates, which are based on 16 hours of light activity and 8 hours of rest, are as follows: 23 m^3/d (range of 23-31 m^3/d) for adult males; 21 m^3/d (range of 18-21 m^3/d) for adult females; and 15 m^3/d for a 10-year-old child. By using different patterns for the time and activity levels, the EPA has proposed a wider range of adult inhalation rates but recommends essentially the same point estimates as the ICRP for "average" adults (EPA, 1985, 1989a, 1991, 1997).

The distribution varies widely because of differences in time-use activity patterns that are developed for outdoor/indoor and occupational/residential exposures. Because activity levels of various individuals and groups can vary to such a significant extent, it is preferable to derive a range of inhalation rates by using activity data specific for the population under study. In the RESRAD code, the yearly inhalation rate is used, which represents the average values for different activity levels both indoors and outdoors for the

Table 5.1-1 Inhalation Rate Distributions

Basis	Distribution Type	Inhalation Rate (m³/d)				References
		Min.	Max.	Mean	Most Likely	
Based on time-weighted average food-energy intakes adjusted for reporting bias	Triangular					Layton, 1993
Males (lifetime average)		13	17		14	
Females (lifetime average)		9.6	13		10	
Based on average age-adjusted daily energy expenditure rates	Triangular					Layton, 1993
Males (18-60+ yr)		13	17		15	
Females (18-60+ yr)		9.9	11		11	
Based on age-adjusted activity patterns and metabolic rates for an "average" day	Triangular					Layton, 1993
Males (20-74 yr)		13	17		16	
Females (20-74 yr)		11	15		13	
"Reference man" - Based on light activity (16 hours) and resting (8 hours)	Triangular					ICRP, 1975
Adult male		23	31		23	
Adult female		18	21		21	
Child		-	-		15	
Based on "typical" outdoor activity levels[a]	Triangular					EPA,1985, 1989a, 1991
Adult female		17	70	25	20	
Adult male		13	79	40	20	
Average adult		-	-	34	20	
Based on "typical" indoor activity levels[b]	Triangular					EPA, 1985, 1989a, 1991
Adult female		7	34	11	15	
Adult male		4	38	21	15	
Average adult		-	-	15	15	
Study of age-dependent breathing rates at realistic activity levels						Roy and Courtay, 1991
0-0.5 yr					1.62	
0.5-2 yr					5.14	
2-7 yr					8.71	
7-12 yr					15.3	
12-17 yr					17.7	

[a] Resting: 28%, light activity: 28%, moderate activity: 37%, heavy activity: 7%.

[b] Resting: 48%, light activity: 48%, moderate activity: 3%, heavy activity: 1%.

residential scenario. The hourly average inhalation rate in RESRAD-BUILD is meant to represent workers in an occupational setting. For assessments involving other specific activities, inhalation rates can be selected that are thought to be representative of these particular activities. Similarly, if receptors of a certain age group are being evaluated, breathing rate values should be selected specifically for that age group.

Layton (1993) proposed three alternative approaches for deriving inhalation rates that are based on oxygen uptake associated with energy expenditures: (1) average daily intakes of food energy from dietary surveys, (2) average daily energy expenditure calculated from ratios of total daily expenditure to basal metabolism, and (3) daily energy expenditures determined from a time-activity survey. These approaches consistently yield inhalation rate estimates that are lower than EPA's best "reasonable worst case" estimates and ICRP (1975) reference values. Layton's inhalation rate estimates fall in the recommended range and may be more accurate values for point estimates. However, the approach needs to be further reviewed and validated in the open literature before these lower, less conservative inhalation rate estimates are used.

The available studies on inhalation rates have been summarized by the EPA (1997). Inhalation rates are reported for adults and children (including infants) performing various activities and for outdoor workers and athletes. The activity levels have been categorized as resting, sedentary, light, moderate, and heavy. Table 5.1-2 summarizes inhalation rate values recommended by the EPA both for long-term and short-term exposure. The daily average inhalation rates for long-term exposure for adults are 11.3 m^3/d for women and 15.2 m^3/d for men.

The residential scenario defines three exposure situations or contexts for resident farmers: indoors, outdoors, and gardening. The inhalation rate parameters represent the annual average breathing rate of the average member of the screening group for these three contexts; Table 5.1-3 summarizes the recommended default values for each. Because of the wide variation in inhalation rates possible for the residential scenario, a triangular distribution was selected to represent the rate of the average member of the critical group. The most likely value was taken to be 8,400 m^3/yr (23 m^3/d) as recommended by Beyeler et al. (1998b) for the on-site residential scenario. A minimum value of 4,380 m^3/yr (0.5 m^3/h) was selected on the basis of recommendations for sedentary adult activities, and the maximum value of 13,100 m^3/yr (1.5 m^3/h) selected corresponds to moderate outdoor activities (see Table 5.1-2). Figure 5.1-1 displays the probability distribution function for inhalation selected for the residential scenario.

For the building occupancy scenario, a triangular distribution is also used for input to RESRAD-BUILD. The most likely inhalation rate value was taken to be 33.6 m^3/d (1.4 m^3/h) as recommended in Beyeler et al. (1998a). The minimum value of 12 m^3/d (0.5 m^3/h) was selected on the basis of recommendations for sedentary adult activities, and

a maximum value of 46 m³/d (1.9 m³/h) was selected because it represented the highest average value reported in Beyeler et al. (1998a) for workers in light industry and falls within the range of moderate to heavy activities for both adults and outdoor workers (Table 5.1-2).

Table 5.1-2 Summary of EPA's Recommended Values for Inhalation

Population	Mean	Population	Mean
Long-Term Exposures		***Short-Term Exposures***	
Infants (<1 year)	4.5 m³/d	Adults	
		Rest	0.4 m³/h
Children		Sedentary Activities	0.5 m³/h
1-2 years	6.8 m³/d	Light Activities	1.0 m³/h
3-5 years	8.3 m³/d	Moderate Activities	1.6 m³/h
6-8 years	10 m³/d	Heavy Activities	3.2 m³/h
9-11 years			
Males	14 m³/d	Children	
Females	13 m³/d	Rest	0.3 m³/h
12-14 years		Sedentary Activities	0.4 m³/h
Males	15 m³/d	Light Activities	1.0 m³/h
Females	12 m³/d	Moderate Activities	1.2 m³/h
15-18 years		Heavy Activities	1.9 m³/h
Males	17 m³/d		
Females	12 m³/d	Outdoor Workers	
		Hourly Average[a]	1.3 m³/h
Adults (19-65+yrs)		Slow Activities	1.1 m³/h
Females	11.3 m³/d	Moderate Activities	1.5 m³/h
Males	15.2 m³/d	Heavy Activities	2.5 m³/h

[a] Upper percentile = 3.3 m³/h.

Source: EPA (1997).

Table 5.1-3 Recommended Default Inhalation Rates for the Residential Scenario

Exposure Context/Parameter	Inhalation Rate (m³/h)	Time Spent (days/year)
Indoors	0.9	240
Outdoors	1.4	40.2
Gardening	1.7	2.92
Average on-site rate	23 m³/d	

Source: Beyeler (1998b).
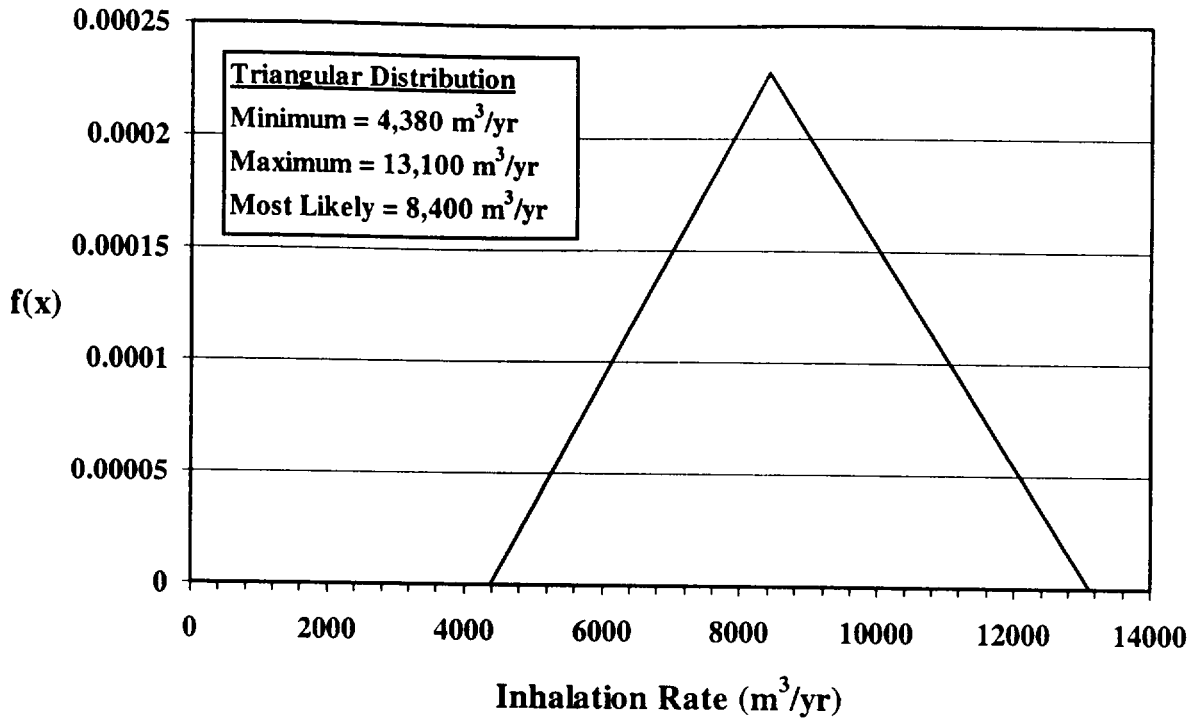
Figure 5.1-1 Inhalation Rate Probability Density Function for RESRAD

Triangular Distribution
Minimum = 4,380 m³/yr
Maximum = 13,100 m³/yr
Most Likely = 8,400 m³/yr

5.2 Drinking Water Intake

Applicable Code: RESRAD

Description: The drinking water intake rate is defined as the average amount of water consumed by an adult per unit of time. It includes juices and beverages containing tap water (e.g., coffee).

Units: liters per year (L/yr)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution:

Underlying mean value:	6.015	Lower quantile value: 0.001
Underlying standard deviation:	0.489	Upper quantile value: 0.999

Discussion: The distribution of the drinking water intake rate generally varies from 0.10 to 3 L/d, depending on the age, body weight, and activity level of the receptor. A rigorous statistical treatment of water intake data for a large data set (n = 26,081; Ershow and Cantor, 1989) is provided by Roseberry and Burmaster (1992). Estimates are provided for (1) tap water intake (the sum of water drunk directly as a beverage and water added to foods and beverages during preparation); and (2) total water intake, which includes tap water intake and intrinsic water intake (i.e., the water intrinsic in foods as purchased). The values associated with tap water intake are more likely to apply for risk assessment purposes.

The mean and standard deviations for the underlying normal distribution for five age categories are provided by Roseberry and Burmaster (1992). Alternatively, the mean and standard deviation for the entire population may be used when intake over a lifetime is being evaluated. Finley et al. (1994) used the same data set to generate age-specific cumulative distributions for drinking water intake. The results of Roseberry and Burmaster (1992) are reported here (see Table 5.2-1) because of ease of use in Monte Carlo analyses. The mean total tap water intake rates for the two adult populations (age 20 to 65 years, and 65+ years) were estimated to be 1.27 and 1.34 L/d, respectively.

Other parameters that correlate with drinking water intake are the body weight and activity level of the receptor evaluated. Temperature and humidity levels also influence drinking water intake rates.

Table 5.2-1 Drinking Water Intake Rate[a] Distributions

Distribution Type	Age Range	Mean	Standard Deviation	Comments
Lognormal				
Total water	<1	6.98	0.29	μ and SD of underlying
	1 - <11	7.18	0.34	normal distribution shown.
	11 - <20	7.49	0.35	Transforms to mL/d. Based
	20 - <65	7.56	0.40	on n = 26,081 (1.5% <1;
	>65	7.58	0.36	21.4% 1-<11; 22.2% 11-<20;
	Total	7.49	0.41	45% 20-<65; 9.7% >65).
Tap water	<1	5.59	0.62	
	1 - <11	6.43	0.50	
	11 - <20	6.67	0.54	
	20 - <65	7.02	0.49	
	>65	7.09	0.48	
	Total	6.86	0.58	

[a] 97.5 percentile intake rate = exp $[\mu + (1.96\sigma)]$,

75 percentile intake rate = exp $[\mu + (0.6745\sigma)]$,

50 percentile intake rate = exp $[\mu]$,

mean intake rate = exp $[\mu + 0.5\sigma^2)]$.

Source: Roseberry and Burmaster (1992) (based on 1977-1978 Nationwide Food Consumption Survey, USDA).

The American Industrial Health Council's (AIHC's) *Exposure Factors Sourcebook* (AIHC, 1994) presents drinking water intake recommendations for adults. The recommended mean drinking water intake is 1.4 L/d, and the reasonable "worst-case" value is 2.0 L/d.

In its *Exposure Factors Handbook*, the EPA (1997) has compiled the available studies on drinking water consumption rate. The EPA has classified the studies as either key studies or relevant studies on the basis of the applicability of their survey designs to exposure assessment of the entire U.S. population. On the basis of the results of the key studies, the recommended drinking water intake rates for different age groups/populations are shown in Table 5.2-2. The table also presents the mean, 50th, 90th, and 95th percentile values.

The age-specific rates for adults recommended by the EPA (1997) are based on data from the 1977-1978 USDA Nationwide Food Consumption Survey (EPA, 1984). The same data were used by Roseberry and Burmaster (1992) and by Ershow and Cantor (1989) to develop intake distributions. In addition, the lognormal distributions derived in

Table 5.2-2 Summary of Recommended Drinking Water Intake Rates[a]

Age Group/ Population	Mean	Percentiles		
		50th	90th	95th
<1 year	0.30 L/day 44 mL/kg-day	0.24 L/day 35 mL/kg-day	0.65 L/day 102 mL/kg-day	0.76 L/day 127 mL/kg-day
<3 years	0.61 L/day	-	1.5 L/day	-
3-5 years	0.87 L/day	-	1.5 L/day	-
1-10 years	0.74 L/day 35 mL/kg-day	0.66 L/day 31 mL/kg-day	1.3 L/day 64 mL/kg-day	1.5 L/day 79.4 mL/kg-day
11-19 years	0.97 L/day 18 mL/kg-day	0.87 L/day 16 mL/kg-day	1.7 L/day 32 mL/kg-day	2.0 L/day 40 mL/kg-day
Adults	1.4 L/day 21 mL/kg-day	1.3 L/day 19 mL/kg-day	2.3 L/day 34 mL/kg-day	
Pregnant women	1.2 L/day 18.3 mL/kg-day	1.1 L/day 16 mL/kg-day	2.2 L/day 35 mL/kg-day	2.4 L/day 40 mL/kg-day
Lactating women	1.3 L/day 21.4 mL/kg-day	1.3 L/day 21 mL/kg-day	1.9 L/day 35 mL/kg-day	2.2 L/day 37 mL/kg-day
Adults in high activity/ hot climate conditions	0.21 to 0.65 L/hour, depending on ambient temperature and activity level			
Active adults	6 L/day (temperate climate) to 11 L/day (hot climate)			

[a] Source: EPA (1997).

Roseberry and Burmaster (1992) were recommended as a good mathematical description of drinking water intake by the EPA (1997). Therefore, the suggested parameter distribution for drinking water intake in RESRAD is taken to be the lognormal distribution for adults in Roseberry and Burmaster (1992). Adjusted for drinking rate input units of liters per year (409.5 L/yr), the adjusted underlying mean and standard deviation are 6.015 and 0.489, respectively. The probability density function is shown in Figure 5.2-1.
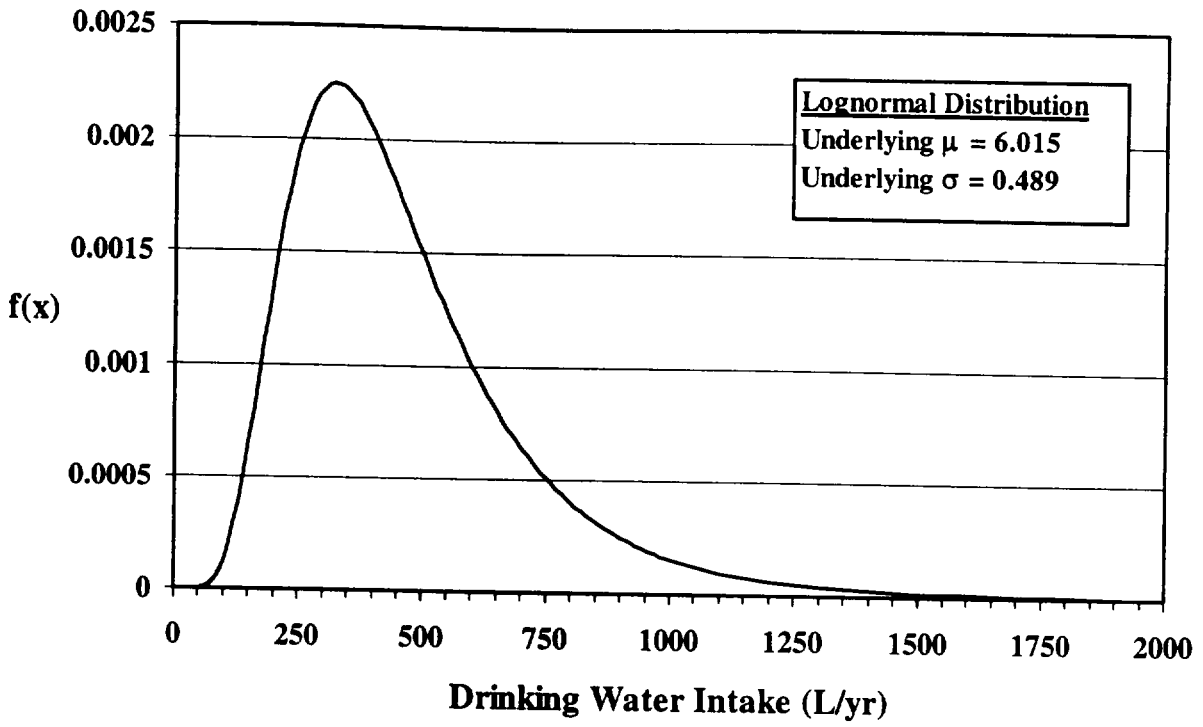
Figure 5.2-1 Drinking Water Intake Probability Density Function

Lognormal Distribution
Underlying μ = 6.015
Underlying σ = 0.489

5.3 Milk Consumption Rate

Applicable Code: RESRAD

Description: The milk consumption rate is the amount of fluid milk (beverage) consumed per year.

Units: liters per year (L/yr)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 60   Maximum: 200   Most likely: 102

Discussion: The milk consumption rate can vary for different population groups, ages, and geographic locations. In RESRAD, the consumption rate of milk is for fluid milk only. This rate is required by the RESRAD computer code when the milk ingestion pathway is active (Yu et al., 1993a).

The EPA's *Exposure Factor Handbook* (EPA, 1997) provides milk consumption rates that were obtained from the USDA's *National Food Consumption Survey* (NFCS) (USDA, 1980, 1992), *Continuing Survey of Food Intakes by Individuals* (USDA, 1996a,b), and *Food Consumption, Prices and Expenditures 1970-1992* (USDA, 1993).

An indication of consumption rates for a variety of foodstuffs is provided in the USDA report *Food Consumption, Prices, and Expenditures 1970-1997* (Putnam et al., 1999). The estimates of food for human consumption are derived by subtracting other measurable uses, such as exports, industrial uses, farm inputs, and end-of year stocks, from total supply (the sum of domestic production, imports and beginning stocks) (Putman et al., 1999). Hence, the data provided in this report would be an upper bound on human consumption assuming no spoilage or wastes. The food consumption rates are grouped by food categories, with several subcategories under the major categories (e.g., major category — dairy products, subcategory — beverage milk). Further information, such as the individual consumption rates for each food type, is provided in the report for each year reported (Putnam et al., 1999).

An average fresh milk consumption rate of 294 g/d was estimated by the NFCS for 1977-1978 (EPA, 1997). This average daily consumption value corresponds to an annual consumption rate of 104 L/yr averaged over all age brackets. The largest milk

consumption rate was in the 10- to 14-year-old age range. This group consumed approximately 456 g/d (162 L/yr), which is over 2.5 times higher than the consumption rate of the age bracket (40-59) that consumed the least amount of milk. The age-bracketed milk consumption rates are provided in Table 5.3-1.

The USDA *Food Consumption, Prices and Expenditures Report* (Putnam, 1999) provides year-bracketed consumption rates for beverage milk for the years 1972-1997. The average beverage milk consumption rate was estimated to be approximately 101 L/yr, which agrees well with the NFCS data. Table 5.3-2 provides the yearly milk consumption rate averaged in four-year intervals. The largest milk consumption rate in a 4-year interval occurred between 1972-1976, when the per capita beverage milk consumption averaged 113 L/yr. After that time, per capita milk consumption declined to the 1997 value of 90 L/yr.

A triangular probability distribution was chosen for the milk consumption rate. The minimum value was taken to be 60 L/yr, which corresponded to the consumption rate of 40-59 age bracket of the NFCS study. The maximum milk consumption rate was set at 200 L/yr, which is equal to the fluid milk consumption rate stipulated in NRC Regulatory Guide 1.109 for a child (NRC, 1977). A value of 102 L/yr was chosen as the most likely value because it is the average of the NFCS and USDA values. Figure 5.3-1 shows the resulting probability density function for the milk consumption rate.

Table 5.3-1 Mean per Capita Intake of Fresh Cow's Milk

Age Group (years)	Fluid Milk (g/d)
<1	272
1-4	337
5-9	446
10-14	456
15-19	405
20-24	264
25-39	218
30-39	183
40-59	169
60+	192
Average	294

Source: EPA (1997).

Table 5.3-2 Annual per Capita Consumption of Beverage Milk

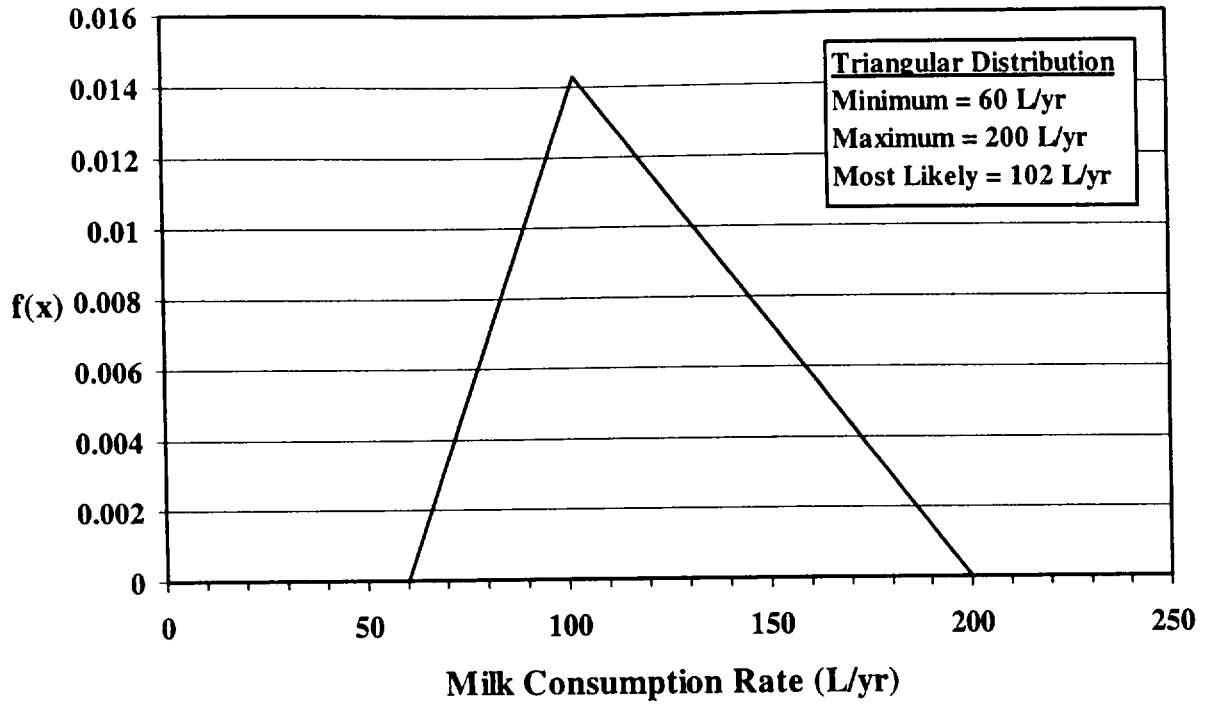| Year	Consumption (L/yr)
1972-1976	112
1977-1981	105
1982-1986	99
1987-1999	97
1992-1996	92
1997	93
Average (1972-1997)	101

Source: Derived from Putnam et al. (1999).

Figure 5.3-1 Milk Consumption Rate Probability Density Function

5.4 Fruit, Vegetable, and Grain Consumption Rate

Applicable Code: RESRAD

Description: The fruit, vegetable, and grain consumption rate is the total quantity of these food items (contaminated and noncontaminated) consumed per year.

Units: kilograms per year (kg/yr)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 135   Maximum: 318   Most likely: 178

Discussion: The fruit, vegetable, and grain consumption rate can vary for different population groups, ages, and geographic locations. In RESRAD, the consumption rate for fruits, vegetables, and grain is a composite value obtained by summing the individual consumption rates for fresh fruits, fresh vegetables (nonleafy), and grain.

The vegetable portion of this parameter does not include leafy vegetables consumed. Leafy vegetable consumption is a separate parameter in the RESRAD computer code (Yu et. al., 1993a). In addition, the fruit, vegetable, and grain consumption rate should only apply to fresh fruits and vegetables. This parameter is used when the plant ingestion exposure pathway is active.

The EPA published the *Exposure Factors Handbook* (EPA, 1997) to summarize data on human behaviors and to recommend values to use in modeling those activities. The consumption rates for fruits, vegetables, and grain provided in the handbook were obtained from the USDA's *National Food Consumption Survey* (USDA, 1980, 1992), *Continuing Survey of Food Intakes by Individuals* (USDA, 1996a,b), and *Food Consumption, Prices and Expenditures 1970-1992* (USDA, 1993).

The *Exposure Factors Handbook* (EPA, 1997) provides intake rates in units of grams of food consumed per kilogram of body weight per day. The data are grouped by age, season, urbanization (central city, nonmetropolitan, and suburban), race, and region (Midwest, Northeast, South, and West). Converting the intake rates into units of kg/yr by multiplying by a single average body weight is inappropriate because intake rates were indexed to the reported body weights of the survey respondents. An average adult body weight of approximately 72 kg was estimated by averaging the combined male-female body weights contained in Table 7-2 of the *Exposure Factors Handbook* (EPA, 1997). Since the

results are grouped by age, the average consumption rate was derived for each food class on the basis of the dietary habits of adults (ages 20-70+). The average consumption rates on a per-kilogram-body-weight basis are provided in Table 5.4-1 for each age group.

An indication of food consumption for a variety of foodstuffs is provided in the USDA report *Food Consumption, Prices, and Expenditures 1970-1997* (Putnam et al., 1999). The estimates of food for human consumption are derived by subtracting measurable uses such as exports, industrial uses, farm inputs, and end-of year stocks from total supply (the sum of domestic production, imports, and beginning stocks) (Putnam et al., 1999). Hence, the data provided in this report would be an upper bound on human consumption assuming no spoilage or wastes. The foods are grouped by totals, fresh fruits/vegetables, and major subcategories (citrus, noncitrus, etc.). Further information, such as the individual consumption rates for each food type, is provided in the report for each year reported (Putnam et al., 1999).

Fresh fruits and vegetables accounted for approximately 42% and 44%, respectively, of the total fruits and vegetables consumed during the 25-year period from 1972 through 1997 (Putnam et al., 1999). The fresh vegetable percentage remained relatively constant throughout the 25-year period, while the fresh fruit consumption rose from 40% from 1972-1976 to 45% in 1997. The fraction of nonleafy fresh vegetables[1] consumed from 1972-1997 was estimated at 0.67 of the total fresh vegetable consumption rate. Table 5.4-2 provides consumption values for fresh fruits, fresh vegetables, and grain for the years 1972-1997 (Putnam et al., 1999).

A probability distribution (triangular, see Figure 5.4-1) for the fruit, vegetable, and grain consumption rate was derived from the information provided in the EPA *Exposure Factor Handbook* (EPA, 1997) and the USDA report *Food Consumption, Prices, and Expenditures 1970-1997* (Putnam et al., 1999). The lower bound of the distribution was obtained by averaging the median per capita consumption rate for ages 20-70+ provided in Table 5.4-1 and multiplying by the average weight of an adult. Correction factors of 0.42 and 0.44 were applied to the fruit and vegetable consumption rate to account for the consumption of fresh fruits and vegetables only. A further correction factor of 0.67 was applied to the vegetable consumption rate to account for the intake of nonleafy vegetables only. These values were summed to yield a single consumption rate for fruit, vegetables, and grains. The upper bound of the distribution was estimated in the same manner, except the 95th percentile was used for the per-capita consumption rate instead of the median value. The average value of the total given in Table 5.4-2 was used for the most likely value of the triangular distribution.

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[1] Nonleafy vegetables are all vegetables except cabbage, cauliflower, broccoli, celery, lettuce, and spinach (EPA, 1997).

Table 5.4-1 Median per Capita Intake of Total Fruits, Vegetables, and Grains (g/kg-d as consumed)
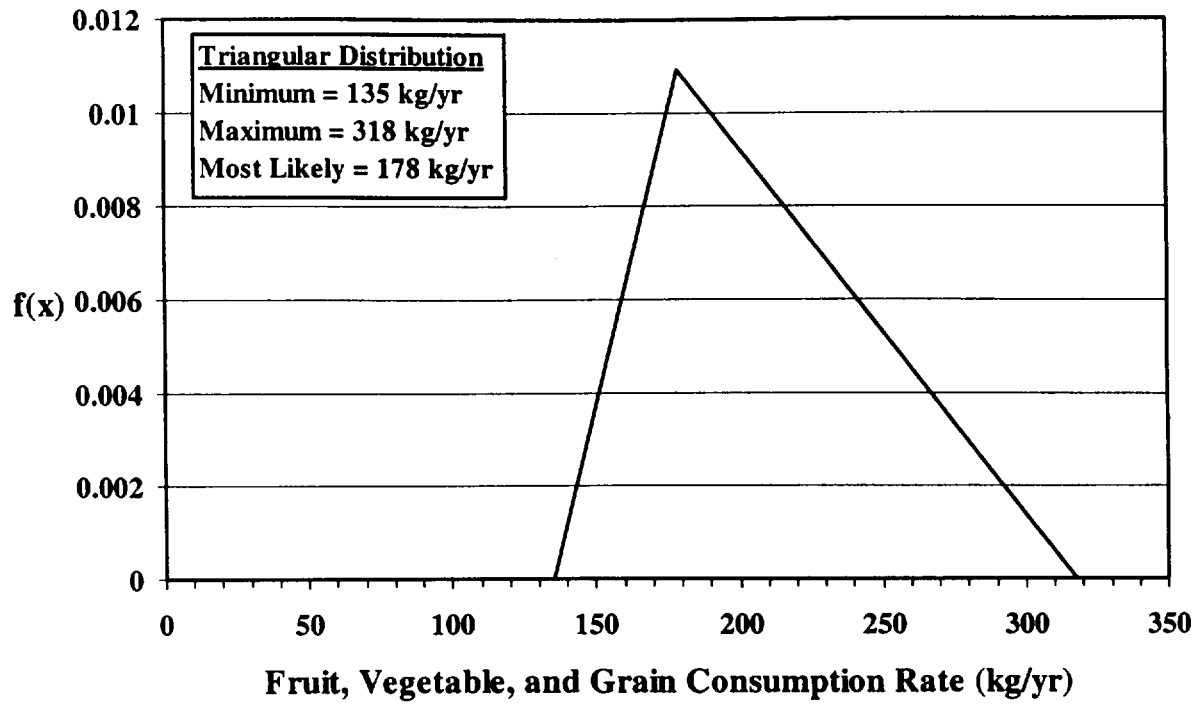
Age Group (years)	Total Fruits	Total Vegetables	Total Grains
<1	14.9	6.8	7.0
1-2	11.8	7.9	10.6
3-5	8.4	7.1	9.5
6-11	5.0	5.5	6.4
12-19	2.2	3.8	3.8
20-39	1.9	3.5	3.1
40-69	2.1	3.7	2.8
70+	3	4.1	3.3

Source: EPA (1997).

Table 5.4-2 Per Capita Consumption Values for Fresh Fruits, Fresh Vegetables, and Grains (kg/yr)

Year	Fresh Fruits	Fresh Vegetables (nonleafy)	Grains	Total
1972-1976	45	45	63	152
1977-1981	47	43	65	154
1982-1986	51	46	69	166
1987-1999	54	50	81	185
1992-1996	57	55	88	200
1997	61	58	91	210
Average (1972-1997)	52	50	76	178

Source: Derived from Putnam et al. (1999).

Triangular Distribution
Minimum = 135 kg/yr
Maximum = 318 kg/yr
Most Likely = 178 kg/yr

Fruit, Vegetable, and Grain Consumption Rate (kg/yr)

Figure 5.4-1 Fruit, Vegetable, and Grain Consumption Rate Probability Density Function

5.5 Aquatic Food Contaminated Fraction

Applicable Code: RESRAD

Description: The aquatic food contaminated fraction is the fraction of aquatic foods that are consumed from the site that are contaminated.

Units: unitless

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 0   Maximum: 1   Most likely: 0.39

Discussion: The aquatic foods contaminated fraction can range from 0 (none of the seafood products consumed are contaminated) to 1 (all seafood products consumed are contaminated). The balance of the aquatic foods (1 - aquatic food contamination fraction) is assumed to come from uncontaminated sources. The parameter is dependent on whether there is an on-site pond capable of producing seafood products, as well as dietary and other habits of the individual being modeled. The aquatic food contamination fraction is required by the RESRAD computer code when the seafood ingestion pathway is active (Yu et al., 1993a).

One measure of this parameter is the percentage of the annual seafood consumption rate from home-caught fish and shellfish. The EPA published the *Exposure Factor Handbook* (EPA, 1997) in part to summarize data on human behaviors and recommend values to use to model those activities. The consumption rates for home-consumed seafood products provided in the handbook were obtained from the USDA's *National Food Consumption Survey* (NFCS) (USDA, 1980, 1992). Data from the 1987-1988 NFCS study were used to generate the homegrown intake rates. These intake rates vary by age, season, and geographic location. Among members of fishing households, home-caught fish accounted for 38% of the total fish consumption for the year (EPA, 1997)

A triangular distribution, as displayed in Figure 5.5-1, is recommended for the aquatic food contamination fraction. Since the limits of the parameter can range from 0 (no aquatic foods consumed are contaminated) to 1 (all aquatic foods consumed are contaminated), these values were chosen for the upper and lower bounds of the distribution. A most likely value of 0.39 was chosen on the basis of the recreational fishing habits and consumption rates provided in the *Exposure Factor Handbook* (EPA, 1997).
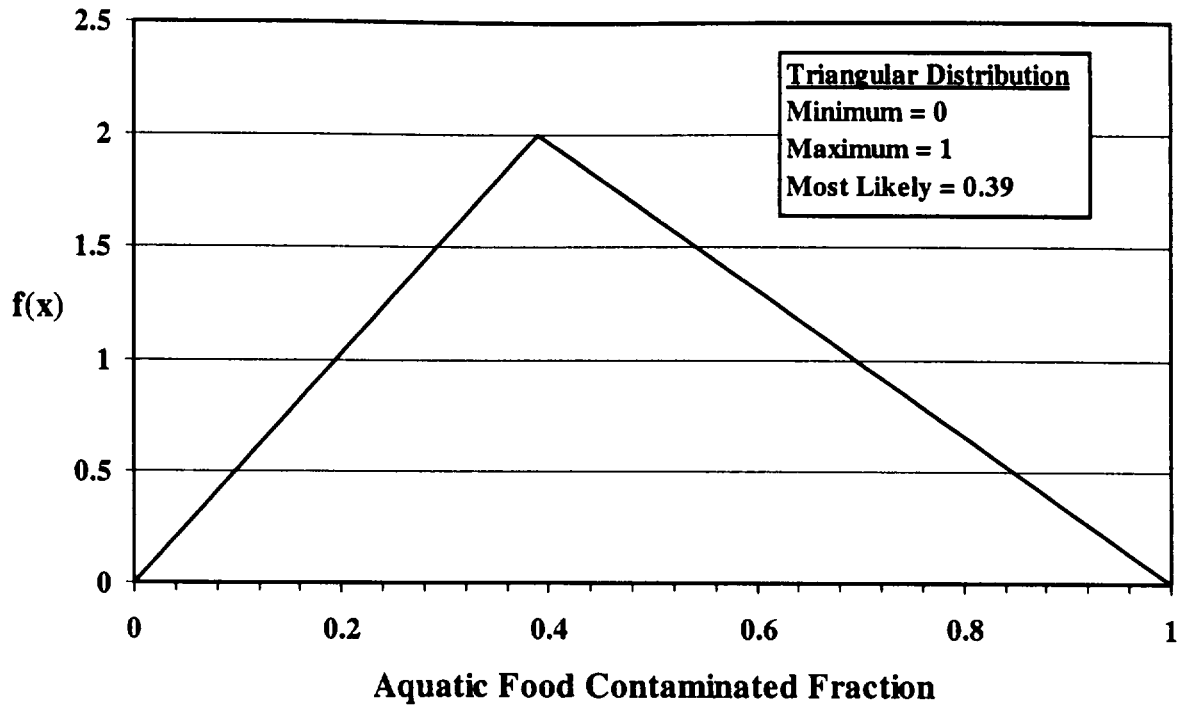
Figure 5.5-1 Aquatic Food Contaminated Fraction Probability Density Function

5.6 Soil Ingestion Rate

Applicable Code: RESRAD

Description: Ingestion rate of soil from outdoor activities.

Units: grams per year (g/yr)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 0   Maximum: 36.5   Most likely: 18.3

Discussion: The soil and dust ingestion rate varies over a wide range, depending on the age, activities, and possible dietary anomalies (e.g., pica, the desire to eat substances not normally eaten) of the receptor, and weather at the time of exposure. To date, most study has been focused on soil and dust ingestion rates for children aged 1 through 6 because of concern over elevated exposures from intensive mouthing behavior in children of this age group. Table 5.6-1 summarizes selected work.

The best data are considered to come from studies that use a mass-balance approach to estimate ingestion rates. That approach measures nonabsorbed tracer elements in soil, dust, and feces and accounts for other dietary sources of the tracers. Estimates of soil and dust ingestion rates for individuals vary from 0 mg/d (Calabrese et al., 1989) to 10 g/d (Kimbrough et al., 1984) for a child exhibiting pica. Information on the amount of soil ingested by children with abnormal soil ingestion behavior is limited. The Calabrese et al. (1991) study included one pica child among the 64 children who participated. In that study, a 3.5-year-old female exhibited extremely high soil ingestion behavior during one of the two weeks of observation. Intake ranged from 74 mg/d to 2.2 g/d during the first week and 10.1 to 13.6 g/d during the second week. These results were based on mass-balance analyses for seven tracer elements. Calabrese and Stanek (1992) concluded that the origin of the soil ingestion for the pica child was from outdoor soil, not from indoor dust. Median soil and dust ingestion rates for children in this age group are generally about 50 mg/d (Binder and Sokal, 1986; Calabrese et al., 1989; Davis and Waller, 1990; Thompson and Burmaster, 1991).

A strong inverse correlation of soil ingestion rate with precipitation has been documented (Van Wijnen et al., 1990), presumably related to the fact that precipitation decreases the opportunity for soil contact. However, no widely accepted method is

Table 5.6-1 Soil and Dust Ingestion Rate Distributions

Distribution Type	μ	SD	Comments	References
Lognormal	91 mg/d	126 mg/d	Age 1-3. Mean and SD of underlying lognormal distribution shown. $n = 65$. Based on the combined data for Al and Si tracers.	Thompson and Burmaster, 1991; based on data from Binder and Sokal, 1986
Lognormal	153 mg/d	852 mg/d	Age 1-4. Median = 29 mg/d. Mean and SD of lognormal distribution shown (underlying normal mean and SD not given). $n = 64$. Based on data for Al tracer.	Calabrese et al., 1989
Normal	5.0 - Daycare 5.2 - Campers	0.81 - Daycare 0.55 - Campers	Age 1-4. Mean and SD of underlying normal distribution shown. $n = 292$ (daycare group); $n = 78$ (campers). Based on combined data for Al, Ti, and acid-insoluble residue tracers.	Van Wijnen et al., 1990
Lognormal	Al-39 mg/d Si-82 mg/d	Al-145 mg/d Si-123 mg/d	Age 2-7 (42% ≤4 years old). Mean and SD of lognormal distribution shown (underlying normal mean and SD not given). $n = 101$. Based on data for Al and Si tracers.	Davis and Waller, 1990
Normal	195 mg/d	53 mg/d	Age applicable to 2 year olds. Although underlying distributions were not normal, the reported values are the mean and SD of mean rates obtained with different tracers, so this distribution approaches the normal (Central Limit Theorem). Based on data for Al, Si, Ti, V and Y tracers.	Sedman and Mahmood, 1994; based on data from Calabrese et al., 1989 and Binder and Sokal, 1986
Lognormal	Al-77 mg/d Si-5 mg/d	Al-65 mg/d Si-55 mg/d	Age 25-41. Mean and SD of lognormal distribution shown (underlying normal mean and SD not given). $n = 6$. Based on data for Al and Si tracers.	Calabrese et al., 1990
Lognormal	10 mg/d	94 mg/d	Age - Adults. $n = 10$. Mass balance studies on 10 adults over a period of 28 days.	Stanek et al., 1997

currently available for determining the relative contribution of outdoor soil versus indoor dust to the daily total ingestion rate, and the effect of climatic variation has yet to be determined (EPA, 1991).

Calabrese et al. (1990) also estimated soil ingestion rates for adults by using a mass-balance approach. Although the number of subjects studied (six) was too small to be certain of the distribution type, the medians were considerably lower than the mean values, suggesting that the distributions are also lognormal, as has been noted for children. The EPA (1991) recommended that the median soil ingestion rate from this study that is based on aluminum as the tracer (i.e., 50 mg/d) be used as the point estimate for adult soil ingestion in occupational settings (except for construction work). A point value of 100 mg/d for adults in residential settings was recommended (EPA, 1989b); presumably, this increased value was intended to account for certain activities that would involve greater soil ingestion than was found in the Calabrese et al. (1990) study.

Calabrese et al. (1989) studied soil ingestion among 64 children between the ages of 1 and 4 years by using eight tracer elements. That study was conducted over eight days during a two-week period and used mass-balance methodology. On the basis of the three most reliable tracer elements, the mean soil intake rate for children was estimated to be 153 mg/d based on aluminum tracer, 154 mg/d based on silicon tracer, and 85 mg/d based on yttrium tracer. Median intake rates were somewhat lower (29 mg/d for aluminum, 40 mg/d for silicon, and 9 mg/d for yttrium), 95th percentile values were 223 mg/d for aluminum, 276 mg/d for silicon, and 106 mg/d for yttrium.

Van Wijnen et al. (1990) studied soil ingestion among Dutch children aged 1 to 5 years old by using a tracer element methodology. A total of 292 children attending daycare centers were sampled during the first of two sampling periods, and 187 children were sampled in the second sampling period; 162 children were sampled during both periods. A total of 78 children were sampled at campgrounds, and 15 hospitalized children were sampled. The mean value for these groups were 162 mg/d for children in daycare centers, 213 mg/d for campers, and 93 mg/d for hospitalized children. The soil intake rates were found to be skewed, and the log transformed data were approximately normally distributed. Geometric means were 111, 174, and 74 mg/d, respectively, for daycare, camping, and hospitalized children. Van Wijnen et al. (1990) suggest that the mean value for hospitalized infants represents background intake of tracers and should be used to correct the soil intake rates for other sampling groups. Using mean values, corrected soil intake rates were 69 mg/d for daycare children and 120 mg/d for campers.

Davis and Waller (1990) used a mass-balance/tracer technique to estimate soil ingestion among children. In that study, 104 children between the ages of 2 and 7 were randomly selected from a three-city area in southeastern Washington State. Soil ingestion rates were highly variable, especially those based on titanium. This study also evaluated

the extent to which differences in tracer concentrations in house dust and yard soil affected soil ingestion rate estimates. The adjusted mean soil/dust intake rates were 64.5 mg/d for aluminum, 160 mg/d for silicon, and 268.4 mg/d for titanium. Adjusted median soil/dust intake rates were: 51.8 mg/d for aluminum, 112.4 mg/d for silicon, and 116.6 mg/d for titanium. This study was conducted over a one-week period.

Thompson and Burmaster (1991) developed parameterized distributions of soil ingestion rates for children based on a reanalysis of the data collected by Binder and Sokal (1986). The mean intake rates were 97 mg/day for aluminum, 85 mg/day for silicon, and 1,004 mg/day for titanium. On the basis of the arithmetic average of aluminum and silicon for each child, mean soil intake was estimated to be 91 mg/day. Statistical testing of the data indicated that only silicon and the average of the silicon and aluminum tracers were lognormally distributed — median: 59 mg/d, standard deviation: 126, arithmetic mean: 91 mg/d.

Sedman and Mahmood (1994) used the results of two children's tracer studies (Calabrese et al., 1989; Davis and Waller, 1990) to estimate average daily soil ingestion in young children and for a lifetime. The average ages of children were 2.4 and 4.7 years, respectively, in these two studies. The mean of the adjusted levels of soil ingestion for a two-year-old child was 220 mg/d for the Calabrese et al. (1989) study and 170 mg/d for the Davis and Waller (1990) study. From the adjusted soil ingestion estimates, based on a normal distribution of means, the mean estimate for a 2-year-old child was 195 mg/d, and the standard deviation of mean was 53 mg/d.

Stanek and Calabrese (1995) recalculated ingestion rates that were estimated in three mass-balance studies (Calabrese et al., 1989; Davis and Waller, 1990 for children's soil ingestion; and Calabrese et al., 1990 for adult soil ingestion) using the best tracer method (BTM). This method allows for the selection of the most recoverable tracer for a particular subject or group of subjects. For adults, Stanek and Calabrese (1995) used data for eight tracers from the Calabrese et al. (1990) study to estimate soil ingestion by the BTM. On the basis of the median of the soil ingestion rates for the best four tracer elements, the average adult soil ingestion rate was estimated to be 64 mg/d, with a median of 87 mg/d. The 90th percentile soil ingestion was 142 mg/d (18 subject weeks for six adults). For children, Stanek and Calabrese (1995) used data on eight tracers from Calabrese et al. (1989) and data on three tracers from Davis and Waller (1990) to estimate soil ingestion rates. On the basis of the median of soil ingestion estimates from the best four tracers in the Calabrese et al. (1989) study, the mean soil ingestion rate was 132 mg/d, and the median was 33 mg/d. The 95th percentile value was 154 mg/d (128 subject weeks, 64 children).

For the 101 children in the Davis and Waller (1990) study, the mean soil ingestion rate was 69 mg/d and the median was 44 mg/d. The 95th percentile estimate was

246 mg/d. When the Calabrese et al. (1989) and Davis and Waller (1990) studies were combined, the soil ingestion was estimated to be 113 mg/d (mean); 37 mg/d (median); and 217 mg/d (95th percentile), using BTM.

Sheppard (1995) summarized the available literature on soil ingestion to estimate the amount of soil ingestion in humans for the purposes for risk assessment. He categorized the available soil ingestion studies into two general approaches: (1) those that measured the soil intake rate with the use of tracers in the soil, and (2) those that estimated soil ingestion based on activity (e.g., hand-to-mouth) and exposure duration. Sheppard assumed that the data from the previous studies were lognormally distributed because of the broad range, the concept that soil ingestion is never zero, and the possibility of very high values. The geometric mean for soil ingestion rate for children under six was estimated to be 100 mg/d. For children above 6 and adults it was estimated to be 20 mg/d.

Stanek et al. (1997) studied soil ingestion in 10 adults (5 males, 5 females) in the age range of 22-45 years during the months of September through November by using the mass-balance approach. Soil ingestion estimates indicated that the average adult ingested 10 mg/d of soil, the upper 95th percentile value was 331 mg/d.

Simon (1998) reviewed much of the available literature on soil ingestion and lists a set of soil ingestion parameters for nine different lifestyle scenarios for adults and children. Values are listed for inadvertent soil ingestion and also for geophagia[1] (intentional soil ingestion). Table 5.6-2 gives the soil ingestion parameters for various lifestyle scenarios from the Simon (1998) study. These parameter values are presented either as triangular distributions, specified as Tri(minimum, mode, maximum) or lognormal distributions, specified as LN(geometric mean, geometric standard deviation). Lifestyle scenarios 1-7 may apply to localized populations within the United States or elsewhere, depending on the knowledge or judgment of the risk assessor. Lifestyle scenarios 8 and 9 would have greater applicability for scenarios outside of the United States. Simon (1998) assigned lognormal distributions to represent inadvertent ingestion for children and adults and triangular distributions for geophagia among adults and children. For the U.S. population, suggested inadvertent ingestion geometric mean values vary from 0.05 g/d to 0.2 g/d for adults and 0.1 g/d to 0.2 g/d for children. The geometric standard deviation of 3.2 was assigned for adults and 4.2 for children.

The EPA has recommended a mean soil ingestion rate of 50 mg/d for adults, but does not have a recommended upper percentile value because of the lack of data (EPA,

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[1] Geophagia is defined to be a condition in which the patient eats inedible substances, as chalk, clay or earth. It is agreed by many that geophagia or earth eating is a special case of pica.

Table 5.6-2 Soil Ingestion Model Parameters for Various Lifestyle Scenarios

Lifestyle Scenarios	Adult		Child (ages 1 through 6 yr)	
	Inadvertent Ingestion (g/d)	Geophagia (g/d)	Inadvertent Ingestion (g/d)	Geophagia (g/d)
Occupations on tilled agriculture land (no homes) – bare part of year, vegetated part of year (Scenario 1)	LN(0.1, 3.2)	0	0	0
Occupations on pasture land (no homes) – heavily vegetated (Scenario 2)	LN(0.05, 3.2)	0	0	0
Occupations on pasture land (no homes) – sparsely vegetated, range land for grazing (Scenario 3)	LN(0.1, 3.2)	0	0	0
Occupations at construction sites (no homes) – distributed by earth-moving, traffic, bulldozing, etc. (Scenario 4)	LN(0.1, 3.2)	0	0	0
Rural lifestyles (w/homes) – heavily vegetated, forests and fields (Scenario 5)	LN(0.1, 3.2)	Tri(1.0, 3.0, 5.0)	LN(0.1, 4.2)	Tri(1.0, 3.0, 5.0)
Rural lifestyles (w/homes) – sparsely vegetated (Scenario 6)	LN(0.2, 3.2)	Tri(1.0, 3.0, 5.0)	LN(0.2, 4.2)	Tri(1.0, 3.0, 5.0)
Suburban lifestyles (w/homes) – including lawns, parks, recreational areas, some gardens (Scenario 7)	LN(0.1, 3.2)	Tri(1.0, 3.0, 5.0)	LN(0.2, 4.2)	Tri(1.0, 3.0, 5.0)
Lifestyles of indigenous peoples (mainly hunters/food gathering/nomadic societies) – wet climates/regions of thick ground vegetation (Scenario 8)	LN(1.0, 3.0)	Tri(1.0, 3.0, 10.0)	LN(3.0, 4.0)	Tri(2.0, 5.0, 10.0)
Lifestyles of indigenous peoples (mainly hunters/food gathering/nomadic societies) – dry climates/regions of sparse ground vegetation (Scenario 9)	LN(2.0, 3.0)	Tri(1.0, 3.0, 10.0)	LN(3.0, 4.0)	Tri(2.0, 5.0, 10.0)

Source: Simon (1998).

1997). Beyeler et al. (1998b), upon review of the adult studies, proposed a triangular distribution with a most likely value of 50 mg/d for the residential farmer scenario and with minimum and maximum values of 0 and 100 mg/d, respectively. As noted in these reports, these estimates are highly uncertain because of the limited data available. The same triangular distribution proposed in Beyeler et al. (1998b) is suggested for use in RESRAD for the residential farmer scenario. The probability density function is shown in Figure 5.6-1. The average of 50 mg/d (18.3 g/yr) is above the 10 mg/d found in the most comprehensive adult study to date (Stanek et al., 1997), but needs to account for the outdoor lifestyle of a residential farming scenario.
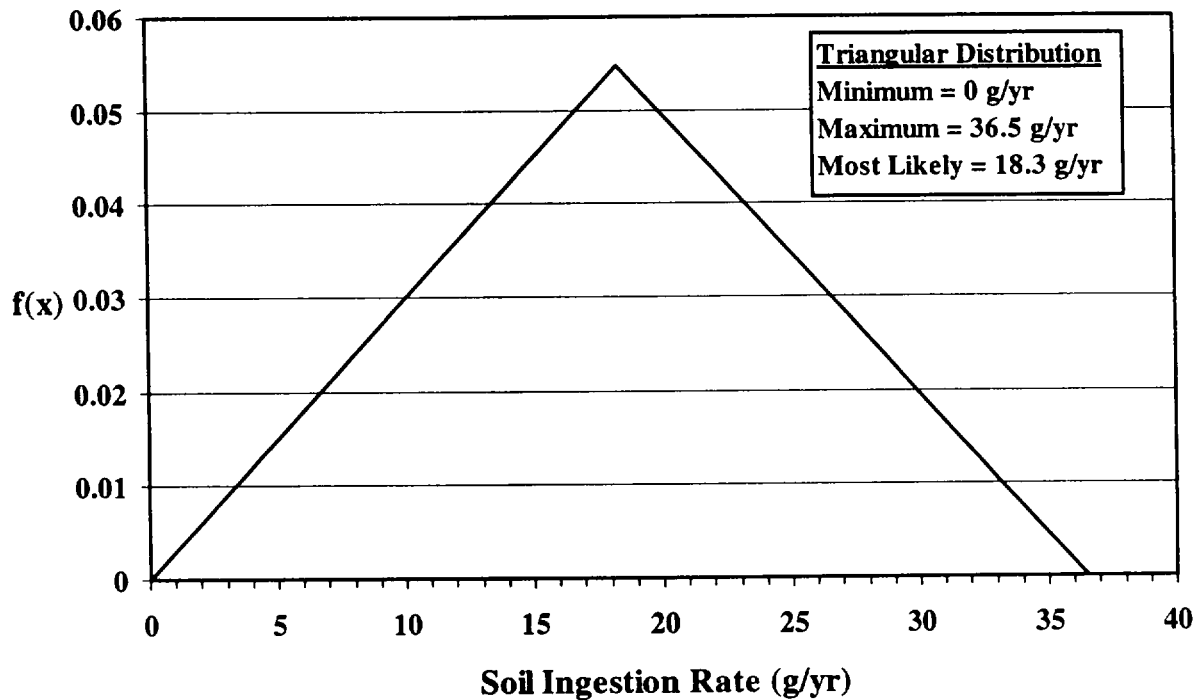
Figure 5.6-1 Soil Ingestion Rate Probability Density Function

5.7 Direct Ingestion Rate

Applicable Code: RESRAD-BUILD

Description: "Direct ingestion" refers to the incidental ingestion of contaminated material directly from the source.

Units: g/h for volume sources
1/h for point, line, and area sources

Probabilistic Input:

Distribution: none recommended

Discussion: The direct ingestion rate is included in the RESRAD-BUILD code for unlikely events when a receptor could directly ingest source material. Such a receptor could be conducting a maintenance or renovation activity that involved physical contact with the source. The direct ingestion rate is normally set to 0 for most calculations.

The magnitude of the direct ingestion rate is highly correlated with other input parameters. For volume sources, the total amount of material ingested may range from 0 to a maximum specified by the mass of the source (area × thickness [Section 8.9] × density [Section 8.1]). In addition, the direct ingestion rate cannot exceed the amount removed per unit time as determined by the source erosion rate (Section 8.2). The soil ingestion rate for RESRAD (Section 5.6) could be used as a guide for this parameter. Indirect ingestion (Section 5.8) must also be taken into account, as must time spent in the room with the source. Also, the direct ingestion rate should not cause the total physical mass of the source to be depleted over the time of exposure and must take into account the mass balance because of erosion of the source resulting from other mechanisms (Section 8.2).

For the other source types (point, line, and area), the direct ingestion rate is expressed as a fraction of the source ingested per hour. This rate may range from 0 to a value less than or equal to the removal rate that is determined by the removable fraction (Section 8.3) and the source lifetime (Section 8.3) input parameters. If the direct ingestion rate is large enough to match the removal rate, then the air release fraction (Section 8.6) input must be set to 0 to maintain mass balance.

5.8 Indirect Ingestion Rate

Applicable Code: RESRAD-BUILD

Description: This parameter represents the ingestion rate of deposited material for a receptor at a specified location inside the building. This rate represents the transfer of deposited contamination from building surfaces to the mouth via contact with hands, food, or other objects. The indirect ingestion rate is expressed as the surface area contacted per unit time.

Units: square meters per hour (m^2/h)

Probabilistic Input:

Distribution: loguniform

Defining Values for Distribution:

Minimum: 2.8×10^{-5} Maximum: 2.9×10^{-4}

Discussion: Only limited information is available on the values for this parameter. As reported in Beyeler et al. (1998a), only eight data references are available (Dunster, 1962; Gibson and Wrixon, 1979; Healy, 1971; Kennedy et al., 1981; Sayre et al., 1974; Lepow et al., 1975; Walter et al., 1980; Gallacher et al., 1984). However, half of these studies concerned intake by children, not adults in an occupational setting. A larger, secondary set of data from soil ingestion studies is available (see Section 5.6), but again, the primary emphasis has been soil ingestion rates of children because of concern over elevated exposures from intensive mouthing behavior in this age group. Only two studies (Calabrese et al., 1990; Stanek et al., 1997) have provided empirical data for soil ingestion in adults. Comprehensive reviews of soil ingestion by humans can be found in EPA (1997) and Simon (1998).

Because the indirect ingestion rate is specified as the surface area contacted per unit time, estimates of daily ingested amount were converted to the proper units by using estimates for deposited contamination (soil) concentrations on surfaces and soil loadings on the hand (Beyeler et al., 1998a). Thus, a large uncertainty for the indirect ingestion rate is expected; in fact, the uncertainty is larger than the anticipated variability across sites (Beyeler et al., 1998a). For this reason, Beyeler et al. (1998a) have proposed two alternative distributions. However, Beyeler's suggested procedure produces an effective ingestion rate. It incorporates the number of hand-to-mouth events per day and transfer efficiencies between surface-to-hand and hand-to-mouth because these factors were not explicitly accounted for in the calculation.

The two alternative distributions were proposed on the basis of mean ingestion rates of 0.5 and 50 mg/d. These rates fall within the 0 to 70 mg/d range for mean ingestion rates thought to be consistent with the empirical data (Calabrese et al., 1990; Calabrese and Stanek, 1995; Stanek et al., 1997). The minimum and maximum ingestion rates were taken to be 0 and 200 mg/d, respectively. In the most comprehensive study, 10 subjects were followed for 28 days, yielding an average ingestion rate of 10 mg soil/d, with an upper 95% value of 331 mg soil/d (Stanek et al., 1997). Dust loadings were assumed to range from 10 mg/m^2, taken to be the lower limit in a residential setting, to 5,000 mg/m^2, taken to correspond to heavily soiled hands.

The resulting loguniform distributions (Table 5.8-1) for the indirect ingestion rate parameter ranged from 4.4×10^{-4} to 4.6×10^{-3} m^2/d, with a mean of 1.8×10^{-3} m^2/d; and from 5.1×10^{-2} to 4.3×10^{-1} m^2/d, with a mean of 1.8×10^{-1} m^2/d. For use in RESRAD-BUILD, a 16-hour day was assumed, resulting in distributions with means of 1.1×10^{-4} and 1.1×10^{-2} for the low and high average ingestion rate distributions presented in Table 5.8-1. As discussed in Beyeler et al. (1998a), an ingestion rate corresponding to 1×10^{-2} m^2/h implies mouthing an area equivalent to the inner surface of the hand once each hour. Such an ingestion rate appears to be an upper bound for a commercial environment. Because adult ingestion rates can often approach zero (the lower bound), the lower ingestion rate distribution has been selected as a default for use in RESRAD-BUILD. Figure 5.8-1 presents the probability density function.

Table 5.8-1 Indirect Ingestion Rates

Parameter	Mean	Lower Limit	Upper Limit
Dust loading (mg/m^2)[a]	320	10	5000
Low ingestion rate input (mg/d)[a]	0.50	0	200
High ingestion rate input (mg/d)[a]	50	0	200
Low ingestion rate estimate (m^2/d)[a]	1.8×10^{-3}	4.4×10^{-4}	4.6×10^{-3}
High ingestion rate estimate (m^2/d)[a]	1.8×10^{-1}	5.1×10^{-2}	4.3×10^{-1}
RESRAD-BUILD input[b]			
Low ingestion rate estimate (m^2/h)	1.1×10^{-4}	2.8×10^{-5}	2.9×10^{-4}
High ingestion rate estimate (m^2/h)	1.1×10^{-2}	3.2×10^{-3}	2.7×10^{-2}

[a] Source: Beyeler et al. (1998a).

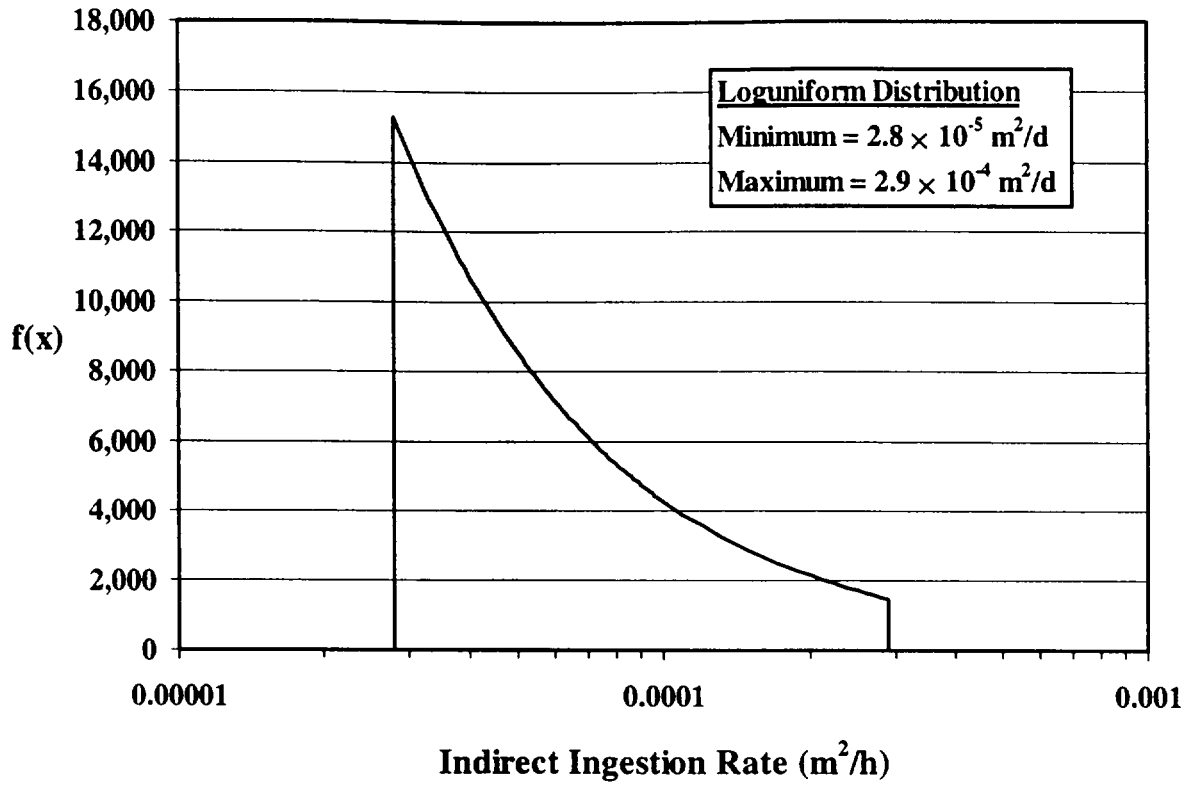[b] Assumes a 16-hour day using the results from Beyeler et al. (1998a).

Figure 5.8-1 Indirect Ingestion Rate Probability Density Function

6 CROPS AND LIVESTOCK PARAMETER DISTRIBUTIONS

6.1 Depth of Roots

Applicable Code: RESRAD

Description: This parameter represents the average root depth of various plants grown in the contaminated zone.

Units: meters (m)

Probabilistic Input:

Distribution: Uniform

Defining Values for Distribution:

Minimum: 0.3   Maximum: 4.0

Discussion: Root depth varies for different plants. For some plants, such as beets, carrots, lettuce, and others, root depth does not extend below about 0.3 m. For other plants, such as fruit trees, the roots may extend 2 or 3 m below the surface; tap roots for some crops (e.g., alfalfa) can extend to 5 m. Most of the plant roots from which nutrients are obtained, however, usually extend less than 1 m below the surface.

This parameter is used to calculate the cover and depth factor for the plant, meat, and milk exposure pathways because edible plants become contaminated through root uptake of radionuclides. Uptake of radionuclides from plant roots is assumed possible only when the roots extend to the contaminated zone and is limited to the fraction of roots that have direct contact with contaminated soil.

Each crop has characteristic rooting habits that it will tend to follow if the soil is deep, uniform, and equally moist throughout. The depth of rooting increases during the growing period. Crops that mature in 2 months usually penetrate only 0.6 to 0.9 m, and crops requiring 6 months to mature may penetrate 1.8 to 3.0 m or more.

When the upper portion of the soil is kept moist, plants will obtain most of their moisture supply from near the surface. As the moisture content of the upper layers decreases, the plants draw more water from the lower layers, which will encourage more root development in the lower levels. Fewer roots exist in the lower portion of the root zone because of the inability of the root system to extract enough moisture from the lower levels.

Generally, the average root-zone depths are reached by the time the foliage of the plant has reached its maximum size. Root-zone depths are limited to the soil depth above the water table.

Tables 6.1-1 and 6.1-2 list rooting depths for a variety of crops. Because growing conditions (e.g., amount of rainfall or temperature) and plant types vary widely across the United States, a uniform distribution spanning the range of potential crops is suggested for use in RESRAD, with a minimum of 0.3 m and a maximum of 4.0 m, as shown in Figure 6.1-1. If specific conditions are known, values from Tables 6.1-1 and 6.1-2 may be used.

Table 6.1-1 Normal Root-Zone Depths of Mature, Irrigated Crops Grown in a Deep, Permeable, Well-Drained Soil

Crop	Depth (m)	Crop	Depth (m)
Alfalfa	1.5-3.0	Grapes	1.2-1.8
Artichokes	1.2	Grass pasture	0.9-1.2
Asparagus	1.8-3.0	Hops	1.5-2.4
Beans	0.9-1.2	Ladino clover	0.6
Beets (sugar)	1.2-1.8	Lettuce	0.3-0.5
Beets (table)	0.6-0.9	Mint	0.9-1.2
Broccoli	0.6	Onions	0.3
Cabbage	0.6	Parsnips	0.9
Cantaloupes	1.2-1.8	Peas	0.9-1.2
Cane berries	0.9-1.2	Potatoes (Irish)	0.9-1.2
Carrots	0.6-0.9	Potatoes (sweet)	1.2-1.8
Cauliflower	0.6	Pumpkins	1.8
Celery	0.9	Radishes	0.3
Citrus	1.2-1.8	Spinach	0.6
Corn (sweet)	0.9	Squash	0.9
Corn (field)	0.9-1.5	Strawberries	0.9-1.2
Cotton	1.2-1.8	Tomatoes	1.8-3.0
Cranberries	0.3-0.6	Turnips	0.9
Deciduous orchards	1.8-2.4	Walnuts	3.7
Grain	1.2	Watermelons	1.8

Sources: Modified from Calvin and Knutson (1983); Peirce (1987); Zipparro et al. (1993).

Table 6.1-2 Range of Active Plant Rooting Depths

Crop	Depth (m)	Crop	Depth (m)
Corn	0.6-1.2	Potatoes	0.15-0.45
Soybeans	0.3-0.6	Peanuts	0.3-0.6
Cotton	0.3-0.9	Tobacco	0.3-0.6
Wheat	0.15-0.3	Grain sorghum	0.15-0.3

Source: EPA (1993).
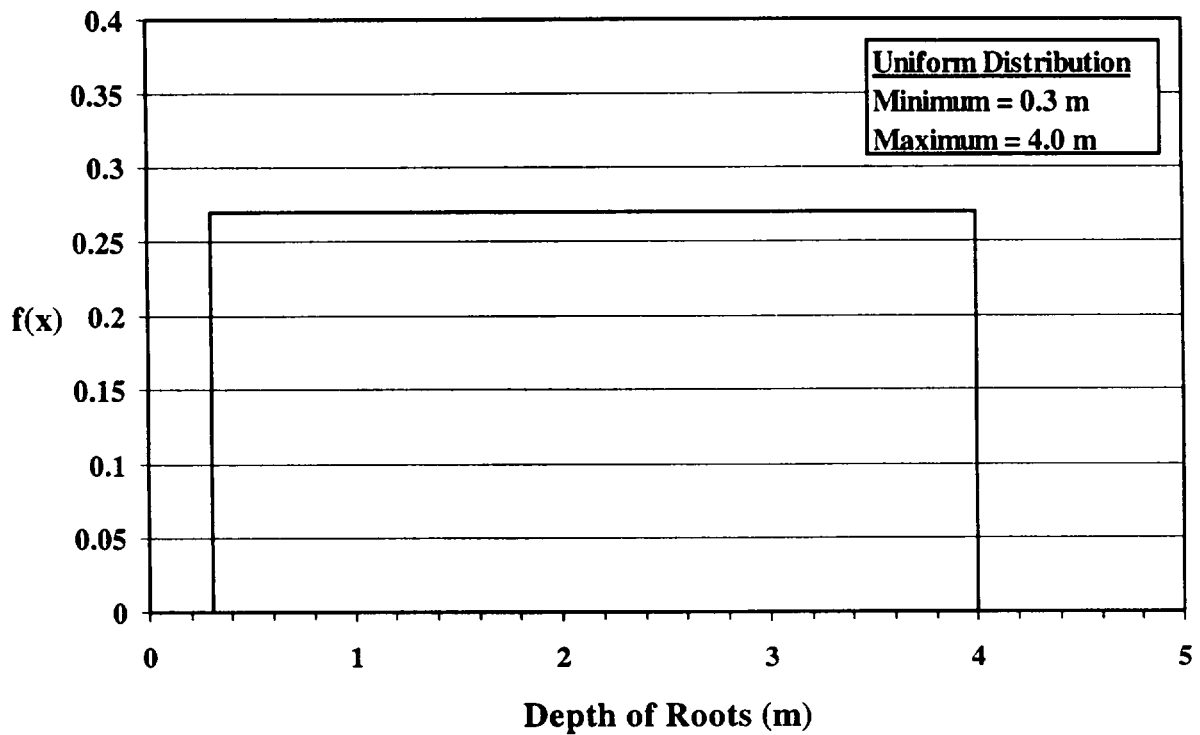
Figure 6.1-1 Depth of Roots Probability Density Function

6.2 Transfer Factors for Plants

Applicable Code: RESRAD

Description: The plant/soil concentration ratios for root uptake are given by the vegetable/soil transfer factors. In the RESRAD code, the plant/soil transfer factor is expressed as the ratio: picocuries per gram (pCi/g) plant (wet)/pCi/g soil (dry) (Yu et al., 1993a).

Units: pCi/g plant (wet) per pCi/g soil (dry)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution: Values are assigned according to the element of the radioactive isotope, as given in Table 6.2-1. Lower and upper quantile input values are 0.001 and 0.999 for all elements.

Discussion: The plant/soil transfer factor, B_v, is defined as the ratio of radionuclide concentration in vegetation to that of the soil. The plant/soil transfer factor of a radionuclide varies in a complex manner with soil properties and the geochemical properties of the radionuclide in the soil. The transfer factor for a given plant type can vary from site to site and season to season. In addition, management practices such as plowing, liming, fertilizing, and irrigating greatly affect the plant/soil transfer ratio (International Atomic Energy Agency [IAEA], 1994). After entering the transpiration stream, radionuclides may not be uniformly distributed within a plant, but instead they tend to concentrate in certain plant organs (Grogan, 1985). Sparse data exist for most radionuclides, and the data that do exist are restricted to only limited vegetation types (National Council on Radiation Protection and Measurements [NCRP], 1999). Even for the most studied radionuclides, the values of the plant/soil transfer factors can vary over several orders of magnitude (IAEA, 1994).

In the RESRAD code, the plant/soil transfer factor is a composite value of multiple vegetation types and is expressed as the ratio: pCi per gram plant (wet) / pCi per gram soil (dry). An example of calculating the composite plant/soil transfer factor is provided in Appendix B of Gnanapragasam and Yu (1997). In other published radiological assessment reports, as discussed below for NUREG/CR-5512, the plant/soil transfer factors are provided for different vegetation types and are given as the ratio of pCi per gram plant (dry)/pCi per gram soil (dry). To convert from the vegetation-specific dry plant/soil transfer

Table 6.2-1 Lognormal Distribution Parameter Values for Plant/Soil Transfer Factors

Element	μ	σ	Element	μ	σ
H	1.57	1.1	Ta	-6.21	1.1
Be	-5.52	1.1	Cu	-3.00	1.0
C[a]	-0.36	0.9	Zn	-0.92	0.9
N[a]	3.40	0.9	Ge	-0.92	1.1
F	-3.91	1.1	As	-2.53	1.1
Na	-3.00	1.0	Se	-2.30	1.1
Mg	-3.5	1.1	Br	-0.92	1.1
Si	-3.9	1.1	Rb	-1.61	1.0
Al	-5.52	1.1	Sr	-1.20	1.0
P	0.00	1.1	Y	-6.21	1.1
S	-0.51	1.1	Zr	-6.91	1.1
Cl	3.00	1.1	Nb	-4.61	1.1
K	-1.20	1.1	Mo	-2.30	1.1
Ca	-0.69	1.1	Tc	1.61	0.9
Sc	-6.21	1.1	Ru	-3.51	0.9
Cr	-4.61	1.0	Rh	-3.51	1.0
Mn	-1.20	0.9	Pd	-2.30	1.1
Fe	-6.91	0.9	Ag	-5.52	0.9
Co	-2.53	0.9	Cd	-0.69	1.1
Ni	-3.00	0.9	W	-0.22	1.0
In	-5.81	1.1	Ir	-3.51	1.1
Sn	-1.20	1.1	Au	-2.30	1.1
Sb	-4.61	1.0	Hg	-1.20	1.1
Te	-2.30	1.0	Tl	-1.61	1.1
I	-3.91	0.9	Pb	-5.52	0.9
Cs	-3.22	1.0	Bi	-2.30	1.1
Ba	-4.61	1.1	Po	-6.9	0.9
La	-6.21	0.9	Ra	-3.22	0.9
Ce	-6.21	1.0	Ac	-6.91	1.1
Pr	-6.21	1.0	Th	-6.91	0.9
Nd	-6.21	1.0	Pa	-4.61	1.1
Pm	-6.21	1.1	U	-6.21	0.9
Sm	-6.21	1.1	Np	-3.91	0.9
Eu	-6.21	1.1	Pu	-6.91	0.9
Gd	-6.21	1.1	Am	-6.91	0.9
Tb	-6.21	1.1	Cm	-6.91	0.9
Ho	-6.21	1.1	Cf	-6.91	1.1

[a] Derived from Yu et al. (1993a).

Source: NCRP (1999) except as noted.

factor to a composite wet plant/soil transfer factor, a dry to wet conversion factor must be determined for each vegetation type. In addition, the vegetation-specific transfer factors must be weighted by relative importance (measured in kilograms) of each vegetable category (Wang et al., 1993). Although the transfer factors may range over a couple of orders of magnitude for different radionuclides, the range among vegetation types for a given radionuclide is not as great (NCRP, 1999).

A lognormal distribution is consistently proposed as most appropriate for the plant/soil transfer factor (Beyeler et al., 1998b). The plant/soil transfer factors were obtained from Appendix D of the National Council on Radiation Protection and Measurements Report 129 (NCRP, 1999), except as noted. The report provides median and geometric standard deviations for composite wet plant/soil transfer factors for each element listed in Table 6.2-1. These values were compared with the values currently used in the RESRAD computer code and were found to be consistent. The parameters describing the lognormal probability distribution of the plant/soil transfer factors for each element were estimated by setting the natural logarithm of the geometric standard deviation equal to σ and setting μ equal to the natural logarithm of the median value given in Appendix D of NCRP Report 129 (NCRP, 1999).

The current version of the RESRAD computer code requires the plant transfer factors to be expressed as the ratio of pCi per gram plant (wet)/pCi per gram soil (dry). Other studies, such as NUREG/CR-5512 (Kennedy and Strenge, 1992), express the transfer factor for the four plant types as the ratio of pCi per gram plant type (dry)/pCi per gram soil (dry). A dry-to-wet weight conversion factor must therefore be applied to make proper comparisons between the transfer factors. An overall average conversion factor of 0.428 has been estimated by Baes et al. (1984). This average factor is based on several factors, including (1) calculation of the dry-to-wet weight conversion factors for exposed produce, protected produce, and grains on the basis of relative importance of various nonleafy vegetables in the United States; and (2) calculation of the average dry-to-wet conversion factor by weighting these calculated values by the relative importance (based on production, in kilograms) of each vegetable category grown in the United States. When an overall average dry-to-wet conversion factor of 0.428 is applied to the plant transfer factors given in Table 6.2-1, the values are in good agreement with the values presented in NUREG/CR-5512 (Kennedy and Strenge, 1992), especially when the transfer factors can vary by a factor of 10 or more for the same vegetation type.

6.3 Transfer Factors for Meat

Applicable Code: RESRAD

Description: The radionuclide transfer factor for meat is the ratio of the concentration of a radionuclide in meat (pCi/kg) to the rate of intake of that radionuclide (pCi/d) by the animal (Yu et al., 1993a). This parameter is used when the meat ingestion pathway is active. In the RESRAD code, the default transfer factors are for beef.

Units: picocuries per kilogram per picocuries per day (pCi/kg per pCi/d)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution: Values are assigned according to the element of the radioactive isotope as given in Table 6.3-1. Lower and upper quantile input values are 0.001 and 0.999 for all elements.

Discussion: The migration of a radioisotope from feed to a meat product is commonly modeled by using a transfer coefficient. This transfer coefficient is defined as the amount of an animal's daily intake of a radionuclide that is transferred to one kilogram of the animal meat product at equilibrium (IAEA, 1994).

For many elements and radionuclides, the transfer factor is derived from sources such as stable element concentrations in feed and animal tissues, extrapolations from single-dose tracer experiments, and comparison of elemental concentrations in associated or unassociated meat, or milk and feed (Ng et. al., 1982).

Many difficulties are associated with the development of transfer factors to meat products:

- *The need for equilibrium* — With a few exceptions, the time required for a radionuclide to reach equilibrium in many animal products (e.g., beef) is so long that few experiments can be conducted sufficiently long to establish equilibrium (IAEA, 1994).

- *Metabolic homeostasis* — Some elements, and therefore their radioisotopes, are subject to homoeostatic control; hence an increase in feed concentrations will not necessarily be reflected in tissues.

Table 6.3-1 Lognormal Distribution Parameter Values for the Transfer Factors for Meat (Beef)

Element	μ	σ	Element	μ	σ
H[a]	-4.42	1.0	Cu	-4.61	0.4
Be	-5.30	1.0	Zn	-2.30	0.3
C[a]	-3.47	1.0	Ge	-1.61	1.0
Na	-2.53	0.2	As	-3.91	1.0
Mg	-5.8	0.2	Se	-2.30	0.9
Si	-8.1	1.0	Br	-3.00	1.0
Al	-7.60	1.0	Rb	-3.51	0.7
P	-3.00	0.2	Sr	-4.61	0.4
S	-1.61	1.0	Y	-6.21	0.9
Cl	-3.22	0.7	Zr	-13.82	0.9
K	-3.91	0.2	Nb	-13.82	0.9
Ca	-6.21	0.2	Mo	-13.82	0.9
Sc	-6.21	1.0	Tc	-9.21	0.7
Cr	-3.51	0.4	Ru	-6.21	0.9
Mn	-6.91	0.7	Rh	-6.21	1.0
Fe	-3.51	0.4	Pd	-8.52	1.0
Co	-3.51	1.0	Ag	-6.21	0.7
Ni	-5.30	0.9	Cd	-6.91	0.9
In	-5.52	1.0	W	-3.22	0.9
Sn	-4.61	1.0	Ir	-6.21	1.0
Sb	-6.91	0.9	Au	-5.30	1.0
Te	-4.96	0.9	Hg	-4.61	1.0
I	-3.22	0.4	Tl	-3.91	1.0
Cs	-3.00	0.4	Pb	-7.13	0.7
Ba	-8.52	0.9	Bi	-6.21	1.0
La	-6.21	1.0	Po	-5.30	0.7
Ce	-10.82	0.9	Ra	-6.91	0.7
Pr	-6.21	1.0	Ac	-10.82	1.0
Nd	-6.21	1.0	Th	-9.21	1.0
Pm	-6.21	1.0	Pa	-12.21	1.0
Sm	-6.21	1.0	U	-7.13	0.7
Eu	-6.21	1.0	Np	-6.91	0.7
Gd	-6.21	1.0	Pu	-9.21	0.2
Tb	-6.21	1.0	Am	-9.90	0.2
Ho	-6.21	1.0	Cm	-10.82	1.0
Ta	-12.21	1.0	Cf	-9.72	1.0

[a] Derived from Hoffman et al. (1982).

Source: NCRP (1999) except as noted.

6-8

- *Effects of chemical and physical form of radionuclide and diet composition* — the availability of a radionuclide for gut uptake differs markedly, depending on the chemical and physical forms of the radionuclide and on the constituents of the diet (Beresford et al., 1989; Howard et al., 1989; Johnson et al., 1968).

- *Influence of age* — The intake of radionuclides by an animal is dependent on the animal's species, mass, age, and growth rate, as well as the digestibility of the feed (Wang et al., 1993). Although the transfer factors are higher for some young animals, this artifact is balanced by the lower feed intake rates of young animals (NCRP, 1999).

The variability in the transfer factors is assumed to follow a lognormal probability distribution (NCRP, 1999). The values for the parameters associated with the lognormal distribution for the meat transfer factors are given for each element and in Table 6.3-1.

The meat transfer factors provided in RESRAD are for beef, since beef is generally consumed in larger quantities in the United States than other meat products (NCRP, 1999). Although the values provided in Table 6.3-1 are for beef, the uncertainty estimates of the meat transfer factors were made to accommodate other meat types (pork, lamb, veal, poultry) (IAEA, 1994; NCRP, 1999).

6.4 Transfer Factors for Milk

Applicable Code: RESRAD

Description: The radionuclide transfer factor for milk is the ratio of the concentration of a radionuclide in milk (pCi/L) to the rate of intake of the same radionuclide by the animal (pCi/d) (Yu et al., 1993a). This parameter is used when the milk ingestion pathway is active. In the RESRAD computer code, the default transfer factors are for cow's milk.

Units: picocuries per liter per picocurie per day (pCi/L per pCi/d)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution: Values are assigned according to the element of the radioactive isotope as given in Table 6.4-1. Lower and upper quantile input values are 0.001 and 0.999 for all elements.

Discussion: The migration of a radioisotope from feed to milk of a dairy animal is commonly modeled by using a transfer coefficient. This transfer coefficient is defined as the amount of an animal's daily intake of a radionuclide that is transferred to one liter of milk at equilibrium (IAEA, 1994).

For many elements and radionuclides, the transfer factor is derived from sources such as stable element concentrations in feed and animal tissues, extrapolations from single-dose tracer experiments, and comparison of elemental concentrations in associated or unassociated meat, or milk and feed (Ng et. al., 1982).

Many difficulties are associated with the development of transfer factors to milk:

- *The need for equilibrium* — With a few exceptions, the time required for a radionuclide to reach equilibrium in many animal products (e.g., milk) is so long that few experiments can be conducted sufficiently long to establish equilibrium (IAEA, 1994).

- *Metabolic homeostasis* — Some elements, and therefore their radioisotopes, are subject to homoeostatic control; hence an increase in feed concentrations will not necessarily be reflected in tissues and milk.

Table 6.4-1 Lognormal Distribution Parameter Values for the Transfer Factors for Milk (Cow)

Element	μ	σ	Element	μ	σ
H[a]	-4.6	0.9	Zn	-4.61	0.9
Be	-13.12	0.9	Ge	-4.61	0.9
C[a]	-4.4	0.9	As	-9.21	0.9
Na	-3.22	0.5	Se	-4.61	0.9
Al	-8.52	0.9	Br	-3.91	0.9
P	-3.91	0.7	Rb	-4.61	0.7
S	-3.91	0.7	Sr	-6.21	0.5
Cl	-3.91	0.5	Y	-9.72	0.9
K	-4.96	0.5	Zr	-14.33	0.7
Ca	-5.81	0.5	Nb	-13.12	0.7
Sc	-5.12	0.9	Mo	-6.21	0.7
Cr	-6.21	0.7	Tc	-6.91	0.7
Mn	-8.11	0.7	Ru	-10.82	0.6
Fe	-8.11	0.7	Rh	-7.60	0.9
Co	-6.21	0.7	Pd	-9.21	0.9
Ni	-3.91	0.7	Ag	-5.12	0.7
In	-8.52	0.9	Cd	-6.21	0.9
Sn	-6.91	0.9	W	-8.11	0.9
Sb	-9.72	0.9	Ir	-13.12	0.9
Te	-7.60	0.6	Au	-11.51	0.9
I	-4.61	0.5	Hg	-7.60	0.7
Cs	-4.61	0.5	Tl	-5.81	0.9
Ba	-7.60	0.7	Pb	-8.11	0.9
La	-9.72	0.9	Bi	-6.91	0.9
Ce	-10.41	0.7	Po	-7.82	0.7
Pr	-9.72	0.9	Ra	-6.91	0.5
Nd	-9.72	0.9	Ac	-13.12	0.9
Pm	-9.72	0.9	Th	-12.21	0.9
Sm	-9.72	0.9	Pa	-12.21	0.9
Eu	-9.72	0.9	U	-7.82	0.6
Gd	-9.72	0.9	Np	-11.51	0.7
Tb	-9.72	0.9	Pu	-13.82	0.5
Ho	-9.72	0.9	Am	-13.12	0.7
Ta	-12.21	0.9	Cm	-13.12	0.9
Cu	-6.21	0.9	Cf	-13.12	0.9

[a] Derived from Hoffman et al. (1982).

Source: NCRP (1999) except as noted.

- *Effects of chemical and physical form of radionuclide and diet composition* — the availability of a radionuclide for gut uptake differs markedly depending on the chemical and physical forms of the radionuclide and on the constituents of the diet (Beresford et al., 1989; Howard et al., 1989; Johnson et al., 1968).

- *Influence of age* — The intake of radionuclides by an animal is dependent on the animal's species mass, age, and growth rate, as well as the digestibility of the feed (Wang et al., 1993). Although the transfer factors are higher for some young animals, this artifact is balanced by the lower feed intake rates of young animals (NCRP, 1999).

The variability in the transfer factors are assumed to follow a lognormal probability distribution. The values for the parameters associated with the lognormal distribution for the milk transfer factors are given for each element in Table 6.4-1.

The milk transfer factors provided in RESRAD are for cow's milk, since cow's milk is generally consumed in larger quantities in the United States than other milk types (NCRP, 1999). To model the doses associated with consuming milk products other than cow's milk, the transfer factors should be adjusted for the appropriate ingestion product (e.g., goat's milk).

6.5 Wet Weight Crop Yields for Nonleafy Vegetables

Applicable Code: RESRAD

Description: The wet weight crop yield is the quantity of nonleafy vegetables that can be produced over an area of land. This parameter is used in calculating the plant-food/soil concentration ratio for foliar deposition and the plant-food/water concentration ratio for overhead irrigation.

Units: kilograms per square meter (kg/m^2)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution:

Underlying mean value :	0.56	Lower quantile value:	0.001
Underlying standard deviation:	0.48	Upper quantile value:	0.999

Discussion: Crop yields vary from state to state. The USDA publishes an annual statistical bulletin listing production rates and estimated crop values for all food commodities. Data from the statistical bulletin *Vegetables: Final Estimates by States, 1992-1997* (USDA, 1999) were used to estimate the crop yields for nonleafy vegetables.[1] The crop yields were found to remain relatively constant over the 6-year interval covered by the report. The data varied the greatest from state to state, with Oklahoma having the smallest nonleafy crop yield (0.6 kg/m^2) and Idaho having the largest (6.8 kg/m^2). The probability distribution function reflects the variance in crop production over the 50 states.

The nonleafy crop yield for a particular state was estimated by subtracting the production rates for leafy vegetables from the total vegetable production rate. States with the largest leafy vegetable production included California, Arizona, and Florida (USDA, 1999). Since the annual crop yields did not vary much over the 6-year period, data from 1992 were used to estimate the nonleafy vegetable crop yields for each state. The nonleafy vegetable crop yield was assumed to be distributed lognormally, and the parameters of the lognormal distribution were estimated from 1992 data for all 50 states. The crop yields were weighted on the basis of the size of the agricultural area of the state. Bayesian techniques were used to estimate the posterior probability densities for the parameters μ and σ. The posterior means for both parameters were then estimated, and

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[1] Nonleafy vegetables include all vegetables except cabbage, cauliflower, broccoli, celery, lettuce, and spinach.

these values were used as the defining values for the probability distribution for the wet weight crop yield. Figure 6.5-1 presents the probability density function.

Wet Weight Crop Yields for Nonleafy Vegetables (kg/m^2)
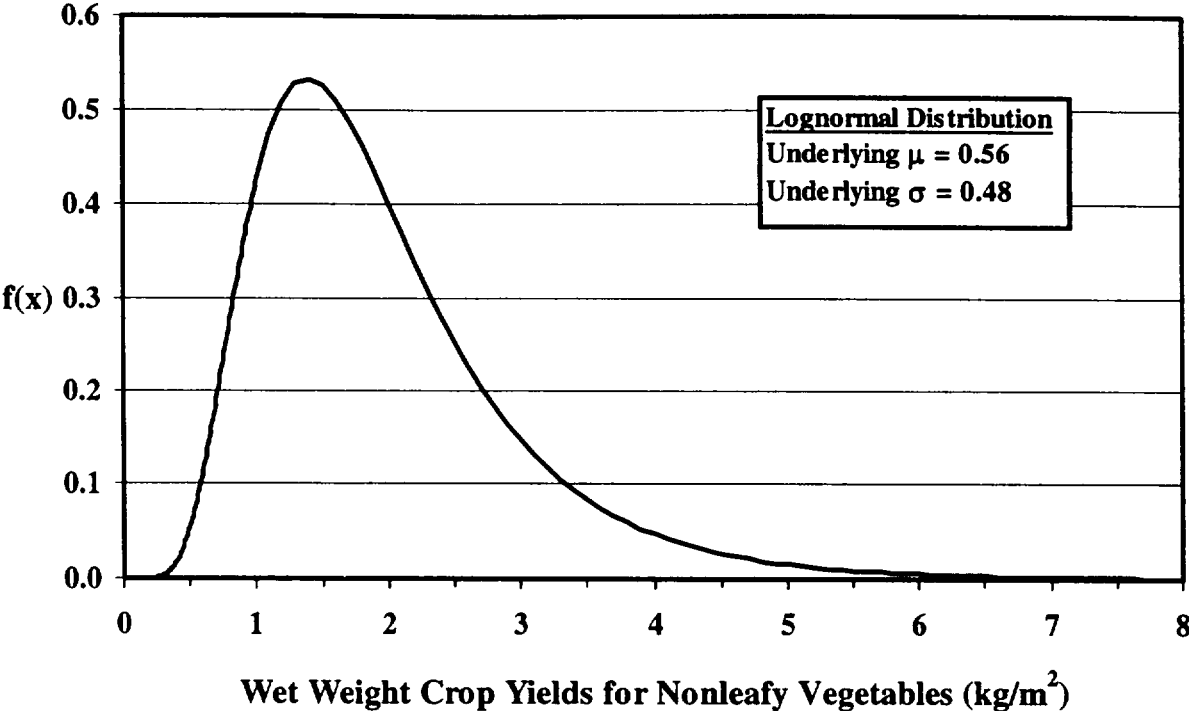
Figure 6.5-1 Wet Weight Crop Yields for Nonleafy Vegetables Probability Density Function

6.6 Weathering Removal Constant

Applicable Code: RESRAD

Description: Some of the airborne contaminants that are intercepted and initially retained by the foliage of plants are removed from the plant by a number processes This removal is modeled by an exponential function of time, and the rate of removal is represented in RESRAD by the weathering removal constant.

Units: year^{-1}

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 5.1   Maximum: 84   Most likely: 18

Discussion: The concentration of contaminants initially intercepted and retained by the foliage of plants decreases over time because of a number of removal processes, including radioactive decay, wash off, wind action, dilution by new growth, and volatilization (IAEA, 1994) This reduction is modeled in RESRAD by a first order removal rate termed the "weathering removal rate," λ_w. Two related parameters are the retention half life, $T_{\frac{1}{2}}$, and the residence time or time constant, τ. These parameters are related by:

$$\lambda_w = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}}$$ (6.6-1)

Brown et al. (1997) report values for the retention half-life submitted by a number experts. These values were converted to removal constants and were used to estimate the values for the triangular distribution suggested here. Retention half-life values ranged from 2 to 15 days for 5th percentile estimates, 7 to 30 days for 50th percentile estimates, and 15 to 50 days for 95th percentile estimates (Brown et al., 1997). Estimates varied in part because of effects specific to plant type and radionuclide species. Maximum, minimum, and most likely retention half-lives of 50, 3, and 14 days were selected. These values correspond to minimum, maximum, and most likely values of 5.1, 84, and 18 yr^{-1}, respectively, for the weathering removal constant. The probability density function is shown in Figure 6.6-1.
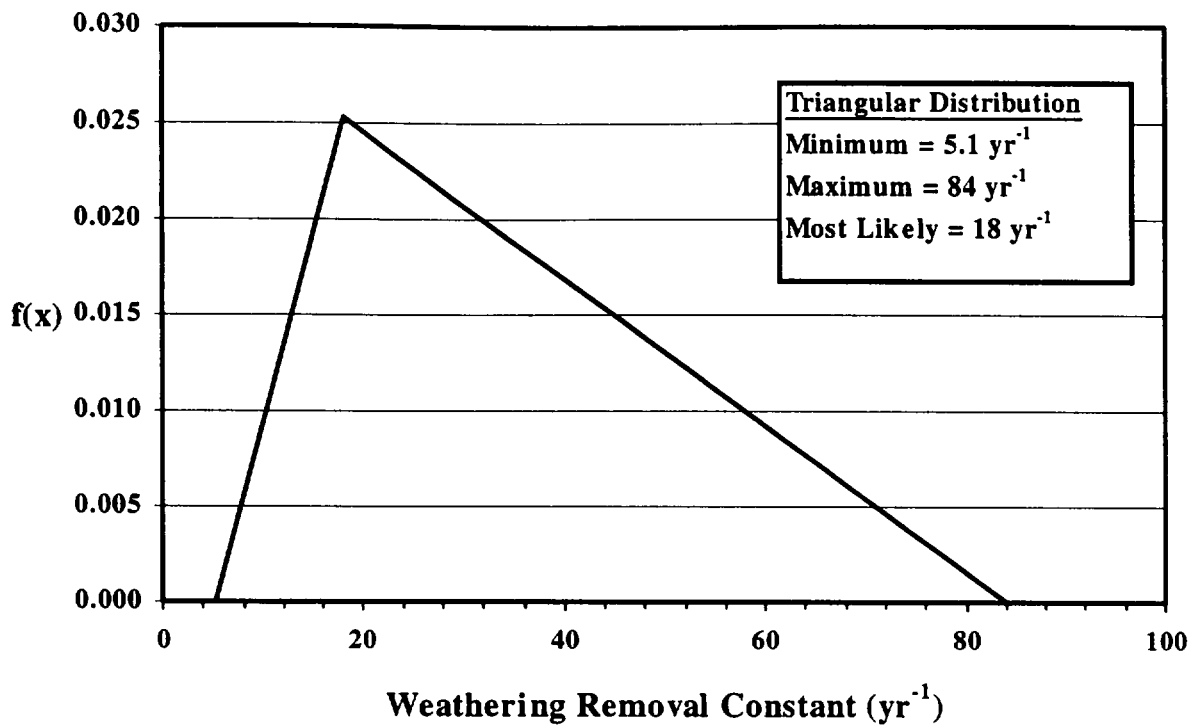
Figure 6.6-1 Weathering Removal Constant Probability Density Function

The chart shows a triangular distribution with:

Triangular Distribution
Minimum = 5.1 yr^{-1}
Maximum = 84 yr^{-1}
Most Likely = 18 yr^{-1}

X-axis: Weathering Removal Constant (yr^{-1})
Y-axis: f(x)

6.7 Wet Foliar Interception Fraction for Leafy Vegetables

Applicable Code: RESRAD

Description: This parameter represents the fraction of airborne contamination wet deposited on an agricultural or pasture area that is intercepted and initially retained by the foliage of leafy vegetables.

Units: unitless

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 0.06   Maximum: 0.95   Most likely: 0.67

Discussion: Retention of wet-deposited contaminants on vegetation is strongly influenced by both the ionic nature of the contaminant species and the amount of rainfall at the time of deposition. Anions are retained much less than insoluble particulates or cations because plant surfaces tend to have a negative charge (Hoffman et al., 1995; Prohl et al., 1995). Thus, chemical species with a higher positive charge tend to be retained the most. The amount of rainfall in a discrete rain event also plays an important part in the amount of deposited contamination that is initially retained (Prohl et al., 1995). The larger the amount of rainfall in the overall event, the less intercepted contamination is retained.

Only an approximation of the probability density function for the wet foliar interception fraction can be made because of the broad application of the distribution in RESRAD to all event types (i.e., different species and rainfall amounts) and because limited data are available for only a few chemical species and associated rainfall amounts. Brown et al. (1997) report values for the wet foliar interception fraction solicited from a number of experts. Wet foliar interception factors for green vegetables ranged from 0.03 to 0.6 for 5th percentile estimates, 0.05 to 0.8 for 50th percentile estimates, and 0.8 to 1.0 for 95th percentile estimates (Brown et al., 1997). Minimum, maximum, and most likely interception fractions of 0.06, 0.95, and 0.67 were selected for use in a triangular distribution. The probability density function is shown in Figure 6.7-1.
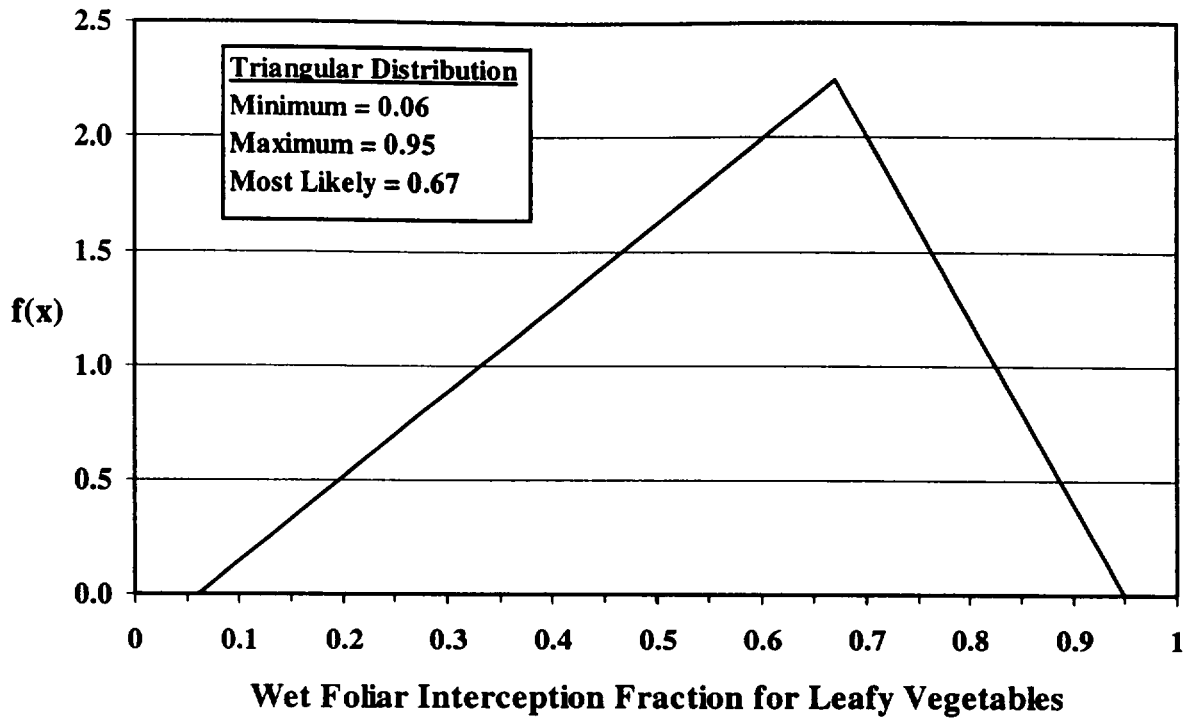
Figure 6.7-1 Wet Foliar Interception Fraction Probability Density Function

6.8 Bioaccumulation Factors for Fish

Applicable Code: RESRAD

Description: The bioaccumulation factor for fish is used to calculate the transfer of a radionuclide from contaminated water through various trophic levels of aquatic foodstuffs consumed by humans. This factor is normally expressed as the ratio of radioactivity in animal tissue to that in water at equilibrium conditions.

Units: picocuries per kilogram (of tissue) per picocurie per liter (of water) (pCi/kg per pCi/L)

Probabilistic Input:

Distribution: lognormal-n

Defining Values for Distribution: Values are assigned specific to each radioactive isotope, as provided in Table 6.8-1.

Discussion: The bioaccumulation factor for an aquatic organism or tissue is the ratio of radionuclide concentration in the whole organism or tissue to the concentration of that same radionuclide in water. The incorporation of a radionuclide into fish is a complex process. Factors such as the age of the fish, feeding habits, freshwater versus marine environments, seasonal variations, and the chemical composition of the water dramatically affect the bioaccumulation factor (Wang et al., 1993; NCRP, 1984). In addition, the method used to estimate the bioaccumulation factor can itself influence the results of the measurements (NCRP, 1984).

Young, rapidly growing fish may accumulate higher levels of biologically active radionuclides than fish in a stationary growth period. The differences in osmoregulatory problems faced by freshwater fish compared with marine fish also produce differences in route of radionuclide uptake (Poston and Klopfer, 1986). In seawater, the salt concentration is high, and marine fish drink large amounts of water and expend considerable energy to excrete salt against the concentration gradient (Wang et al., 1993). In freshwater, fish retain salt and excrete a large amount of water. Therefore, radionuclides in the water column, present either as dissolved species or sorbed onto particulate matter, are more prone to gastrointestinal absorption by marine species than by freshwater species (Poston and Klopfer, 1986). The chemical composition of water can also influence the bioaccumulation of radionuclides by freshwater biota. Recommendations have been made to use different bioaccumulation factors depending on the mineral content of the water (NCRP, 1984).

In the literature, bioaccumulation factors are derived by a number of methods, and the reported values vary widely (Wang et al., 1993). Historically, radioactivity in animal tissue is estimated on the basis of ash weight, dry weight, wet weight, and whole body burdens, or muscle tissue. These different measurement methods can dramatically affect the computed bioaccumulation factor of the fish. As an example, estimating the bioaccumulation factor on the basis of the whole-body burden of a fish for bone-seeking radionuclides (radium, strontium) would lead to an overestimate of the concentration in the muscle tissue (NCRP, 1984). This overestimation would ultimately lead to an overestimate of the dose to a receptor from the ingestion of fish. Radioactivity in water is measured on the basis of filtered or unfiltered water. Since a significant fraction of some elements in water may be in the suspended phase, bioaccumulation factors based on filtered samples may be much greater than the bioaccumulation factors on unfiltered samples (NCRP, 1984).

The bioaccumulation factors presented in this section were obtained from Wang et al. (1993). On the basis of the research of Hoffman and Baes (1979) and Vanderploeg et al. (1975), it was assumed that the bioaccumulation factors were distributed lognormally. Values for the parameter μ (the underlying mean) for the lognormal distributions were obtained by taking the natural logarithm of the suggested value in Table 12 of Wang et al. (1993). Since bioaccumulation factors can range over orders of magnitude, the geometric standard deviation was set to 3 for most elements, and the parameter σ (standard deviation) for the lognormal distribution was estimated by taking the natural logarithm of the geometric standard deviation.

Table 6.8-1 Lognormal Distribution Parameter Values for Bioaccumulation Factors for Fish

Element	μ	σ	Element	μ	σ
H	0	0.1	Sn	8.0	1.1
Be	4.6	1.1	In[a]	9.2	1.1
C	10.8	1.1	Sb	4.6	1.1
N	12	1.1	Te	6.0	1.1
F	2.3	1.1	I	3.7	1.1
Na	3	1.1	Cs	7.6	0.7
Al[a]	6.2	1.1	Ba	1.4	1.1
P	10.8	1.1	La	3.4	1.1
S	6.9	1.1	Ta[a]	4.6	1.1
Cl	6.9	1.1	Ce	3.4	1.1
K	6.9	1.1	Pr	4.6	1.1
Ca	6.9	1.1	Nd	4.6	1.1
Sc	4.6	1.1	Pm	3.4	1.1
Cr	5.3	1.1	Sm	3.2	1.1
Mn	6	1.1	Eu	3.9	1.1
Fe	5.3	1.1	Gd	3.2	1.1
Co	5.7	1.1	Tb	3.2	1.1
Ni	4.6	1.1	Ho	3.2	1.1
Cu	5.3	1.1	W	3.2	1.1
Zn	6.9	1.1	Ir	2.3	1.1
Ge[a]	8.3	1.1	Au[a]	3.5	1.1
As	5.7	1.1	Hg	6.9	1.1
Se	5.1	1.1	Tl[a]	9.2	1.1
Br	6.0	1.1	Pb	5.7	1.1
Rb	7.6	1.1	Bi	2.7	1.1
Sr	4.1	1.1	Po	4.6	1.1
Y	3.4	1.1	Ra	3.9	1.1
Zr	5.7	1.1	Ac	2.7	1.1
Nb	5.7	1.1	Th	4.6	1.1
Mo	2.3	1.1	Pa	2.3	1.1
Tc	3.0	1.1	U	2.3	1.1
Ru	3.0	1.1	Np	3.4	1.1
Rh	3.0	1.1	Pu	3.4	1.1
Pd	3.0	1.1	Am	3.4	1.1
Ag	1.6	1.1	Cm	3.4	1.1
Cd	5.3	1.1	Cf	3.2	1.1

[a] NCRP (1996).

Source: Based on Wang et. al. (1993) except as noted.

7 BUILDING CHARACTERISTICS PARAMETER DISTRIBUTIONS

7.1 Indoor Dust Filtration Factor

Applicable Code: RESRAD

Description: The indoor dust filtration factor represents the fraction of outdoor contaminated dust that is available indoors.

Units: unitless

Probabilistic Input:

Distribution: uniform

Defining Values for Distribution:

Minimum: 0.15   Maximum: 0.95

Discussion: The indoor dust filtration factor, the ratio of the long-term indoor-to-outdoor air concentrations of particulates, provides a measure of a building's effectiveness at removing particulate contaminants from the outdoor air that enters the building. This parameter is sometimes referred to as an inhalation shielding factor or a dose reduction factor when applied to inhalation exposures. The contribution of outdoor air to indoor particulate levels is primarily a function of a building's ventilation rate (including infiltration) and the indoor deposition velocity of the particulates.

As further discussed in Section 7.4, the ventilation rate of buildings depends on the climate and season. For example, aside from mechanical ventilation, infiltration of outdoor air depends on temperature, wind speed, and quality of building construction. Earlier investigations found indoor/outdoor air concentration ratios for different building types ranging from close to 0 up to 1 (see Table 7.1-1). Even for office or industrial building types, with the mechanical ventilation systems turned off, air exchange can still be significant, and estimates of the indoor/outdoor air concentrations ratios could range above 0.1 when all outdoor entrances are closed (Engelmann, 1992).

It is believed that particulates of less than 10 μm in aerodynamic diameter are able to enter buildings with the same efficiency as nonreactive gases (Wallace, 1996). However, larger contaminant particles will deposit faster than smaller particulates, posing less of a radiological inhalation risk (Fogh et al., 1997).

Table 7.1-1 Indoor/Outdoor Air Concentration Ratios

Pollutant	Structure	Measured Indoor/Outdoor Ratio	Reference
Total suspended particulates	Homes and public buildings	0.16 to 0.51	Yocum et al., 1971
0.1–20 μm dust particulates	Old/new homes/university buildings	< 0.1 to 0.42	Alzona et al., 1979
Ca, Fe, Zn, Pb, Br	Homes and public and commercial buildings	0.043 to 0.85 (excluding Zn)	Cohen and Cohen, 1979
Particulates, iodine, noble gases	Wood or concrete construction	Calculated DRFs of 0.072 to 1	Kocher, 1980
Be-7	Danish and Finnish homes	0.23 to 0.86	Christensen and Mustonen, 1987
Various radioisotopes	Danish home	0.1 to 0.5	Roed and Cannell, 1987
Noble gases, methyl iodide, elemental iodine, aerosols 0.1 to 2 μm	Homes, large buildings, manufacturing facilities	Calculated DRFs of 0.004 to 1	Brenk and De Witt, 1987

A comprehensive review by Wallace (1996) indicates that numerous studies show indoor particulate concentrations can exceed outdoor concentrations because of indoor sources. When only considering outdoor sources, mean values are expected to be close to 0.5. Table 7.1-2 lists estimates of the indoor/outdoor ratio made by Wallace (1996) based on the results of the EPA's Particle Team (PTEAM) study of residential housing. An average value of approximately 0.57 was found for PM_{10}, which is between the values estimated for the fine particle fraction ($PM_{2.5}$) and the coarse particle fraction (difference of PM_{10} and $PM_{2.5}$), 0.67 and 0.48, respectively. These values were derived with the assumption of decay rates of 0.39, 0.65, and 1.01 h^{-1} for fine particles, PM_{10}, and the coarse particles, respectively, with the decay rate given by:

$$k = \frac{k_d S}{V},$$

(7.1-1)

where

k_d = the deposition velocity,

Table 7.1-2 Fraction of Outdoor Particles Found Indoors at Equilibrium (results from the PTEAM Study)

Statistic	Daytime (sample size = 174)			Overnight (sample size = 175)		
	Fine	PM_{10}	Coarse	Fine	PM_{10}	Coarse
Mean	0.68	0.58	0.49	0.66	0.55	0.46
Standard deviation	0.17	0.19	0.20	0.15	0.17	0.17
Standard error	0.013	0.015	0.015	0.012	0.013	0.013
Geometric mean	0.66	0.55	0.45	0.64	0.53	0.42
Minimum	0.28	0.19	0.13	0.28	0.19	0.13
25th percentile	0.55	0.42	0.32	0.55	0.43	0.34
Median	0.70	0.58	0.47	0.66	0.54	0.43
75th percentile	0.83	0.75	0.65	0.79	0.69	0.59
Maximum	0.95	0.93	0.89	0.94	0.90	0.85

Source: Wallace (1996).

S = interior surface area, and

V = interior volume.

The indoor/outdoor ratios were estimated using these decay rates and average air exchange rates from the PTEAM study using the relationship:

$$\frac{C_{in}}{C_{out}} = \frac{Pa}{a+k},$$

(7.1-2)

where

C_{in} = indoor particulate concentrations,

C_{out} = outdoor particulate concentrations,

P = the penetration factor (set equal to 1), and

a = the building air exchange rate (h^{-1}).

If the average air exchange rate found in Murray and Burmaster (1995) for residential housing (0.76 h^{-1}), is used in the above relationship, the estimated

indoor/outdoor ratio for PM_{10} would be 0.54, in good agreement with the values of 0.58 and 0.55 for daytime and overnight conditions, respectively, as presented in Table 7.1-2.

Limited measurement data are available for occupational settings. Table 7.1-1 shows that a fairly wide range is possible. As discussed further in Section 7.4, a wide range of air exchange rates, and therefore a wide range in indoor/outdoor concentration ratios, is expected for commercial buildings. Except for isolated instances (e.g., electronic manufacturing "clean" rooms) or shipping/receiving intensive enterprises, indoor/outdoor concentration ratios for residential settings are not expected to differ greatly, on average, from light industrial environments because the ratios depend on air exchange rates, and human comfort depends (in part) on air exchange rates. Because the air exchange rates can vary considerably with climate and season, as well as the difference attributable to particle size and occupational setting, it is not reasonable to assign a most likely value to the indoor dust filtration factor (indoor/outdoor air dust concentration ratio). Thus, a uniform distribution is selected for a generic setting, with minimum and maximum values of 0.15 and 0.95 as suggested by the results in Table 7.1-2. The probability density function is shown in Figure 7.1-1.
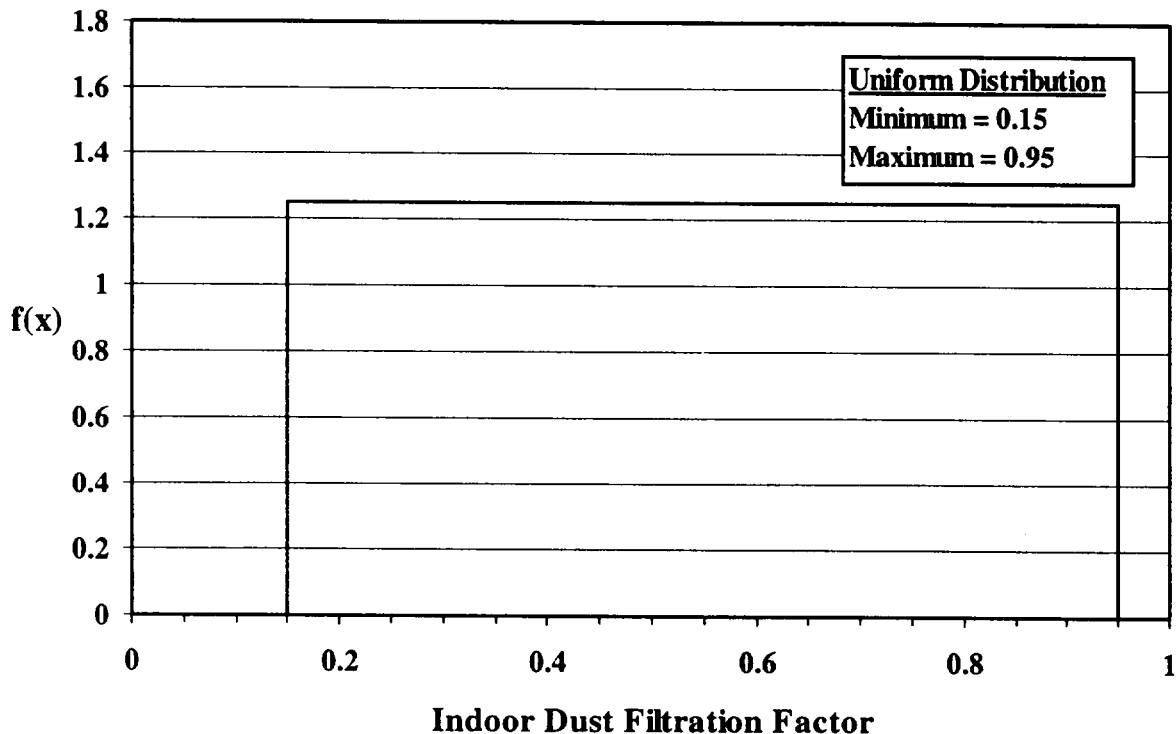
Figure 7.1-1 Indoor Dust Filtration Factor Probability Density Function

7.2 Resuspension Rate (Indoor)

Applicable Code: RESRAD-BUILD

Description: The resuspension rate (indoor) represents the rate at which material deposited on interior surfaces is resuspended into the indoor air. Resuspension is the result of airflow or a mechanical disturbance, such as walking across a surface or sweeping.

Units: 1/s

Probabilistic Input:

Distribution: loguniform

Defining Values for Distribution:

Minimum: 2.8×10^{-10} Maximum: 1.4×10^{-5}

Discussion: Indoor resuspension of contamination can lead to internal exposure via inhalation. The resuspension rate is the fraction of deposited particles resuspended per unit time. Factors that can affect resuspension include the type of disturbance (air flow vs. mechanical), the intensity of the disturbance, the type of surface, particle size distribution, and physical and chemical characteristics of the particles.

Relatively little work has been done in measuring or estimating indoor resuspension rates. The most recent work by Thatcher and Layton (1995) monitored an SF_6 tracer in a residential setting under varying conditions. Results based on particle size are given in Table 7.2-1. These results demonstrate that the larger particle sizes are more susceptible to resuspension. Earlier studies of indoor resuspension of radioactive contamination (Brunskill, 1967; Fish et al., 1967; Glauberman et al., 1967; Jones and Pond, 1967; Mitchell and Eutsler, 1967; Spangler and Willis, 1967) reported the extent of resuspension in terms of a resuspension factor, the ratio of airborne contamination to the amount deposited on surfaces.

Healy (1971) reviewed some of the earlier work on resuspension factors and estimated resuspension rates using the following approximation:

$$\lambda_r = R_f \frac{V}{A} \lambda_v ,$$

(7.2-1)

Table 7.2-1 Indoor Resuspension Rates

Resuspension Rate (1/s)	Resuspension Factor (m⁻¹)[a]	Conditions	Reference	Comments
2.8×10^{-10} 1.2×10^{-10} 5.0×10^{-9} 2.3×10^{-8} 1.1×10^{-7} 9.4×10^{-9}		0.3-0.5 μm particles 0.5-1 μm particles 1-5 μm particles 5-10 μm particles 10-25 μm particles > 25 μm particles	Thatcher and Layton, 1995	Estimated for residence with four residents performing "normal" activities. Assumed air exchange rate of 0.3 h⁻¹.
2.8×10^{-8}		"Characteristic value" for a uranium diffusion plant	Healy, 1971	Quoted from study by Spangler and Willis (1967).
1.7×10^{-6} 5.6×10^{-7} 2.8×10^{-7} 1.9×10^{-6}	1.9×10^{-4} 3.9×10^{-5} 9.4×10^{-6} 7.1×10^{-4}	Vigorous work including sweeping (ZnS) Vigorous walking (ZnS) Collecting contaminated samples (ZnS) Light sweeping with fans on for circulation (CuO)	Healy, 1971	Estimated from data in Fish et al. (1967) on measurements of ZnS and CuO tracers.
8.3×10^{-7} 5.6×10^{-6} to 1.4×10^{-5}[b]	1.2×10^{-4} 3.8×10^{-3}	Walking in socks, two separate experiments	Healy, 1971	Estimated from Brunskill (1967).
0 to 3×10^{-6}	0 to 1.77×10^{-4}	No movement up to about 100 steps per minute, minimum value observed where movement was involved (14 steps per minute) was 6×10^{-9} s⁻¹ (3×10^{-7} m⁻¹)	Healy, 1971	Estimated from Jones and Pond (1967) for activity on different floor types contaminated with plutonium oxide or plutonium nitrate.

[a] Where applicable, the resuspension factor used by Healy (1971) to derive an estimated resuspension rate is given.

[b] Assumed number of air changes per hour ranged between 2 and 5.

where

λ_r = the resuspension rate,

R_f = the resuspension factor,

V = the room volume,

A = the contaminated surface area, and

λ_v = the ventilation rate.

Healy's estimates are given in Table 7.2-1. Beyeler et al. (1998a) have also reviewed the earlier work in the context of resuspension factors rather than rates.

A loguniform distribution is suggested to represent the resuspension rate because of the limited data available and the wide range of estimated values. All values in

Table 7.2-1 contain inherent assumptions with respect to ventilation rates and contaminant floor loadings. However, the wide range in the estimated values can be attributed primarily to differences in particle size and indoor human activity levels. To represent an occupational setting, the lowest value involving any type of activity in Table 7.2-1 was chosen, 2.8×10^{-10} s^{-1}. Similarly, the largest value in Table 7.2-1, 1.4×10^{-5} s^{-1}, was chosen as the maximum value for the distribution. The probability density function selected for the indoor resuspension rate is shown in Figure 7.2-1.
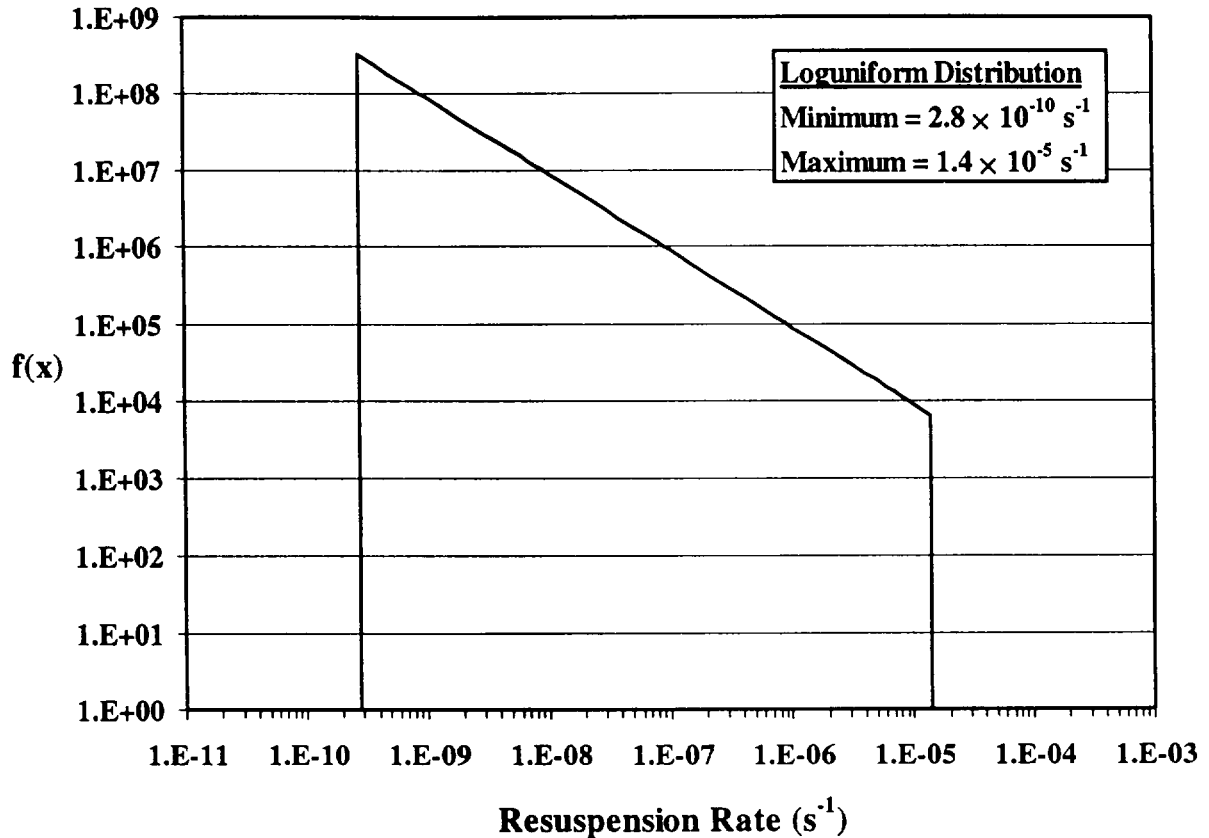
Figure 7.2-1 Indoor Resuspension Rate Probability Density Function

7.3 Shielding Density

Applicable Code: RESRAD-BUILD

Description: This parameter represents the effective density of shielding between a receptor and a radiation source.

Units: grams per cubic centimeter (g/cm^3)

Probabilistic Input (allowed only for concrete):

Distribution: uniform

Defining Values for Distribution:

Minimum: 2.2   Maximum: 2.6

Discussion: The type of shielding material along with the shielding thickness and density determines the gamma attenuation properties of the shield. This parameter is important for the external exposure pathway. For situations where only air is between the source and receptor, the shielding thickness should be set to 0 and the density becomes immaterial. The type of shielding material will often determine the density.

In the RESRAD-BUILD code, the user must input the shielding characteristics for each source-receptor pair (e.g., if there are 4 sources and 6 receptors, the code would require 24 shielding characteristics). RESRAD-BUILD accommodates eight types of shielding materials: concrete, water, aluminum, iron, lead, copper, tungsten, and uranium. Table 7.3-1 gives the density range (if appropriate) and a single value of density for the RESRAD-BUILD shielding materials that have a narrow range (except concrete). The table lists ranges for cast iron and gives a single-value density for other materials. The values are taken from the *Health Physics and Radiological Health Handbook* (Shleien, 1992) and from the *CRC Handbook of Chemistry and Physics* (Lide, 1998). Table 7.3-2 provides the concrete density from three different sources: *Health Physics and Radiological Health Handbook* (Shleien, 1992), *Properties of Concrete* (Neville, 1996), and *Standard Handbook for Civil Engineers* (Merritt et al., 1995). The value used in the code is for ordinary concrete. If the type of concrete is known, a uniform distribution between the given range for a known concrete type can be used. The probability density function for concrete shielding density is displayed in Figure 7.3-1.

Table 7.3-1 Density of Shielding Materials (except concrete) Allowed in RESRAD-BUILD

Material	Density Range (g/cm^3)	Normal Density (g/cm^3)
Aluminum	$-^a$	2.7
Copper	–	8.96
Lead	–	11.35
Steel	–	7.8
Cast iron	7.0-7.4	
Water	–	1.0
Tungsten	–	19.3
Uranium	–	19.1
Iron	–	7.87

[a] – = data not available.

Sources: Shleien (1992); Lide (1998).

Table 7.3-2 Concrete Density from Various Sources

Aggregate	Concrete Density (g/cm^3)		
	Shleien (1992)	Neville (1996)	Merritt et al. (1995)
Ordinary (silicacious) or normal weight	2.2-2.4	2.2-2.6	2.3
Heavy weight	$-^a$	–	2.4-6.15
Limonite (goethite, hyd. Fe_2O_3)	2.6-3.7	–	–
Ilmenite (nat. $FeTiO_3$)	2.9-3.9	–	–
Magnetite (nat. Fe_3O_4)	2.9-4.0	–	–
Limonite and magnetite	–	–	3.35-3.59
Iron (shot, punchings, etc.) or steel	4.0-6.0	–	4.0- 4.61
Barite	3.0-3.8	–	3.72
Lightweight	–	0.3-1.85	0.55-1.85
Pumice	–	0.8-1.8	1.45-1.6
Scoria	–	1.0-1.85	1.45-1.75
Expanded clay and shale	–	1.4-1.8	–
Vermiculite	–	0.3-0.8	0.55-1.2
Perlite	–	0.4-1.0	0.8-1.3
Clinker	–	1.1-1.4	–
Cinders without sand	–	–	1.36
Cinders with sand	–	–	1.75-1.85
Shale or clay	–	–	1.45-1.75
Cellular	–	0.36-1.5.	–
No-fines	–	1.6-2.0	1.68-1.8
No-fines with light weight aggregate	–	0.64-higher	–
Nailing	–	0.65-1.6	–
Foam	–	–	0.3-1.75

[a] – = data not available.
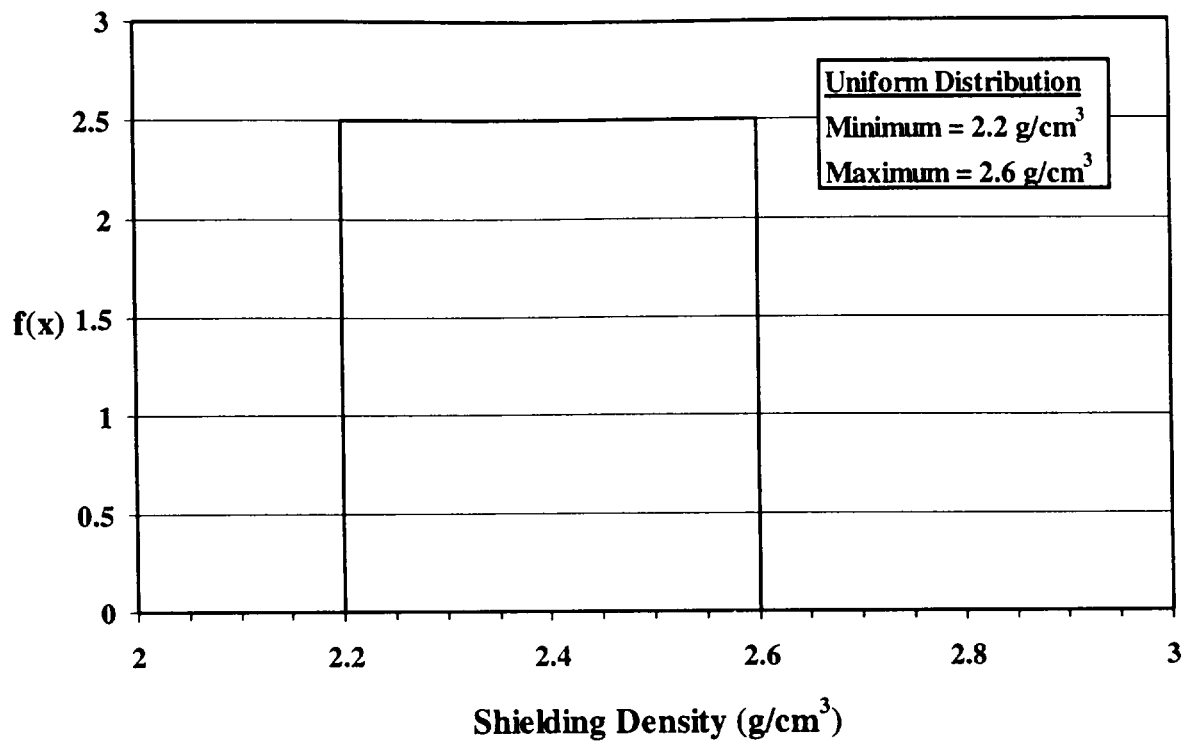
Figure 7.3-1 Concrete Shielding Density Probability Density Function

7.4 Air Exchange Rate for Building and Room

Applicable Code: RESRAD-BUILD

Description: The air exchange (or ventilation) rate for a building or a room is the total volume of air in the building or room replaced by outside air per unit of time.

Units: 1/h

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution:

Underlying mean value: 0.4187   Lower quantile value: 0.001
Standard deviation: 0.88   Upper quantile value: 0.999

Discussion: Air exchange involves three processes: (1) infiltration – air leakage through random cracks, interstices, and other unintentional openings in the building; (2) natural ventilation – air flow through open windows, doors, and othe designed openings in the building; and (3) forced, or mechanical, ventilation – controlled air movement driven by fans.

The average infiltration rate for a building can be expressed as the number of air changes per hour or air exchange rate (h^{-1}). A single building can have a range of air exchange rates depending on environmental conditions at a particular time (e.g., seasonal/diurnal ambient wind speed and temperature); other factors include building type, construction, and ventilation system. A number of studies have attempted to characterize building air exchange rates under different environmental conditions for buildings with different leakage characteristics.

A comprehensive study of residential ventilation rates was published by Pandian et al. (1993). To evaluate the distribution of ventilation rates of a large population of homes in the United States, the researchers analyzed a Brookhaven National Laboratory (BNL) database consisting of more than 4,000 residential perfluorocarbon tracer (PFT) measurements from approximately 100 individual studies. Table 7.4-1 presents summary statistics from that study on air exchange rates in the U

Table 7.4-1 Residential Air Exchange Rates (h⁻¹) Distribution Characteristics

Distribution Type	Min.	Max.	Mean	SD	Comments	References
Lognormal	0.3	2.2	0.9	1.8	Charleston, S.C. (n = 20 houses)	Doyle et al., 1984
	0.2	2.3	0.6	1.8	Colorado Springs, Colo. (n = 16 houses)	
	0.3	2.2	0.5	2.1	Fargo, N.D. (n = 11 houses)	
	0.7	1.4	1.0	1.3	Portland, Maine (n = 11 houses)	
	0.2	2.3	0.8	1.8	All cities (n = 58 houses) Calculated infiltration rates based on post-weatherization measurements of "effective leakage area"	
Normal					Pre-retrofit in one house:	Berk et al., 1981
	0.36	0.71	0.62	0.25	n = 17 measurements with fan on	
	0.18	0.56	0.33	0.14	n = 11 measurements with fan off Post-retrofit in one house:	
	0.22	0.69	0.49	0.11	n = 16 measurements with fan on	
	0.10	0.33	0.20	0.08	n = 11 measurements with fan off	
Normal	0.08	0.27	0.17	0.06	n = 12 energy-efficient houses	Lipschutz et al., 1981
Lognormal	0.1	3.1	0.5 median		n = 312 houses in North America	Grimsrud et al., 1983, as
	0.1	3.6	0.9 median		Subsample of low-income housing	cited in Godish, 1989
Lognormal	0.17	1.33	0.33 median		n = 8 mobile home measurements	Godish and Rouch, 1988
	0.18	1.45	0.36 median		n = 10 UFF-insulated home measurements	
Normal					n = 9 houses in upstate New York	Offermann et al., 1982
	0.22	0.50	0.35	0.08	With mechanical ventilation off	
	0.47	0.78	0.63	0.10	With mechanical ventilation on	
Normal					n = 10 houses in Washington state	Lamb et al., 1985
	0.40	0.98	0.27		Pre-weatherization retrofit	
	0.23	1.00	0.30		Post-weatherization retrofit	

Table 7.4-1 (Cont.)

Distribution Type	Min	Max	Mean	SD	Comments	References
Lognormal						
			0.89	3.44	All regions (*n* = 1,836) geometric mean, SD	Pandian et al., 1993
			0.34	1.88	Northwest (*n* = 423)	
			0.40	2.07	Northeast (*n* = 423)	
			1.86	3.02	Southwest (*n* = 990)	
			1.99	3.28	All regions (*n* = 1,836) arithmetic mean, SD	
			0.42	0.33	Northwest (*n* = 423)	
			0.60	2.23	Northeast (*n* = 423)	
			3.25	3.79	Southwest (*n* = 990)	
			0.76	0.88	All regions All seasons (*n* = 2844)	Murray and Burmaster, 1995
			0.55	0.47	All regions Season 1 (*n* = 1139)	
			0.65	0.57	All regions Season 2 (*n* = 1051) arithmetic mean, SD	
			1.50	1.53	All regions Season 3 (*n* = 529)	
			0.41	0.58	All regions Season 4 (*n* = 125)	
			0.40	0.30	Region 1 All seasons (*n* = 467)	
			0.55	0.48	Region 2 All seasons (*n* = 496)	
			0.55	0.42	Region 3 All seasons (*n* = 332)	
			0.98	1.09	Region 4 All seasons (*n* = 1,549)	
			0.66	0.87	West Region (arithmetic mean and SD)	Koontz and Rector, 1995
			0.57	0.63	North Central Region	
			0.71	0.60	Northeast Region	
			0.61	0.51	South Region	
			0.63	0.65	All	
			0.47	2.11	West Region (geometric mean and SD)	
			0.39	2.36	North Central Region	
			0.54	2.14	Northeast Region	
			0.46	2.28	South Region	
			0.46	2.25	All	

residences. The authors present both arithmetic and geometric means and standard deviations, as well as percentile distributions.

Murray and Burmaster (1995) also used the data compiled by BNL using the PFT technique to estimate univariate parametric probability distributions for air exchange rates for residential structures in the United States. The analysis was characterized by four key points: the use of data for 2,844 households; a four-region breakdown based on heating degree days; estimation of lognormal distributions as well as provision of empirical (frequency) distributions; and provision of these distributions for all of the data. The authors summarized distributions for subsets of the data defined by climate region and season. The coldest region (region 1) was defined as having 7,000 or more heating degree days, the colder region (region 2) as 5,500-6,999 degree days, the warmer region (region 3) as 2,500-5,499 degree days, and the warmest region (region 4) as fewer than 2,500 degree days. The months of December, January, and February were defined as season 1; March, April, and May as season 2; June, July, and August as season 3; and September, October, and November as season 4. The authors concluded that the air exchange rate was well fit by lognormal distributions for small samples sizes except in a few cases. The mean and standard deviations are listed in Table 7.4-1. The authors recommended that the empirical or lognormal distribution may be used in indoor air models or as input variables for probabilistic health risk assessments.

In a study sponsored by the EPA (Koontz and Rector [1995]), a similar data set as analyzed by Murray and Burmaster (1995) was used, but an effort was made to compensate for the nonrandom nature of the data by weighting results to account for each state's share of occupied housing units. As shown in Table 7.4-1, the results of Murray and Burmaster (1995) are similar to those for Koontz and Rector (1995).

Air exchange rates from other representative residential studies are also summarized in Table 7.4-1. The type of distribution can vary, depending on the type of study. For example, a survey of various housing types by Grimsrud et al. (1983) demonstrated that houses generally have air exchange rates that fall in a lognormal distribution between 0.1 and approximately 3 h^{-1}, with most clustered in the 0.25-0.75 range; however, some older ("leaky") houses, including low-income housing, had infiltration rates exceeding 3 h^{-1}. In contrast, Lipschutz et al. (1981) obtained measurements of air infiltration into 12 energy-efficient houses in Oregon by using a tracer gas decay analysis. A narrow range of values was found (0.08-0.27 h^{-1}), reflecting the extremely "tight" building construction and ventilation systems installed in the houses.

Doyle et al. (1984) measured air exchange rates in 58 weatherized houses during a 4- to 5-month period during both winter and summer sampling periods. The houses were located in Fargo, North Dakota; Colorado Springs, Colorado; Portland, Maine; and Charleston, North Carolina. The investigators determined the geometric means and

geometric standard deviations for air exchange rates for each city and for the entire sample. Because of the relatively small number of measurements in each city, conclusions about the geographic distribution of air exchange rates are limited. However, combining the data for the cities provides an overall lognormal distribution of 0.8 ± 1.8 h^{-1} (ranging from 0.2 to 2.3 h^{-1}), which appears to encompass most air exchange rates determined in other studies.

Studies on the air exchange rates of large commercial buildings have been much more limited. Table 7.4-2 lists results from some studies on commercial buildings. It can be seen that these values are relatively close to those for residential construction. Although the primary outside air source for large buildings is the mechanical ventilation system, infiltration is the primary outside air source for residential homes (American Society of Heating, Refrigeration, and Air-Conditioning Engineers [ASHRAE], 1997). In either case, a continuous supply of outside air is required to dilute and eventually remove indoor contaminants. Thus, the air exchange requirements are expected to be similar for both residential and commercial construction. However, differences in local airflow and temperature, as well as air exchange, may be required to maintain workers' comfort according to their activity level.

Table 7.4-2 Outside Air Exchange Rates for Commercial Buildings

Building Air Exchange Rate (h^{-1})	Building Description	Reference
0.33 – 1.04	Large office buildings	Persily and Grot, 1985
0.9	The National Archive Building	Silberstein and Grot, 1985
	38 commercial buildings studied in the Pacific Northwest during all seasons of the year. Two buildings were sampled twice at different times of the year.	Turk et al., 1987
	Number of buildings:	
0.0 – 0.5	3	
0.5 – 1.0	10	
1.0 – 1.5	9	
1.5 – 2.0	8	
2.0 – 2.5	6	
2.5 – 3.0	2	
3.0 – 3.5	0	
3.5 – 4.0	1	
4.0 – 4.5	1	
0.6, 4.0, and 8.2	Three buildings in an office/laboratory complex	Weschler et al., 1989

Turk et al. (1987) examined the outdoor exchange rates of 38 buildings in the Pacific Northwest. The buildings included schools, libraries, and office buildings in mild and harsh climates measured during different seasons of the year. Results are shown in Table 7.4-2. The arithmetic mean and standard deviation are 1.52 h^{-1} and 0.873, respectively. Although this set of data is limited, the mean falls between the arithmetic means determined Pandian et al. (1993) and Murray and Burmaster (1995), 1.99 and 0.76 h^{-1}, respectively, for residential air exchange rates. The air exchange data from Persily and Grot (1985) and Silberstein and Grot (1985), as shown in Table 7.4-2, fall within the range observed by Turk et al. (1987). The study of a laboratory/office complex by Weschler et al. (1989) has two values outside this range, 4.0 and 8.2 h^{-1}. However, maximum values of 11.77 and 45.6 h^{-1} were used by Murray and Burmaster (1995) and Pandian et al. (1993), respectively.

While the data on commercial building air exchange rates are limited, the distribution of rates is expected, in part because of human comfort considerations, to be similar to residential structures when averaged over the United States for all four seasons of the year. Thus, a generic lognormal distribution has been assigned to the building exchange rate to represent an average over all conditions. The mean and standard deviation of the distribution are those obtained by Turk et al. (1987), 1.52 h^{-1} and 0.88, respectively. As discussed above, the mean falls within the average mean found by different residential studies and is consistent with other commercial building studies. The standard deviation is the same as observed by Murray and Burmaster (1995). Because of the limited data set and variations across different industries, climates, and seasons, this distribution is only an approximation to potential building air exchange rates for light industry. Figure 7.4-1 displays the probability density function for the building air exchange rate. The same lognormal distribution is assigned to room exchange rates because the building air exchange rate is an average of the rooms within.
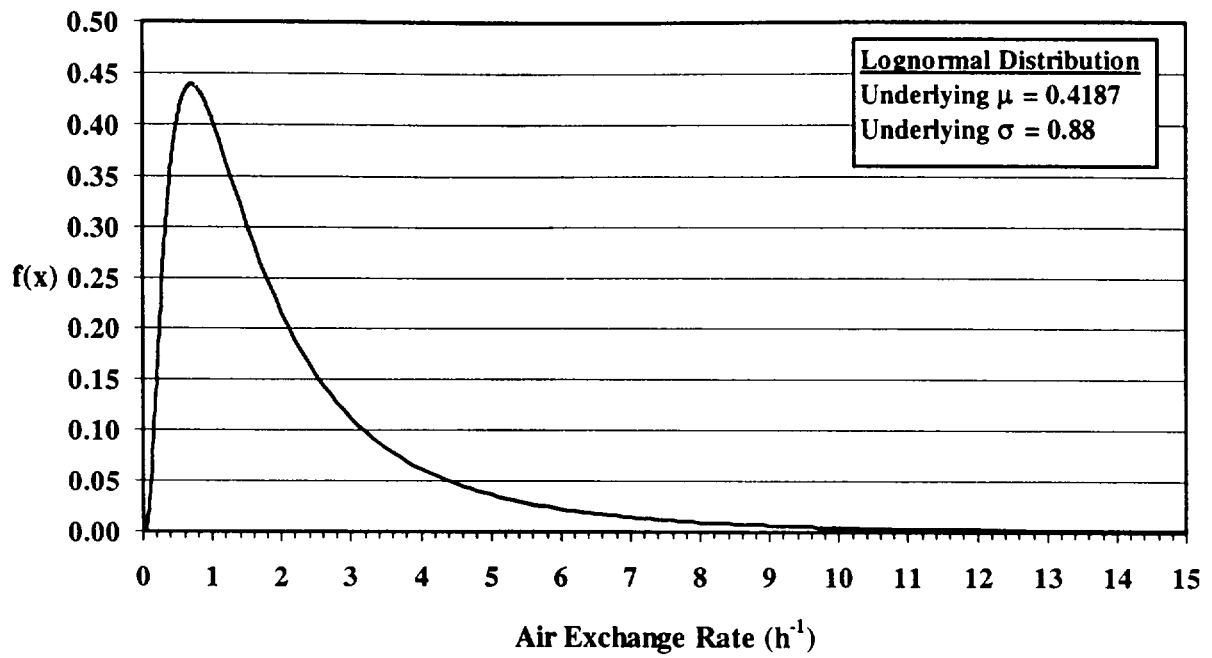
Figure 7.4-1 Building and Room Air Exchange Rate Probability Density Function

7.5 Deposition Velocity (Indoor)

Applicable Code: RESRAD-BUILD

Description: This parameter represents the indoor deposition velocity of contaminant particles in the building air.

Units: meters per second (m/s)

Probabilistic Input:

Distribution: loguniform

Defining Values for Distribution:

Minimum: 2.7×10^{-6} Maximum: 2.7×10^{-3}

Discussion: The deposition velocity characterizes the rate at which particles in the indoor air deposit on a surface. The decay rate, λ_d, of particles in indoor air due to deposition is often expressed as:

$$\lambda_d = \frac{v_d A_d}{V} ,$$

(7.5-1)

where

v_d = the deposition velocity,

A_d = the surface area available for deposition, and

V = the volume of air.

For indoor deposition, the deposition velocity depends on particle and room properties. Important particle properties include diameter, density, and shape; room properties include air viscosity and density, turbulence, thermal gradients, and surface geometry.

Nazaroff and Cass (1989) have developed a relationship for the indoor deposition velocity of particulates as a function of particle size. Such theoretical calculations are not likely to produce satisfactory results because of lack of knowledge about near-surface flow conditions (Nazaroff et al., 1993), but they can provide insight into the general trend of

deposition velocity as a function of particle size. Figure 7.5-1 presents an idealized representation of deposition velocity on a floor as a function of particle size on the basis of the methodology in Nazaroff and Cass (1989). A similar trend is observed for deposition of particles outdoors (Sehmel, 1980).

Because deposition velocities depend on particle size, it is expected that the probability density function distribution of deposition velocities is dependent on the particle size distribution. The particle size distribution in the atmosphere typically exhibits three modes (Seinfeld and Pandis, 1998). Fine particles (particles less than 2.5 μm in diameter) can be divided into two modes, the nuclei mode and the accumulation mode. The nuclei mode (particles approximately 0.005 to 0.1 μm in diameter) contains the largest number of particles in the atmosphere but represents only a few percent of the total mass of airborne particles (Seinfeld and Pandis, 1998). Nuclei mode particles are formed from condensation of atmospheric gases, such as combustion products. Depletion of nuclei mode particles occurs primarily through coagulation with larger particles. The accumulation mode (particles approximately 0.1 to 2.5 μm in diameter) accounts for a large portion of the aerosol mass. Accumulation mode particles are formed through coagulation of particles in the nuclei mode and through condensation of gases onto smaller particles. Because removal mechanisms are not as efficient for this size range, particles tend to accumulate (hence the term "accumulation mode"). Coarse particles (diameters greater than 2.5 μm) constitute the third mode. Coarse mode particles are formed primarily from mechanical processes. Other sources of coarse particles include windblown dust and plant particles.

Each of the three particle size modes can be well characterized by lognormal distributions (John, 1993). Using the means and standard deviations from Whitby and Sverdrup (1980), Figure 7.5-2 demonstrates the trimodal nature of the particle size distributions commonly found. Similar distributions are expected for indoor air concentrations, with the exception of some indoor source contributions, because, as discussed in Section 7.1, the building shell has been shown to be an insignificant barrier to particle sizes under 10 μm.

A broad probability density function distribution is expected for the deposition velocity when comparing the trend in deposition velocity with the distribution of particles by size (Figures 7.5-1 and 7.5-2, respectively) and taking into consideration the variability of each. Experimental estimates provide support for such an assumption, as shown in Tables 7.5-1 through 7.5-3. Also, because deposition is dependent on local airflow patterns (Nazaroff and Cass, 1989), in conjunction with particle size and mass, a small difference in the local air handling system (such as changes due to climate or season) can easily cause a shift in deposition velocity. Because the deposition velocity input in RESRAD-BUILD is used for all particle sizes and species under a potential range of airflow conditions, a loguniform distribution is assigned, with minimum and maximum values of 2.7 x 10^{-6} m/s and 2.7 x 10^{-3} m/s, respectively, as found in Tables 7.5-1 through 7.5-3. This distribution is shown in Figure 7.5-3.
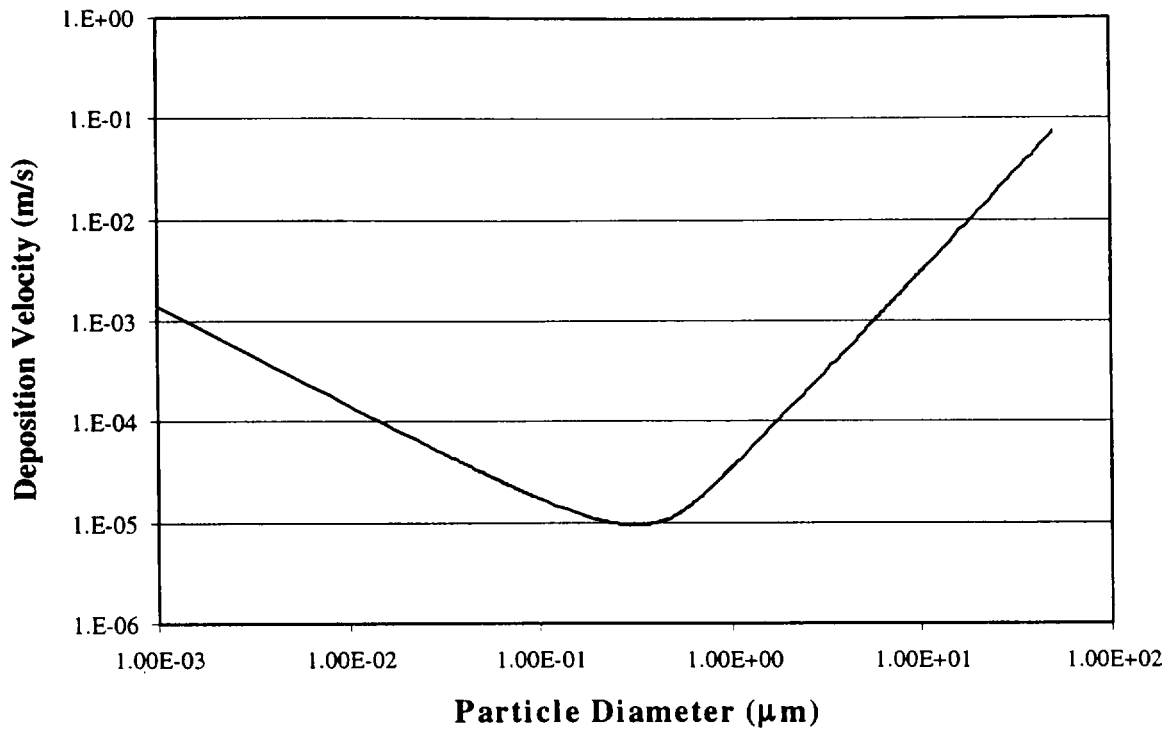
Figure 7.5-1 Idealized Representation of Indoor Particle Deposition Velocity
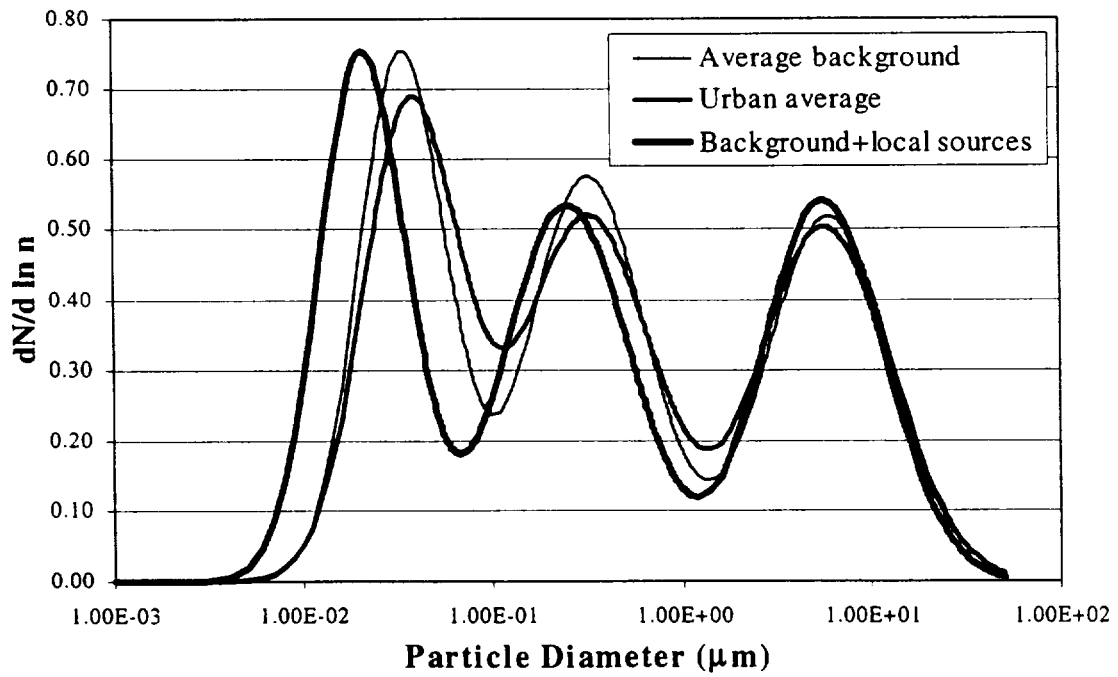
Figure 7.5-2 Trimodal Nature of Aerosol Particle Size Distribution

Table 7.5-1 Estimated Indoor Deposition Velocities by Particle Size

Particle Size (μm)	Deposition Velocity (m/s)	Comments	Reference
0.71	1.7×10^{-5}	[7]Be with natural air exchange	Lang, 1995
1.4	1.3×10^{-5}		
2.8	6.7×10^{-5}		
0.71	1.33×10^{-4}	[7]Be with forced air exchange	
1.4	2.66×10^{-4}		
2.8	3.88×10^{-4}		
1-2	1.7×10^{-4}	Data Set 1 (different sample dates using SF_6 tracer)	Thatcher and Layton, 1995
2-3	3.7×10^{-4}		
3-4	5.1×10^{-4}		
4-6	1.1×10^{-3}		
1-2	1.9×10^{-4}	Data Set 2	
2-3	5.0×10^{-4}		
3-4	5.6×10^{-4}		
4-6	1.2×10^{-3}		
1-5	3.1×10^{-4}	Data Set 3	
5-10	9.1×10^{-4}		
10-25	1.6×10^{-3}		
>25	2.7×10^{-3}		
0.07	1.72×10^{-5}	Estimates based on data in Offermann et al. (1985) from cigarette combustion	Nazaroff and Cass, 1989
0.10	2.7×10^{-6}		
0.12	3.8×10^{-6}		
0.17	3.8×10^{-6}		
0.22	4.7×10^{-6}		
0.26	8.9×10^{-6}		
0.35	8.2×10^{-6}		
0.44	8.7×10^{-6}		
0.56	9.8×10^{-6}		
0.72	1.51×10^{-5}		
0.91	1.3×10^{-4}		
<2.5	3×10^{-5} and 3×10^{-5}	Sulfate ion particulates at two locations	Sinclair et al., 1985
2.5-15	1×10^{-2} and 2×10^{-3}	Calcium ion particulates at two locations	

Table 7.5-2 Estimated Deposition Velocities by Particle Size in Residences with and without Furniture

Particle Size (μm)	Average Deposition Velocity (m/s)	
	Without Furniture	With Furniture
0.5	6.1×10^{-5}	8.2×10^{-5}
2.5	1.33×10^{-4}	1.73×10^{-4}
3.0	1.37×10^{-4}	2.25×10^{-4}
4.5	2.88×10^{-4}	2.88×10^{-4}
5.5	3.04×10^{-4}	3.24×10^{-4}

Source: Fogh et al. (1997).

Table 7.5-3 Estimated Indoor Deposition Velocities for Various Radionuclides

Isotope	Mean Deposition Velocity (m/s)
Cs-137	6.4×10^{-5}
Cs-134	6.2×10^{-5}
I-131 (particulate)	1.1×10^{-4}
Be-7	7.1×10^{-5}
Ru-103	2.0×10^{-4}
Ru-106	1.7×10^{-4}
Ce-141	3.1×10^{-4}
Ce-144	3.9×10^{-4}
Zr-95	5.8×10^{-4}
Nb-95	1.9×10^{-4}

Source: Roed and Cannell (1987).

Loguniform Distribution
Minimum = 2.7×10^{-6} m/s
Maximum = 2.7×10^{-3} m/s
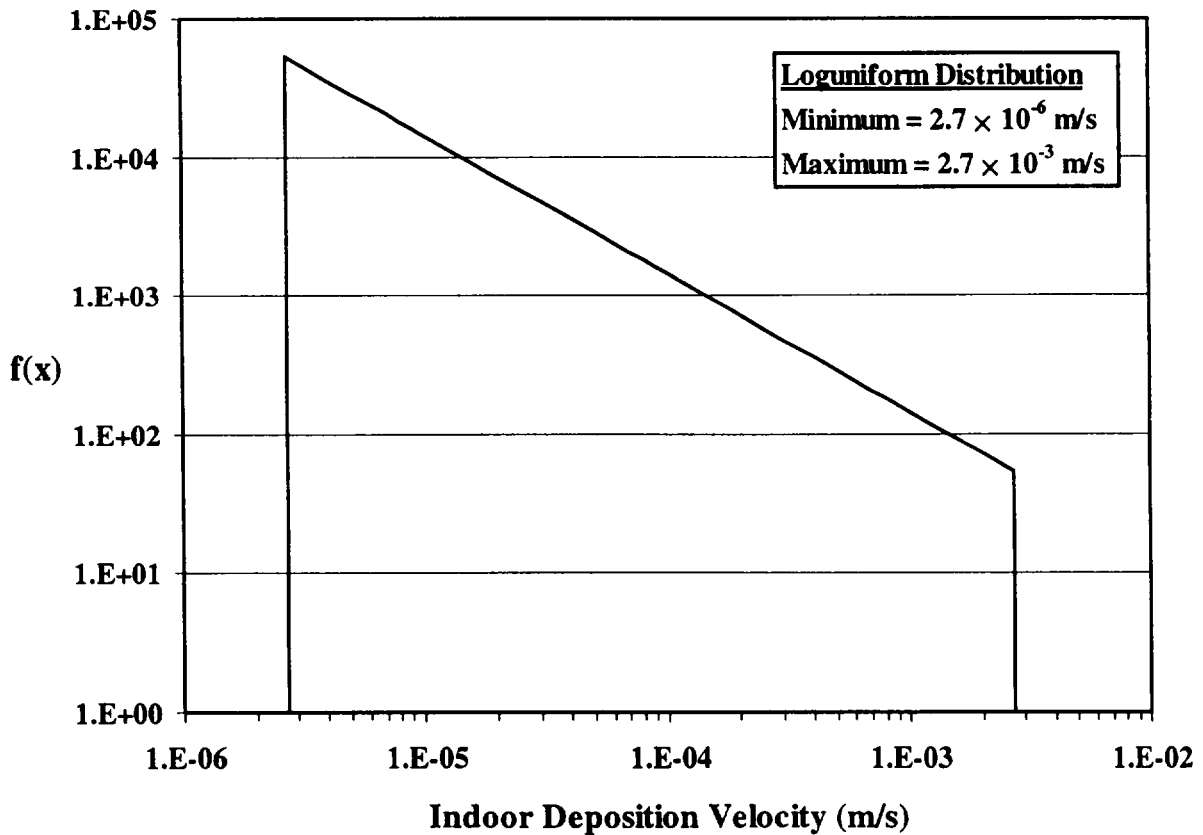
Figure 7.5-3 Indoor Deposition Velocity Probability Distribution

7.6 Indoor Fraction

Applicable Code: RESRAD, RESRAD-BUILD

Description: The indoor fraction is the fraction of time an individual spends inside the residence (RESRAD) or the contaminated building (RESRAD-BUILD).

Units: unitless

Probabilistic Input:

Distribution: user-defined continuous with linear interpolation

Defining Values for Distribution: See Table 7.6-1 for the input values.

Discussion: In RESRAD-BUILD, the indoor fraction is used in the exposure calculations to calculate the amount of time spent at each receptor location. Actual exposure times at each location are estimated by multiplying the exposure duration by the indoor fraction and the fraction of time at the receptor location.

With the exposure duration given in units of days in RESRAD-BUILD, the indoor fraction is represented by the fraction of the day an individual spends indoors at work in the case of occupational exposure. Beyeler et al. (1998a) examined records from the Bureau of Labor Statistics (BLS) concerning the hours at work for persons employed in the agricultural and nonagricultural industries (BLS, 1996). The distribution given in Table 7.6-2 was based on the assumption that full-time nonagricultural workers spent 35 hours or more a week at work. However, some workers may spend some time outside.

Table 7.6-1 Cumulative Distribution Functions for the Indoor Fraction

| Cumulative Probability | Indoor Fraction | |
	RESRAD	RESRAD-BUILD
0	0	0.003
0.05	0.375	0.0347
0.25	0.521	0.306
0.50	0.625	0.365
0.75	0.809	0.403
0.90	0.938	0.469
0.95	0.992	0.500
0.98	1.0	0.542
0.99	1.0	0.594
1.0	1.0	0.692

Table 7.6-2 Relative Frequency of Hours Worked by Persons Working 35 Hours or More per Week

Hours Worked per Week[a]	Relative Frequency[a]	Assuming a 5-Day Work Week	
		Hours per Day	Fraction of Day
35-39	9.96×10^{-2}	7-7.8	0.325
39-41	4.81×10^{-1}	7.8-8.2	0.342
41-48	1.59×10^{-1}	8.5-9.6	0.400
49-59	1.53×10^{-1}	9.8-11.8	0.492
60-65	1.08×10^{-1}	12-13	0.542

[a] Source: Beyeler et al. (1998a).

The EPA's *Exposure Factors Handbook* (EPA, 1997) contains a comprehensive review of human activity patterns, including time spent at work. That review extracts data for time spent at work from the most complete and current study on activity patterns (Tsang and Klepeis, 1996). Table 7.6-3 summarizes a number of distributions, including distributions for time spent indoors at unspecified work locations in a plant/factory/ warehouse. The distribution for full-time workers in the plant/factory/warehouse category is expected to be the best representation for workers in the building occupancy scenario and is the default for RESRAD-BUILD. For perspective, the 50th percentile value for this distribution, 0.365, corresponds to an 8.76-hour work day. The cumulative distribution function for the indoor fraction is shown in Figure 7.6-1.

For RESRAD, the indoor fraction is the fraction of time spent inside the building where the receptor is afforded shielding from the contaminated soil. This situation translates into the amount of time spent indoors at a residence when evaluating the residential farmer scenario. The EPA's comprehensive review of human activity patterns (EPA, 1997) also contains statistics on the amount of time spent indoors at a residence. Table 7.6-4 summarizes the relevant subset of distributions provided in the *Exposure Factors Handbook* (EPA, 1997) for this time fraction. The distribution chosen to represent the average members of the critical group (adult males) in the residential farmer scenario was that for the 18-64 year age group. This distribution is almost identical to that for the male population group and close to those for all subjects and the female population group. Figure 7.6-2 presents the cumulative distribution function for the indoor fraction parameter in RESRAD.

Table 7.6-3 Statistics for Fraction of Time Spent Indoors at Work

Category	Population Group	N[a]	Min	Max	Percentiles 5	25	50	75	90	95	98	99
Fraction per Day Indoors at a Plant/Factory/Warehouse												
All		383	0.001	0.692	0.021	0.243	0.354	0.394	0.465	0.490	0.535	0.594
Gender	Male	271	0.001	0.692	0.021	0.253	0.358	0.399	0.469	0.500	0.542	0.604
Gender	Female	112	0.003	0.569	0.010	0.218	0.354	0.385	0.417	0.469	0.490	0.500
Age (years)	18-64	353	0.003	0.692	0.021	0.267	0.361	0.396	0.465	0.490	0.535	0.594
Employment	Full-Time	333	0.003	0.692	0.035	0.306	0.365	0.403	0.469	0.500	0.542	0.594
Fraction per Day Spent Indoors at Work (unspecified)												
All		137	0.003	0.680	0.010	0.125	0.306	0.385	0.460	0.563	0.653	0.667
Gender	Male	96	0.007	0.680	0.014	0.170	0.328	0.415	0.531	0.583	0.667	0.680
Gender	Female	41	0.003	0.542	0.010	0.063	0.194	0.344	0.382	0.410	0.542	0.542
Age (years)	18-64	121	0.003	0.680	0.010	0.167	0.313	0.389	0.458	0.551	0.590	0.667
Employment	Full-Time	97	0.007	0.680	0.010	0.208	0.333	0.406	0.479	0.566	0.667	0.680

[a] Number of subjects in the survey.

Source: Derived from cumulative minutes per day spent indoors listed in EPA (1997).
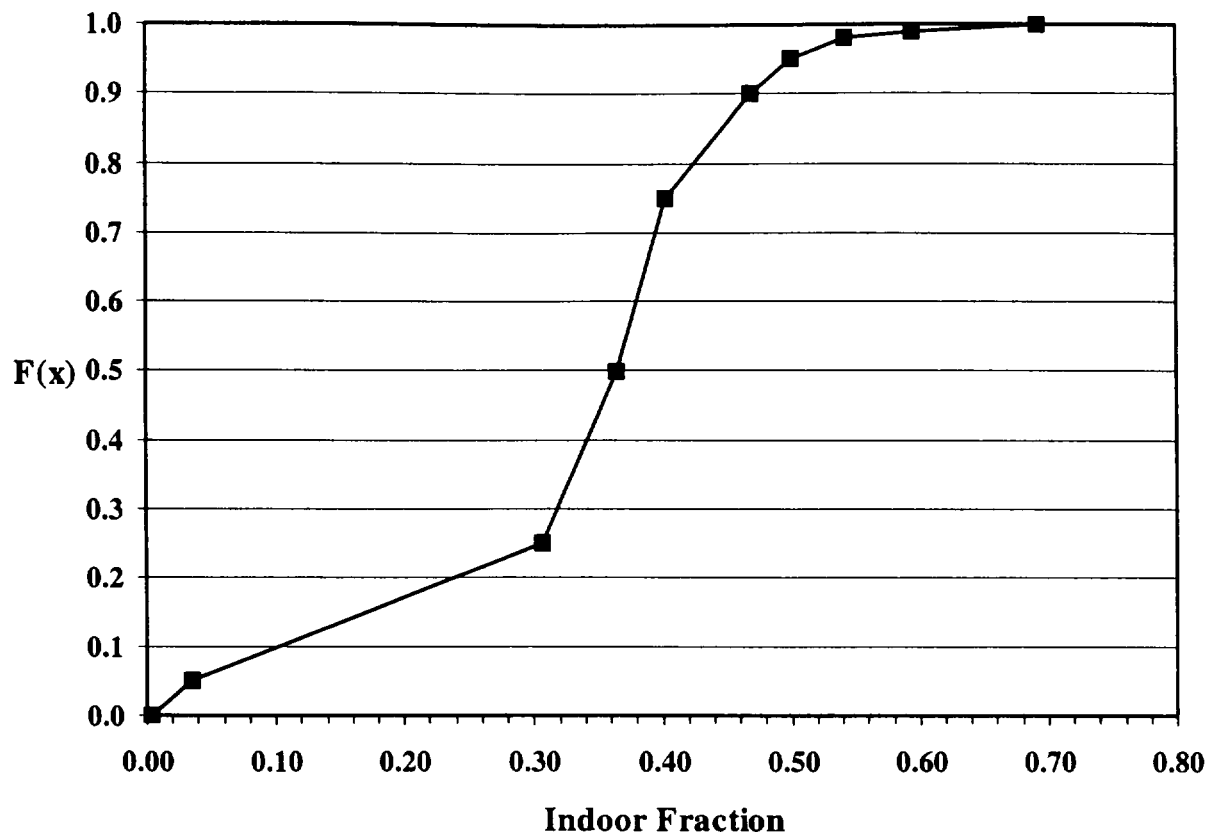
Figure 7.6-1 Indoor Fraction Cumulative Distribution Function for RESRAD-BUILD

Table 7.6-4 Statistics for Fraction of Time Spent Indoors in a Residence[a]

Category	Population Group	N[b]	Min.	Max.	Percentiles							
					5	25	50	75	90	95	98	99
Fraction per Day Indoors in a Residence (all rooms)												
All		9,343	0.006	1	0.399	0.552	0.684	0.858	0.969	1	1	1
Gender	Male	4,269	0.006	1	0.375	0.521	0.625	0.806	0.938	0.993	1	1
Gender	Female	5,070	0.021	1	0.431	0.583	0.729	0.889	0.986	1	1	1
Age (years)	18-64	6,022	0.006	1	0.375	0.521	0.625	0.809	0.938	0.992	1	1

[a] Derived from cumulative minutes per day spent indoors listed in EPA (1997).

[b] Number of subjects in the survey.
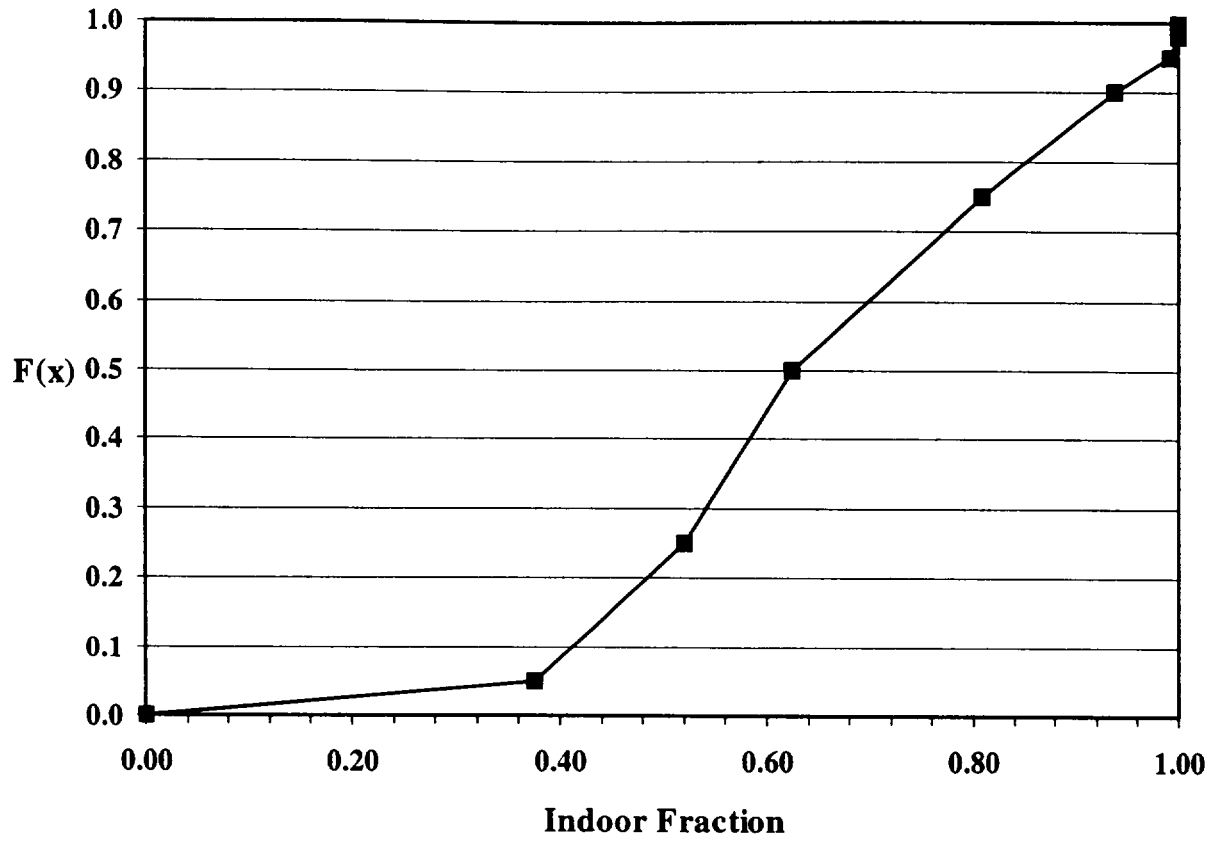
Figure 7.6-2 Indoor Fraction Cumulative Distribution Function for RESRAD

7.7 Room Area

Applicable Code: RESRAD-BUILD

Description: This parameter represents the floor area of a specific room in the building.

Units: square meters (m^2)

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 3   Maximum: 900   Most likely: 36

Discussion: The room area is used in determining the mixing volume of each distinct air flow volume (room) and the equilibrium of resuspension and deposition. Studies concerning room size distribution are not available. An arbitrary distribution has been selected as a default for use in application of RESRAD-BUILD to commercial buildings. Site-specific distributions or deterministic values should be used if available.

A triangular distribution is used to represent the room area. A minimum value of 3 m^2 (approximate room dimensions of 1.5 x 2 m) was chosen to represent such areas as utility rooms or storage closets in a commercial environment. A maximum value of 900 m^2 (slightly less than 10,000 ft^2) was chosen to represent larger areas that would correspond to the area of rooms housing such functions as light industrial assembly lines, small to intermediate warehouse operations, or large assembly halls. However, office space is generally required in support of such larger operations. Such a requirement skews the room size distribution toward smaller room area, suggesting that a uniform distribution between the minimum and maximum areas is not appropriate. The choice of a most likely value for a triangular distribution was arbitrary and attempted to account for this observation. A most likely value of 36 m^2 (390 ft^2) was chosen. This value lies above what might be expected for the area for a single-occupant office room (approximately 12 m^2, 3 m x 4 m) and is in the range of what might be expected for a multi-occupant office room. Figure 7.7-1 presents the probability density function suggested for the room area.
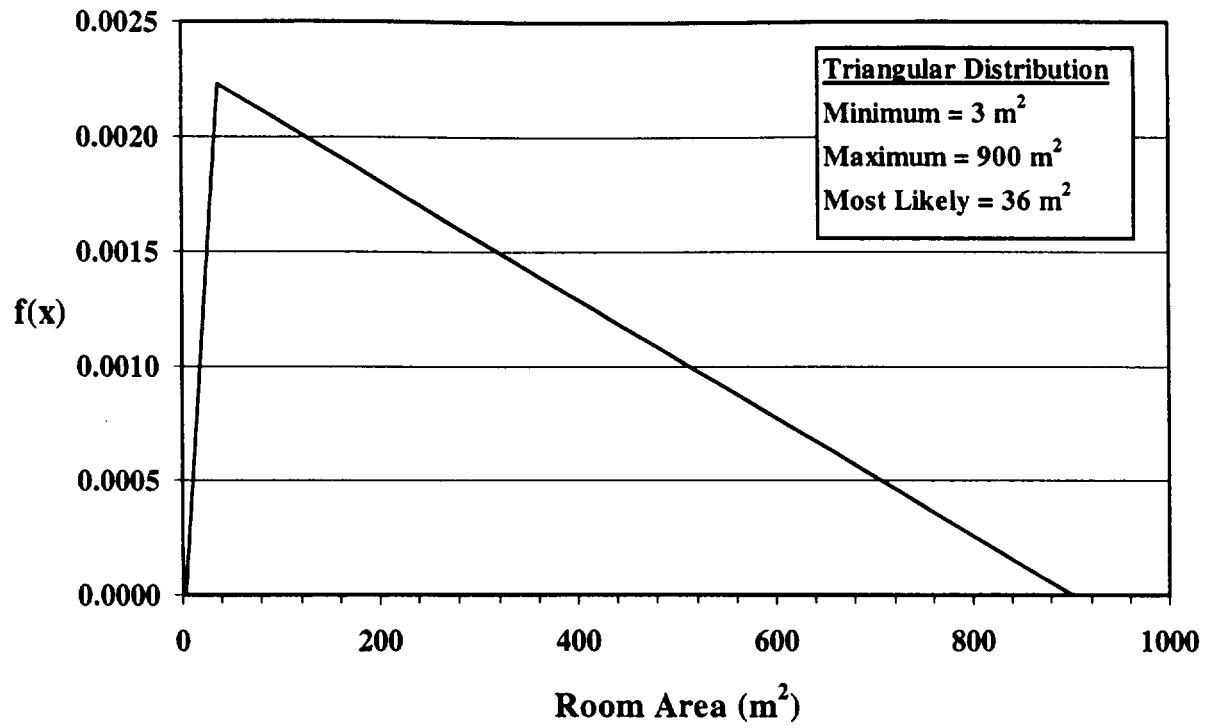
Figure 7.7-1 Probability Density Function for Room Area

Triangular Distribution
Minimum = 3 m^2
Maximum = 900 m^2
Most Likely = 36 m^2

7.8 Room Height

Applicable Code: RESRAD-BUILD

Description: The room height is the distance between the floor and the ceiling of a specific room in the building.

Units: meters (m)

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 2.4   Maximum: 9.1   Most likely: 3.7

Discussion: The room height is used in determining the mixing volume of each distinct air flow volume (room) and the equilibrium of resuspension and deposition. Over half the new single-family homes constructed annually have room heights of 2.4 m (8 ft), as shown in Table 7.8-1. The 2.4-m (8 ft) height is considered to be typical of residential housing (EPA, 1997). Minimum room heights of 2.1 m (7 ft) below beams and girders are required by the Council of American Building Officials, with a ceiling height of not less than 2.3 m (7.5 ft) for half of the required area (National Association of Home Builders [NAHB], 1998). The U.S. Department of Housing and Urban Development requires a minimum ceiling height of not less than 2.1 m (7 ft) for at least half of the floor area and 1.9 m (6 ft 4 in.) under ducts and beams.

No comprehensive study of room height in commercial buildings exists. Room height can vary within the same occupational setting as well as between industries. Room height may also vary according to climate (because of energy efficiency considerations). A typical room height in commercial buildings is 3.7 m (12 ft) (EPA, 1997). A minimum of 2.4 m (8 ft) is found in smaller rooms, such as those used for individual offices or conference rooms. Larger room heights are found in warehousing (shipping/receiving) operations, which may have room heights of up to approximately 9.1 m (30 ft). Thus, for the occupational scenario, a triangular distribution is used for the room height, with a most likely value of 3.7 m and minimum and maximum values of 2.4 and 9.1 m, respectively. This distribution is a rough generalization, and site-specific data should be used when available. The probability density function is shown in Figure 7.8-1.

Table 7.8-1 Room Height in New Conventional and Manufactured Homes, 1996

Room Height (m) [ft]	Conventional Homes (First Floor), Percent of Total	Manufactured Homes, Percent of Total
≤ 2.1 [≤ 7]	0.1	48.2
2.3 [7.5]	1.6	37.4
2.4 [8.0]	57.8	5.1
2.6 [8.5]	0.8	1.5
2.7 [9.0]	24.2	7.7
> 2.7 [> 9]	15.5	–

Source: NAHB (1998).
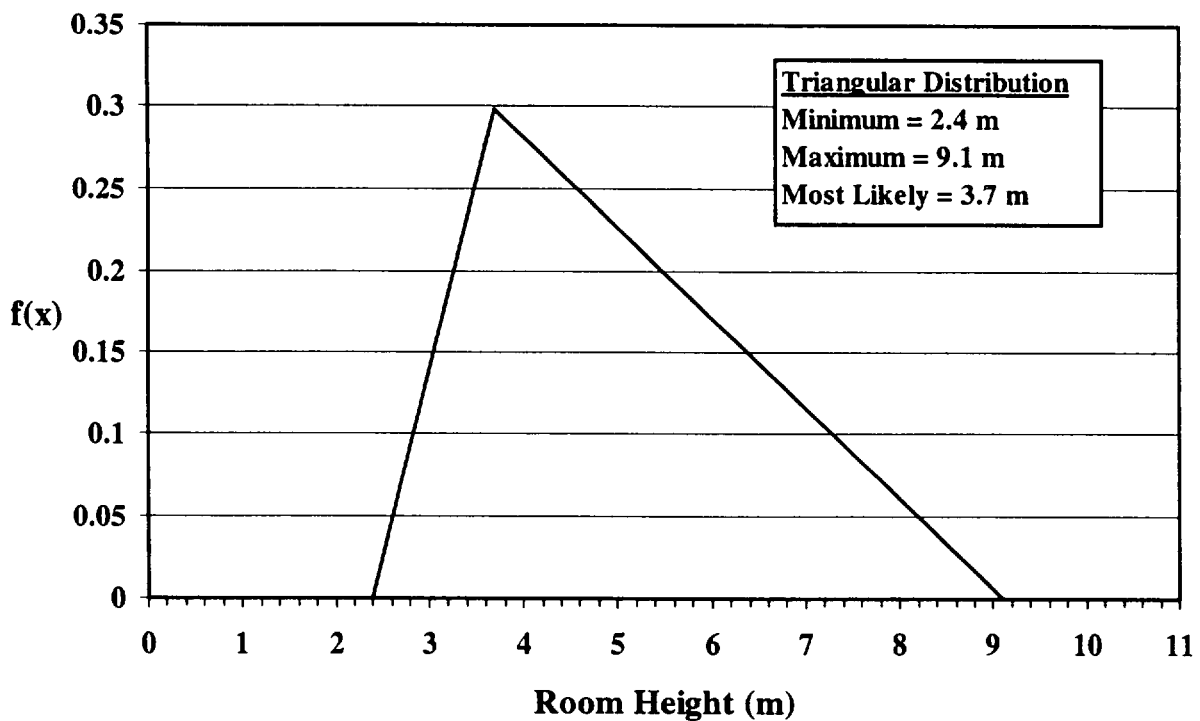
Figure 7.8-1 Room Height Probability Density Function

7.9 Shielding Thickness

Applicable Code: RESRAD-BUILD

Description: This parameter represents the effective thickness of shielding between a source and receptor pair.

Units: centimeters (cm)

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 0   Maximum: 30   Most likely: 0

Discussion: The shielding thickness parameter is used in determining the attenuation of direct external radiation from each source to each receptor. Shielding thickness only affects the external exposure pathway. For situations where only air is present between the source and receptor, the shielding thickness is 0. The RESRAD-BUILD code requires the shielding thickness for every source and receptor pair (e.g., if there were 4 sources and 6 receptors, the code would require 24 [6 × 4] shielding thickness input values). The same shielding object might be assigned different thicknesses for different source-receptor pairs because of geometry considerations. It is highly recommended that the shielding thickness value be obtained from a direct measurement based on the site-specific condition. For example, to calculate dose for a receptor in a room other than the room in which the source is located, a shielding thickness equivalent to the wall thickness should be assumed.

Floor and wall thicknesses vary depending on the type of building and type of construction. To estimate the total contaminated volume of concrete from DOE facilities, Ayers et al. (1999) assumed an average concrete thickness of 12 in. (30 cm) in a building. For external exposure calculations, this thickness approximates an infinite thickness for alpha-emitters, beta-emitters, and X-ray or low-energy photon emitters. A shielding thickness of 30 cm would reduce the dose significantly from the external exposure pathway for all radionuclides, including high-energy gamma emitters.

Little information is available for the shielding thicknesses in actual D&D situations; therefore, a triangular distribution is assumed. The maximum value is assumed to be 30 cm, the minimum value is chosen as 0 cm, and the most likely value also is chosen to be 0 cm (this assumption would yield most conservative dose results for the external exposure pathway). The probability density function is shown in Figure 7.9-1.
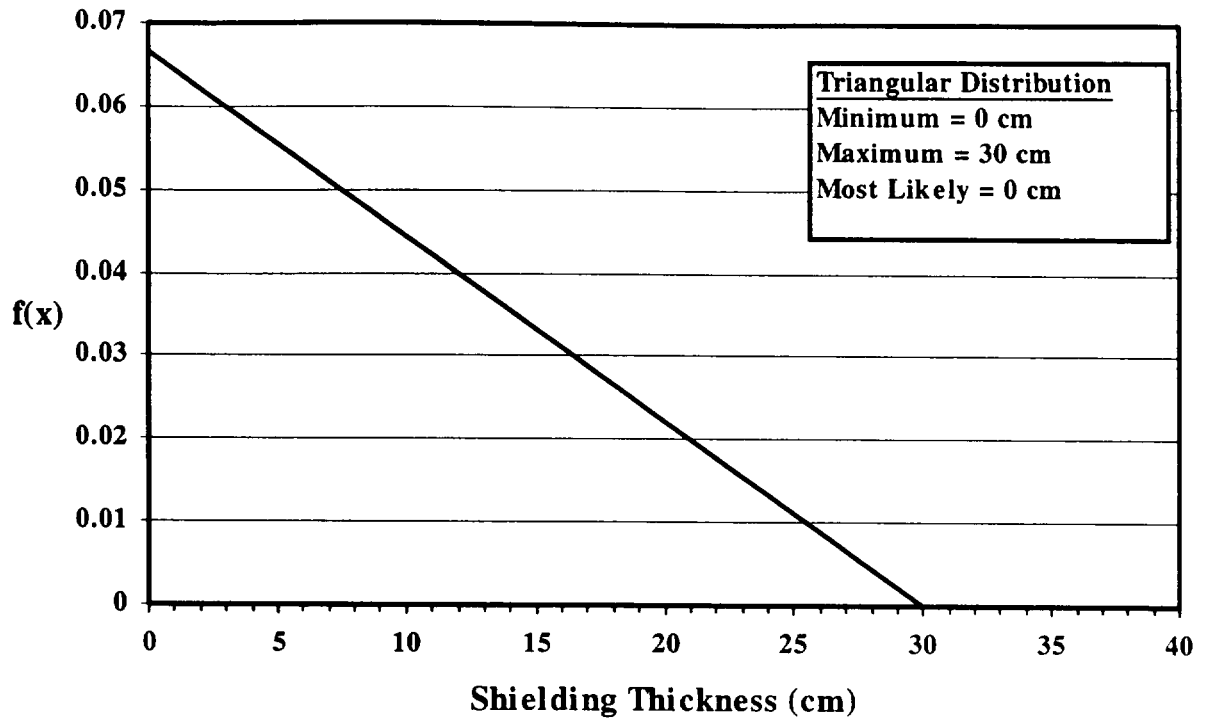
Figure 7.9-1 Shielding Thickness Probability Density Function

7.10 External Gamma Shielding Factor

Applicable Code: RESRAD

Description: The shielding factor for external gamma radiation is the ratio of the external gamma radiation level indoors on-site to the radiation level outdoors on-site. It is a function of the shielding that building materials provide against the penetration of gamma radiation.

Units: unitless

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

Underlying mean value:	-1.3	Lower limit:	0.044[1]
Underlying standard deviation:	0.59	Upper limit:	1

Discussion: A single external shielding factor is used to account for the attenuation of gamma radiation by building materials. The external shielding factor is the fraction of outdoor external gamma radiation level that is present indoors. The parameter can range from 0 (complete attenuation) to 1 (no attenuation).

Home construction type has a dramatic effect on the attenuation of gamma radiation. Concrete and brick attenuate gamma radiation more effectively than wood; hence, a house built on a concrete slab or built with a full basement will have a lower external shielding factor (i.e., will provide more protection) than a house built with a crawlspace without a finished concrete floor. Similarly a house that has exterior walls made of brick or stone will have a lower external shielding factor than a house with outer walls made of wood or other building materials. Data obtained from the U.S. Census Bureau indicates that approximately 20% of the new homes constructed during the years 1993-1999[2] were built on a crawlspace (U.S. Department of Housing and Urban Development, 1996,1999). Approximately 43% of homes constructed in the same period were built on a slab, and the remaining 37% of the homes were built either on a full or partial basement (U.S. Department of Housing and Urban Development, 1996, 1999). Data obtained from the same sources showed that 27% of the homes built in the U.S. between 1996-1999[2] used brick or stone as the principal building material for the exterior walls. Approximately

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[1] Corresponds to the cumulative probability of 0.1%.

[2] Data from 1999 are only from the first three quarters of the year.

56% of the homes constructed within the same period had primary exterior walls made of either wood or vinyl/aluminum siding, while the remaining 17% had exterior walls made of stucco (U.S. Department of Housing and Urban Development, 1999).

External shielding factors were estimated for five different radioisotopes — Cs-137, Co-60, Mn-54, U-238, and Ra-226 — for four different home construction types. The types considered were (1) a brick home constructed over a full basement or on a slab, (2) a frame house constructed over a full basement or on a slab, (3) a frame house constructed with a crawlspace, and (4) a frame house constructed with a partial basement. The shielding factors were estimated with RESRAD-BUILD using five source geometries. The full basement/slab was modeled by placing a 15-cm (6-in.) concrete shield over the surface contamination, while the crawlspace was modeled by placing a 2.5-cm (1-in.) shield over the surface contamination. The brick and wooden walls were modeled using a 10-cm (4-in.) concrete and 2.5-cm (1-in.) wooden shield, respectively. It was assumed a person in the house spent 50% of the time completely shielded by the brick or wooden walls and 50% of the time by a window (essentially unshielded). The external shielding factors provided in Table 7.10-1 for the scenarios listed above are average values for the radionuclides that were analyzed. The shielding factors presented in the table were found to be consistent with those obtained from previous studies (NRC, 1975; Jensen, 1983; Golikov et al., 1999).

The probability distribution for the external shielding factor was obtained by combining the results from the RESRAD-BUILD computer code with the data obtained from the U.S. Department of Housing and Urban Development (1996, 1999). The external shielding factor was assumed to be distributed lognormally, and Bayesian techniques were used to estimate the parameters of the distribution. The posterior means of μ and σ were used to characterize the probability distribution for the external shielding factor. The probability density function is shown in Figure 7.10-1.

Table 7.10-1 External Shielding Factors

Scenario	External Shielding Factor
Brick House Constructed with a Slab or Full Basement	0.17
Frame House Constructed with a Slab or Full Basement	0.21
Frame House Constructed with a Crawlspace	0.81
Frame House Constructed with a Partial Basement	0.51
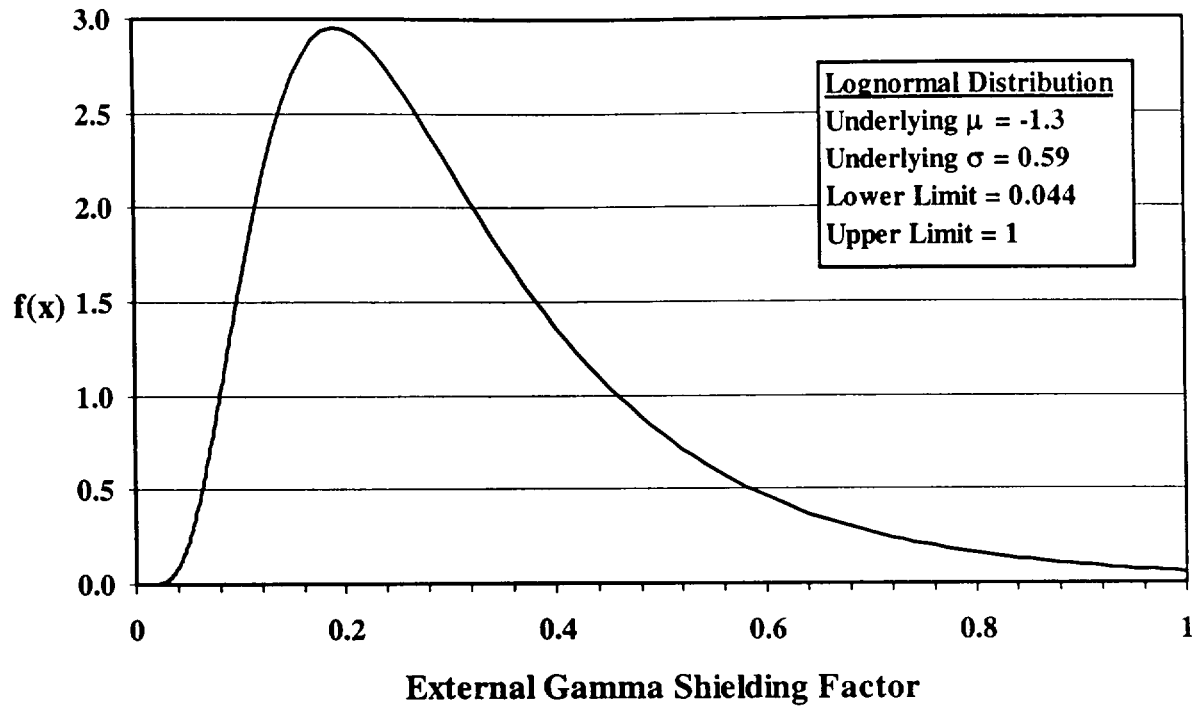
Figure 7.10-1 External Gamma Shielding Factor Probability Density Function

8 SOURCE CHARACTERISTICS PARAMETER DISTRIBUTIONS

8.1 Source Density, Volume Source

Applicable Code: RESRAD-BUILD

Description: The source density parameter represents the effective density of each cylindrical layer (region) in an idealized volume source.

Units: grams per cubic centimeter (g/cm^3)

Probabilistic Input (allowed only for concrete):

Distribution: uniform

Defining Values for Distribution:

Minimum: 2.2   Maximum: 2.6

Discussion: The source density parameter is used to calculate the total amount of radionuclides in the source volume, and it affects the external pathway doses. In the RESRAD-BUILD code, the volume source can be defined with up to five distinct parallel regions (or layers) located along the direction parallel to the partition, each consisting of homogeneous and isotropic materials. RESRAD-BUILD allows the following eight materials: concrete, water, aluminum, iron, lead, copper, tungsten, and uranium. Each source layer is defined by its physical properties, such as thickness, density, porosity, radon effective diffusion coefficient, radon emanation fraction, and erosion rate. Table 8.1-1 lists the density range (if appropriate) or a single value of density for the RESRAD-BUILD materials that have a narrow range of density (except concrete). The table lists a range for cast iron and a single value of density for each of the other materials. The values are taken from the *Health Physics and Radiological Health Handbook* (Shleien, 1992) and from the *CRC Handbook of Chemistry and Physics* (Lide, 1998) (for cast iron, uranium and tungsten). Table 8.1-2 provides the concrete density from three different sources: *Health Physics and Radiological Health Handbook* (Shleien, 1992), *Properties of Concrete* (Neville, 1996), and *Standard Handbook for Civil Engineers* (Merritt et al., 1995). The value used in the code is for ordinary concrete. If the type of concrete is known, a uniform distribution between the given range for a known concrete type can be used. The probability density function for the concrete source density is shown in Figure 8.1-1.

Table 8.1-1 Density of Shielding Materials (except concrete) Allowed in RESRAD-BUILD

Material	Density Range (g/cm^3)	Normal Density (g/cm^3)
Aluminum	$-^a$	2.7
Copper	–	8.96
Lead	–	11.35
Steel	–	7.8
Cast iron	7.0-7.4	
Water	–	1.0
Tungsten	–	19.3
Uranium	–	19.1
Iron	–	7.87

[a] – = data not available.

Sources: Shleien (1992); Lide (1998).

Table 8.1-2 Concrete Density from Various Sources

	Concrete Density (g/cm^3)		
Aggregate	Shleien (1992)	Neville (1996)	Merritt et al. (1995)
Ordinary (silicacious) or normal weight	2.2-2.4	2.2-2.6	2.3
Heavy weight	$-^a$	–	2.4-6.15
Limonite (goethite, hyd. Fe_2O_3)	2.6-3.7	–	–
Ilmenite (nat. $FeTiO_3$)	2.9-3.9	–	–
Magnetite (nat. Fe_3O_4)	2.9-4.0	–	–
Limonite and magnetite	–	–	3.35-3.59
Iron (shot, punchings, etc.) or steel	4.0-6.0	–	4.0- 4.61
Barite	3.0-3.8	–	3.72
Lightweight	–	0.3-1.85	0.55-1.85
Pumice	–	0.8-1.8	1.45-1.6
Scoria	–	1.0-1.85	1.45-1.75
Expanded clay and shale	–	1.4-1.8	–
Vermiculite	–	0.3-0.8	0.55-1.2
Perlite	–	0.4-1.0	0.8-1.3
Clinker	–	1.1-1.4	–
Cinders without sand	–	–	1.36
Cinders with sand	–	–	1.75-1.85
Shale or clay	–	–	1.45-1.75
Cellular	–	0.36-1.55	–
No-fines	–	1.6-2.0	1.68-1.8
No-fines with light weight aggregate	–	0.64-higher	–
Nailing	–	0.65-1.6	–
Foam	–	–	0.3-1.75

Figure 8.1-1 Concrete Source Density Probability Distribution Function

[a] – = data not available.

8.2 Source Erosion Rate, Volume Source

Applicable Code: RESRAD-BUILD

Description: The source erosion rate parameter represents the amount of contaminated material [expressed as the thickness of the layer (distance perpendicular to the contaminated surface)] removed per unit of time.

Units: centimeters per day (cm/d)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 0.0   Maximum: 5.6×10^{-7} Most likely: 0.0

Discussion: The source erosion rate is highly dependent on the location of the contamination. In the building occupancy scenario, contamination on walls could remain indefinitely if located in little-used areas not subject to periodic washing or cleaning. Furthermore, such residual wall contamination could have been covered with paint or another type of sealant during prior remediation or general maintenance activities. In addition, little or no wear also can be expected for some floor areas for the same reasons. At the other extreme are contaminated floor areas subject to heavy foot traffic or vehicle traffic, such as in warehousing operations. However, such areas are usually covered (carpet or tile), sealed, or waxed on a periodic basis, thus reducing the potential for erosion.

A triangular distribution was selected to represent the source erosion rate. A value of 0 was chosen for both the minimum and most likely values because contamination on both walls and floors in little-used areas can be expected to remain in place indefinitely. Even high-use areas may not experience erosion if they remain protected by paint or sealant. Under normal occupancy conditions (not remedial activities), a maximum value is expected as a result of traffic over floor areas. Contaminated wood, concrete, and (possibly) ceramic tile are expected to be the primary flooring materials affected. Contaminated carpet would be expected to have been removed by remedial activities. However, aside from studies on abrasion, little information is available in the general literature on normal wear of concrete or wood surfaces over extended periods of time.

A rough approximation for the maximum value can be obtained by considering that any eroded materials would become airborne for at least short periods of time. A

conservative assumption was made that all airborne indoor particulate matter is a result of erosion of the floor surface. Typically, outdoor air is a significant source of indoor air particulate concentrations (see Section 7.1), but this contribution was not considered. The erosion rate of a concrete floor was estimated to maintain an average particulate air concentration of 100 $\mu g/m^3$ (Section 4.6) with a room air exchange rate of 1.52/h (Section 7.4). A floor area of 36 m^2 (Section 7.7), a room height of 3.7 m (Section 7.8, used to estimate the room volume), and a concrete density of 2.4 g/cm^3 (Section 8.1) were used. The estimated erosion rate was 5.6×10^{-7} cm/d. Figure 8.2-1 shows the probability density function used for the source erosion rate.

In the case of renovation or remedial actions, the source erosion rate can be quite high. For example, thin-volume sources in wood or concrete could be removed in seconds with power sanders or sandblasting techniques. Other examples include the complete removal of wood, carpet, or drywall sections within seconds to minutes. For such a scenario, the user can input values appropriate to the contaminated source and removal technique under consideration.
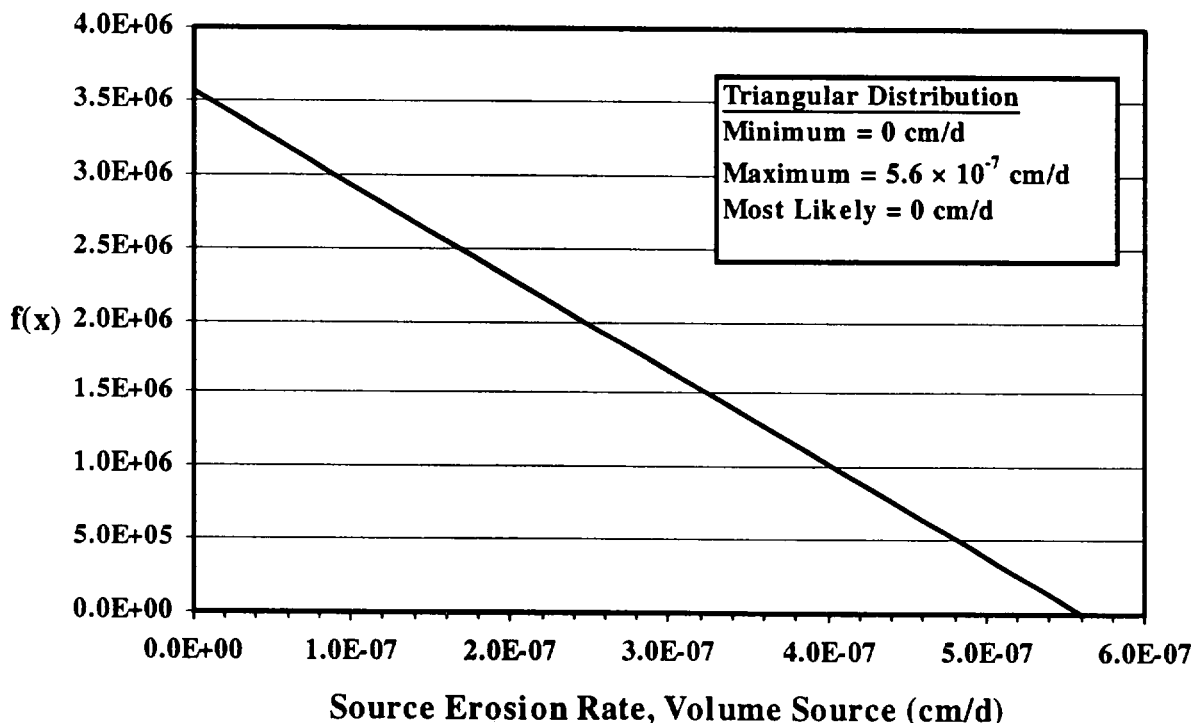
Figure 8.2-1 Source Erosion Rate Probability Density Function

8.3 Removable Fraction

Applicable Code: RESRAD-BUILD

Description: The removable fraction is the fraction of a line or area source that can be removed.

Units: unitless

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum value: 0.0   Maximum value: 1.0   Most likely: 0.2

Discussion: The removable fraction can account for various events that reduce the amount of source activity over time. In RESRAD-BUILD calculations, this fraction of the source will be linearly removed between time 0 and the "time of source removal." Source activity may be reduced over a period of time as a result of such events as surface washing (chemical and mechanical action) or foot or equipment traffic if the source is on the floor (mechanical action). Because source activity could remain on a wall indefinitely or be removed entirely because of heavy traffic across floor contamination, the default distribution for the removable fraction ranges from 0 to 1 for use in a triangular distribution. Figure 8.3-1 displays the distribution's probability density function.

For most radionuclides, the DOE *Radiological Control Manual* (DOE, 1994a) allows a maximum removable concentration that is 20% of the maximum allowable total surface contamination for most radionuclides except for some transuranics and tritium (Table 2-2 in DOE, 1994a). The maximum allowed removable transuranic or tritium contamination is 4% or 100%, respectively, of the maximum allowable surface contamination. However, conditions may exist under these restrictions for unrestricted use where for all radionuclides, the removable surface contamination constitutes 20% of the surface contamination. For the NRC, maximum acceptable removable concentrations are 20% of the average surface concentrations for all radionuclides (Table 1 in NRC, 1974), but like the DOE regulations, the removable fraction can be higher than 0.2 if overall surface concentrations are lower. Thus, a triangular distribution, as shown in Figure 8.3-1, is suggested for the removable fraction, with a most likely value of 0.2 and minimum and maximum values of 0 and 1, respectively, as discussed above.
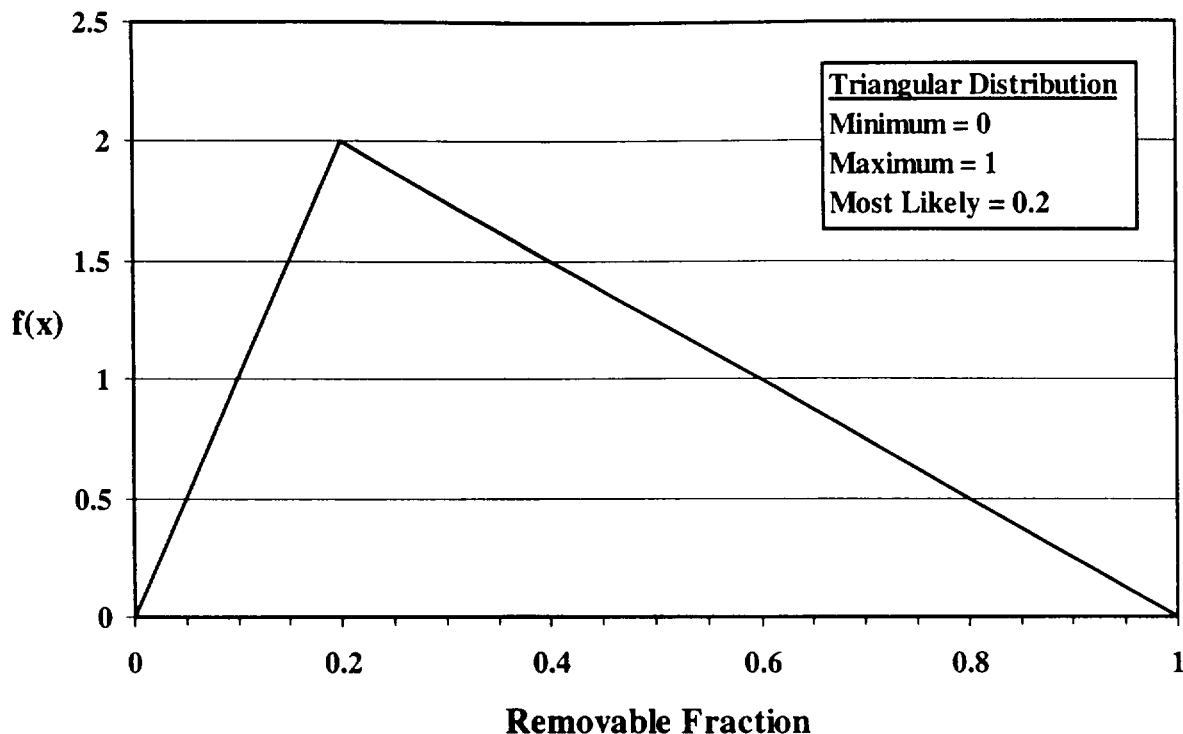
Figure 8.3-1 Removable Fraction Probability Distribution

For specific situations, a number of factors must be considered, including location of the contamination (e.g., wall or floor and proximity to human activity), the nature of the contaminated surface (e.g., type of material [chemical and physical properties]), the original form of the contaminant (chemical and physical properties [e.g., powder versus liquid and chemical reactivity]) and the removal mechanism (such as washing or foot traffic).

Smear tests are often used to determine the amount of "fixed" versus "non-fixed" (or removable) contamination (Frame and Abelquist, 1999). Although the definition of removable contamination varies, it applies to radioactive "contamination which is removable or transferrable under normal working conditions" (International Organization for Standardization [ISO], 1988) or "radioactivity that can be transferred from a surface to a smear test paper by rubbing with moderate pressure" (NRC, 1979a,b) or "radioactive material that can be removed from surfaces by non-destructive means such as casual contact, wiping, brushing, or washing" (DOE, 1994a). However, smear tests can vary because of the material of the smear wipes used and the potential use of a wetting agent (Frame and Abelquist, 1999). Also, smear tests will vary for the reasons listed above. Table 8.3-1 lists results from early experiments demonstrating that the nature of the contamination and of the surface can influence how easily removable the radioactive contamination can be. Thus, a specific distribution for the removable fraction must be

made on a case-by-case basis. Other measurement tests in the past have included tape and modified air sensor tests. Table 8.3-2 presents some results comparing these methods with smear tests on different surfaces.

Table 8.3-1 Influence of Surface and Contaminant Types on Smear Tests

Percentage Contamination Removed	Contamination	Surface	Comments	Reference
1 to 3	Low level from normal use	Granolithic concrete floor		Brunskill (1967)
50			Water wash of floor	
0.1 to 0.2	Plutonium nitrate	Paper	Plutonium nitrate or oxide in solution was applied to the floor and allowed to dry for 16 hours	Jones and Pond (1967)
6		Waxed and polished linoleum		
20 to 30		Polyvinyl chloride		
10 to 20	PuO_2	Polyvinyl chloride		
20 to 30		Unwaxed linoleum		
50 to 60		Waxed and polished linoleum		

Table 8.3-2 Percent Removal of Contamination for Different Sampling Methods[a]

Surface	Removal (%)		
	Adhesive Paper	Smear	Modified Air
Polyethylene	70.3	56.6	10.9
Glass	75.0	64.6	27.2
Plexiglass	78.0	71.3	15.8
Fiberboard (waxed)	53.8	44.3	10.2
Fiberboard (scrubbed)	56.9	23.5	9.0
Fiberboard (untreated)	73.4	23.5	6.6
Formica	73.4	70.6	26.5
Aluminum (painted)	70.0	50.3	24.8
Asphalt floor tile (untreated)	58.6	48.5	14.6
Asphalt floor tile (waxed)	74.5	74.5	30.3
Concrete (unsealed)	55.5	39.5	22.0
Concrete (sealed [seal and wax 1])	62.2	59.5	24.0
Concrete (sealed [seal and wax 2])	54.8	47.7	27.2
Concrete (greased)	43.5	37.5	1.32
Stainless steel	67.7	50.5	10.5

[a] Modified air sampler (referred to as a "smair" sampler by the authors) causes air intake to blow across the sample surface when the sample head is pressed against a surface.

Source: Royster and Fish (1967); contamination was simulated by thorium dioxide dust particles approximately 1 μm in diameter at a concentration of about 1 $\times$ 10^6 particles per square centimeter.

8.4 Source Porosity

Applicable Code: RESRAD-BUILD

Description: The source porosity is the ratio of the pore volume to the total volume of a representative sample of the source material.

Units: unitless

Probabilistic Input (allowed only for concrete):

Distribution: uniform

Defining Values for Distribution:

Minimum: 0.04   Maximum: 0.25

Discussion: The source porosity parameter is used in RESRAD-BUILD to calculate the diffusion of radon and tritium from a volume source and is applicable to the tritium inhalation and the radon inhalation pathways. This parameter is only required as input if a tritium volume source is selected or if radon (radon-220 and radon-222) precursors are entered as part of the volume source.

Porosity may range from 0 to 1 and may be reported as a decimal fraction or as a percentage. Input to the RESRAD-BUILD code is as a decimal fraction. A value of 0 represents a material that is completely solid, without any void spaces. On the other extreme, a porosity approaching 1 represents a material that is made up mostly of void spaces. Building materials such as concrete, brick, or rock typically have porosities ranging from 0 to 0.3.

Widespread variations in concrete porosity are observed because of the differences in the aggregates used, water/cement ratios in the cement paste, and curing conditions. Cement paste in concrete occupies from 23 to 36% of the total volume (Culot et al., 1976), sand 25 to 30%, and aggregates the remainder. Overall porosity of concrete depends on the porosity of the cement paste as well as of the aggregates. The porosity of concrete was found to range from 0.05 to 0.25 (Culot et al., 1976).

The porosity estimated for a concrete structure made of Portland cement was found to vary from 0.04 to 0.20 (Frankowski et al., 1997). Table 8.4-1 gives the bulk density and porosity of the rocks commonly used as building materials (Bever, 1986). Materials used for thermal insulation tend to have a very high air content, with porosities

approaching 1. Material porosity tends to be inversely correlated with material density; low porosity materials tend to have higher densities than any porous materials.

On the basis of the definition of porosity, the porosity of a material could be evaluated by directly measuring the pore volume and the total volume. The American Society for Testing and Materials (ASTM) has established a standard procedure (B 276) for cemented carbide to rate three types of porosities, depending on the pore diameters (Type A, pore diameters < 10 μm; Type B, pore diameters between 10 and 25 μm; and Type C, covering porosity developed by the presence of free carbon). Similarly, ASTM has developed standard test methods for porosity of metal structure parts, and porosity tests for electrodeposits and related metallic coatings (http://www.astm.org/sitemap.html).

For generic applications, a uniform distribution from 0.04 to 0.25 is suggested for the source porosity for concrete. The minimum and maximum values were those reported by Frankowski et al. (1997) and Culot et al. (1976), respectively. The probability density function is shown in Figure 8.4-1.

Table 8.4-1 Bulk Density and Porosity of Rocks Commonly Used as Building Materials

Rock	Bulk Density (g/cm^3)	Porosity (%)
Granite	2.6-2.7	0.5-1.5
Basalt	2.8-2.9	0.1-1.0
Sandstone	2.0-2.6	0.5-25.0
Limestone	2.2-2.6	0.5-20.0
Gneiss	2.9-3.0	0.5-1.5
Marble	2.6-2.7	0.5-2.0

Source: Bever (1986).
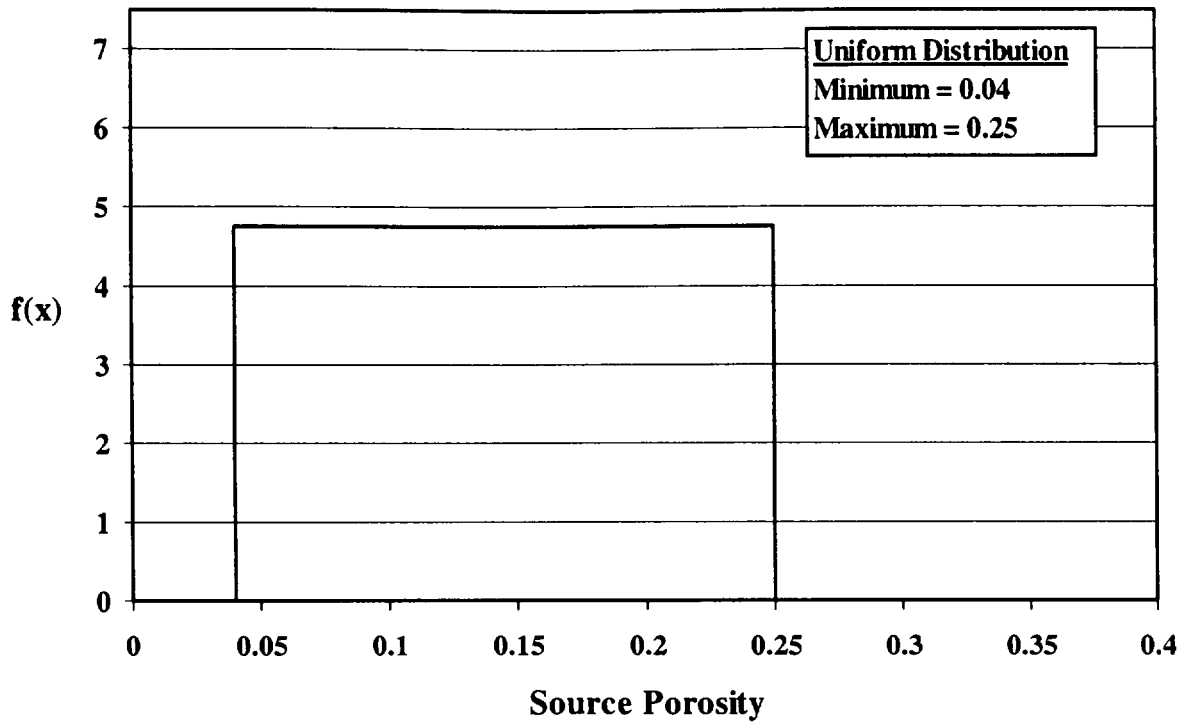
Figure 8.4-1 Concrete Source Porosity Probability Density Function

8.5 Volumetric Water Content

Applicable Code: RESRAD-BUILD

Description: The volumetric water content is the volume of water per unit volume of the porous material.

Units: unitless

Probabilistic Input (allowed only for concrete):

Distribution: uniform

Defining Values for Distribution:

Minimum value: 0.04   Maximum value: 0.25

Discussion: The volumetric water content is used in RESRAD-BUILD when evaluating the radiological risks from a volume source contaminated with tritium. The assumption is made that any tritium is present as tritiated water. Because the contamination is assumed to result from a recent spill, the amount of water in the volume source is expected to be within the range of the concrete's total porosity. Thus, the distribution for the volumetric water content is expected to be the same as the source porosity (Section 8.4). In any case, the maximum value assigned to the volumetric water content should not be greater than the maximum of the source porosity.

8.6 Air Release Fraction

Applicable Code: RESRAD-BUILD

Description: The air release fraction is the amount of the contaminated material removed from the source that is released into the air and in the respirable particulate range.

Units: unitless

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 1×10^{-6} Maximum: 1   Most likely: 0.07

Discussion: The fraction released to the air is the amount of the contaminated material removed from the source that is actually suspended in air; the balance of the material is assumed to be instantaneously removed from the room. It is a dimensionless parameter that can range from 0 (all eroded material is removed instantaneously from the room) to 1 (all eroded material is suspended instantaneously in the respirable room air). This parameter depends strongly on the erosion process. Dusting would result in low erosion rates, but a relatively high fraction of removed material may become suspended in air. Vacuuming may result in higher erosion rates than dusting, but a smaller fraction would become airborne; a significant fraction would be trapped in the vacuum. Mechanical disturbances such as sanding, scraping, or chipping result in a high contaminant removal rate but usually generate a relatively small fraction of particulates released to air. Most of the eroded material tends to fall to the floor and is removed from the room by housekeeping activities.

The RESRAD-BUILD code requires an air release fraction input for each source. Entering 0 means that none of the removable material will be released to the air that is respirable. The dose contributions from deposition, immersion, dust inhalation, and indirect ingestion are effectively suppressed. Entering 1 is very conservative because it will maximize the dose contributions from these pathways. Note that if either the removable fraction or erosion rates are 0, the contributions from these pathways will be suppressed no matter what value is given to the air release fraction.

The DOE handbook on airborne release and respirable fractions (RFs) (DOE, 1994b) provides a compendium and analysis of experimental data from which airborne

release fractions[1] (ARFs) and RFs[2] may be derived. The data are given by the physical form of the material affected (e.g., gas, liquid, solid, surface contamination) and different suspension stresses (e.g., spill, thermal stress, shock wave, blast stress). The ANS has published an American National Standard for airborne release fractions at nonreactor nuclear facilities (ANS, 1998).

For materials in gaseous form, such as H-3, the recommended airborne release fraction is 1.0. All materials in the gaseous state can be transported and inhaled; therefore, the respirable fraction is also 1.0 (DOE, 1994b).

The DOE handbook provides release fractions for three categories of solid materials: metals, nonmetallic or composite solids, and powders. The bounding ARF for plutonium metal formed by oxidation at elevated temperature was found to be 3×10^{-5}, with an RF value of 0.04. ARF and RF values of 1×10^{-3} and 1.0 were assessed to be bounding during complete oxidation of metal mass (DOE, 1994b). The bounding values for contaminated, noncombustible solids were found to be 0.1 and 0.7 for ARF and RF, respectively (these release values are for loose surface contamination on the solid, not the solid as a whole).

Little information is available for the building occupancy scenario air release fraction; therefore, a triangular distribution based on above data is used to generate distribution. The maximum value is assumed to be 1 (for gaseous forms), the minimum value chosen is that for plutonium metal ($3 \times 10^{-5} \times 0.04 = 1.2 \times 10^{-6}$), and the mode (most likely value) is the bounding value for contaminated noncombustible solids ($0.1 \times 0.7 = 0.07$). The probability density function is displayed in Figure 8.6-1.

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[1]   The airborne release fraction is the amount of radioactive material that can be suspended in air and made available for airborne transport.

[2]   The respirable fraction is the fraction of airborne radionuclides as particulates that can be transported through air and inhaled into the human respiratory system. This fraction is commonly assumed to include particles of 10-μm aerodynamic equivalent diameter and less.
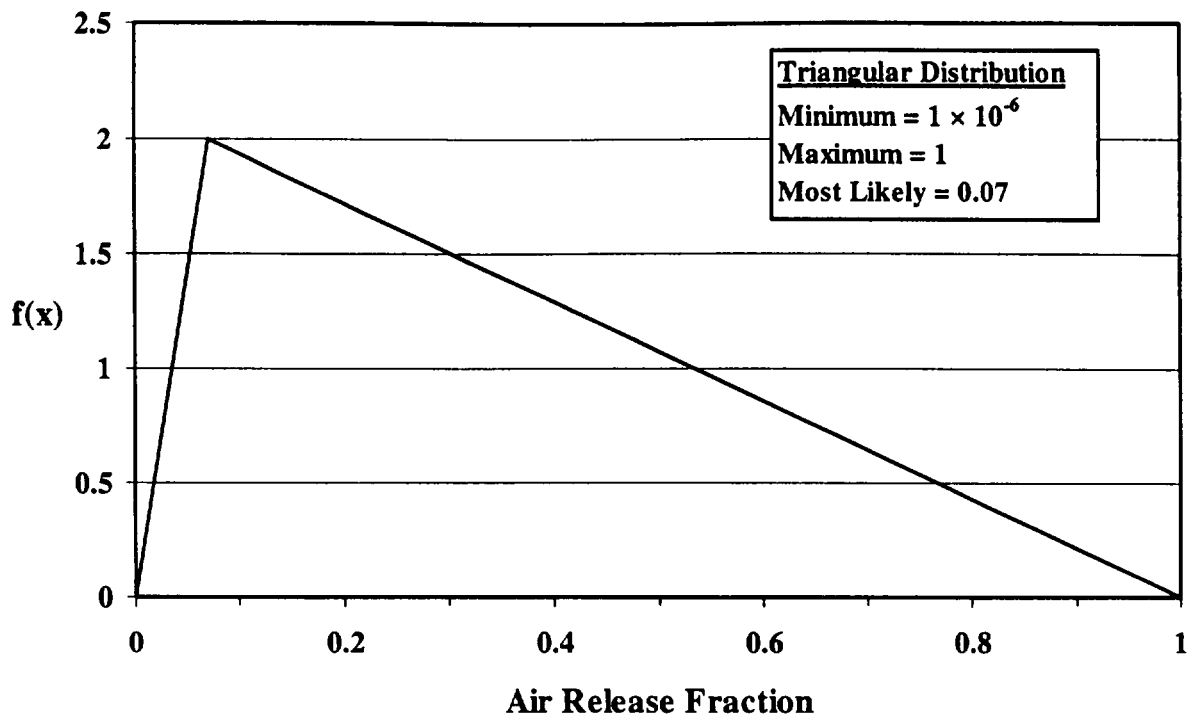
Figure 8.6-1 Air Release Fraction Probability Density Function

8.7 Wet + Dry Zone Thickness

Applicable Code : RESRAD-BUILD

Description: This parameter represents the depth from the surface of the contaminated material to the deepest point of the contaminated zone.

Unit: centimeters (cm)

Probabilistic Input (allowed only for volume contamination with tritium):

Distribution: uniform

Defining Values for Distribution:

Minimum: 5   Maximum: 30

Discussion: The wet+dry zone thickness parameter is used in RESRAD-BUILD in modeling the emission rate of tritiated water (HTO) vapor from the contamination source to the indoor atmosphere. In a tritium-handling facility, tritium contamination of the construction material and the equipment is recognized as an important source in defining the requirements for atmospheric cleanup and personnel protection. Tritium released during the handling process can quickly sorb to surfaces of the surrounding materials (e.g., concrete walls and floors) and can diffuse through many of them, resulting in contamination of the bulk as well as of the surface. The tritium that is absorbed/adsorbed to the surrounding materials can then be desorbed and released to the indoor air. This sorption/desorption process is generally referred to as the "tritium soaking effect" in tritium-handling facilities.

Tritium released from the tritium-handling facilities can be in different chemical forms; the most common ones are tritium gas (HT) and tritium oxide, or HTO. In general, sorption and desorption of HT occurs faster than that of HTO; however, the total amount sorbed and desorbed is greater for HTO than for HT (Wong et al., 1991; Dickson and Miller, 1992). On the other hand, HT can easily be converted to HTO in the environment. Experimental data concerning the tritium soaking effect on construction metals also showed that about 90% of the tritium desorbed from metal samples was in the form of HTO, although the samples were exposed to an atmosphere of HT (Dickson and Miller, 1992). Because of the conversion from HT to HTO and the potentially longer time required for degassing of HTO (desorption and subsequent release from the contaminated material to the indoor air), the tritium model incorporated into the RESRAD-BUILD code considers only the potential degassing of HTO after the tritium handling operation ended.

Among all the materials that can become contaminated, concrete is of special concern because of its porous nature. The high porosity of concrete materials makes them more vulnerable to the permeation of tritiated water, which can spread out inside the concrete matrix after the initial surface absorption/adsorption. In RESRAD-BUILD, the degassing (i.e., the release) of the HTO vapor is assumed to be controlled by diffusion of the free HTO molecules from inside of the concrete matrix to the concrete-atmosphere interface (the "free" molecules are the HTO molecules that are not bound to the concrete matrix and are available for diffusion, see discussion for the "water fraction available for evaporation" parameter, Section 8.10).

The diffusion of HTO is assumed to proceed like a peeling process in which the HTO molecules closer to the concrete-atmosphere interface will be released earlier than those farther from the interface. As the release process continues, a region free of free HTO molecules (i.e., the dry zone), will be formed, and its thickness will increase over time. The dry zone thickness then represents the path length for the subsequent diffusion. The region inside the concrete where the free HTO molecules are distributed is called the wet zone. As the dry zone becomes thicker, the thickness of the wet zone decreases accordingly. In fact, the sum of the dry zone thickness and the wet zone thickness is assumed to remain the same throughout the diffusion process.

Although diffusion of the HTO vapor to the bulk of concrete materials in a tritium handling facility is recognized (Wong et al., 1991), direct detection of the extent of spreading into the bulk (i.e., dry+ wet zone thickness) is not possible because of the short range of the beta radiation (DOE, 1991). However, judging by the high porosity of concrete materials, spreading of the HTO vapor throughout the entire thickness is possible if the exposure is of sufficient duration. Therefore, the thickness of the concrete wall is assumed for the "dry+wet zone thickness" parameter, which, on the basis of engineering judgments, can be as much as 30 cm. A low bound of 5 cm is selected because bulk contamination will not be extensive for a short exposure period. The probability density function is shown in Figure 8.7-1.
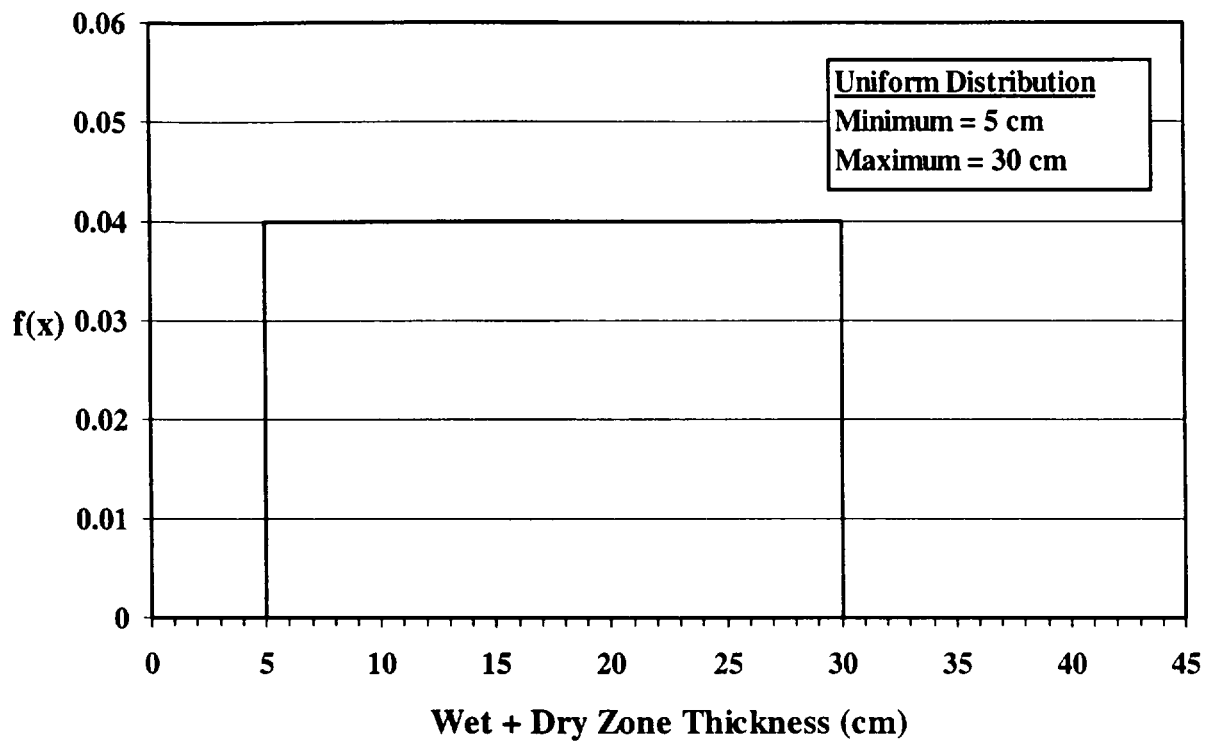
Figure 8.7-1 Wet + Dry Zone Thickness Probability Density Function

8.8 Time for Source Removal or Source Lifetime

Applicable Code : RESRAD-BUILD

Description: This parameter represents the time over which surface contamination is removed. The parameter is used in conjunction with the "removable fraction of source material" parameter (Section 8.3) and the "air release fraction" (Section 8.6) to obtain the emission rate of radionuclides into the indoor air.

Unit: days (d)

Probabilistic Input (allowed only for surface contamination):

Distribution: triangular

Defining Values for Distribution:

Minimum: 1,000   Maximum: 100,000   Most likely: 10,000 (27.4 yr)

Discussion: The RESRAD-BUILD model considers the potential entrainment of loose contamination from a contaminated surface to the indoor atmosphere. The entrainment rate of the loose contamination is calculated by using the "removable fraction" parameter, the "time for source removal or source lifetime" parameter, and the total contaminant inventory on the surface. Information on the "time for source removal or source lifetime" parameter is not directly available from the open literature; therefore, the potential range of this parameter was inferred on the basis of information on other, related parameters.

Different mechanisms can result in the entrainment of loose surface particles to the atmosphere. Mechanical abrasion during renovation activities would result in the highest entrainment rate in the shortest period of time. However, for normal building occupancy conditions, renovation activities were excluded from consideration.

According to the American Nuclear Society, an air release rate of 4×10^{-5}/h is a conservative value for use in estimating the potential exposure resulting from release of solid powders piled up on a heterogeneous surface (e.g., concrete, stainless steel, or glass) under the condition of normal building ventilation flow (ANS, 1998). That rate is equivalent to a lifetime of approximately 1,040 days (or 2.85 years). Although the loose particles on the contaminated source are not exactly the same as a pile of solid powders, the value for the free solid powders can be used to derive a lower bounding lifetime value for the loose materials.

Another suggestion by the ANS is an air release rate of 4×10^{-6}/h for solid powders that are covered with a substantial layer of debris or are constrained by indoor static conditions (ANS, 1998). This rate is equivalent to a lifetime of approximately 10,000 days (27.4 yr). The loose contaminants on a contaminated surface can be considered as being restricted by some weak physical binding force and would, therefore, behave like the constrained solid powders. The lifetime of the constrained solid powders can be used as the most likely value for the loose contaminants.

Erosion of the surface layer from the contaminated material can eventually occur over a long period of time, if there is no constant maintenance. Therefore, all the loose contaminants have the opportunity of being released to the environment. To consider this extreme case, a lifetime of 300 years (~100,000 days) was assumed. The probability density function is shown in Figure 8.8-1.

Another factor that is frequently used in the literature for estimating air concentrations from surface sources is the resuspension factor. The resuspension factor is not used in the RESRAD code, but it is a quantity closely related to the source lifetime for a surface source. Assuming a surface source on the floor with a removable fraction of 0.2 (Section 8.3) and an air release fraction of 0.07 (Section 8.6), the resuspension factor can be estimated from the source lifetime. A floor area of 36 m² (Section 7.7), a room height of 3.7 m (Section 7.8), and a room air exchange rate of 1.52 h⁻¹ (Section 7.4) were used. In this case, the source lifetime of 10,000 days is equivalent to a resuspension factor of 1×10^{-8}/m.
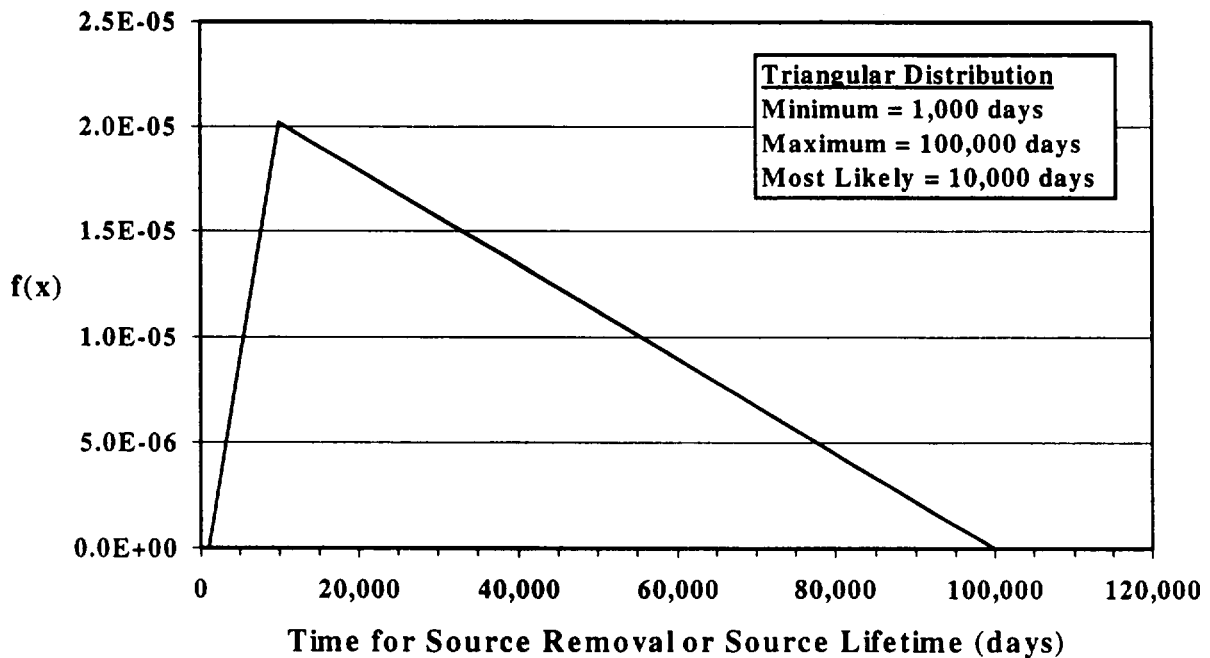
Figure 8.8-1 Time for Source Removal or Source Lifetime Probability Density Function

8.9 Source Thickness, Volume Source

Applicable Code: RESRAD-BUILD

Description: This parameter represents the thickness of each layer in an idealized volume source. This parameter does not apply to area, line, or point sources.

Units: centimeters (cm)

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 2.5   Maximum: 30   Most likely: 15

Discussion: RESRAD-BUILD allows consideration of a total of five distinct regions (layers) in a volume source. The contamination is within these regions, and the total thickness of the volume source is the sum of the thicknesses of these regions. The code requires a source thickness (in centimeters) for every layer of each volume source. The source thickness depends upon the detail of modeling desired. For example, a wall could be modeled as a single layer or multiple layers (e.g., a sequence of paint, drywall, framing gap, drywall, and paint), with up to five layers per source. It is highly recommended that the source thickness be obtained from direct measurement or be estimated on the basis of the applicable building codes. The contaminated layer thickness and position should be based on site-specific measurement.

With the exception of sources resulting from neutron activation, most volume activity in buildings will be limited to small areas (hot spots) or rather shallow sources. For the case of neutron activation, volume sources could extend deep into the volume of a building structure. The thickness of building structure materials will place a limit on the potential thickness for volume sources. Ayers et al. (1999) noted that the contamination of concrete usually results from spills, contaminated dust, or other surficial deposition. In some instances, the contaminants may migrate into the concrete matrix, particularly over time and under environmental stresses. Cracks and crevices may also provide routes for contaminants to spread deeper into the concrete matrix. To estimate the total contaminated volume of concrete from DOE facilities, Ayers et al. (1999) assumed contamination to 1-in. (2.5-cm) depth and an average concrete thickness of 12 in. (30 cm) in a building. For external exposure calculations, this thickness will approximate an infinite thickness for alpha-emitters, beta-emitters, and X-ray or low-energy photon emitters. DandD and RESRAD-BUILD use 15 cm as the default source thickness for a volume source.

Little information is available for the source thicknesses in real decommissioning and decontamination situations; therefore, on the basis of above data, a triangular distribution is assumed for source thickness. The maximum value is assumed to be 30 cm, the minimum value is chosen as 2.5 cm, and the most likely value is the 15-cm default used in DandD and RESRAD-BUILD codes for volume sources. Figure 8.9-1 presents the probability density function for the source thickness.
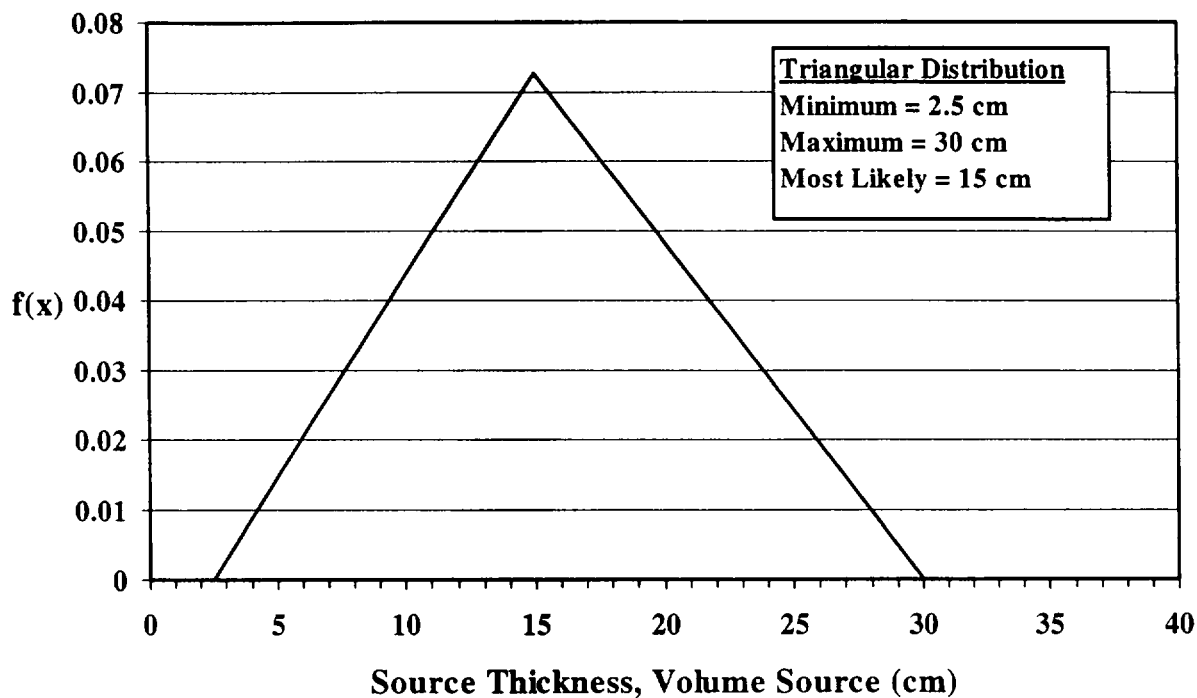
Figure 8.9-1 Source Thickness Probability Density Function

8.10 Water Fraction Available for Evaporation

Applicable Code : RESRAD-BUILD

Description: This parameter is used in estimating the potential release rate of tritiated water (HTO) vapor from a volume contamination source. It is the fraction of the total amount of tritiated water that will be released to the indoor air through the diffusion mechanism under room temperature.

Unit: unitless

Probabilistic Input (allowed only for volume contamination with tritium)

Distribution: triangular

Defining Values for Distribution:

Minimum: 0.5   Maximum: 1.0   Most likely: 0.75

Discussion: In a tritium-handling facility, tritium contamination of the construction material and the equipment is recognized as an important radiation source in defining the requirements for atmospheric cleanup and personnel protection. Tritium released during the handling process can quickly sorb to surfaces of the surrounding materials and can diffuse through many of them, resulting in both bulk (volumetric) and surface contamination. The tritium that is absorbed or adsorbed to the surrounding materials can then be desorb from the materials and released to the indoor air. This sorption/desorption process is generally referred to as the "tritium soaking effect" in tritium-handling facilities.

Tritium released from the tritium-handling facilities can be in different chemical forms; the most common ones are tritium gas (HT) and tritium oxide, or tritiated water (HTO). In general, sorption and desorption of HT occurs faster than that of HTO; however, the total amount sorbed and desorbed is greater for HTO than for HT (Wong et al., 1991; Dickson and Miller, 1992). On the other hand, HT can easily be converted to HTO in the environment. Experimental data concerning the tritium soaking effect on construction metals also showed that about 90% of the tritium desorbed from the metal samples was in the form of HTO, although the samples were exposed to atmosphere of HT (Dickson and Miller, 1992). Because of the conversion from HT to HTO and the potentially longer time required for degassing of HTO (desorption and subsequent release from the contaminated material to the indoor air), the tritium model incorporated in the RESRAD-BUILD code considers only the potential degassing of HTO after the tritium-handling operation has stopped.

Among all the materials that can become contaminated, concrete is of special concern because of its porous nature. The high porosity of concrete materials makes them more vulnerable to the permeation of tritiated water, which can spread out inside the concrete matrix after the initial surface absorption/adsorption. In RESRAD-BUILD, the degassing (i.e. the release) of the HTO vapor is assumed to be controlled by diffusion of the HTO molecules from inside of the concrete matrix to the concrete-atmosphere interface.

The diffusion rate is estimated on the basis of information on extent of the contamination (thickness of dry zone, thickness of dry zone + wet zone, and area of contamination), characteristics of the source material (porosity and moisture content), tritium inventory (tritium concentration), and indoor humidity. Because not all the tritium in the source material is available for diffusion under ordinary building occupancy conditions, estimation of the release rate has to take into account the fraction of tritiated water available for evaporation and diffusion.

According to the experimental observations by Numata and Amano (1988), water exists in concrete in two states: free water and bound water. Free water is the liquid water that fills the pore space and capillaries in the concrete. Bound water is the water that combines with constitute compounds in concrete or the constituent itself. The fraction of free water was determined by Numata and Amano (1988) in their thermal desorption experiments as the fraction that was desorbed from concrete samples when the heating temperature was less than 200°C. The existence of free water versus bound water was verified in the investigation by Ono et al. (1992), who studied sorption and desorption of tritiated water on paints. That study found that recovery of tritium sorbed to various paint materials was not complete by gas sweeping under 30°C. Residual tritium sorbed was recovered by heating up the samples up to 800°C. Although the samples used by Ono et al. (1992) were different from the concrete samples used by Numata and Amano (1988), it is quite conclusive that some tritiated water can form strong bounding with the source materials. In the RESRAD-BUILD tritium model, it is assumed that under ordinary building occupancy conditions, only the water that fills the pore space and capillaries of the concrete materials will evaporate and diffuse to the indoor atmosphere.

Numata and Amano (1988) reported that the fraction of free tritiated water in concrete samples depended on duration of the previous exposure of the samples to tritiated water vapor. Shorter exposure duration resulted in larger fraction of free tritiated water. However, as the exposure duration was increased to more than 60 days, equilibrium values were observed. The fraction of free tritiated water at equilibrium was 0.72 for hardened cement paste and 0.74 for mortar. The fraction of free ordinary water was lower than that for tritiated water because the ordinary water originally exists in the samples and was the residual water left during crystallization of the cement samples. The free fraction was about 0.58 for both hardened cement paste and mortar samples.

The free fractions of ordinary water reported by Numata and Amano (1988) are consistent with the suggestion in DOE (1994b) regarding the air release fraction of tritiated water from concrete materials under accidental conditions that can cause the temperature to reach as high as 200°C. Tritiated water was assumed in the DOE report to be used in concrete formation, which is the same role as ordinary water in Numata and Amano's experiments.

It can be deduced from the above discussions that (1) the free fraction of tritiated water in concrete materials used in tritium-handling facilities is greater than the free fraction of ordinary water in the same materials, and (2) the free fraction of tritiated water in the concrete materials can be very high if exposure duration of the concrete materials to tritiated water was very short. Therefore, a triangular distribution with a minimum of 0.5, a maximum of 1.0, and a most likely value of 0.75 was assumed for the "free water fraction available for evaporation" parameter. The probability density function is shown in Figure 8.10-1.
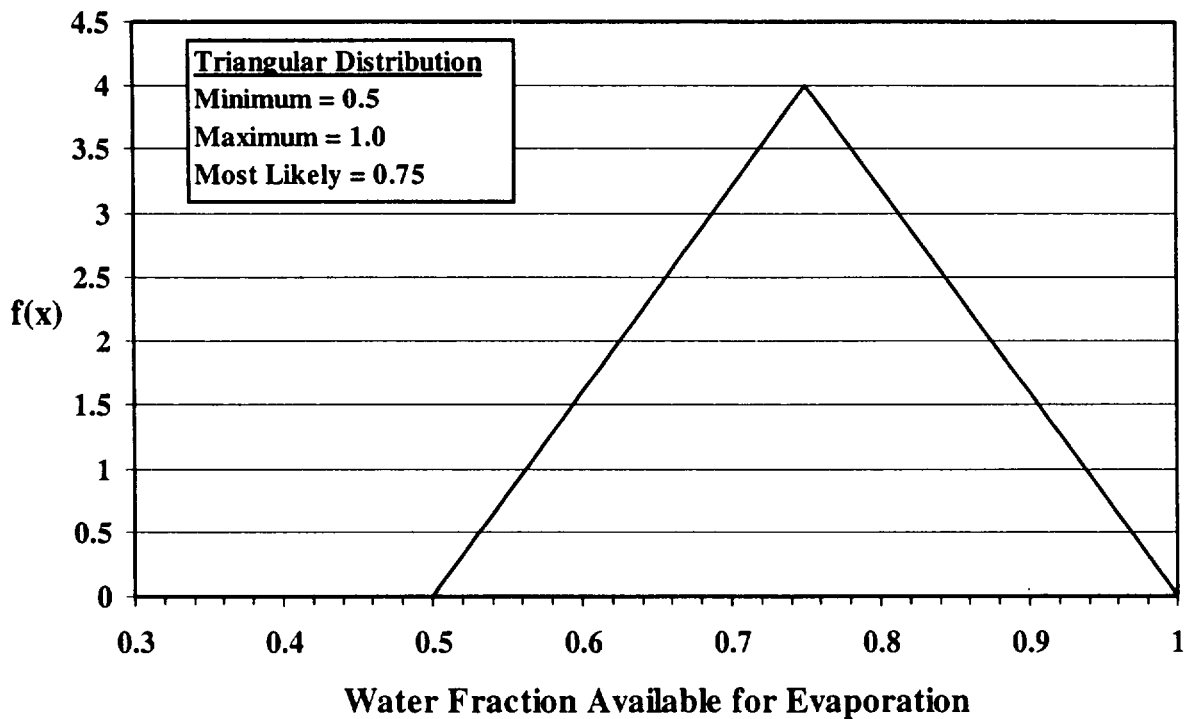
Figure 8.10-1 Water Fraction Available for Evaporation

8.11 C-14 Evasion Layer Thickness in Soil

Applicable Code: RESRAD

Description: This parameter represents the maximum soil thickness layer through which carbon-14 (C-14) can escape to the air by conversion to carbon dioxide (CO_2).

Units: meters (m)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 0.2   Maximum: 0.6   Most likely: 0.3

Discussion: One of the important pathways involving the radiological dose to humans from soil contaminated with C-14 is the plant ingestion pathway. In addition to direct root uptake from soil and foliar deposition of dust particles contaminated with C-14, carbon in gases volatilized from the soil is directly incorporated into the plant by the process of photosynthesis.

Inorganic and organic reactions convert most forms of soil carbon to CO_2. Because of the volatile nature of CO_2, soil carbon is usually lost to the air, where it becomes absorbed in plants through photosynthesis. The concentration of C-14 in air above a contaminated zone depends on the volatilization (evasion) rate of carbon from the soil, the size and location of the source area, and meteorological dispersion conditions.

Sheppard et al. (1991) measured the rate of C-14 loss from soils in outdoor lysimeter experiments and also investigated the vertical mobility of representative inorganic and organic C-14-labeled compounds in unsaturated soil for both net-leaching and net-capillary rise scenarios. The two soils (one retentive and other with low retention) chosen allowed investigation of the importance of organic matter and native carbonate content on C-14 mobility. The retentive soil was very fine sandy loam with high carbonate content, and the low retention acidic soil had no carbonate content (medium sand). Sheppard et al. (1991) observed upward movement of C-14 (perhaps linked to volatilization) up to the depth of 60 cm for the low retention acidic soil. Some upward movement was observed in all soil samples analyzed (activity ratio for the upward movement of 20 cm was >0.2). Amiro et al. (1991) assumed evasion layer thickness of 0.3 m in estimating C-14 flux from soil to the atmosphere.

On the basis of the above information, C-14 evasion layer thickness is assigned triangular distribution, with minimum of 0.2 m, a maximum value of 0.6 m, and a most likely value of 0.3 m. The probability density function is shown in Figure 8.11-1.
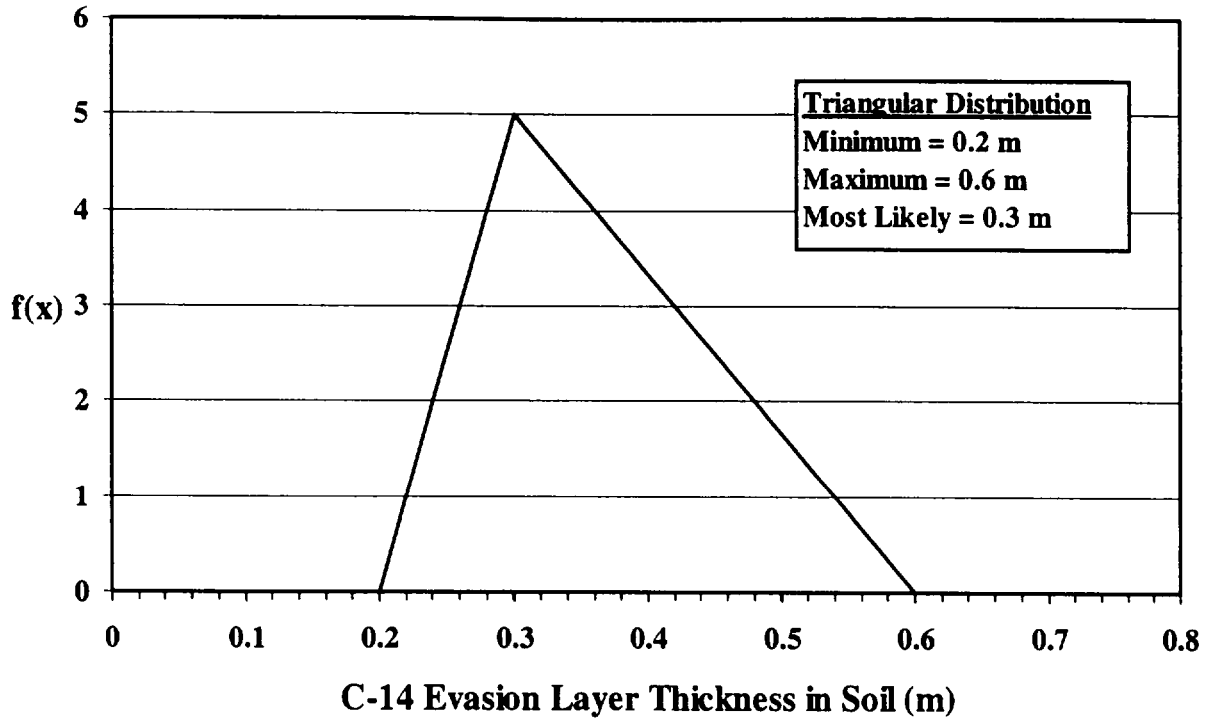
Figure 8.11-1 C-14 Evasion Layer Thickness in Soil Probability Density Function

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APPENDIX A:

PARAMETRIC DISTRIBUTION TYPES

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PARAMETRIC DISTRIBUTION TYPES

This appendix discusses the form and characteristics of each of the parametric distributions available in the Latin Hypercube Sampling (LHS) module that may be used to represent input parameters in the RESRAD and RESRAD-BUILD codes. Table A.1 summarizes the continuous probability density distribution functions and the required input for the LHS module.

A.1 Beta Distribution

The LHS code incorporates a four-parameter beta distribution that has the probability density function:

$$f(x) = \frac{1}{B(p,q)} \frac{(x-A)^{p-1}(B-x)^{q-1}}{(B-A)^{p+q-1}} , \qquad (A-1)$$

where $B(p,q)$ is the beta function,

$$B(p,q) = \int_0^1 t^{p-1}(1-t)^{q-1} dt , \qquad (A-2)$$

p and q are shape parameters, and A and B are the endpoints of the distribution. This distribution is very flexible and is often used to fit empirical data. The shape of the distribution can vary widely depending on the relationship of p and q to one another. This flexibility also makes the beta distribution useful for approximating distributions when there are insufficient data.

As discussed below in the section on the maximum entropy distribution (Section A.7), the beta distribution may be used in cases where estimates for the minimum (A), maximum (B), mean (μ), and standard deviation (σ) are available, but little else is known. In such a case, the shape parameters can be estimated according to Lee and Wright (1994):

$$p = (\mu - A)\left[\frac{(\mu-A)(B-\mu)\big/\sigma^2 - 1}{B-A}\right] , \qquad (A-3)$$

Table A.1 Continuous Probability Density Distribution Functions

Distribution	Input Variables			
Beta	A (minimum)	B (maximum)	p (shape factor)	q (shape factor)
Exponential Types				
Exponential	λ			
Bounded exponential	λ	A (minimum)	B (maximum)	
Truncated exponential	λ	lower quantile value	upper quantile value	
Gamma	α (shape factor)	β (scale factor)		
Inverse Gaussian	μ	λ		
Lognormal Types				
Lognormal	μ (mean)	error factor		
Lognormal-b	value at 0.001 quantile	value at 0.999 quantile		
Lognormal-n	mean of underlying normal distribution	standard dev. of underlying normal distribution		
Bounded lognormal	μ (mean)	error factor	A (minimum)	B (maximum)
Bounded lognormal-n	mean of underlying normal distribution	standard dev. of underlying normal distribution	A (minimum)	B (maximum)
Truncated lognormal	μ (mean)	error factor	lower quantile value	upper quantile value
Truncated lognormal-n	mean of underlying normal distribution	standard dev. of underlying normal distribution	lower quantile value	upper quantile value
Loguniform Types				
Loguniform	A (minimum)	B (maximum)		
Piecewise loguniform	number of intervals	# observations per interval 1...	# observations per interval n	first point, end point sequence
Maximum Entropy	A (minimum)	B (maximum)	μ (mean)	
Normal Types				
Normal	μ (mean)	σ (standard deviation)		
Normal-b	value at 0.001 quantile	value at 0.999 quantile		
Bounded normal	μ (mean)	σ (standard deviation)	A (minimum)	B (maximum)
Truncated normal	μ (mean)	σ (standard deviation)	lower quantile value	upper quantile value
Pareto	α	β		
Triangular	a (minimum)	b (most likely)	c (maximum)	
Uniform Types				
Uniform	A (minimum)	B (maximum)		
Piecewise uniform	number of intervals	# observations per interval 1...	# observations per interval n	first point, end point sequence
User Defined Types				
With linear interpolation (CDF input)	n (number of ordered pairs)	ordered pair 1	ordered pair 2 ...	ordered pair n
With logarithmic interpolation (CDF input)	n (number of ordered pairs)	ordered pair 1	ordered pair 2 ...	ordered pair n
With density function input	n (number of ordered pairs)	ordered pair 1	ordered pair 2 ...	ordered pair n
Weibull	α	β		

and

$$q = \frac{(\mu - A)(B - \mu)}{\sigma^2} - 1 - p \ . \tag{A-4}$$

A.2 Exponential Distribution

The probability density function for the exponential distribution is:

$$f(x) = \lambda \ e^{-\lambda x} \qquad \text{for } x \geq 0, \tag{A-5}$$

with the mean given by $1/\lambda$. The variable λ represents the average rate of occurrence of successive, independent, random events. Purely random Poisson processes exhibit such behavior. Examples include radioactive decay, accidents, and storm events.

A.3 Gamma Distribution

The gamma distribution represents the sum of a series of exponentially distributed random variables. The probability density function for the two-parameter form of the gamma distribution (sometimes referred to as "the incomplete gamma function") is:

$$f(x) = \frac{\beta^\alpha x^{(\alpha-1)} e^{-\beta x}}{\Gamma(\alpha)} \text{ with } x > 0, \ \alpha > 0, \ \beta > 0, \text{ and}$$

$$\tag{A-6}$$

$$\Gamma(\alpha) = \int_0^\infty y^{(\alpha-1)} e^{-y} dy \quad \text{or} \quad \Gamma(\alpha) = (\alpha - 1)! \text{ for integers,}$$

where $\Gamma(\alpha)$ is the gamma function. The α parameter determines the shape of the function, and the β parameter controls the scale. If the shape parameter is set to 1, the gamma distribution becomes a scalable exponential distribution. The mean for the gamma distribution is α/β. The gamma distribution is appropriate for representing the time required for α independent events to take place for nonrandom events that occur at a constant arrival rate β. This distribution is often used to describe system reliability (the length of life of industrial equipment).

A.4 Inverse Gaussian

The probability density function for the inverse Gaussian distribution is given by:

$$f(x) = \sqrt{\frac{\lambda}{2\pi x^3}} e^{-\left(\frac{\lambda(x-\mu)^2}{2\mu^2 x}\right)}. \tag{A-7}$$

The distribution was originally derived as a limiting form of distribution of sample size in certain sequential probability ratio tests. More information can be found in Johnson et al. (1994).

A.5 Lognormal Distribution

The lognormal distribution is defined by the logarithm of a normal distribution and is given by the following probability density function:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\left(\frac{(\ln x - \mu)^2}{2\sigma^2}\right)} \quad \text{with } x > 0, \tag{A-8}$$

where μ and σ are the mean and standard deviation of the underlying normal distribution. One advantage of this two-parameter form is that it can take on only positive values. Whereas the normal distribution may be thought of as describing a random variable that is the sum of independent effects, the lognormal distribution may be thought of as describing a random variable that is the result of multiplicative processes. The lognormal distribution has the functional form that is often used for describing dilution of matter in water or air. Environmental concentrations of contaminants in air and water generally follow a lognormal distribution (Ott, 1995).

A.6 Loguniform Distribution

The loguniform distribution is a variation on the uniform distribution. Similar to the uniform distribution, the loguniform distribution is useful when little is known about the distribution between the minimum and maximum values, but may be more appropriate when a large range exists between these values. The probability density function for the loguniform distribution is:

$$f(x) = \frac{1}{x(\ln b - \ln a)} \quad \text{for } a < x < b, \tag{A-9}$$

with the mean given by

$$\frac{b - a}{\ln b - \ln a}. \tag{A-10}$$

A.7 Maximum Entropy Distribution

The maximum entropy distribution implemented in the LHS code is a truncated exponential distribution where the user specifies the mean and the lower and upper bounds of the distribution. In general, the inference of maximum entropy produces broad distributions because it ensures that no mathematical possibility is ignored while using limited data. With knowledge of up to four properties of a distribution (lower and upper bounds, mean, standard deviation), a suitable maximum entropy distribution may be assigned (see Cullen and Frey [1999] for more information). A uniform distribution may be assigned using only estimates of the upper and lower bounds; a normal distribution may be assigned using only estimates of the mean and standard deviation; an exponential distribution may be assigned using only estimates of the lower (and upper) bound(s) in conjunction with the mean; and a beta distribution may be assigned using estimates of the lower and upper bounds, the mean, and the standard deviation.

A.8 Normal Distribution

The normal distribution is defined by the following probability density function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left(\frac{(x-\mu)^2}{2\sigma^2}\right)} \quad \text{with} \ -\infty < x < \infty, \tag{A-11}$$

where μ is the mean ($-\infty < \mu < \infty$) and σ is the standard deviation ($\sigma > 0$) of the random variable x. The normal distribution is also known as the Gaussian distribution and has the well-known bell-shaped curve, being symmetric about the mean with points of inflection at $X = x \pm \mu$. Thus, it is completely defined by the mean and standard deviation.

The theoretical basis for the application of the normal distribution lies in the central limit theorem. For a random variable x with mean μ and standard deviation σ, this theorem

states that the random variable Z has a distribution that approaches the standard normal distribution as $n \rightarrow \infty$ where n is the sample size and

$$Z = \frac{(\bar{x} - \mu)\sqrt{n}}{\sigma}.$$ (A-12)

The distribution of means of independent sample sets of a distribution or combination of distributions tends toward the normal distribution as the number of sample sets becomes large. The original distribution itself need not be a normal distribution. In summary, the central limit theorem suggests that any random variable representing the sum of a large number of independent processes or effects would tend to be normally distributed.

Because the normal distribution has infinite tails, the LHS module incorporated in RESRAD and RESRAD-BUILD provides three normal distribution options. Available are the normal distribution itself and two restricted versions, truncated normal (sampled between lower and upper quantile values input by the user) and bounded normal (sampled between lower and upper distribution values input by the user).

A.9 Pareto Distribution

The Pareto distribution was originally developed to account for the distribution of income over a population. The probability density function for the Pareto distribution can be given as:

$$f(x) = \frac{\alpha\beta^{\alpha}}{x^{\alpha+1}} \text{ for } x \geq \beta.$$ (A-13)

The mean for the Pareto distribution is given by:

$$\mu = \frac{\alpha\beta}{\alpha - 1} \text{ for } \alpha > 1.$$ (A-14)

A.10 Triangular Distribution

The triangular distribution is used to model situations where there is an absence of data. The probability density function for the triangular distribution is:

$$f(x) = \begin{cases} \dfrac{2(x-a)}{(c-a)(b-a)} & a \leq x \leq b \\[4mm] \dfrac{2(c-x)}{(c-a)(c-b)} & b \leq x \leq c, \end{cases} \qquad \text{(A-15)}$$

with the mean given by:

$$\frac{a+b+c}{3}, \qquad \text{(A-16)}$$

where the minimum and maximum occur at a and c, respectively, and the most likely value at b (the apex of the triangle). The value of b must satisfy $a \leq b \leq c$.

A.11 Uniform Distribution

All points within an interval having a uniform distribution, also known as the rectangular distribution, are equally likely. The probability density function for the uniform distribution is:

$$f(x) = \frac{1}{b-a} \quad \text{for } a \leq x \leq b, \qquad \text{(A-17)}$$

where a and b are the minimum and maximum values of the range of the random variable considered. The mean and variance of a uniform distribution are $(a+b)/2$ and $(b-a)^2/12$, respectively. If the only available data for a random variable are the minimum and maximum values, the maximum entropy distribution for such a case would be a uniform distribution. See the section above on maximum entropy distribution if the mean of the distribution is also known.

A.12 Weibull Distribution

The Weibull distribution is often used as a time-to-failure model as an alternative to the exponential distribution. The Weibull distribution is also sometimes known as the Frechet distribution. The probability density function for the Weibull distribution is given as:

$$f(x) = \left(\frac{\alpha}{\beta}\right)\left(\frac{x}{\beta}\right)^{(\alpha-1)} e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \quad \text{for } \alpha > 0 \text{ and } \beta > 0 , \tag{A-18}$$

where α is the shape parameter and β is the scale parameter. When $\alpha = 1$, the Weibull distribution reduces to the exponential distribution. When $\alpha = 2$, the Weibull distribution has the form of the Rayleigh distribution.

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ATTACHMENT D

TESTING OF THE RESRAD PROBABILISTIC MODULES

Prepared by

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TABLE OF CONTENTS

CONTENTS (Cont.)

TABLES

FIGURES

FIGURES (Cont.)

ABBREVIATIONS

CFR	Code of Federal Regulations
DCGL	derived concentration guideline level
DOE	U.S. Department of Energy
LHS	Latin hypercube sampling
NRC	U.S. Nuclear Regulatory Commission
PCC	partial correlation coefficient
PRCC	partial rank correlation coefficient
SRC	standardized regression coefficient
SRP	Standard Review Plan
SRRC	standardized rank regression coefficient
TEDE	total effective dose equivalent

TESTING OF THE RESRAD PROBABILISTIC MODULES

1 INTRODUCTION

On July 21, 1997, the U.S. Nuclear Regulatory Commission (NRC) published the License Termination Rule (Title 10, Code of Federal Regulations, Part 20 [10 CFR 20], Subpart E), which establishes requirements for nuclear facility licensees who are terminating their licensed operations. The NRC's approach to demonstrate compliance with the license termination rule is based on a philosophy of moving from simple, prudently conservative calculations toward more realistic simulations, as necessary, using dose modeling to evaluate exposure to residual radioactivity in soil and structures. Such potential exposures are evaluated for two scenarios: building occupancy (for contamination on indoor building surfaces) and residential (for contaminated soil).

The objective of dose modeling is to assess the total effective dose equivalent (TEDE) to an average member of the *critical group*[1] from residual contamination, including any contamination that has reached ground sources of drinking water. The assessment offers a reasonable translation of residual contamination into estimated radiation doses to the public. Compliance with the NRC-prescribed dose criteria can then be assessed from the modeling results.

As part of the development of site-specific implementation guidance supporting the License Termination Rule and development of a Standard Review Plan (SRP) on Decommissioning, the NRC recognized the need to perform probabilistic analysis with codes that could be used for site-specific modeling. Such modeling capabilities exist with the RESRAD (Yu et al., 1993) and RESRAD-BUILD (Yu et al., 1994) codes. These two codes were developed at Argonne National Laboratory (Argonne) under sponsorship of the U.S. Department of Energy (DOE). These DOE codes possess the following attributes: (1) the software has been widely accepted and there is already a large user base, (2) the models in the software were designed for and have been successfully applied at sites with relatively complex physical and contamination conditions, and (3) verification and validation of the codes are well documented (Yu, 1999; NUREG/CP-0163 [NRC, 1998]). The RESRAD codes have been used primarily

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[1] The *critical group* is defined as an individual or relatively homogenous group of individuals expected to receive the highest exposure under the assumptions of the particular scenario considered (NUREG/CR-5512 [Kennedy and Strenge, 1992]). The average member of the critical group is an individual assumed to represent the most likely exposure situation on the basis of prudently conservative exposure assumptions and parameter values within the model calculations.

to derive site-specific cleanup guidance levels (the derived concentration guideline levels, or DCGLs) on the basis of the deterministic method.

In 1999, the NRC tasked Argonne to modify the RESRAD and RESRAD-BUILD codes for use with the NRC's license termination compliance process and SRP. For use in this NRC process, the codes must meet specifications consistent with the current NRC modeling guidelines. Thus, the primary objectives of this project are for Argonne to (1) develop parameter distribution functions and perform probabilistic analysis with the RESRAD and RESRAD-BUILD computer codes, and (2) develop necessary computer modules, external to the RESRAD and RESRAD-BUILD codes, that incorporate the parameter distribution functions for conducting the probabilistic analyses. These modules will contain user-friendly features based on a specially designed graphic-user interface (GUI). They will be tailored to use the RESRAD and RESRAD-BUILD codes to perform site-specific probabilistic dose assessments in support of decontamination and decommissioning of potentially radiologically contaminated sites.

This document reports on one of a series of steps undertaken by Argonne to meet NRC's requirements. The effort reported here builds on the information provided in a series of letter reports to the NRC leading to development of parameter distributions and the required probabilistic capabilities for RESRAD and RESRAD-BUILD. Those reports are described in the following paragraphs.

Parameter Categorization (Kamboj et al., 1999)[2]: All the input parameters used in the RESRAD and RESRAD-BUILD codes (totaling about 200 parameters) were listed, categorized, and defined. The parameters were classified as relating to physical, behavioral, or metabolic attributes. Any parameter that would not change if a different group of receptors was considered was classified as a physical parameter. Any parameter that would depend on the receptor's behavior and the scenario definition was classified as a behavioral parameter. A parameter representing the metabolic characteristics of the potential receptor and that would be independent of the scenario being considered was classified as a metabolic parameter.

Parameter Ranking (Cheng et al., 1999)[3]: A strategy was developed to rank the RESRAD and RESRAD-BUILD input parameters and identify parameters for detailed distribution analysis. The parameters were divided into three levels of priority: 1 (high priority), 2 (medium priority), and 3 (low priority). The parameters were ranked on the basis of four criteria: (1) relevance of the parameter in dose calculations, (2) variability of the radiation dose as a result of changes in the parameter value, (3) parameter type (physical, behavioral, or metabolic), and (4) availability of data on the parameter in the

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[2] This report is included as Attachment A of the main document.

[3] This report is included as Attachment B of the main document.

literature. For each criterion, a numeric score (0-9) was assigned to each parameter, with a low score assigned to parameters with a higher priority and a high score assigned to parameters with lower priority under the considered criterion. The final priority ranking of each parameter was assigned on the basis of its total numeric score for the four ranking criteria. The lower the total score, the higher the priority assigned.

Parameter Distribution (Biwer et al., 2000)[4]: Value distributions were developed for those parameters identified as of high or medium priority in the RESRAD and RESRAD-BUILD codes. A total of about 70 parameters were selected for analysis. These parameters were deemed to be the ones most relevant to the NRC objective of demonstrating compliance with the radiological criteria for decommissioning and license termination. Development of distributions entailed gathering and analyzing relevant data from NRC-sponsored work and from an extensive literature search using library and Internet resources. However, it was recognized that many of the parameters in question have not been well tested or can vary significantly from site to site or even within the same site. Therefore, the focus was on analyzing the available data and making the most plausible distribution assignments for each selected parameter for use in an initial round of dose calculations.

Probabilistic Dose Analysis (Kamboj et al., 2000): The effects of parameter distribution on the estimated doses, taking into account parameter correlations, were assessed for the residential scenario with RESRAD and for the building occupancy scenario with RESRAD-BUILD. The interim versions of the probabilistic modules for the two codes (RESRAD version 5.95+ and RESRAD-BUILD version 2.9+) were used. The analysis took into account long-term transport of residual radionuclides in the environmental media and associated exposure pathways. For RESRAD, the peak dose within a 1,000-year time frame was captured, and for RESRAD-BUILD, the initial dose (i.e., at time 0) was calculated and used as the peak dose. The probabilistic analysis was performed by using the stratified sampling of the Latin hypercube sampling (LHS) method for a collection of input parameter distributions. The probabilistic analysis demonstrated the process of using the integrated RESRAD and RESRAD-BUILD codes and the probabilistic modules, together with the parameter distributions, for dose assessment at a relatively complex site.

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[4]   This report is included as Attachment C of the main document.

Probabilistic Modules (LePoire at al., 2000): The probabilistic modules developed for the RESRAD and RESRAD-BUILD codes are described and their use illustrated, including (1) description of the software design and requirements and (2) a user's manual for the probabilistic modules that facilitate the uncertainty analysis. The report is to be used in conjunction with the RESRAD and RESRAD-BUILD manuals (Yu et al., 1993, 1994), which describe the methods and parameters for those codes. A sample case and demonstration of the use of the probabilistic modules is provided. A detailed discussion of the LHS sampling method and a summary of parameter distributions are included in the appendixes.

Probabilistic Module Testing (this report): This report includes four major sections. Section 1 provides background information and summaries of the previous tasks accomplished in this project. Section 2 describes software component testing during development. The integrated system testing of the calculations, interface, and distribution are presented in Section 3. Section 4 provides the procedure and results from the beta testing phase. The NRC comments and Argonne responses regarding the beta testing phase are included in Appendix A.

2 DEVELOPMENT UNIT TESTING

Tests were performed as the components for the software system were under development. These components included the sampling method, the results calculations, and the results presentation. The testing of the sampling method and calculation of the results were nearly comprehensive in that they covered all possible variable distributions, all pathways, and most radionuclides. The results presentation was point checked for consistency of the different presentations of the same data in the interactive tables, interactive graphics, and reports. An example of the precision calculation is shown and compared with the software result.

2.1 Testing the Probabilistic Inputs Sampling Program

The Latin hypercube sampling (LHS) program used in this effort was developed by Sandia National Laboratories. The program, received in May 1999, had been written to run on different computer systems. It required some minor changes to run in the PC environment as Lahey Fortran 77 executable. A number of changes, primarily formatting, were also required to produce the desired LHS report. Three minor changes to the computational code were also necessary to overcome compilation errors and run time errors. This section describes the minor changes to the computational code and the testing of the resulting LHS executable to verify that the samples produced conformed to the specifications.

There are many ways to define and specify the parameters necessary to characterize a distribution. In most of the common cases (e.g., mean, standard deviation, minimum, maximum), these are unambiguous. However, some distributions use parameters such as alpha, beta, lambda, P, Q, and error factor whose definition may be neither obvious nor unique. Thus, it was necessary to understand the parameters as used in the LHS code and to describe them in the help screen to the probabilistic inputs screen. It was also necessary to verify that all the distributions were being sampled as intended, for quality control purposes.

2.1.1 Changes to the Computational Statements in the Code

The three changes made in computational statements are as follows:

* Subroutine BETALN (A,B)
  The entry statement to GAMALN did not have any arguments; this caused a compilation error. When the necessary arguments were included, the compilation was successful. The computed value had to be named GAMALN. (It was called BETALN in the original code.)

- Subroutine CHKDAT (PAR, A, MAXA)
  The code crashed when an attempt was made to sample a Beta distribution. The cause was as follows: This subroutine does the checks on the parameters for the distributions that have four or fewer parameters. The check on the parameters of the beta distribution was placed at the end of the original file after the checks for most of the other distributions. The variable PAR = "BETA " was five characters long (including the final blank character) for a beta distribution. The if blocks that tested the conditions for a number of distributions had the statement IF (PAR(1:6) .EQ....... This caused an error when executed on a PAR (= "BETA ") that was only five characters long. The check for the BETA parameters was moved ahead of the checks for all distributions that needed the IF (PAR(1:6) .EQ. statement.

- Subroutine NewCrd (Card, lunit, lend)
  The variable Maxi was not defined before it was used in the first Do i=1, Maxi statement. It was defined following the aforementioned do loop. The definition was moved up.

2.1.2 Conditions on the Parameters Defining the Different Distributions

The subroutines in the LHS code that checked the inputs were studied to determine the conditions imposed on the parameters defining the different distributions. Some of these conditions are inherent to the distributions (e.g., the mean of a lognormal distribution has to be positive value), while others are due to the algorithms used in the code (e.g., the minimum and the maximum specified for the normal distribution can not be more than 4.75 standard deviations away from the mean). All conditions that are inherent to the distributions and the conditions imposed by the algorithms used in the code are described in the help screen to the probabilistic inputs screen. The input interface checks to make sure that these conditions are satisfied before accepting the values input by the user. The inputs that violate the conditions turn red when the update parameter distribution button or the previous/next parameter scroll button are pressed.

2.1.3 Verifying That the Samples Conformed to the Specified Distributions

An input file was created containing each of the 34 distributions available in the probabilistic interface of RESRAD and RESRAD-BUILD. Three repetitions of 250 samples were generated for each of these 34 distributions with the LHS code. The three cumulative distribution functions (cdf) of the samples generated for the three repetitions were compared with the cdf generated by other means (explicit directly evaluatable analytical expressions of the cdf were use when available, otherwise the functions in Excel spreadsheet were used.) The cumulative distribution functions generated for all 34 distributions matched the cumulative distribution functions computed by other means.

2.1.4 Dimensioning Limits

The LHS program uses a number of arrays (subscripted variables) of fixed dimensions. These arrays impose limits on the number of uncertain variables, the number of observations, the number of non-zero correlations, and the product of the number of uncertain variables and the number of observations. The current limits are shown in Table 2.1. An LHS program with expanded limits (see Table 2.1) has also been compiled, but it is not included in the distribution file because of its large size.

2.1.5 Testing the Correlation and Regression Program

The Correlation and Regression (PCCSRC) program used was developed by Sandia National Laboratories. The program had been incorporated into RESRAD in the early 1990s. It has now been taken out of the RESRAD executable and is a separate executable. A number of variables in PCCSRC were changed to dynamic dimensioning so as not to restrict the number of observations or repetitions that could be used in the probabilistic analysis. A number of variables in the matrix inversion subroutine in PCCSRC were also changed to double precision to avoid round-off errors. The new Correlation and Regression program (CorrReg) also contains a number of subroutines to produce the necessary probabilistic input files and the probabilistic output file to produce the coefficients requested by the user.

2.1.6 Verifying the Correlation and Regression Program

The probabilistic inputs and the resulting probabilistic dose from a previous inter-model comparison exercise (BIOMOVS II Steering Committee, 1996) were processed by the correlation and regression program (CorrReg). The partial correlation coefficients (PCC), the standardized regression coefficients (SRC), the partial rank correlation coefficients (PRCC), and the standardized rank regression coefficients (SRRC) computed by the code (Table 2.2) agreed with those that had been previously computed manually using a spreadsheet program (PlanPerfect).

TABLE 2.1. Limits of the LHS Sampling Options

Quantity	Current limit	Expanded limit
Number of uncertain variables (Nvar)	501	701
Number of observations (Nobs)	2,001	2,001
Number of non-zero correlations (Ncv)	501	701
Nvar x Nobs	400,000	1,400,000
Size of LHS executable	6,140KB	17,287KB

TABLE 2.2. Comparison between Code-Calculated Coefficients and Coefficients Calculated Manually Using a Spreadsheet Program

Variable	Code (CorrReg) Computed Coefficients				Coefficients Computed on Spreadsheet			
	PCC	SRC	PRCC	SRRC	PCC	SRC	PRCC	SRRC
1	0.04	0.01	-0.02	-0.01	0.04	0.01	-0.01	-0.01
2	0.97	0.49	0.88	0.82	0.97	0.49	0.88	0.82
3	0.15	0.02	-0.02	-0.01	0.14	0.02	-0.03	-0.01
4	-0.2	-0.03	0.05	0.02	-0.20	-0.03	0.05	0.02
5	0.02	0	0.11	0.05	0.02	0.00	0.12	0.05
6	0.05	0.01	0.09	0.04	0.04	0.01	0.09	0.04
7	0.12	0.02	0.13	0.06	0.12	0.02	0.14	0.06
8	0.98	0.6	0.55	0.28	0.98	0.60	0.54	0.28
9	-0.02	0	-0.09	-0.04	-0.02	0.00	-0.09	-0.04
10	0.98	0.57	0.15	0.06	0.98	0.57	0.15	0.06
11	0.06	0.01	-0.06	-0.03	0.05	0.01	-0.06	-0.03
12	0.25	0.03	0.11	0.05	0.25	0.03	0.11	0.05
13	0.2	0.03	-0.06	-0.03	0.19	0.03	-0.06	-0.03
14	0.06	0.01	-0.02	-0.01	0.06	0.01	-0.01	-0.01
15	-0.2	-0.03	-0.2	-0.09	-0.21	-0.03	-0.20	-0.09
16	-0.1	-0.01	-0.08	-0.04	-0.13	-0.01	-0.08	-0.04
17	-0.02	0	0.02	0.01	-0.04	0.00	0.02	0.01
r^2	0.99	0.99	0.84	0.84		0.99		0.84

2.2 CALCULATION INTEGRATION TESTING

The probabilistic modules were tested during the development mode for their proper execution and for the reasonableness of the results. Most of the testing was done when the analysis for Subtask 1.4 was in progress. Many problems identified during the initial testing were later rectified. The modules were tested with all radionuclides in the RESRAD and RESRAD-BUILD databases. The testing was also done for all pathways. The rank correlation between input parameters was tested. The results obtained with the deterministic runs were compared with those from the probabilistic run.

2.2.1 Testing of Radionuclides

Testing was conducted to verify that the probabilistic modules would run with all the radionuclides in RESRAD and RESRAD-BUILD databases. For this testing, all the parameters assigned distributions in the Subtask 1.3 report (Biwer et al., 2000) were assumed to be uncertain in nature (i.e., those parameters were assigned distributions). It was found that the modules ran for all radionuclides except Cm-245 in RESRAD. Earlier, problems with branching radionuclides (Sb-125, Eu-152, Pu-241, etc.) were identified which were later rectified. The RESRAD code was also modified to handle large variations in Kd values in different zones and among progeny radionuclides. The Subtask 1.4 report (Kamboj et al., 2000) provides probabilistic results for all radionuclides except Cm-245 using interim versions of the RESRAD (version 5.95+) and RESRAD-BUILD (version 2.9+) codes. The code was modified to remove the problems with Cm-245.

2.2.2 Testing of All Pathways

The available pathways in RESRAD and RESRAD-BUILD were tested to verify that for individual pathways, only parameters expected to affect that pathway were actually found to be sensitive parameters. For the probabilistic dose analysis in Subtask 1.4, two scenarios — residential and building occupancy — were analyzed. The RESRAD code was used to analyze the residential scenario, and RESRAD-BUILD was used to analyze the building occupancy scenario. Except for radon, all pathways were active for the two scenarios. The results of the analyzes indicated that pathway doses were reasonable and that sensitive parameters and pathways were consistent (i.e., if external pathway was the dominant pathway, the most sensitive parameter was external gamma shielding factor, and if plant ingestion was the dominant pathway, the most sensitive parameter was the plant transfer factor).

2.2.3 Testing of Input Correlations

To test input correlations, some parameters were assigned rank correlations. The LHS output was checked to see the actual correlations used in the sample run. It was observed that unit positive or negative correlations (+1 or -1) could not be specified between the input parameters. The rank correlations >-1 and <1 are allowed in the probabilistic modules. Some parameters are highly correlated, such as total porosity and effective porosity. For those parameters, high input rank correlations should be used.

2.2.4 Comparing Deterministic and Probabilistic Results

Deterministic and probabilistic results were compared to ensure the proper integration of the probabilistic module with the RESRAD deterministic module. As mentioned in the Subtask 1.6 report (LePoire et al., 2000), when the user-specified case is run, the deterministic values are used to generate the standard deterministic analysis. The deterministic analysis uses no information from the specified probabilistic distributions. If probabilistic analysis has been specified by choosing one or more parameter for analysis and the number of observations and number of repetition is at least 1, then probabilistic calculations will also be performed.

In the probabilistic analysis, a probability distribution is specified for each input parameter of uncertain value. Samples (number equal to the number of observations times the number of repetitions in the probabilistic module) are generated from each of the input parameter distributions according to the sampling technique (LHS or Monte Carlo). One sample from each input parameter distributed is selected, depending on the specified correlations among the input uncertain parameters. This one sample constitutes a sample run. In this way, sample runs equal to the number of observations times the number of repetitions are generated.

The results from the probabilistic sample runs were compared with the deterministic RESRAD run. For that comparison, five parameters (density of contaminated zone, depth of roots, contaminated zone erosion rate, plant transfer factor, and external gamma shielding factor) were assigned probabilistic distribution. In all, 10 sample runs were performed in the probabilistic analysis (the radionuclide selected was Co-60). In the deterministic runs, the values of the uncertain parameters were chosen from the values in the probabilistic run (LHS sample input vectors from the LHS report). All 10 deterministic runs (equal to the number of sample runs) were performed. The resultant total dose and pathway doses from the deterministic runs were compared with the values from the probabilistic run. No significant differences were identified. This result means that the level of difference in the output (no differences within the first two or three significant figures) matches the level of differences in the input (no differences within the first two or three significant figures). The differences in the input are caused by the need to manually input numbers into the interface at the accuracy of 2 to 3 significant figures. This comparison verifies that the correct values from the probabilistic module are transferred to the RESRAD deterministic module.

2.3 OUTPUT INTERFACE CALCULATIONS

The percentile and statistics of the interactive tables and the report were compared. Slight differences were found in some circumstances. These differences are attributed to the slightly different calculational approaches. The interactive tables calculate statistics on the

basis of each repetition and then take the average of those values. The report calculates the statistics on the basis of the complete set of data over all the repetitions.

The tables and graphs were compared. The results were the same. It was decided to maintain the data point at the initial contamination placement (time = 0) in the plots with a logarithmic time scale. These data will be plotted on the far left axis, which usually also contains the data with the time equal to 1 year.

Correlations in the output report were reviewed. These calculations are performed by the suite of routines developed by Sandia to support the LHS method. It was found that some correlations were reported as zero when there was known to be a correlation. This situation was attributed to the nonconvergence of the routines within the software. The software was altered to support double precision calculations. This change yielded much better convergence and better reporting of the correlations.

Data stored in the database were analyzed and compared with the results of the "Quick Tour" case. In this example, there were 3 repetitions of 100 samples. The statistics for the average and 50% percentile were reported as 9.35 ± 1.04 and 5.56 ± 0.00957, respectively. From the database, the average peak dose from the 100 samples in each repetition was calculated; results are shown in Table 2.3. The average of the averages matches the reported number. The standard deviation of the three numbers was also computed and then divided by the square root of the number of points to estimate the standard deviation of the underlying total average. This number (after dividing the sum by $2*3$) agrees with the report number.

From the database, the peak doses from the 100 samples in each repetition were sorted, and those with rank from 48 to 53 are shown in Table 2.4. The 50th percentiles have the rank of 50. The average of these 50th percentiles agrees with the reported number. The standard deviation of the three repetitions was also computed and then divided by the square root of the number of points to estimate the standard deviation of the underlying total average. The result agrees with that in the report.

Table 2.3. Example Statistical Uncertainty Calculation of the Average Peak Dose

Rep	Avg	(Ai-At)^2
1	8.737	0.370881
2	11.366	4.0804
3	7.935	1.990921
Total	9.346	1.036195

TABLE 2.4. Example Statistical Uncertainty Calculation for the 50th Percentile

Ranked Sample Number	Repetition 1	Repetition 2	Repetition 3	Repetition Average	Precision
48	5.5560002	5.5279999	5.5510001	5.545	0.00704
49	5.5710001	5.5289998	5.5580001	5.552667	0.010136
50	5.5770001	5.5370002	5.5630002	5.559	0.009568
51	5.5900002	5.5469999	5.572	5.569667	0.01018
52	5.5929999	5.553	5.579	5.575	0.009568
53	5.6069999	5.559	5.5900002	5.585333	0.011473

3 INTEGRATED TESTING

The calculation, interface, and distribution aspects of the fully integrated system were tested. A scenario case is described and the results from the software are interpreted. The interface was reviewed with modern user interface heuristics as a guide. The distribution process was checked for completeness, compatibility, and security from viruses over a range of operating systems.

3.1 CALCULATIONS

This section analyzes a hypothetical test case to demonstrate the use of the various features of the probabilistic RESRAD code. The case that was used was selected because it is relatively simple but still illustrates the workings of the code.

3.1.1 Scenario Description

One radionuclide, Ra-226, is considered at initial concentrations of 30 pCi/g. Probabilistic analysis is performed on a total of eight input variables; details are given in Table 3.1.

While most of the distributions used here are those identified as national (default) distributions, the distributions for outdoor time fraction and indoor time fraction were specified for this illustrative example only. The variables selected for this simple case all have a linear effect on the dose; that is, the contributions of each of these variables to the total dose are additive. Knowing, a priori, how the variables influence the endpoint of interest, the peak of the mean doses at the graphical times used in this case helps illustrate the use of the various outputs available in RESRAD.

3.1.2 Case Implementation and Interpretation

The variables for the probabilistic analysis were specified by opening the input form containing the variable and then selecting that variable for uncertainty analysis. If a national (default) distribution was identified for that variable in Subtask 1.3, that distribution along with the defining parameters were automatically filled into the uncertainty input screen from the database. When a national (default) distribution was not available, a distribution was chosen from the drop-down list box, and appropriate defining parameters were input for this illustrative example.

TABLE 3.1. Input Parameters and Their Distributions Selected for Probabilistic Analysis

Input Variable	FORTRAN Name	Distribution	Distribution's Statistical Parameters
Fish transfer factor for Ra	BBIO(88,1)	LOGNORMAL-N	3.9 1.1
Milk transfer factor for Ra	BRTF(88, 3)	LOGNORMAL-N	-6.91 0.47
Meat transfer factor for Ra	BRTF(88, 2)	LOGNORMAL-N	-6.91 0.693147
Plant transfer factor for Pb	BRTF(82,1)	LOGNORMAL-N	-5.52 0.916291
Fish transfer factor for Pb	BBIO(82,1)	LOGNORMAL-N	5.7 1.1
Outdoor time fraction	FOTD	UNIFORM	0.01 0.4
Indoor time fraction	FIND	UNIFORM	0.33 0.67
Drinking water intake	DWI	TRUNCATED LOGNORMAL-N	6.015 0.489 0.001 0.999

A negative correlation was specified between the indoor and outdoor time fractions because these two variables are likely to be inversely related. A negative correlation between the indoor and outdoor time fractions was also necessary to ensure that the total time fraction did not exceed 1. For the purpose of this example, a rank correlation coefficient of -0.75 was used. As shown in Figure 3.1, a rank correlation coefficient of -0.6 is sufficient to ensure that the time constraint is not violated.

Correlation between the drinking water intake and the outdoor time fraction was added to illustrate the care that needs to be taken when specifying multiple correlations for a given variable. If, for example, a rank correlation coefficient of 0.7 is specified between the drinking water intake and the outdoor time fraction, and no (or zero) correlation is specified between the drinking water intake and the indoor time fraction, then the sampling program will not be able to find a set of inputs that satisfy the specified correlations. This situation occurs because there will be some correlation between the drinking water intake (DWI) and the indoor time fraction (FIND) when the correlations specified between DWI and the outdoor time fraction (FOTD) and between the indoor and outdoor time fractions are satisfied. This situation will be indicated in the LHS report. The report will caution that the
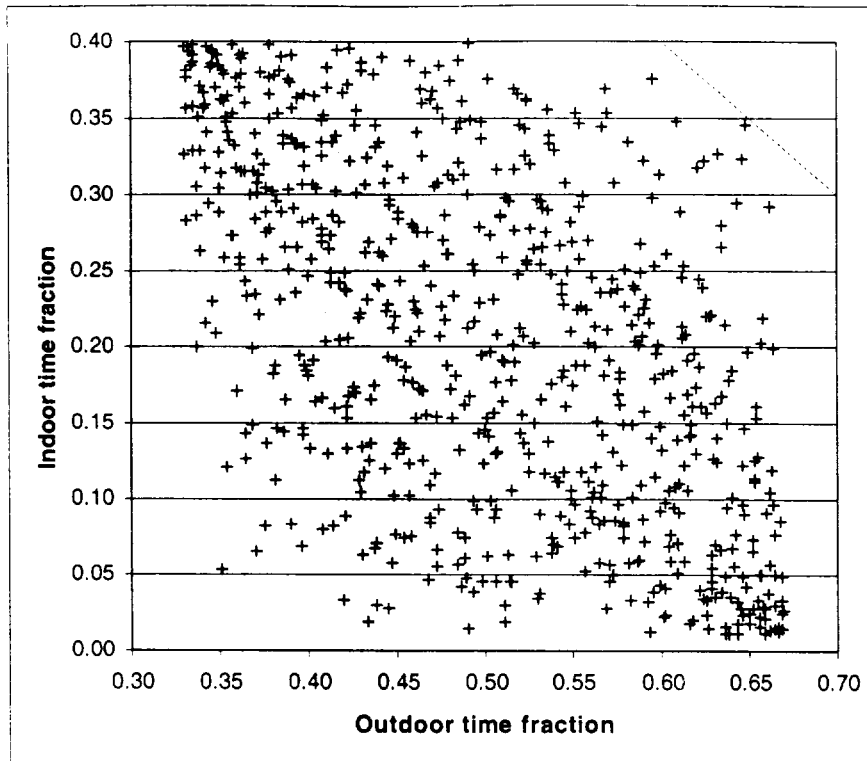
FIGURE 3.1 Scatter Plot of Indoor Time Fraction against
Outdoor Time Fraction for a Rank Correlation Coefficient
of -0.6

specified rank correlation matrix is not positive definite. It will suggest an adjusted rank correlation matrix. The rank correlations suggested by the code between the three pairs of variables in this case is: FIND ↔FOTD = -0.7345, DWI ↔FOTD = +0.6856, and DWI ↔FIND = -0.0105. While the suggested adjusted rank correlation matrix is quite close to the specified one in this example, that does not always happen, and the user must look at the LHS report to ensure that any adjustments to the rank correlation matrix suggested by the code are acceptable.

The number of observations taken from each distribution affects the accuracy of the predicted probabilistic outputs. An indication of the accuracy of the prediction can be obtained by repeating the probabilistic runs with a different set of observations. The user can accomplish this by specifying the number of repetitions. The range of the predicted outputs for different sample sizes (i.e., number of observations) is shown in Figures 3.2 through 3.4. Five different sample sizes of 10, 12, 25, 50, and 100 were analyzed, each with seven repetitions. The three outputs considered were the peak of the mean dose at graphical times, the median dose at 299 years, and the 90% dose at 299 years. (The peak of the mean dose occurred at 299 years for all seven repetitions of each of the five sample sizes.) As would be expected, the predictions of the peak of the mean dose are of a
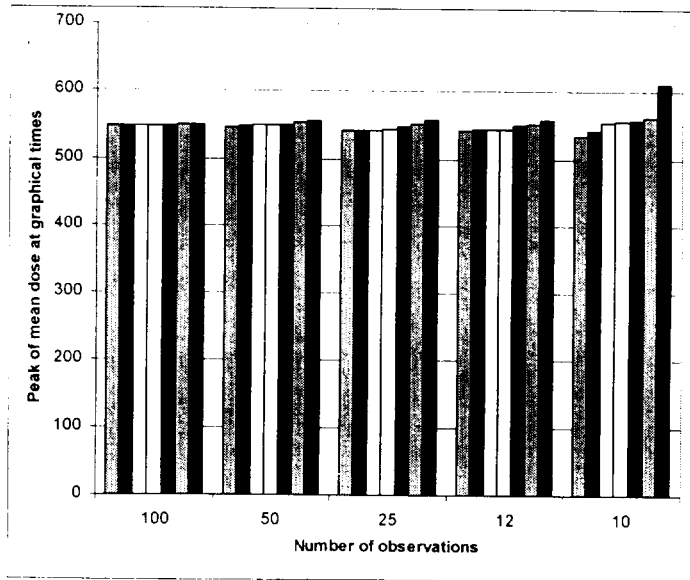
FIGURE 3.2 Variation of the Peak of the Mean Dose at Graphical Times with Sample Size, for Seven Repetitions
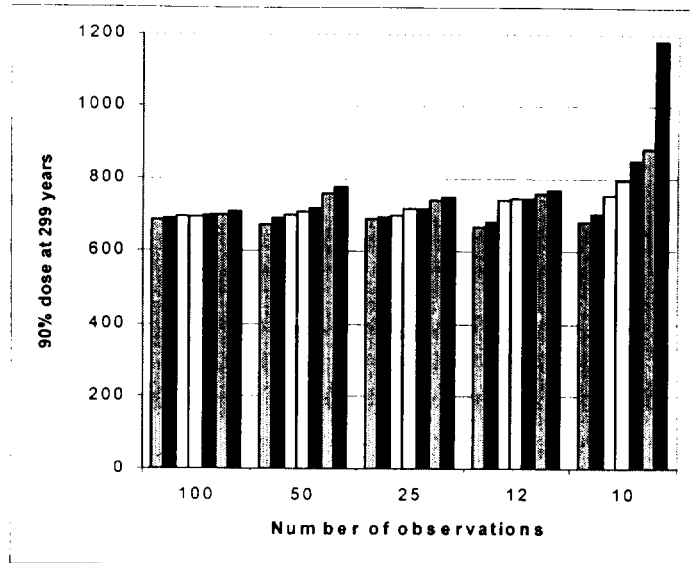
FIGURE 3.3 Variation of 90% Dose at 299 Years with Sample Size, for Seven Repetitions
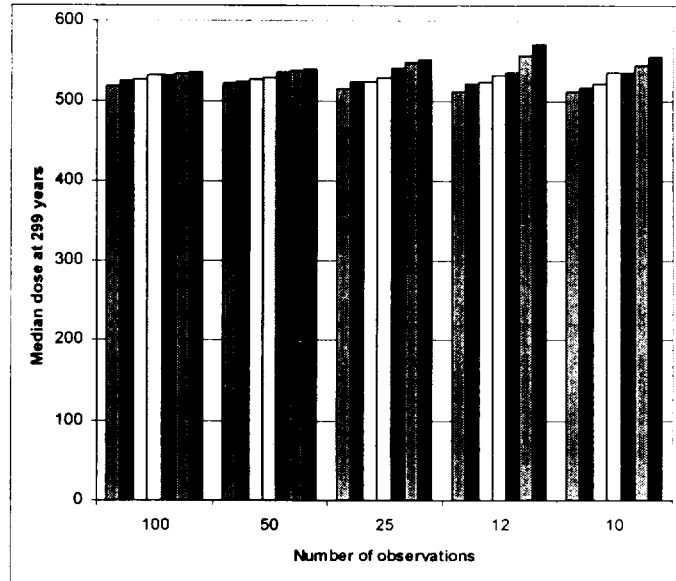
FIGURE 3.4 Variation of Median (50%) Dose at 299 Years with Sample Size, for Seven Repetitions

narrower range than the 90% dose for any given sample size. The user may wish to increase the sample size until the desired accuracy is achieved.

One way of judging the relative importance of the different probabilistic variables for their influence on the output is by the regression and correlation coefficients. The probabilistic RESRAD code offers the user a choice of four different coefficients: the partial correlation coefficient (PCC), the standardized regression coefficient (SRC), the partial rank correlation coefficient (PRCC), and the standardized rank regression coefficient (SRRC). Each is appropriate for different situations. In this example, the outputs are linearly related to the probabilistic input variables. The PCC and the SRC are more appropriate for a case where this relationship is linear or nearly so. On the other hand, the PRCC and the SRRC are suitable for cases where the output is nonlinearly related to the inputs. The user can decide on the set of parameters to be used by comparing the coefficient of determination (R-square) shown in the uncertainty report for the linear model and the nonlinear model. The coefficient of determination is a measure of the variation in the output that is explained by the probabilistic input variables. In this example, the coefficient of determination for the linear model is close to 1.0, while that for the nonlinear model is close to 0.9.

The selection of the appropriate model (linear or nonlinear) narrows the available coefficients to two. Each of the two are again suitable under different circumstances. This example was chosen so the outputs are strictly linear in the inputs. When the output is strictly linearly related to the inputs (or is very nearly so), the PCCs for all input variables will be unity (or very nearly so). In such a case, the SRC is the appropriate coefficient for

17

judging the relative importance of the influence of the input variables on the predicted output. Strong correlations between the input variable will give rise to large, spurious SRCs. When strong correlations exist between the input variables, the PCC would be a better indicator of their relative importance. Tables 3.2 through 3.5, extracted from the uncertainty output, show the coefficients for the case with 100 observations and 7 repetitions.

Another way of evaluating the influence of the input variables on the predicted output is to view the scatter plots between the output and each of the inputs. The interactive results screen of the code allows the user to view these scatter plots. Scatter plots of the two most significant parameters, on the basis of their influence on the peak dose from all pathways, are shown in Figures 3.5 and 3.6. These are the same two parameters that were identified as being the most significant by the SRC.

3.1.3 Summary

The identification of the parameters that have a significant influence on the chosen output is not always straightforward. RESRAD provides a number of tools, including scatter plots, temporal plots of the mean dose and selected dose percentiles, and four correlation and regression coefficients to facilitate their identification. Each of these tools is appropriate under different circumstances. Sometimes additional analysis is required to determine the significant parameters.

3.2 INTERFACE TESTING

Extensive testing was performed to check different aspects of the interface design as specified in the Subtask 1.6 report - "Probabilistic Modules for the RESRAD and RESRAD-BUILD Computer Codes" (LePoire et al., 2000). A subsistence farmer scenario was used to test the RESRAD code. A building occupancy scenario was used to test the RESRAD-BUILD code. Because the testing followed the instructions provided in the user's manual (Subtask 1.6 report), the instructions themselves were tested for clarity and for consistency with the actual design.

3.2.1 Data Input

Data input to the uncertainty module include selection of input parameters and specification of sampling parameters, sampling technique, grouping of observations, desired probabilistic output, distribution characteristics, and correlation between parameters. Testing of data input was conducted to check the following: (1) acceptance of specification(s), (2) removal of specification(s), and (3) modification of specification(s). When more than one way exists for making a specification, all the available means were

TABLE 3.2. Partial Correlation Coefficients for Peak of the Mean Dose

Coefficient = Repetition =	PCC 1		PCC 2		PCC 3		PCC 4		PCC 5		PCC 6		PCC 7	
Variable	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff
BBIO(88,1)	8	1.00	8	1.00	8	1.00	8	1.00	8	1.00	8	1.00	8	1.00
BRTF(88, 3)	7	1.00	7	1.00	7	1.00	7	1.00	7	1.00	7	1.00	7	1.00
BRTF(88, 2)	6	1.00	6	1.00	6	1.00	6	1.00	6	1.00	6	1.00	6	1.00
BRTF(82,1)	2	1.00	2	1.00	2	1.00	3	1.00	2	1.00	2	1.00	2	1.00
BBIO(82,1)	4	1.00	5	1.00	5	1.00	3	1.00	4	1.00	4	1.00	5	1.00
FOTD	5	1.00	5	1.00	5	1.00	5	1.00	5	1.00	5	1.00	5	1.00
FIND	2	1.00	2	1.00	2	1.00	3	1.00	2	1.00	2	1.00	2	1.00
DWI	2	1.00	2	1.00	2	1.00	3	1.00	2	1.00	2	1.00	2	1.00
R-SQUARE		1.00		1.00		1.00		1.00		1.00		1.00		1.00

TABLE 3.3. Standardized Regression Coefficients for Peak of the Mean Dose

| Coefficient = Repetition =	SRC 1		SRC 2		SRC 3		SRC 4		SRC 5		SRC 6		SRC 7	
Variable	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff
BBIO(88,1)	8	0.00	8	0.00	8	0.00	8	0.00	8	0.00	8	0.00	8	0.00
BRTF(88, 3)	7	0.01	7	0.02	7	0.01	7	0.01	7	0.02	7	0.01	7	0.02
BRTF(88, 2)	6	0.02	6	0.02	6	0.02	6	0.02	6	0.02	6	0.02	6	0.02
BRTF(82,1)	2	0.46	2	0.46	2	0.47	2	0.45	2	0.48	2	0.45	2	0.48
BBIO(82,1)	5	0.05	5	0.05	5	0.05	5	0.07	5	0.06	5	0.06	5	0.05
FOTD	4	0.14	4	0.14	4	0.14	4	0.13	4	0.15	4	0.14	4	0.13
FIND	3	0.35	3	0.35	3	0.35	3	0.33	3	0.37	3	0.34	3	0.33
DWI	1	0.75	1	0.76	1	0.77	1	0.74	1	0.80	1	0.74	1	0.78
R-SQUARE		1.00		1.00		1.00		1.00		1.00		1.00		1.00

TABLE 3.4. Partial Rank Correlation Coefficients for Peak of the Mean Dose

Coefficient = Repetition =	PRCC 1		PRCC 2		PRCC 3		PRCC 4		PRCC 5		PRCC 6		PRCC 7	
Variable	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff
BBIO(88,1)	6	-0.05	7	-0.05	8	-0.02	8	0.01	7	0.04	7	-0.04	7	-0.07
BRTF(88, 3)	8	0.02	5	-0.09	6	-0.11	3	0.20	4	0.25	6	-0.09	5	-0.10
BRTF(88, 2)	4	0.25	6	0.05	4	0.26	7	0.06	8	0.03	4	0.21	8	0.02
BRTF(82,1)	1	0.84	1	0.74	1	0.80	1	0.79	1	0.82	1	0.76	1	0.79
BBIO(82,1)	5	0.18	4	0.22	5	0.13	5	0.17	6	0.12	5	0.12	4	0.28
FOTD	7	0.03	8	0.01	7	0.03	6	-0.14	5	0.22	8	0.01	6	0.1
FIND	3	0.32	3	0.25	3	0.27	4	0.17	3	0.50	3	0.26	3	0.38
DWI	2	0.75	2	0.68	2	0.66	2	0.73	2	0.64	2	0.67	2	0.65
R-SQUARE		0.95		0.90		0.92		0.92		0.93		0.92		0.93

TABLE 3.5. Standardized Rank Regression Coefficients for Peak of the Mean Dose

| Coefficient = Repetition =	SRRC 1		SRRC 2		SRRC 3		SRRC 4		SRRC 5		SRRC 6		SRRC 7	
Variable	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff
BBIO(88,1)	7	-0.01	7	-0.02	8	-0.01	8	0.00	7	0.01	7	-0.01	7	-0.02
BRTF(88, 3)	8	0.00	5	-0.03	7	-0.03	5	0.06	5	0.07	6	-0.03	6	-0.03
BRTF(88, 2)	4	0.06	6	0.02	4	0.08	7	0.02	8	0.01	4	0.06	8	0.01
BRTF(82,1)	2	0.36	2	0.35	2	0.38	2	0.37	3	0.40	2	0.33	3	0.36
BBIO(82,1)	5	0.04	4	0.07	6	0.04	6	0.05	6	0.03	5	0.03	5	0.08
FOTD	6	0.03	8	0.01	5	0.04	3	-0.17	4	0.27	8	0.01	4	0.12
FIND	3	0.27	3	0.26	3	0.27	4	0.15	2	0.53	3	0.28	2	0.38
DWI	1	0.85	1	0.85	1	0.80	1	0.96	1	0.66	1	0.86	1	0.76
R-SQUARE		0.95		0.90		0.92		0.92		0.93		0.92		0.93
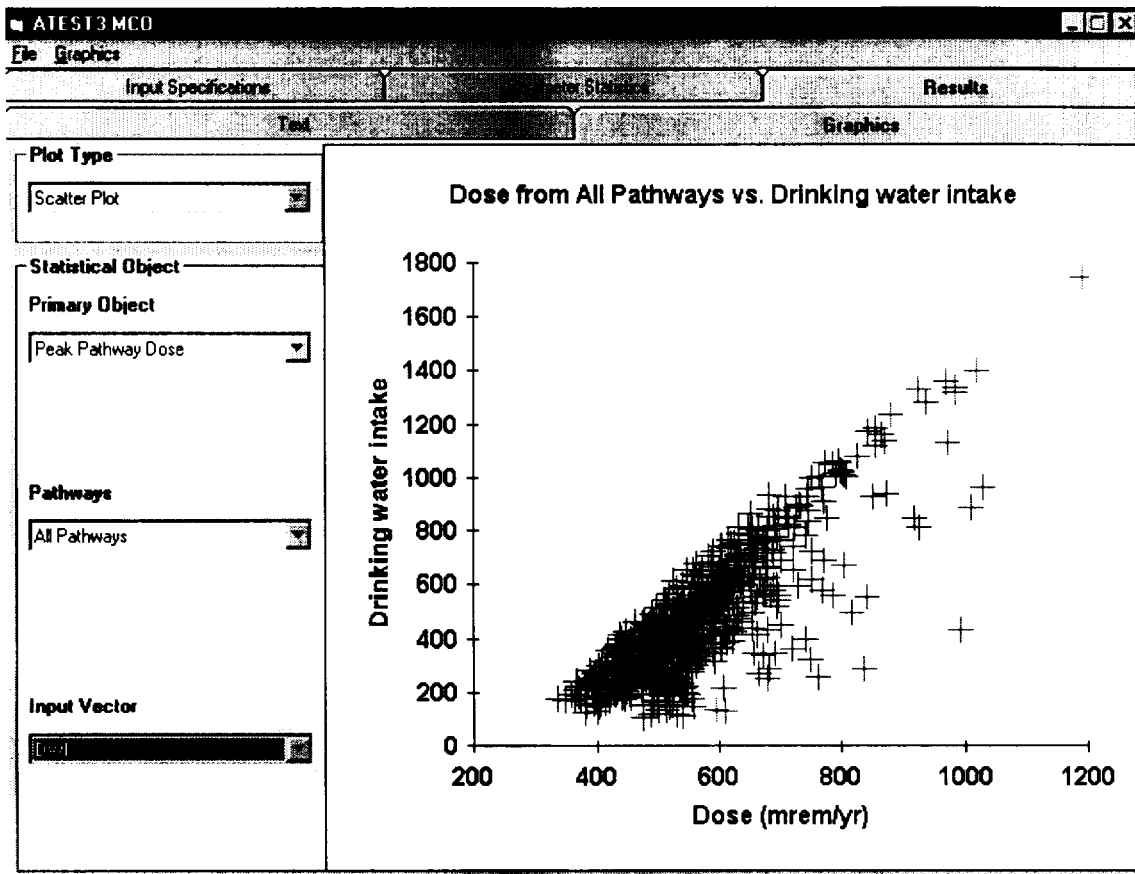
FIGURE 3.5 Scatter Plot of Drinking Water Intake and Peak Total Dose from All Pathways, All Repetitions Combined

tested. For example, selection of an input parameter can be done by pressing the F8 key, clicking the uncertainty analysis button on the menu bar, or viewing the uncertainty analysis summary after highlighting the desired parameter. The testing showed that both the RESRAD and RESRAD-BUILD codes successfully accepted data input for uncertainty analysis and allowed for modifications, as they were intended to.

3.2.2 Default Distribution Integration

Default distribution parameters were developed and documented in the Subtask 1.3 report (Biwer et al., 2000) for a total of 66 parameters (RESRAD and RESRAD-BUILD combined). The uncertainty analysis module incorporates all the default values and presents them as templates for modification. Testing of the uncertainty module was conducted to verify consistency between the suggested values in the document and the built-in values in the module. Some input parameters have values that are independent of radionuclides. Some input parameters, such as distribution coefficients, however, have values that are radionuclide-specific. For the first case, two or three radionuclides were
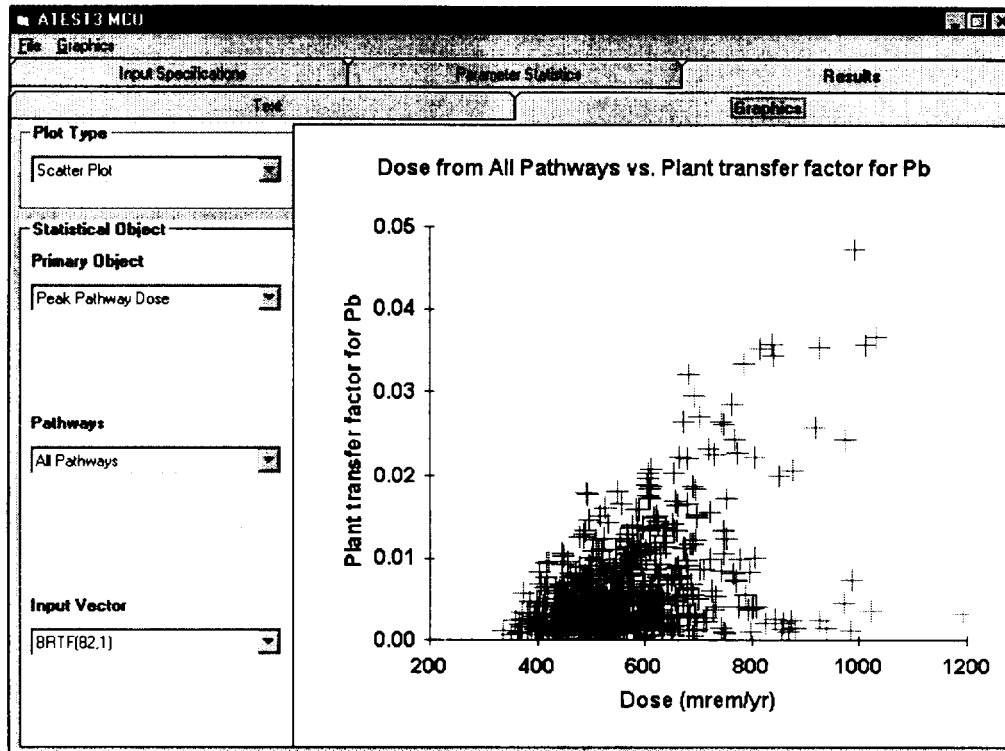
FIGURE 3.6 Scatter Plot of Soil-to-Plant Transfer Factor for Lead and the Peak Dose from All Pathways, All Repetitions Combined

randomly selected for testing. For the second case, each individual radionuclide was selected for testing. Test results showed that the suggested distribution parameters were accurately incorporated into the uncertainty analysis module.

3.2.3 Data Output

After input specifications are finished, the RESRAD and RESRAD-BUILD codes can be run to generate calculation results. The output includes two text report files and various graphic illustrations. Testing of the data output includes viewing, printing, and retrieving the generated text report files, obtaining statistical information on-line, and creating various graphic illustrations. The RESRAD and RESRAD-BUILD uncertainty modules perform these tasks successfully in accordance with the design principles specified in the user's manual . For graphic illustrations, the uncertainty module allows the user to edit the graphics (X-axis, Y-axis, title, and legend) and print them directly or copy and paste them to another document. This graphic editing feature is very useful for preparing risk assessment reports related to the use of RESRAD and RESRAD-BUILD codes.

3.2.4 File Saving

The input specifications to the uncertainty analysis module, as well as the calculational results, can be saved. The testing of the file-saving functions involved saving the input information both to an existing file and to a new file and saving the text results to a new file. The user can save the entire text report or just part of the report. Tables in the text report can also be manually exported to a Microsoft Excel spreadsheet for further editing and manipulation. The RESRAD and RESRAD-BUILD uncertainty modules performed these tasks successfully. In response to beta testing review comments, an easier way to save all files with a standard basename was implemented with a check box in the "Title" window.

3.2.5 Help

On-line help on manipulation of the uncertainty module, such as help in saving data and viewing results and definitions of the distribution parameters, is available in the RESRAD and RESRAD-BUILD codes. Testing of this feature focused on availability, clarity, and thoroughness of the help file. For the 67 parameters selected for uncertainty analysis in the testing, the uncertainty module was able to provide corresponding help content for the distribution characteristics specified. The help content is clear and useful.

3.2.6 Manual

The testing of various aspects of the uncertainty module was performed following instructions provided in the users manual (the Subtask 1.6 report). Although the manual does not cover and demonstrate every single feature incorporated in the interface design, it provides clear guidance on every major task that will be encountered when using the uncertainty analysis module. The features that are not covered (e.g., editing graphics), are self-explanatory and can be easily manipulated by a user with experiences in using commercial spreadsheets and graphic packages. In general, the manual is useful and is of sufficient depth for exploring each design feature.

3.3 DISTRIBUTION TESTING

3.3.1 Creating the Distribution CD

The computer codes RESRAD 6.0, Release 1, and RESRAD-BUILD 3.0, Release 1, and the corresponding sample files were distributed on CD-ROM. The files were distributed in the following manner. A self-extracting executable named *RESRAD 6.0 Beta.exe* was created for RESRAD by using the InstallShield computer code. A self-extracting executable

named *RESRAD-BUILD 3.0 Beta.exe* was created for the RESRAD-BUILD computer code. The sample files for RESRAD were compressed with WinZip, and the compressed file was named *RESRAD sample files.zip*. Similarly, the sample files for the RESRAD-BUILD computer code were compressed, and the compressed file was named *RESRAD-BUILD sample files.zip*. These files were then copied to a writable CD-ROM for access on any computer with either Windows 95, Window 98, Windows 2000, or Windows NT 4.0 (Service Pack 3 or later) operating system. The virus-detecting software Command Antivirus was then used to check the CD-ROM for known viruses. Similar procedures were followed for later versions.

3.3.2 Testing the Distribution CD

The files on the CD-ROM were tested for functionality on a Pentium 200 MHZ personal computer (PC) with 64 MB RAM, 3.6 gigabytes of hard disk space, and a 17-inch color monitor with a resolution of 800 x 600 dpi. The operating system loaded on the computer was Windows NT 4.0 (Service Pack 5). Before installation of the files, the hard disk drive of the PC was reformatted and Windows NT 4.0 (Service Pack 5) was reinstalled. The disk was partitioned into a single NTFS partition. Following the installation of the operating system, the program WinZip was installed so the sample files could be extracted.

The CD-ROM containing all files was placed into the CD-ROM reader, and the self-extracting executable *RESRAD 6.0 Beta.exe* was initialized to launch the RESRAD 6.0, Release 1, setup program. The instructions provided by the setup program were followed, and RESRAD was installed into the default subdirectory (c:\resrad). After this installation, the computer was restarted in accordance with instructions. Similar procedures were followed to setup RESRAD-BUILD 3.0, Release 1.

The RESRAD and RESRAD-BUILD sample files contained in *RESRAD sample files.zip* and *RESRAD-BUILD sample files.zip* were then extracted into c:\resrad and c:\winbld respectively.

The RESRAD 6.0 beta icon on the desktop was then double clicked and the RESRAD code was launched to ensure proper installation. The sample file *CO60UN9.RAD* was loaded from c:\resrad and the calculation was performed. After RESRAD completed the calculation, RESRAD was closed, and a similar procedure was used to test the installation of RESRAD-BUILD.

After documenting the successful installation of the two computer codes, RESRAD, RESRAD-BUILD, and all supporting files were removed from the PC using the uninstall program provided with RESRAD and RESRAD-BUILD. The hard disk drive of the PC was reformatted again, and Windows NT 4.0 (Service Pack 5) and WinZip were reinstalled. The distribution CD-ROM was inserted into the CD-ROM reader and the same procedures were

followed as described above; however, this time RESRAD-BUILD 3.0, Release 1, was installed first, followed by RESRAD 6.0, Release 1. Both computer codes installed and executed properly once again.

4 NRC BETA TESTING

4.1 PROCEDURE

The draft modules and user's manual were delivered to the NRC for a 1-month beta test. Early problems were identified through a videoconference soon after the delivery. Also at this time a demonstration was given to the interested NRC participants. The cover letter on the delivery of the draft requested that the comments be categorized into installation problems, serious errors that prevent further testing, calculational problems, annoyances, and misunderstandings. The first two types of problems were to be dealt with immediately, while the less severe problems would be dealt with in the course of the beta test. At the videoconference, no major installation issues were identified, but two serious problems were identified that resulted in software crashing. One of the two problems only occurred during unusual user entry for the deterministic setting. The other problem was irreproducible. Neither of these two problems delayed further beta testing of the software.

4.2 SUMMARY OF COMMENTS AND RESOLUTION

Some major changes made to the software package as a result of the comments from NRC testers included the following:

- The default distribution arguments for the mass loading factor for inhalation were changed. The beta version had inconsistent units for the distribution.

- The statistic definitions were tested.

- File management was enhanced by adding the probabilistic files to the list that gets renamed with the "Save All" command. A list of files was provided for users that want to zip the complete case into one file.

- Template files were provided that had probabilistic variables defined with correlations.

- The "Update Parameter Distribution" button was removed and that function is now performed automatically. This function had been the source of much confusion.

- Many other interface issues were fixed for a more robust and easier to use interface.

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APPENDIX A:

**ARGONNE RESPONSES TO NRC COMMENTS ON TESTING OF
THE DRAFT (RELEASE 1) PROBABILISTIC RESRAD, VERSION 6.0,
AND RESRAD-BUILD, VERSION 3.0, CODES**

APPÈNDIX A:

ARGONNE RESPONSES TO NRC COMMENTS ON TESTING OF THE DRAFT (RELEASE 1) PROBABILISTIC RESRAD, VERSION 6.0, AND RESRAD-BUILD, VERSION 3.0, CODES

NRC staff conducted preliminary evaluation and testing of the beta version of the integrated system of RESRAD 6.0 and RESRAD-BUILD 3.0 computer codes. Staff did not have sufficient time to critically test and evaluate these two codes for adequacy and consistency of the results generated. Therefore, the current comments are preliminary and will be refined and updated as staff continue to conduct additional testing, and evaluation, of the results generated using these two codes.

NRC staff is quite satisfied with the overall quality of the software developed by Argonne National Laboratory (ANL). ANL had integrated the deterministic RESRAD and RESRAD-BUILD codes with the probabilistic module and the Latin Hypercube Sampling (LHS) routine, in spite of the short turn around time and tight completion schedule. The newly developed integrated software system incorporated the default parameter distributions and contained input/output interfaces that appear to function well with RESRAD and RESRAD-BUILD software. Staff recognizes that the contractor, ANL expended significant efforts to develop additional outputs to support NRC's additional needs, especially those associated with the calculation of the peak values of averaged annual dose.

Based on staff's limited testing of the codes and review of the May 2000 Draft User's Guide/Report entitled: "Probabilistic Modules for the RESRAD and RESRAD-BUILD Computer Codes", the following comments are offered.

A.1 RESRAD VERSION 6.0

1. The code generated unusually high doses for analysis using U-234, U-235, U-238, and Th-232 radionuclides. The problem was traced to the assumed statistical distribution for the mass loading factor for inhalation which was determined to be in the wrong units. This needs to be corrected in the final version of the code or it will give results that are off by six orders of magnitude.

Response: This has already been fixed.

2. In a series of runs using different sample sizes, staff found that the difference between results, in some cases, were larger than what should have been expected based upon the calculated confidence in the result. This could point out a potential problem with the statistic being used to represent the confidence. Even if it is

determined that the right statistic is being used, it would appear that the use of 3 repetitions is too few to calculate a meaningful confidence (note: with the use of more repetitions, the confidence interval should be reduced, which will result in an even greater disparity between staff results and the calculated confidence levels in the results). It is recommended that at least 20 or 30 repetitions should be made before any confidence intervals are reported, otherwise this could lead to a false sense of confidence in the results. [See comment Number 35 for a related comment].

Response: Argonne will test and document in the Subtask 1.7 report. However, 20 to 30 repetitions seems to be quite high. We believe it would be better to use a combination of fewer repetitions and more observations (sample size). For example, instead of using 20 repetitions, one can use 7 repetitions and increase the number of observations by a factor of 3-4. This combination will provide a better measure of the range of the quantity of interest in about the same run time as using 20 repetitions with the smaller sample size.

3. Staff attempted to duplicate the exercise presented in "Appendix C: Quick Tour" of the draft report "Probabilistic Modules for the RESRAD and RESRAD-BUILD Computer Codes." Staff used similar sensitivity and uncertainty conditions and input data as well as hardware compatible with that used by ANL. Staff noted the following observations in executing the code under similar conditions:

    a) The time needed for executing the run lasted a few hours instead of 8 minutes, as was indicated in the draft report.

    b) The estimated doses were much higher by approximately a factor of 10 than those reported in the draft report.

    c) In certain runs, the execution was terminated early without completion of the run and the error message "floating point" was reported appeared on the screen.

Response: (a) The quick tour was performed using one dose integration point and one risk integration point as stated on page C.2, in order to quickly demonstrate the code. If the default settings of 17 dose integration points and 257 risk integration points are used, run time will be longer. Because dose is the desired output, it would be best to specify a maximum of 17 dose integration points and one risk integration point in a regular run. When the "quick" tour was rerun with a maximum of 17 dose integration points and one risk integration point, it took 1½ hours to execute. (b) Most of the probabilistic dose output valves were lower than the single point dose outputs. The deviations were greater for the lower percentiles. The only dose quantity that was higher than the values reported in the Subtask 1.6 draft report was the standard deviation of the dose. (c) Argonne was not able to reproduce this error.

4. NRC staff will need more information on how the sensitivity analyses is being performed for the peak of the mean dose values in order to know whether or not the approach used is consistent with that recommended in the Standard Review Plan for Decommissioning (SRP). Specifically, in the SRP, we recommend that total doses at the time of the peak mean dose be used as the output measure in the sensitivity analysis.

Response: The correlation and regression statistics are generated by using the total dose (summed over all nuclides and all pathways) for each observation at the time of the peak of the mean total dose. This approach is consistent with the dose values recommended in the Standard Review Plan for Decommissioning (SRP).

5. In some cases, the code generated a run time error when users attempted to print a graph from the "Results/Graph" window (i.e., when clicking on Print Graph under Graphics). The code kicks you out of the graphics window and back to the RESRAD input screen.

Response: Argonne was not able to reproduce the problem.

6. Staff attempted to print text reports directly, from the Output menu. The following difficulties were encountered by certain users:

    a. It was difficult to fit the text within the margins of the standard page.

Response: The fit to page button is on the toolbar. This function adjusts the font to fit all the pages in a report to one page width. This results in too small a font when there are many repetitions. The form of the report will be changed to print only one repetition per page.

    b. When printing the LHS report or the uncertainty report, staff noted multiple blank pages and/or printing one line only on a page.

Response: The LHS report is mostly generated from the Sandia post-processor and is in a slightly different format. The code has been changed to display this file in the standard Micrrsoft Notepad editor/viewer.

    c. General printing problems: selecting and retaining the selection of "landscape", printing all pages when all" is selected. Only the MS LineDraw font seems to correctly display/print the characters. Staff would like to have a print preview option to ensure print job is correctly configured.

Response: Argonne is unable to duplicate the landscape problem. The suggested method for printing the reports is to use MS LineDraw and select the "fit to page" toolbar option.

The user can still import the reports into other word-processors and handle the report. This option will be stated in the manual. Print previewing can be done in those software packages.

    d.   In another experience, when the user attempted to print the file MCSUMMAR.REP from the print menu in the code, he got a blank paper only. When user tried to print only one page of this file, he got the whole file, also blank. However, staff had no trouble printing the file after reading it into WordPerfect 8.

Response: Argonne was unable to duplicate this problem. The print control worked fine with specified pages. The printing of blank pages may be related to the issues addressed in Comment 6a.

7.   Staff had a difficult time getting the code to run to completion when attempting to perform analyses using more than four repetitions. For example, staff attempted to run the code using a single radionuclide (Cl-36), 200 samples, on a computer with a Pentium III (400 MHZ) processor. The following are various error messages were noted:

RESWIN, Run-time error '70', Permission denied
Poly.dll floating point invalid
Run error

Response: Argonne will fix this by ensuring that the interactive output is closed before running or saving.

8.   The current procedure to specify the default distribution for each parameter is extremely tedious. Given that the code is designed specifically for doing probabilistic analyses and will be largely used for that purpose, it should be designed so that the default distributions are automatically used. For the sake of efficiency and effectiveness in running the code in the probabilistic mode, if possible, staff suggest that the whole input file be made interactive.

Response: The suggestion made by NRC staff is good. However, to implement the suggestion will require modification of the code. In order to meet the deadline set by NRC, Argonne will provide a template file containing default distributions for all general (i.e., non-radionuclide-specific) parameters.

9.   When a deterministic RESRAD run is completed, the five deterministic report files (*.rep) are generated, along with the deterministic graphics file, the output file (output.fil), and the message file (message.fil). Uncertainty report files from earlier runs are not deleted, and will appear if the user selects the option to view them.

Thus, following a run, a user may be viewing results from two different runs. This is further complicated if the user modifies data and updates an existing file.

Response: Argonne will modify the code so that the probabilistic results from a previous run will be deleted after the "Run" button is pressed.

Also, when a user saves a file, only the input files are saved. The user must independently save each report file and the graphics files. If this is not done, some or all of the output files will be overwritten by the next run. This is a significant loss since the uncertainty runs take much longer than the deterministic runs to complete. In addition, while a user may open a new or existing input file, the results from the last run will still appear if view is selected. Further, when viewing an output file, the user has the option of saving that particular file, or the user may select "save all". However, selecting "Save All" command would save only the five deterministic output report files (concen, daudose, detailed, intrisk, and summary). Thus, the "Save All" command has not been updated to also save the two uncertainty report files (lhs.rep and mcsummar.rep).

Response: The save all command will be modified to save the two uncertainty reports.

To solve this problem, staff suggests that the code save the report and graphics files with the input file, in a single file, with a single command. This would improve the transportability of the files (the input with all the results). This would also ensure that individual output files are not inadvertently lost, requiring the time-consuming runs to be re-run. This would also ensure that a user is not viewing results from two different runs at the same time. Before modifying an input file, the user should be prompted to save the existing input file and associated output files and warned that all existing output files will be cleared before proceeding.

Response: This suggestion cannot be implemented, but we will modify the code to list files, and we will look into the ability of command line using WinZip to accomplish this.

10. Unless corrected by the user, the density, total porosity and effective porosity distributions for the contaminated zone, the saturated zone, and the unsaturated zone units are uncorrelated. This leads to unrealistic combinations of (1) density and total porosity and (2) effective porosity and total porosity within a given LHS input vector. To evaluate this, the LHS vector data for a single replication were evaluated. For the CZ, SZ and UZ, the implied specific gravity for each vector was calculated by from the density and the total porosity values:

CZ Specific Gravity

SZ Specific Gravity

UZ Specific Gravity
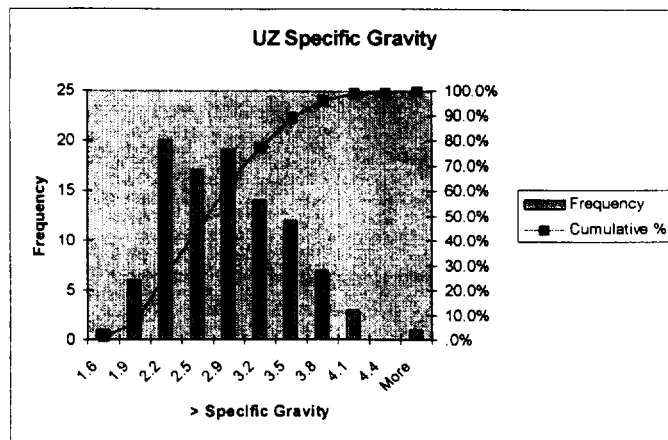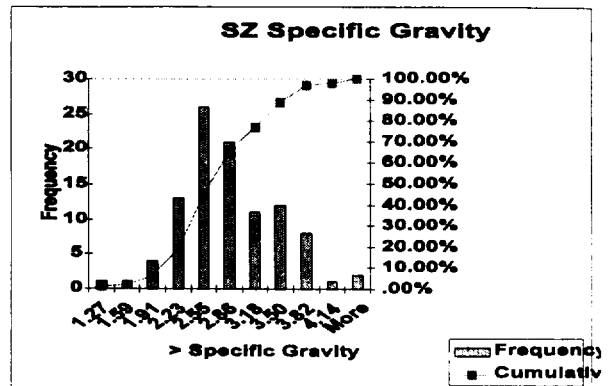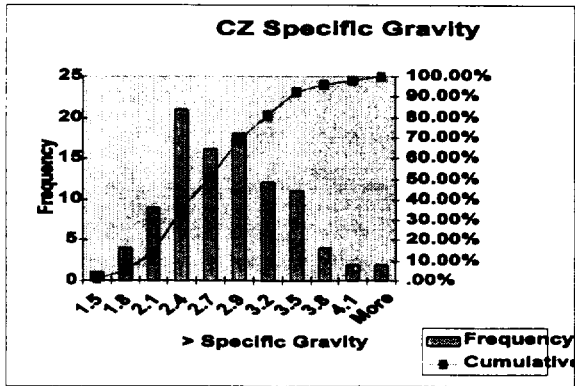
The data indicates that the lack of correlation between the density and total porosity distributions leads to unrealistically low and high specific gravity values.

Similarly, for the SZ and UZ, the ratio of the effective porosity to the total porosity was calculated:

SZ Ratio Effective porosity:Total porosity
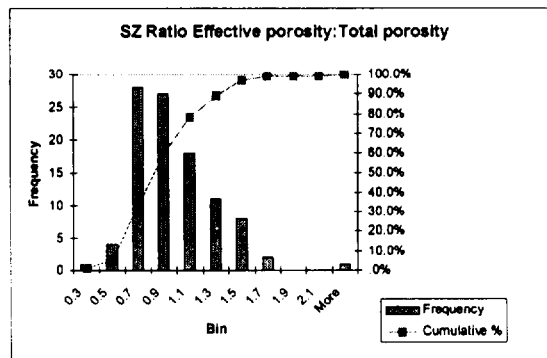
The data indicate that the lack of correlation between the effective porosity and total porosity distributions results in combinations where the effective porosity exceeds the total porosity.

Staff offers two suggested solutions: (1) Redefine the independent parameters to be specific gravity, total porosity and ratio of effective porosity to total porosity, and have density and effective porosity be internally calculated dependent parameters; (2) permanently and properly bound and correlate the distributions for density, total porosity and effective porosity.

Response: The first suggested solution will require (1) modification of the RESRAD code and (2) collection of distribution data for the ratio of effective porosity to total porosity. The second suggested solution of setting a default correlation for density, total porosity, and effective porosity can be done only for the default distributions. If the user changes the distributions, the default correlation may not work. Therefore, no default correction will be provided in the template file to be submitted to NRC. However, use of correlation coefficient among parameters has been discussed in the Subtask 1.4 report.

11.   In the Monte Carlo summary report (i.e., MCSUMMAR.REP), the parameter Fortran labels should be replaced with more descriptive labels. In addition, the report should flag any default distribution that has been changed and it should identify any assumed correlations used in the analysis.

Response: All these features are in the interactive report, and the correlations are also listed in the LHS report. MCSUMMAR.REP may be modified in the future to include this information.

12.   When the code gives an error message it refers the user to the OUTPUT.FIL file for further details; however, if the error occurs during the Monte Carlo runs, the only information provided is that the code is starting the uncertainty runs. The code should be designed to periodically dump information into the OUTPUT.FIL file while executing the uncertainty runs in an attempt to provide more information on the possible source of the error.

Response: This is a good suggestion. Argonne will incorporate this before 6.0 is finalized.

13.   When highlighting a parameter (e.g., by pressing F8), the parameter is displayed in the parameter list. By pressing OK , highlighting the same parameter again, and pressing F8, the parameter is not displayed again. The parameter will not be re-displayed until after a different parameter is selected and F8 is pressed, and then the user returns to the original parameter.

Response: Argonne fixed this.

14.   The Uncertainty Analyses Summary window cannot be closed without saving. Using "cancel current form" put the window in background, and it reappears when

executing Run. There should be a button on every window/form providing the user the option of exiting without saving changes.

Response: The values in the deterministic input screens are stored in a variable array, and it is possible to exit without saving the information in the deterministic screens. The information in the probabilistic input screen is not stored anywhere else; it is written to a file when the "save file" command is issued. Thus, if the user selects a variable and then does not want to perform uncertainty analysis on that variable, the user must use the "remove parameter" button to "remove the parameter" from the uncertainty screen. If the user does not want to run uncertainty analyses on all of the selected parameters, then the user could use the "suppress uncertainty analysis this session" option. Also see the response to Comment 30.

15. The Source window cannot be exited without saving changes. There should be a button on every window/form providing the user the option of exiting without saving changes.

Response: This comment is the same as Comment 14. See response to Comment 14.

16. When the program is opened, the radon pathway is not selected, by default. However, if New file is selected, the radon pathway is selected, by default. Having the radon pathway turned off should consistently be the default.

Response: This comment pertains to the regular RESRAD code. Argonne will look into this matter and make it consistent, if appropriate.

17. Staff performed probabilistic dose analysis using three default cases with both RESRAD 5.95 and 6: (1) Co-60, (2) U-238, and (3) Co-60 plus U-238. RESRAD 6 was run without uncertainty analysis (i.e., the default deterministic case). The results were identical. However, the speed was dramatically increased:

	RESRAD 5.95	RESRAD 6 (beta)
Co-60	8.23 seconds	2.47 seconds
U-238	25.21 seconds	3.11 seconds
Co-60 & U-238	41. 15 seconds	3.31 seconds

Response: The number of progress of computation messages has been reduced in version 6.0 to reduce execution time. The write to file operations were taking more time than the computations with the faster computers.

18. File management - User should have the option to delete files from with the "File Open" window by selecting the file, right-clicking, and selecting "Delete."

Response: This feature is not supported in Visual Basic software that Argonne used.

19. When user selects a nuclide and then select distributions for parameters associated with that nuclide (e.g., Kd). Subsequently, when select another nuclide and deleting the first; the distributions associated with the first nuclide remain, and cause the run to fail after execution has started. Code should verify that distributions for nuclide-dependent parameters are included only if the nuclide is included.

Response: Argonne will look into this.

20. When the "Uncertainty" window is open; pressing F8 twice will result in a run-time error and the program will abort.

Response: Argonne will fix this.

21. When the Uncertainty window is closed, the last parameter on the list that does not have a distribution specified is deleted. However, if there is more than one parameter on the list that does not have a distribution specified, only the last on the list is removed; the others remain. ANL need to address this issue and resolve it if it has the potential to cause the code to crash or produce erroneous results.

Response: The "Update Parameter Distribution" button has been removed to address many problems users are having with the update of information on this form. This feature will be clarified further in the manual.

22. Uncertainty Graphics - Temporal plot: the user should be able to plot the mean and multiple percentiles at the same time, for a given repetition. Plotting the mean and multiple percentiles on the same graph allows the user to evaluate the spread of the dose results over time.

Response: This will be a good feature to add to the graphic output. Argonne will look into this but with a low priority.

23. After using the program for a while, the process of entering distributions becomes rather tedious. The user must move through each data window, select each parameter, press F8, and see if the uncertainty window comes up. If it does, there may or may not be a default distribution available. In all, there are approximately 127 non-radionuclide specific parameters; The program allows the user to specify distributions for 122 of these parameters. Of the 122 parameters, 40 have default

distributions. In addition, there are 13 parameters for which the user specifies values for each individual radionuclide. The user may specify distributions for twelve of these parameters. Of the twelve, seven have default distributions. The process of specifying distributions becomes a trial and error process. There is no efficient way to determine with confidence that all default distributions have been considered.

A possible solution is to add an "Uncertainty Analysis" button under the existing "C-14" button in the set of "Modify Data" buttons. This button would take the user to the Uncertainty Analysis window (the F8 window). There could be two parts to the Parameter Distribution tab: General parameters and Radionuclide-specific parameters. Under the General parameters tab, the user would be presented with a table of all 122 parameters for which distributions may be specified. Next to each, the currently specified deterministic value would appear with a check box. If a default distribution is available, that would also be shown, with a check box. Finally, a box labeled "user-specified distribution" would be shown, followed by the drop-down list of possible distribution types and space for the user to specify the values defining the selected distribution. This would allow the user, through a single step, to see all the parameters for which distributions may be specified and see which parameters have default distributions available. The user can quickly and systematically check off the default distributions they want or specify their own distributions. The user can quickly and confidently determine whether all default distributions have been considered. A similar tab would present similar information for each radionuclide in the inventory.

Response: This is an excellent suggestion. To implement this suggestion, extensive coding and redesigning of the input screen will be required. With time and budget constraints, Argonne will, instead, develop a template file that contains all the default distributions for the general parameters. See response to Comment 8.

24. The F8 window should indicate somewhere the units for each parameter.

Response: Argonne agrees with the comment. If time permits, Argonne will address this suggestion after higher priority issues have been addressed.

25. After an uncertainty run is completed, the deterministic reports are generated and are consistent with those generated in a deterministic run. However, the deterministic graphics ("Graphic Output" from the menu bar or "Standard Graphics") from the Navigator are not available and the following error message is displayed:
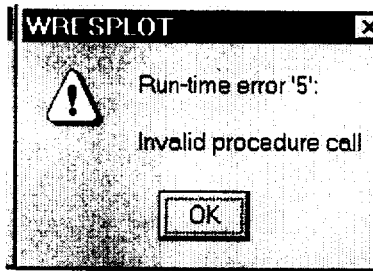
Response: Argonne is not able to reproduce this situation.

26. After completing an uncertainty run, staff viewed several reports. When staff selected the "Standard graphics" option the code displayed an error message as in comment 25 above. After staff viewed the report file, staff selected the "save all" option, and the code saved the five deterministic output report files. Then, when staff selected the interactive output button from the navigator, the code displayed the following window :
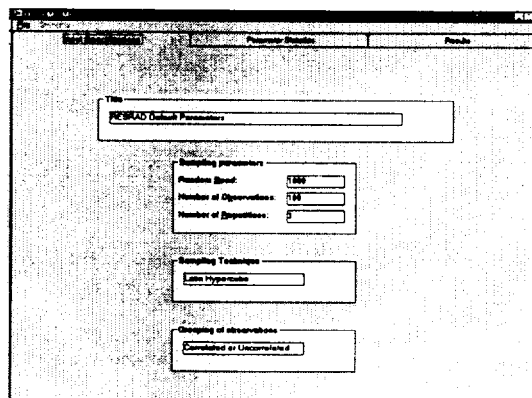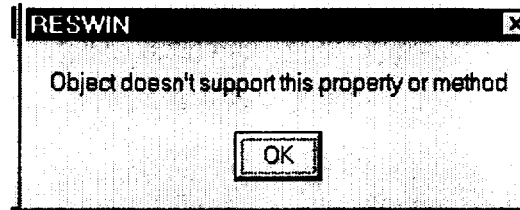

Response: Argonne is not able to reproduce this situation.

27. When staff selected the "Results" tab, the code displayed the following error message:
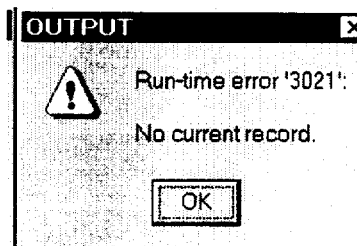
Response: This problem has been fixed.

28. General report viewing problems: The LHS report does not display correctly, page by page. Also, in moving from one page to the next, some data is repeated. When staff attempted to highlight text in the LHS report and convert to Excel; the following error message appeared:

```
┌─────────────────────────────────────────┐
│ RESWIN                               [X] │
├─────────────────────────────────────────┤
│                                          │
│  Object doesn't support this property or method │
│                                          │
│              ┌────────┐                  │
│              │   OK   │                  │
│              └────────┘                  │
│                                          │
└─────────────────────────────────────────┘
```

The viewer then locked up, and after several other error messages, the viewer and RESRAD code shut down.

Response: The "Export to Excel" feature will be removed. The user can still copy and paste text between applications and then parse the data.

29. One of the default distributions differs slightly from the Subtask 1.3 report: Wind.

Response: Argonne will look into this.

30. If a parameter is chosen for uncertainty analysis that does not have a default distribution the variable description nor the user selected distribution will not be "held" in the tab window called parameter distributions if the user selects the tab window "Input Rank Correlations". This can be recreated by 1. selecting modifying data. 2. select Contaminated zone parameters 3. Select Area of contaminated zone. 4. Press F8 or hit the uncertainty button. 5. select the parameter distributions tab 6. input a distribution 7. go to the Input Rank Correlations tab. 8. go back to Parameter distributions and the variable is lost.

Response: The user inputs in and changes to the information in the statistics of uncertain variable frame of the parameter distribution tab will be stored in the form only if the update parameter distribution button is pressed or if the previous/next parameter scroll button is pressed. This in essence is the way to cancel changes. Argonne will clarify this in the Subtask 1.6 manual.

31. The uncertainty button does not work consistently. Start RESRAD. 1. Select modify data. 2. Select contaminated zone parameters. 3. Select area of contaminated zone. 4. Press the uncertainty button. 5. No variables were given in the parameter distributions tab. The same thing happens if you go directly from a parameter with a default distribution to one with no default distribution and if the

user press the "uncertainty" button. ANL need to correct this problem as appropriate.

Response: Argonne will clarify this issue in the Subtask 1.6 manual. The variable is shown in the parameter distribution tab, but it will be remov. d if the user does not specify a distribution and the associated parameters. See also response to Comment 30.

32. If the parameter cell is highlighted and deleted and the mouse is moved to the top of the screen the code crashes with the error: "Run-time error '400' Form already displayed; can't show modally."

Response: Argonne will fix this.

33. The distribution help screen in the uncertainty analysis window does not turn off after hitting the black "close X" in the upper right hand corner. If you click on the "X", every two times you modify the parameters in the distribution, the help screen reappears or every time you select the distribution type it will reappear. ANL need to fix this problem as appropriate.

Response: Argonne will fix this.

34. When staff tried to save the input file after changing it from 3 to 1 repetition; the message "access denied" was reported and then the code bombed off. ANL definitely need to fix this problem as appropriate.

Response: Argonne could not replicate this problem. Please provide input files and Argonne will look into this issue.

35. This comment represent an individual NRC staff's (Dr. Richard Codell's) view or idea regarding alternate approach for deriving confidence level. It is recognized that the current schedule may not allow performing significant modification in the current mathematical formulation. However, ANL may evaluate the merits of the proposed idea. Staff believes that the current method of making multiple Monte Carlo repetitions for the LHS set to show the confidence in the results is tedious. Staff believes that this is a time-consuming way of showing the result. Staff believes that ANL can show confidence in a single repetition. To get a quantitative estimate of confidence using the multiple-repetition method would require many repetitions, not the 3 to 7 used as given in the draft report example. Staff believes that ANL should add the following, straightforward statistics to each repetition so that one can get a measure of the confidence in the mean and the percentiles of the distributions.

a) Confidence in the mean - For a normally distributed quantity, the confidence in the mean can be expressed (Bowen and Bennett, 1988, Section 3.5.2):

$$\overline{X} - t_{1-\frac{\alpha}{2}} (n-1)\frac{S}{\sqrt{(n)}} \le \mu \le \overline{X} + t_{1-\alpha/2}(n-1)\frac{S}{\sqrt{(n)}}.$$

where $\overline{X}$ = the sample mean, μ = the population mean, S = the sample standard deviation, and $t_p(n-1)$ = the value of the Student's t distribution for probability p, and n-1 degrees of freedom. For samples of 100 or more, you can substitute the normal variate for the t distribution. For 95% confidence, this would be approximately 1.96, so the confidence limits would be

$$\overline{X} \pm 1.96 \frac{S}{\sqrt{(n)}}$$

Although this strictly applies to only the normal distribution, it is approximately correct even if the distribution is not normal.

a) Confidence in the percentiles of the distribution.

For the order statistics of the distribution, assuming a large sample (100 or more) points, the probability that the actual 90th (or other) percentile falls between two particular order statistics is:

$$F\left(\frac{H-.5-pn}{S}\right) - F\left(\frac{L-.5-pn}{S}\right)$$

where F = the cumulative normal distribution function, H and L are the order in the sorted distribution of values, p = percentile, and S = sample standard deviation. For the 95% confidence bounds, the first term is 0.975 and the second term is 0.025, and the arguments of F are 1.96 and -1.96, respectively. Solving for H, therefore, which is the order where the upper bound confidence is 95%:

$$H = 1.96 \ S + 0.5 + pn$$

Staff did not have an opportunity to demonstrate these results, but it would be interesting to compare the results from the multiple repetitions to the direct method.

*[Dr. Codell's follow-up question on comment 35 during the 6/1/2000
teleconference with ANL is as follows:*

*Does the 90th percentile dose presented in the code output file represent the
90th percentile of each realization or of the peak dose?]*

*Response: Argonne will test different methods and report in the Subtask 1.7 report.
Some of the statistics might not apply to the non-randomly sampled LHS observations.
Regarding Dr. Codell's question, the answer depends on the quantity to which the
percentile refers to: (1) The previously existing output in the uncertainty report
(mcsummary.rep) with the heading "MC Cumulative probability summary for total dose
over pathways" combines the observations (realizations) of all repetitions to produce
single estimates of the 90% of the dose from all pathways due to all the nuclides at
each of the user-specified times. (2) The new output in the uncertainty report
(mcsummary.rep) with the heading "Summary of dose at graphical times, repetition I"
uses the observations (realizations) of the Ith repetitions to produce estimates of the
90% of the dose from all pathways due to all the nuclides at each of the graphical
times. Thus, there will be as many estimates of the 90% dose at each graphical time as
there are repetitions.*

36. Saving files is not discussed in the users manual. There was uncertainty in how
the files could be saved after the computer calculations. The main, or data, files
were identified in the manual as the only files that were to be saved. Saving the
files as .MCO and by using the File/Save All and File/View Another File in the
View-SUMMARY.REP is not addressed in the manua. . The files generated by the
probabilistic calculations appear not to be saved making it difficult to retrieve
probabilistic reports a week or two after the calculations have been performed. In
addition, there needs to be a easier way to save all fil s generated after a
computer calculation. One way to do this is to have a SAVE command that would
safe all files after any calculation.

*Response: Argonne will add discussion in the manual regarding saving input and output
files.*

37. Some calculations terminated unexpectantly before the run was completed. One
calculation involving secular equilibrium using U238, U234, Th230, Ra226 and
Pb210 at concentrations of 100 pCi/g for all radionuclides terminated before
running Ra226. The Error Message said: FORTRAN Abort, Check end of
OUTPUT.FIL for details. Examination of this file indicated the run terminated with
the statement "Starting uncertainty analysis..." The computer was turned off,
RESRAD was ran again using the same problem and the dose calculation was
completed. It may have been a memory problem. The computer that ran the
calculation had 96 MB of RAM.

Response: Argonne was unable to replicate this problem. Please provide input data files.

38. RESRAD does not display the Dose, Risk etc. calculated results for all the dose pathways, External, Ingestion and Inhalation. These pathways are identified on the Navigator Dialog Box under the Pathway/Input Tab on the main RESRAD screen, but only selected pathways are calculated and displayed via the probabilistic Interactive Output/Results/Text output (All Pathways) and the deterministic Standard Graphics/Pathway (External and Inhalation; no Ingestion) output. The printed Summary Files reports apparently provide only ingestion and inhalation dose results (as indicated by the dose conversion factors on page 2 for these pathways), but on page 7 the table summarizing the pathway selections shows direct mostly gamma (external) radiation and inhalation exposure pathways. The results would be more useful to the dose analyst, if both the probabilistic and deterministic text outputs report the dose for the inhalation, ingestion and direct gamma (external) radiation exposure pathways.

Response: Argonne will consider NRC staff's suggestions.

39. The error dialog box appeared after a run stayed on the screen for more than fifteen minutes. Access to the Interactive/Output/Results was denied and the following dialog box appeared:
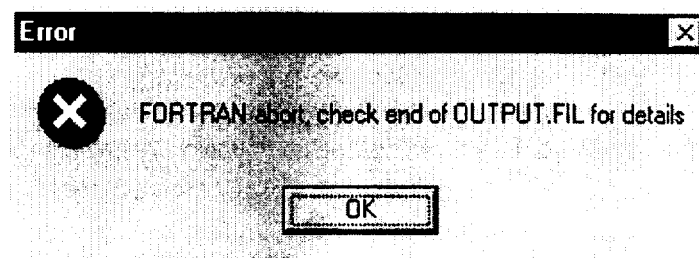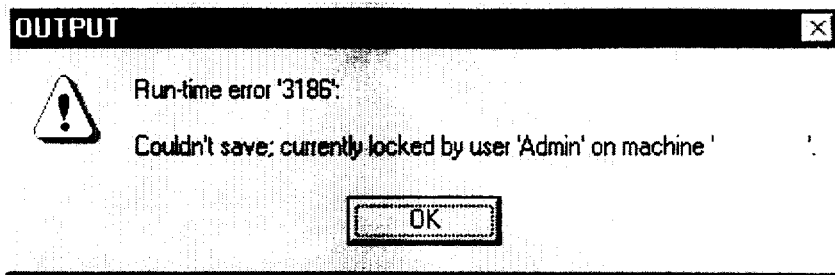

Response: Argonne was not able to duplicate this problem.

40. The user's manual needs to provide a discussion of the risk calculations and the conversion factors for determining excess cancer risks.

Response: The calculation of risk and risk coefficients is explained in detail in the next version of the RESRAD manual.

41. The following error appeared while attempting to run RESRAD while WordPerfect 8 was open and being used. The OUTPUT.FIL indicated the uncertainty analysis would not start

```
┌─────────────────────────────────────────────────────────┐
│ OUTPUT                                              [×]   │
├─────────────────────────────────────────────────────────┤
│   /!\   Run-time error '3186':                           │
│         Couldn't save; currently locked by user 'Admin'  │
│         on machine '          '.                         │
│                                                          │
│                  ┌──────────┐                            │
│                  │    OK     │                            │
│                  └──────────┘                            │
└─────────────────────────────────────────────────────────┘
```

Response: Argonne was unable to duplicate this problem.

42. The Interactive Output/Results/Text output screen show the results up to 90th percentile level. We would like to see 95-Th percentile results displayed also.

Response: Argonne will try to implement this suggestion, but as a low-priority task.

43. Could RESRAD be modified to calculate the dose as CCDF type output?. NRC's Advisory Committee for Nuclear Waste (ACNW) has recommended this type of output for risk-informed performance assessments in accordance with current NRC policy.

Response: RESRAD reports CDF. CCDF = 1 - CDF. So it would be a simple matter for the user to use the CDF plots to find the CCDF of interest.

44. Page 3 references NUREG/CR-5512 as the reference for the term "critical group". The reference should be the report in which this term first appeared. That would be in the National Academy of Science/National Research Council report on High-Level Radioactive Waste.

Response: NUREG/CR-5512 is the reference that has been used in the previous NUREG and Letter Reports.

45. In the "HELP on Statistical Distribution" screen from the Uncertainty Analysis Input Summary, there are no distributions shown for Kds for U238, U234 and Th230. Please provide the distributions as appropriate.

Response: The distribution is shown, but it hugs the two axes when liner scale is used because this is a log normal distribution with a range of many (8 to 10) orders of magnitude. It might show better on a log scale, which currently is not an option in the code.

46. Has the RESRAD output been tested by a hand calculation to ensure the calculated results are indeed the actual results? Have validation and testing of the

code been sufficient and comprehensive enough to ensure that the calculated results are indeed reasonably accurate, of good quality and technically defensible?

Response: The deterministic results of RESRAD have been verified, and Argonne has performed manual testing of probabilistic aspects. This testing will be reported in the Subtask 1.7 letter report.

47. The solubility options appears to work fine. Using radionuclide solubility data for U238 in the test case described in Appendix C, RESRAD version 6.0 gave lower dose values compared to those values obtained when using Kds for U238. The May 2000 draft user's manual/report should be revised so that it provide a short write up on the use of solubility data and indicate how the results would vary from those obtained using the default Kd values. The only difficulty encountered was how to add probabilistic data for radionuclide solubilities. Staff would welcome any ANL suggestions or technical guidance in the user's manual and improvement in the code features to overcome this difficulty.

Response: The use of the solubility option in RESRAD is described in the RESRAD Manual. Currently the solubility variable is not supported for probabilistic analysis.

48. The source term option was difficult to use. Using the fraction method is probably not a good way to go. If possible, staff suggest that the model uses absolute release rates in units of Ci/year or pCi/year.

Response: This is functionality of the deterministic RESRAD code.

49. If one changes the default values to provide user data, it's not clear how the user adds the probabilistic data to the model. When the default Kd data for U238 was changed by adding different Kd data, the calculated dose were different. But the code appeared to use the same probabilistic data. Is this consistent with the code's intent ? How does the user provide their own probabilistic data to the code for calculations? This should be discussed clearly in the user's manual and an example should be provided to illustrate the method for inputting such data into the code for performing dose analysis.

Response: Argonne will clarify in the user's guide the relationship between deterministic values and probabilistic values.

A.2 RESRAD-BUILD, VERSION 3

1. Version 3.0 lacks a good user's guide. The last manual, published in 1994, described methods, parameters, and detailed mathematical models for

Version 1.5. ANL need to develop a comprehensive and friendly user's guide to include practical examples (variations of source types, wall regions, etc.). In addition to a description of capabilities, scenarios, ANL need to develop probabilistic and LHS features especially, considering the anticipated availability of the code to the public.

Response: Argonne is currently updating the RESRAD and RESRAD-BUILD deterministic manuals under DOE contract. The LHS features in RESRAD and RESRAD-BUILD are discussed in the Subtask 1.6 NUREG report

2. The graphic user-interface, layout, and report generation of the beta code appears to be identical (except for integration of probabilistic and LHS capabilities) to that of its predecessor, which is expected to be welcomed by veteran users. Similarity of the two codes will minimize the learning curve for users unfamiliar with the probabilistic distribution functions and analyses integrated into the latest version.

Response: Comment noted; no action required.

3. Test cases "co603.inp", "co606.inp", "u2383.inp", and "u2386.inp" were unzipped from the CD-ROM and run using the parameter values saved in the respective input files. The conceptual model or basis for the various parameter selections in the files were not apparently provided in the May 2000 draft report or CD-ROM, and, therefore, it was unclear as to why certain parameter values (i.e., time, building, receptor, and source parameters) were changed from their default settings. The resulting outputs are attached, but were not reviewed due to insufficient time.

Response: These files are from the Subtask 1.4 analysis and are discussed in the Subtask 1.4 report.

4. The interactive output of the "Uncertainty Analysis Parameter Input Summary" window and various tabs was very user-friendly. Yellow highlighting of defaults in the "Variable Description" in the "Parameter distributions" tab clearly demonstrated its usefulness and purpose.

Response: Comment noted; no action required.

5. The basis for selecting the various parameter default distributions and other values in the "Sample specifications", "Parameter distributions", "Input Rank Correlations", and "Output Specifications" tabs in the "Uncertainty Analysis Parameter Input Summary" window was assumed to be reviewed by NRC staff and documented, and, therefore, was not looked at in detail due to insufficient time.

Response: No action necessary.

6. The "Doing Calculations" window, which displays the number of Monte Carlo samples, and estimated and real times appears to be very helpful in optimizing a run, even though the estimated time seemed to be very conservative as compared to the actual run time.

Response: Comment noted; no action required.

7. It is unclear what report the radionuclide inventory in the code's database was obtained. Is the radionuclide inventory in RESRAD-BUILD Version 3.0 consistent with RESRAD Version 6.0? If not (this is believed to be the case), will it be possible to add radionuclides via a patch without creating a new version?

Response: The number of radionuclides in the RESRAD and RESRAD-BUILD codes are different. It is possible to add radionuclides to RESRAD-BUILD and make it consistent with RESRAD. However, this can not be done via a patch. Adding radionuclides to RESRAD-BUILD is beyond the scope of the current task assignment.

8. Will the cumulative probability, scatter, and temporal plots be available in the final version of the code? If so, will NRC staff have an opportunity to review this?

Response: These features are included in the Release 1 of the beta version of the codes.

9. It would be interesting to compare calculated surface contamination levels for the radionuclides published in 63 FR 64134 (Nov. 18, 1998) using the probabilistic RESRAD-BUILD V3.0 and DandD V2.01 beta codes (as performed with the DandD screen V1.01 code and DandD V2.01 beta code). This comparison was not conducted due to insufficient time.

Response: No action necessary.

10. The output text report is titled "RESRAD-BUILD Program Output, Version 2.36." This title should be changed to Version 3.0.

Response: Argonne will fix this.

11. The highlights of the fixed versus the uncertain parameters with, or without, defaults are unclear. In other words, users cannot identify which parameters are fixed or uncertain and which parameters have default distributions.

Response: This would be a nice feature to have, but there is not enough time to incorporate it for this version.

12. The three parameters: resuspension rate, deposition velocity, and the air flow/exchange rates should be correlated. It is unclear how these parameters will maintain realistic values or ranges through the probabilistic analysis.

Response: Some correlations among parameters were discussed in the Subtask 1.4 report.

13. To be consistent with NRC's 10 CFR Part 20, Subpart E regulatory requirements, ANL need to mention the NRC's "25 mrem dose limit" with appropriate verbage to distinguish it from the U.S. Department of Energy (D.O.E's) "30 mrem dose limit" that appeared in this RESRAD-BUILD version 3.0.

Response: The U.S. Department of Energy is also using 25 mrem/yr dose limit in the proposed 10 CFR Part 834. The new RESRAD and RESRAD-BUILD manuals and codes will use 25 mrem/yr as the default dose limit.

APPENDIX B:

**ARGONNE RESPONSES TO THE FINAL NRC COMMENTS
ON EVALUATION AND BETA TESTING OF THE DRAFT
(RELEASE 2) PROBABILISTIC RESRAD VERSION 6.0,
AND RESRAD-BUILD, VERSION 3.0, COD: 3**

APPENDIX B:

ARGONNE RESPONSES TO THE FINAL NRC COMMENTS ON EVALUATION AND BETA TESTING OF THE DRAFT (RELEASE 2) PROBABILISTIC RESRAD VERSION 6.0, AND RESRAD-BUILD, VERSION 3.0, CODES

NRC staff appreciate Argonne National Laboratory's (ANL) continuous efforts and cooperation to address staff concerns and comments to optimize the performance of these widely used and important codes. Staff conducted additional evaluation and testing of the beta version (Release 2) of the integrated system of RESRAD 6.0 and RESRAD-BUILD 3.0 computer codes. Staff noted that many of the previous comments made on Release 1 beta version of the codes have been resolved whereas others remained unresolved. Staff understands the time and resource constraints to resolve all comments, especially those comments pertaining to certain code enhancement (i.e. nice to have features but not really important nor would necessarily lead to more accurate results) and ease of execution. However, staff believes that ANL should strive to optimize the codes' essential performance aspects and eliminate any serious bugs affecting proper (i.e. correct or technically sound) and effective code execution. In addition, the code should perform well for simultaneous handling of uncertainty of all sensitive parameters with default distributions as well as other uncertain parameters with no pre-defined distributions. The comments listed below include unresolved comments that were identified previously for Release 1 (May 5, 2000) code versions, as well as new comments from testing the Release 2 (June 28, 2000) versions of the codes.

B.1 NRC/NMSS COMMENTS

1. The code would not allow treatment of certain parameters that did not have default parameter distributions as uncertain (i.e., staff could not assign specific parameter distributions), when all the default distributions are used. For example, when staff treated the source concentration as uncertain, in one analysis, it would not allow treatment of the well pumping rate as uncertain. In another example, the code would not allow treatment of any of the C-14 data (e.g., C-14 concentration, fraction of vegetation that absorb carbon, evasion flux, etc.) as uncertain. Staff believes that this is a new problem with Release 2 of the code.

    Response: During the video conference, the circumstances surrounding this problem were duplicated (i.e., not going to the output specification tab). This problem will be fixed.

2. The current default values of time integration parameter (e.g., the maximum number of points) for the dose and the risk are 17 and 257 respectively. These values caused the code to execute for several hours instead of several minutes. In some instances, the execution was terminated early without completion of the run and an error message "floating point" was reported on the screen. It appears to staff that using the combination of default values of 17 and 257 may have caused this problem.

Response: There are two places where the user can control the number of the integrated points: (1) the user can set preference in the title screen not to do time-integrated probabilistic risk by unchecking the "time-integrated probabilistic risk" check box. If this box is unchecked, the number of time integration points is set to one, not only for the current run, but also for all subsequent probabilistic runs. So, if probabilistic risk was never the desired output, the user can set this preference option. (2) The user can also suppress time-integrated probabilistic risk for a given session by unchecking the "Total risk at each of the user specified times" box in the Output specification tab of the uncertainty form. Using smaller numbers of integration points may reduce the accuracy of the calculated dose and risk. Therefore, the default values will remain the same, yet users will be provided with instructions and multiple options as discussed above.

3. The same chemical compounds of the same element should have the same geochemical properties. For example , all uranium radionuclides with the same physicochemical composition should have the same distribution coefficient (Kd) and solubility. It is possible to use the correlation to account for this but it is very awkward and slow.

Response: This problem is understood, but because of time and budget constraints, it was agreed not to address this issue now.

4. If you start to specify a correlation, you have to complete it . There is no way to escape, except to complete it and then to delete it. It is awkward, because you cannot **easily realize ahead of time** what variable you are using since the code only displays the short name or acronym. It will give you the complete description of the variable, but in order to see it, you must start the correlation input procedure. If it turned out to be something you did not want, you have to complete the correlation calculations first before you can try another correlation calculation with another set of parameters.

Response: The code has been modified to allow users to change the selection of the first and second variables. The instructions in the manual will also clarify this issue.

5. Staff see no good way to specify the time duration (i.e. the number of years the waste was buried. There is a place for it under the specification of nuclides, but the number of years seems to be unchangeable. Staff cannot find a good explanation for this. ANL staff need to explain, remove, reconcile and correct this undesirable inflexibility and limitation of the code.

Response: During the video conference the circumstances surrounding this problem were duplicated (time since placement set, water concentration set, time zeroed out). This problem will be fixed.

6. The Uncertainty Analyses Summary window cannot be closed without saving. Using "Cancel current form" put the window in background, and it reappears when executing "Run." There should be a button on every window/form that provide the user the option of exiting without saving changes.

Response: This situation is an inconvenience that would take much effort to change. It was agreed in the video conference to not pursue this issue now.

7. The Source window cannot be exited without saving changes. There should be a button on every window/form providing the user the option of exiting without saving changes.

Response: This situation also is an inconvenience that would take much effort to change. It was agreed in the video conference to not pursue this issue now.

8. General printing problems: selecting and retaining the selection of "landscape", printing all pages when "all" is selected. Only the MS Line Draw font seems to correctly display/print the characters. Suggest having a print preview option to ensure print job is correctly configured.

Response: Several code modifications have been made to resolve these issues:

1. *The "Printer Setup" option from the menu was not saving the landscape/portrait option. However, the "Print" option from the menu or the toolbar allowed access to the printer properties. These properties include the landscape/portrait option that are saved and used. We have removed the "Printer Setup" option from the menu. This change ensures reliable printing without removing any features.*

2. *The option to print all pages was not working properly. This problem has been fixed.*

3. *All fonts except MSLine Draw and Courier New will be removed from the font list.*

9. File management - User should have the option to delete file s from the File Open window by selecting the file, right-clicking, and selecting Delete.

Response: This option is not a standard feature of the development environment (Visual Basic 4). The lack of this feature is a user inconvenience that would take much effort to change. It was agreed to not pursue this issue now.

10. Select a nuclide. Select distributions for parameters associated with the nuclide (e.g., Kd). Select another nuclide and delete the first. The distributions associated with the first nuclide remain, and cause the run to fail after execution has started. Code should verify that distributions for nuclide-dependent parameters are included only if the nuclide is included.

    This was tested again and the program crashed. This appears to be an obvious "bug" that ANL need to fix.

Response: The ability to delete a nuclide with uncertainty parameters already set was demonstrated in the video conference. NRC will review this problem to see if there are special circumstances in which this fix does not work. It is true that the parameters associated with the deleted nuclide remain in the uncertainty form (at least for the current session in the case of Kd values), but this does not cause the code to crash. The parameters are left in so the user can reselect the nuclide and perform analysis on the nuclide properties during the same session.

11. When the uncertainty window is closed, the last parameter on the list that does not have a distribution specified is deleted. However, if there is more than one parameter on the list that does not have a distribution specified, only the last on the list is removed; the others remain. This was tested again and the program crashed. This again appears to be an obvious "bug" that ANL need to fix.

Response: This problem has been recognized and has been fixed in a version later than beta release 2.

12. When a deterministic RESRAD run is completed, the five deterministic report files (*.rep) are generated, along with the deterministic graphics file, the output file (output.fil), and the message file (message.fil). Uncertainty report files from earlier runs are not deleted, and will appear if the user selects the option to view them. Thus, following a run, a user may be viewing results from two different runs. This is further complicated if the user modifies data and updates an existing file.

When a user saves a file, only the input files are saved. The user must independently save each report file and the graphics files. If this is not done, some or all of the output files will be overwritten by the next run. This is a significant loss since the uncertainty runs take much longer than the deterministic runs to complete.

While a user may open a new or existing input file, the results from the last run will still appear if view is selected.

Also, when viewing an output file, the user has the option of saving that particular file, or the user may select "save all". However, "save all " saves only the five deterministic output report files (concen, daudose,detailed, intrisk and summary). Please reconcile.

Suggestion: Save the report and graphics files with the input file, in a single file, with a single command. This would improve the transportability of the files (the input with all the results). This would also ensure that individual output files are not inadvertently lost, requiring the time-consuming runs to be repeated. This would also ensure that a user is not viewing results from two different runs at the same time. Before modifying an input file, the user should be prompted to save the existing input file and associated output files and warned that all existing output files will be cleared before proceeding.

ANL's resolution of the problem in Release 2 of the codes is not clear. Using "Save All" now saves the MC and LHS reports in addition to the five deterministic reports. With respect to clearing out probabilistic results from the preceding run with the execution of each new run (deterministic or probabilistic), it is not clear that the problem has been fixed. Problems identified and communicated by NRC staff to ANL for resolution after the testing of the Release 1 version of the codes still seem to exist. Please reconcile.

Response: (1) The code has been modified so that "Save All" now saves 10 files, including the five deterministic report files (summary.rep, concent.rep, daudose.rep, detailed.rep, intrisk.rep), the deterministic graphics file (graphics.asc), the two probabilistic report files (mcsummar.rep, lhs.rep), and the two files that contain the raw uncertainty data (uncgrpto.bin, uncpeak.asc). The four probabilistic files from the previous runs are deleted when the run command is issued. (2) Those users who want the "Save All" command to be issued automatically after each run can set this preference in the "Title" form. If the "Save All files after each run" box is checked these 10 files (6 for deterministic runs) will be saved automatically after all subsequent runs until this preference is changed. (3) The file used by the interactive output is always saved. (4) Files from previous runs will still be available if saved; however, access to

them will be gained by explicitly specifying the case name. The probabilistic graphics file will be cleared so that the user is assured that the files readily accessible from the results interface will be for the current case.

13. Uncertainty Graphics - Temporal plot: The user should be able to plot the mean and multiple percentiles at the same time, for a given repetition. Plotting the mean and multiple percentiles on the same graph allows the user to evaluate the spread of the dose results over time. Providing this user suggested practical display feature would greatly improve the usefulness of this code output feature.

Response: This situation is a user inconvenience that would take much effort to change. It was agreed in the video conference to not pursue this issue now. The uncertainty output report (MCSUMMAR.REP) contains tables of the minimum, maximum, mean, median, 90%, 95%, 97.5%, and 99% dose at each graphical time for each repetition. Look for "Summary of dose at graphical times, repetition 1" in the index of that report.

14. After using the program for a while, the process of entering distributions becomes rather tedious. The user must move through each data window, select each parameter, press F8, and see if the uncertainty window comes up. If it does, there may or may not be a default distribution available. In all, there are approximately 127 non-radionuclide specific parameters. The program allows the user to specify distributions for 122 of these parameters. Of the 122 parameters, 40 have default distributions. In addition, there are 13 parameters for which the user specifies values for each individual radionuclide. The user may specify distributions for twelve of these parameters.

> Of the twelve, seven have default distributions. The process of specifying distributions becomes a trial and error process. There is no efficient way to determine with confidence that all default distributions have been considered. Staff suggest that ANL attempt to make this procedure for entering the parameter distributions more systematic, comprehensive, efficient and effective than the trial and error method that the user (s) have to go through.

> NRC staff would like to propose the following possible solution: Add a "Uncertainty Analysis" button under the existing "C-14" button in the set of "Modify Data" buttons. This button would take the user to the Uncertainty Analysis window (the F8 window). There could be two parts to the Parameter Distribution tab: General parameters and Radionuclide-specific parameters. Under the General parameters tab, the user would be presented with a table of all 122 parameters for which distributions may be specified. Next to each, the currently specified deterministic value would appear with a check box. If a default distribution is available, that would also be shown, with a check box.

Finally, a box labeled "user-specified distribution" would be shown, followed by the drop-down list of possible distribution types and space for the user to specify the values defining the selected distribution. This would allow the user, through a single step, to see all the parameters for which distributions may be specified and see which parameters have default distributions available. The user can quickly and systematically check off the default distributions they want or specify their own distributions. The user can quickly and confidently determine whether all default distributions have been considered. A similar tab would present similar information for each radionuclide in the inventory.

Response: This issue has been addressed through the development and distribution of the template file NONNUCL.TEM, in both RESRAD and RESRAD-BUILD. It will be made more visible placed by including *.TEM files in the file dialog box.

15. The F8 window should indicate somewhere the units for each parameter.

Response: It was agreed in the video conference to not pursue this issue now.

16. Unless corrected by the user, the density, total porosity and effective porosity distributions for the contaminated zone, the saturated zone, and the unsaturated zone units are uncorrelated. This leads to unrealistic combinations of (1) density and total porosity and (2) effective porosity and total porosity within a given LHS input vector. It appears that this problem was brought to ANL staff attention for resolution in previous reviews of project reports and after the testing of the Release 1 versions of the codes on June 1, 2000. If possible, ANL need to address and resolve this problem.

To evaluate this, the LHS vector data for a single replication were evaluated. For the CZ, SZ and UZ, the implied specific gravity for each vector was calculated by using the density and the total porosity values:. The results are presented below in graphical form.

The results indicate that the lack of correlation between the density and total porosity distributions leads to unrealistically low and high specific gravity values.

CZ Specific Gravity

SZ Specific Gravity

UZ Specific Gravity
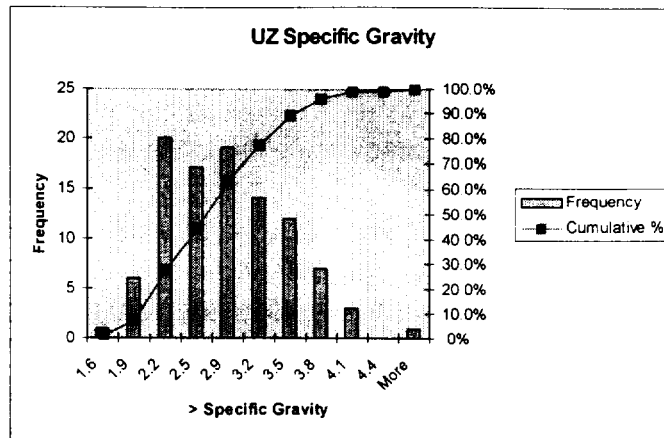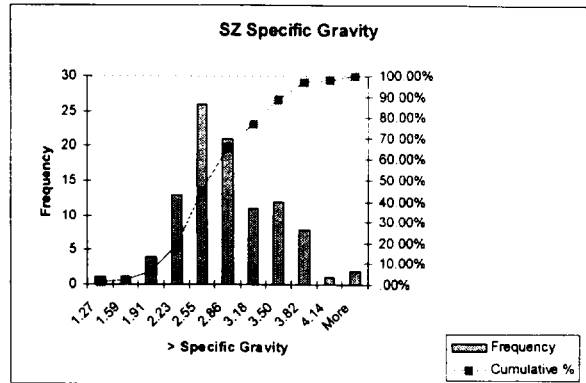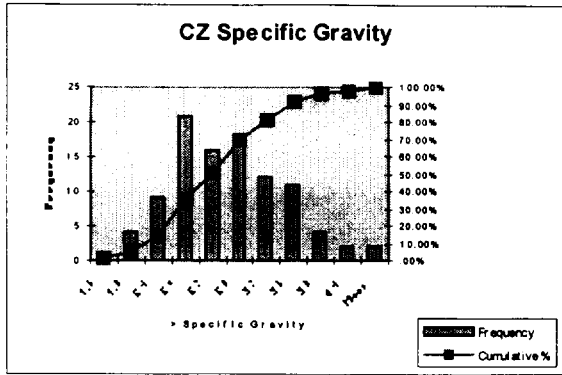
Similarly, for the SZ and UZ, the ratio of the effective porosity to the total porosity was calculated and the results are presented below in graphical form.
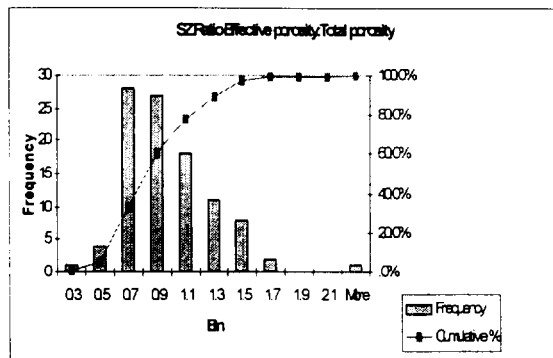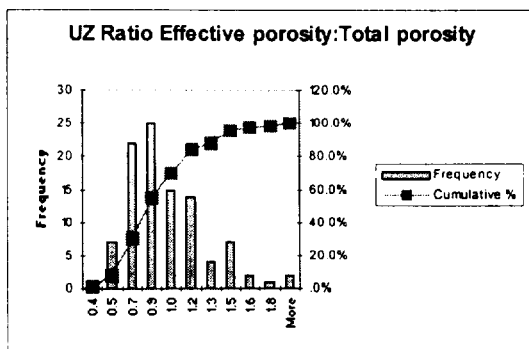
UZ Ratio Effective porosity:Total porosity

SZ Ratio Effective porosity:Total porosity

The results indicate that the lack of correlation between the effective porosity and total porosity distributions led to combinations where the effective porosity exceeds the total porosity.

NRC staff would like to suggest two solutions: (1) Redefine the independent parameters to be specific gravity, total porosity and ratio of effective porosity to total porosity, and have density and effective porosity be internally calculated dependent parameters; (2) permanently and properly bound and correlate the distributions for density, total porosity and effective porosity.

Response: This issue is understood and has been previously discussed. It would take much effort to change. It was agreed in the video conference to not pursue this issue now.

17. One of the default distributions differs slightly from the Subtask 1.3 report: Wind. Default values for "wind" still inconsistent. Please reconcile.

Response: It was explained that the limits of the distribution in the Subtask 1.3 report could not be represented with the LHS sampling routine. The distribution limits were set as close to the Subtask 1.3 reported values as possible and still maintain a distribution that LHS could handle.

18. Staff recommend that ANL generate a template file to include all sensitive parameters with default distributions. This file is necessary to reduce the burden on the users of going through each specific input parameter.

Response: This suggestion has been done; please see response to comment 14 above.

B.2 NRC/RES/DRAA COMMENTS

1. The user's manual should provide more background information on the Cut-off Half, Graphical Parameters and Time integration Parameters listed under "*Change Title*". In addition, the manual should provide some guidance on what numbers should be chosen for the Maximum numbers of points for both Dose and Risk as the choice of these two values can considerably effect the time RESRAD runs an application.

Response: These issues will be addressed in the new RESRAD and RESRAD-BUILD manuals to be issued by DOE.

2.   The manual is still not clear on how the user would add probabilistic data to situations where (a) there is a default value, but no probabilistic data are provided and (b) where the user has better probabilistic data than the default probabilistic data and (c) in the situations where there are no default data and no probabilistic numbers(e.g., cover depth, solubility limit). Do the users have to contact the code developers to change or add probabilistic data or can the users do it themselves? How would the user's do it?

Response: The user's guide covers these issues, and it will be reviewed for clarity. Also, a brief help message pops up when the user selects a parameter for which no default exists.

3.   On page 10, second column, third paragraph seem to indicate if the user wants to have all non-nuclide specific parameters that have defined default distributions to be set for probabilistic analysis, a template file should be used. The template to be found in "**File\Open\NonNucl.tem.NonNucl.Tem**" could not be found under "**File\Open**".

Response: A template file is provided; please see the previous response to Comment 14 in Section B.1.

4.   Add title, date, RESRAD version to "**lhs.rep**" and "**filename.smp**" report. Both start out with just "**Random Seed = 1000.**"

Response: This suggestion has been done.

5.   The user's manual should indicate the LHS Report (LHS REP) for each case needs to be saved separately in the "**lhs.rep**" using "**File\Save As...**" We could not locate files with the "**.lhs**" extension. Apparently "lhs" reports are not saved with an ".lhs" extension but they are saved here as "**.rep.txt**" reports. Using "**Save All**" in the Summary or Uncertainty Report doesn't save the "**lhs**" reports. It's also noted the "**.smp**" report appears to include the input Latin hypercube sampling (LHS) data.

Response: The manual describes how the "Save All" command works and the file descriptions. The *.lhs files are not output files but are the probabilistic input files created when the user saves the input data.

6.   Page 16. Table 2. List of Probabilistic Files. Could not locate "**.buo files**". The " **.buo**" files are not listed in the Summary reports when "**Save All**" is used. Also, add "**.lhs**" if files are save with an " **.lhs** " extension. For " **.prb** ", add "**and Uncertainty Analysis**".

Response: BUO files are generated only for RESRAD-BUILD runs, as is specified in the user's manual.

7. We notice the Pathways in Interactive Output\Results are indicated as "All Pathways", but there are no categories specifically listed for specifying the dose for ingestion, exposure, and inhalation. We especially need the dose for the ingestion pathway listed separately because this is the pathway most likely to contribute to the total dose.

Response: The interactive output contains options for looking at each pathway and at combinations of pathways.

8. **The following comment is from Dr. Phil Meyer of the Pacific Northwest Laboratory:** "Writing the detailed output to a database file is a good idea and we're happy the full set of output data is easily accessible for additional analysis. We had a problem once when Access for Office 2000 tried to convert the *.mco* file to *.mdb* and wasn't successful. We actually had to rerun a Monte Carlo simulation because Access overwrote and corrupted the *.mco* file during the attempted conversion. We were wondering why the output database file isn't written in the more recent *.mdb* format.

Response: At the time the probabilistic versions were developed, MS Access 97 was the latest version. The software uses Access 2 because of the compatibility with the development environment (Visual Basic 4). To upgrade the software to a MS Access 97 would require significant effort. A workaround was found for the identified problem — first convert the database file to Access 97 and then convert the Access 97 database to Access 2000. The inability to convert the database file directly to Access 2000 is an issue for Microsoft. This issue should be included in a readme file or the user's manual.

9. ANL Note: The following comments have been addressed in the previous Response to Comments after Beta Release 1. There are no further comments or responses.

   1. Both RESRAD-BUILD Versions 2.37,and 3.0 lacks a good user's guide. The last manual, published in 1994, described methods, parameters, and detailed mathematical models for Version 1.5. A comprehensive user's guide to include practical examples (variations of source types, wall regions, etc.) in addition to a description of capabilities, scenarios, probabilistic and LHS features needs to be developed especially considering the anticipated availability of the code to the public.

2.   The graphic user-interface, layout, and report generation of the beta code appears to be identical (except for integration of probabilistic and LHS capabilities) to that of its predecessor, which is expected to be welcomed by veteran users. Similarity of the two codes will minimize the learning curve for users unfamiliar with the probabilistic distribution functions and analyses integrated into the latest version.

3.   Test cases "co603.inp", "co606.inp", "u2383.inp", and "u2386.inp" were unzipped from the CD-ROM and run using the parameter values saved in the respective input files. The conceptual model or basis for the various parameter selections in the files were not apparently provided in the May 2000 draft report or CD-ROM, and, therefore, it was unclear as to why certain parameter values (i.e., time, building, receptor, and source parameters) were changed from their default settings. The resulting outputs are attached, but were not reviewed due to insufficient time.

4.   The basis for selecting the various parameter default distributions and other values in the "Sample specifications", "Parameter distributions", "Input Rank Correlations", and "Output Specifications" tabs in the "Uncertainty Analysis Parameter Input Summary" window was assumed to be reviewed by NRC staff and documented for previous subtasks of the project, and, therefore, was not looked at in detail due to insufficient time.

5.   It is unclear from what report the radionuclide inventory in the code's database was obtained. Is the radionuclide inventory in RESRAD-BUILD Version 3.0 consistent with RESRAD Version 6.0? If not (this is believed to be the case), will it be possible to add radionuclides via a patch without creating a new version? It would be interesting to compare calculated surface contamination levels for the radionuclides published in 63 FR 64134 (Nov. 18, 1998) using the probabilistic RESRAD-BUILD V3.0 and DandD V2.01 beta codes (as performed with the DandD screen V1.01 code and DandD V2.01 beta code). This comparison may be useful in testing the performance of RESRAD-BUILD 3.0 Release 2 version.

6.   It will be interesting to test the performance of the cov ، using common building occupancy scenario (NUREG/CR-5512 Vol. 1) and sensitive parameters related to suspension rate and resuspension factor.

7.   The highlights of the fixed versus the uncertain parameters with, or without, defaults are unclear. In other words, users cannot identify which parameters are fixed or uncertain and which parameters have default distributions.

8. The three parameters: resuspension rate, deposition velocity, and the air flow/exchange rates should be correlated. It is unclear how these parameters will maintain realistic values or ranges throughout the probabilistic analysis calculations.

B.3 NRC/NMSS COMMENTS ON THE JUNE 2000 DRAFT LETTER REPORT "TESTING OF THE RESRAD PROBABILISTIC MODULES"

1. The report states that the correlation analysis agreed with those previously computed manually; however, it does not provide any specific examples of such analysis and the results to support this statement. For example, what is being defined by "agreed". More elaboration should be provided on the comparison.

Response: The test report will be reviewed and elaborated on as necessary.

2. The report states that no significant differences were found in comparing the deterministic and probabilistic results. However, again it is not clear what is meant by "no significant difference". Additional elaboration should be provided.

Response: The test report will be reviewed and elaborated on as necessary.

3. The report did not include vivid examples to demonstrate actual performance of the code. In other words, the integrated testing was conducted on Ra-226 only rather than on radionuclide mixtures representing typical inventory, and residual radioactivity at nuclear facilities and competing environmental pathways. Therefore, testing of parameter uncertainties and their impacts on dose outputs are not adequately addressed. In addition, evaluation of code performance regarding approaches to uncertainty treatment for dose compliance is lacking. Please reconcile.

Response: The test report Section 2.2.1 states that all nuclides except one were tested and reported in Subtask 1.4. Since the calculational aspects of the code were not changed, these results stand. The detailed analysis later in the test report was meant to clarify analysis issues, not to be a comprehensive test over all input conditions. No modifications are necessary.

2. TITLE AND SUBTITLE

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8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

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Argonne, IL 60439

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

T. Mo, NRC Project Manager

11. ABSTRACT *(200 words or less)*

RESRAD and RESRAD-Build codes are part of the RESRAD family of codes developed by the U.S. Department of Energy. For many years these deterministic codes have been used as dose assessment tools for cleanup efforts at sites contaminated with radioactive materials. The RESRAD code applies to the cleanup of soil, and the RESRAD-Build code applies to the cleanup of buildings and structures.

The existing (deterministic) RESRAD 6.0 and RESRAD-Build 3.0 codes were adapted for use (with the U.S. Nuclear Regulatory Commission's (NRC's) Standard Review Plan for Decommissioning, NUREG-1727) as site-specific and probabilistic dose analysis tools for demonstrating compliance with the license termination rule (10 CFR Part 20, Subpart E) in a risk-informed manner.

This report documents the procedure used to enhance the deterministic RESRAD and RESRAD-Build codes for probabilistic dose analysis. A six step procedure was used in developing default parameter distributions and the probabilistic analysis modules. These six steps include (1) listing and categorizing parameters, (3) developing parameter distributions, (4) testing parameter distributions for probabilistic analysis, (5) developing probabilistic modules, and (6) testing the integrated system of probabilistic modules and codes. These six steps are discussed and summarized in this report. Steps 4 and 5 are documented in separate NUREG/CR reports (NUREG/CR-6676 and NUREG/CR-6692, respectively). The documentation for steps 1, 2, 3, and 6 are included in this report as attachments.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Probabilistic Modules for RESRAD and RESRAD-BUILD computer codes, NMSS Decommissioning Standard Review Plan (NUREG-1727), demonstrating compliance with the license termination rule, risk-informed regulation, probabilistic and site-specific radiation dose analysis, parameter distributions, uncertainty analysis of calculated dose and sensitivity analysis of the dose to input parameters, Latin Hypercube Sampling, regression analysis, correlation coefficients, scatter plots, testing of RESRAD probabilistic modules, U.S. Nuclear Regulatory Commission, U.S. Department of Energy

13. AVAILABILITY STATEMENT

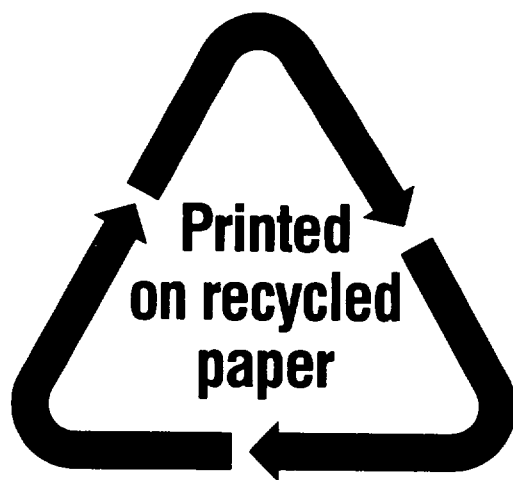unlimited

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