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**METEOROLOGY AND DEMOGRAPHY MODELS FOR RISK ASSESSMENT OF
ACCIDENTAL ATMOSPHERIC RELEASES OF NUCLEAR MATERIALS
PHASE 2 METHODOLOGY**

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FOREWORD

This work is a revision of the meteorology and demography models outlined in Determination of Performance Criteria for High-Level Solidified Nuclear Waste (NUREG-0279, July 1977).¹

There are three basic differences between this model and that used in NUREG-0279. They are: (1) the integration of the plume and puff models were increased from 100 km to 1000 km to be more conservative and to capture a greater portion of the downwind population dose, (2) the integration of the puff model was modified to avoid a double counting problem found in the method used in NUREG-0279, and (3) a modification of the population model for federal waste repository calculations was made, which made the population density curve a continuous function with distance.

Generally, if the accumulated doses beyond 100 km are discounted, the new results are within about a factor of 2 of results in NUREG-0279.

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PHASE 2 METHODOLOGY

ABSTRACT

Models are derived for determining the risk of release to the atmosphere of radioactive materials during nuclear waste handling. Such releases might occur in three phases of the nuclear waste handling cycle: (1) at fuel reprocessing plants during handling and interim storage, (2) during transportation to a permanent storage area, or (3) at the permanent disposal area (federal waste repository). Gaussian diffusion equations for both plume- and puff-type releases are used with demographic models to assess relative integrated population doses. Given a unit release and assuming an equal accident probability, we conclude that the largest risk would be from a transportation accident in a metropolitan area. The effect of a release during transportation in a rural area or at a fuel reprocessing plant would be one to two orders of magnitude less, while at a federal waste repository the population dose would be three or more orders of magnitude less than for the metropolitan transportation accident.

METEOROLOGY

In the event of an accidental release of solidified radioactive waste at a fuel reprocessing plant (FRP), along a transportation route, or at a federal waste repository (FWR), a portion of the waste might become airborne and affect populations downwind. Therefore, it is important to estimate the dispersion and deposition of such debris. For our calculations, we assume a unit-curie release at 1 m above the ground. The initial source is assumed to have a 1 m radius. At the FRP or the FWR, it is possible to have either a continuous release (plume), an instantaneous release (puff), or perhaps something between those two extremes. In a transportation accident, the most likely type of release is the puff.

GAUSSIAN EQUATIONS FOR PLUME AND PUFF RELEASES

The Gaussian diffusion equations for the two types of releases at the surface are given below. For a plume, using sector-averaging over a 22.5° arc,

$$\chi/Q = \left(\frac{2}{\pi}\right)^{3/2} \frac{4}{\sigma_z \bar{u} x} \exp\left(-\frac{1}{2} \frac{h^2}{\sigma_z^2}\right), \quad (1)$$

where χ = surface air concentration on plume centerline (Ci/m^3), Q = source term (Ci/y), $\bar{u}$ = mean surface wind speed (m/y), σ_z = vertical standard deviation of radioactivity (m), x = distance downwind (m), and h = height of plume centerline above ground (m).

For a puff,

$$(\chi/Q)_i = \frac{1}{\sqrt{2\pi}^{3/2} \sigma_{x_i} \sigma_{y_i} \sigma_{z_i}} \exp\left(-\frac{1}{2} \frac{h^2}{\sigma_{z_i}^2}\right), \quad (2)$$

where Q is in curies and the subscripts signify instantaneous values of the standard deviation in the x (downwind), y (crosswind), and z (vertical) directions. Since a plume meanders about an average trajectory at an angular variation dependent on the atmospheric stability while a puff is influenced only by the winds along its trajectory, the σ values for a plume are larger than those for a puff in similar conditions of stability and wind speed.

In addition to surface concentration, surface deposition has been incorporated into the calculations. This modification of the diffusion equations involves the use of a deposition velocity that represents the rate of particulate impaction with the surface due to turbulent eddies near the ground. A deposition velocity of 0.01 m/s has been assumed, and the above equations have been modified in our calculations to include plume depletion as deposition occurs.

For the purpose of an accident analysis, we have considered both an average and a worst case. The average was made by assuming a Pasquill-Gifford

"D" stability with a 5-m/s wind speed. To determine the worst case, we have estimated the upper envelope of concentration for both plumes and puffs for the following stability categories and wind speeds:

Stability category	Wind speed, m/s
A	1
B	3
C	4
D	5
E	2
F	1

Average and worst case analytical equations for both unit-source continuous and instantaneous surface releases (plume and puff, respectively) are given in Table 1; the distance parameters are 0.1 to 1000 km from the source. Graphs of these functions are shown in Figs. 1 and 2. Similar equations for the deposition can be obtained by multiplying Eqs. (1) and (2) by 3×10^5 , the deposition velocity in m/y.

TABLE 1. Analytical expressions for estimating relative concentrations of surface deposition from a solidified nuclear waste accident.^a

Type of estimate	Plume	Puff
Average case χ/Q D stability, $u = 5$ m/s	$5.6 \times 10^{-8} x^{-1.7}$	$1.2 \times 10^4 x^{-3.7}$
Worst case χ/Q (upper envelope)	$1.3 \times 10^{-6} x^{-2.0}$	$1.3 \times 10^5 x^{-3.9}$

^a χ/Q is relative concentration (y/m^3 for a plume and $1/m^3$ for a puff); x is distance downwind (m); plume or puff height is 1 m, and deposition velocity is 3×10^5 m/y.

FIG. 1. Graph of analytical expressions for a plume. Release height is 1 m. Sector averaging was used.

FIG. 2. Graph of analytical expressions for a puff. Release height is 1 m.

Nearly all near-ground diffusion experiments to determine σ values have been made to distances less than 100 km, and therefore errors in χ/Q may be large beyond 100 km. However, the individual doses at the longer distances are small. Since the Gaussian equations will be used to determine population dose for the entire contiguous 48 states, the integrated dose between 100 and 1000 km was chosen to provide a more conservative estimate than that obtained to only 100 km.

Concentrations obtained from the worst case expression for a plume of unit source strength have been compared with concentrations from a similar model developed under NRC guidance for nuclear power stations (Preparation of Environmental Reports, 1976, p. 7-1).² At a distance of 100 m from an accident, our expression for a plume (Table 1) yields a χ/Q about a factor of 5 greater than the value obtained from the method used in Preparation of Environmental Reports. The concentrations from both methods are the same at about 6 km. At 100 km, the Table 1 expression gives a concentration about a factor of 3 less than that indicated by Preparation of Environmental Reports.

DEMOGRAPHY

To estimate the total population dose (out to 1000 km) from an accident involving solidified nuclear waste, it is convenient to express population by analytic equations. Consideration of population density (the number of persons per unit area) simplifies the formulation of such equations.

It is assumed that the rural population density, ρ , is uniform. In and around towns and cities, the population density can be approximated using Gaussian curves. General expressions for such population densities are:

1. From the accident site to the nearest city ($0 < x < x_c$),

$$\rho = (\rho_c - \rho_s) \exp \left[-b_1 (x - x_c)^2 \right] + \rho_s ; \quad (3)$$

2. From the city to outlying rural areas ($x > x_c$),

$$\rho = (\rho_c - \rho_r) \exp \left[-b_2 (x - x_c)^2 \right] + \rho_r ; \quad (4)$$

where b_1 and b_2 are coefficients determining the shape of the Gaussian curves, and where x = distance downwind from the accident (m), x_c = distance from the accident to the city (m), ρ_s = population density at the accident site (persons/m²), ρ_c = population density in the city (persons/m²), and ρ_r = rural population density (persons/m²).

FUEL REPROCESSING PLANT DEMOGRAPHY

We assume that future FRPs will be located in sparsely populated regions. Such plants will likely have small towns (population less than 10,000) within easy commuting distance.

Since it represents the state of the art in reprocessing plants, the Barnwell Nuclear Fuel Plant (BNFP) (see Ref. 3), located on the eastern edge of the Savannah River Plant (SRP) in South Carolina, was selected as a typical site for defining the constants in Eqs. (3) and (4). The BNFP is situated advantageously with the sparsely populated SRP to its west. Therefore, only the population to the east was considered. The BNFP environmental statement was used in determining the regional demography. The constants substituted into Eqs. (1) and (2) (ρ in units of persons/m²) are: $b_1 = 0.08$, $b_2 = 0.05$, $x_c = 1.2 \times 10^4$ m (distance from FRP to the city of Barnwell), $\rho_s = 5 \times 10^{-6}$ persons/m², $\rho_c = 1 \times 10^{-4}$ persons/m² (average population density of the city of Barnwell), and $\rho_r = 2.2 \times 10^{-5}$ persons/m² (average population density of contiguous U.S.).

The specific equations for this site are then:

1. Within 12 km of the FRP,

$$\rho = 9.5 \times 10^{-5} \exp [-0.08(0.001x - 12)^2] + 5 \times 10^{-6}, \quad (5)$$

2. Beyond 12 km,

$$\rho = 7.8 \times 10^{-5} \exp [-0.05(0.001x - 12)^2] + 2.2 \times 10^{-5}. \quad (6)$$

Figure 3 is a plot of population density Eqs. (5) and (6) for an FRP; however, in this figure ρ has units of persons/km².

FIG. 3. Population density vs distance from a hypothetical accident at a fuel reprocessing plant. A town of 5000 people is 12 km downwind.

TRANSPORTATION DEMOGRAPHY

Urban Site

The population distribution in the Dallas-Fort Worth area was modeled as a typical demography for transportation accidents involving solidified radioactive waste in urban areas. This particular region was selected because:

- The rail lines and truck routes through Dallas-Fort Worth could be used to transport solid nuclear waste to a sparsely populated FWR that may be located in the southwestern U.S.

- Central Texas has a high occurrence of tornadoes. Although it is not likely, a large tornado might be able to pick up and rupture a solidified waste transportation cask.

- Dallas-Fort Worth was the tenth largest metropolitan area in the U.S. in 1973.⁴

For the purposes of this study, we assume an accident in the center of the metropolitan area (area of maximum population density). Also, we assume that the population density falls off in a Gaussian fashion to the rural area. The 1973 population density of the Dallas-Fort Worth metropolitan area was 114 persons/km².⁵ The total metropolitan area is 21,700 km². Within the city limits of Dallas, the 1970 population density was 1230 persons/km², while the area was 688 km².⁴ If we assume that the city limits form a circle, it would have a radius of 15 km; the radius of the metropolitan area under the same assumption would be 83 km. Using these assumptions, one can determine the Gaussian equation for the population density ρ in units of persons/m² as

$$\rho = 1.26 \times 10^{-3} \exp(-1 \times 10^{-9} x^2) , \quad (7)$$

where x is the radial distance in meters from the center of the city. At a distance of 63,600 m, ρ equals the average U.S. population density of 2.2×10^{-5} persons/m². Hence, beyond this distance, $\rho = 2.2 \times 10^{-5}$. Figure 4 shows a plot of Eq. (7) with ρ in persons/km². The coefficient of 1.26×10^{-3} was chosen so that the curve between 0 and 1.5×10^4 m (radius of the city limits) gives equal areas of the city above and below the average population density of 1.23×10^{-3} persons/m².

FIG. 4. Population density vs distance from a hypothetical transportation accident at the center of an urban area.

Rural Site

The demography of a rural transportation accident is assumed uniform over distance. Then, $\rho = \rho_r$ at all distances, where ρ_r is the 1973 contiguous U.S. average population density of 2.2×10^{-5} persons/m².

FEDERAL WASTE REPOSITORY DEMOGRAPHY

The population distribution around the Nevada Test Site (NTS) has been used in this study as typical of that around an FWR site.⁶ The city of Las Vegas dominates the population density within a few hundred km of NTS. Therefore, since the wind blows toward Las Vegas less than 5 percent of the time, its population has been omitted in order to obtain a "most likely" population dose. Hence, the population was averaged over 16 km bands, excluding the population of Las Vegas. From 100 to 300 km, the population density was allowed to increase exponentially to 2.2×10^{-5} persons/m². Beyond 300 km, ρ was assumed to be constant. With the NTS population data fitted to Gaussian curves by Eqs. (3) and (4), the equations for population density ρ in units of persons/m² are

1. Within 45 km,

$$\rho = 3.8 \times 10^{-7} \exp \left[-4 \times 10^{-3} (0.001x - 45)^2 \right], \quad (8)$$

2. From 45 to 100 km,

$$\rho = 1.8 \times 10^{-7} \exp \left[-4 \times 10^{-4} (0.001x - 45)^2 \right] + 2.0 \times 10^{-7}, \quad (9)$$

3. From 100 to 300 km,

$$\rho = 2.2 \times 10^{-5} \exp \left[-1 \times 10^{-4} (0.001x - 300)^2 \right] + 2.0 \times 10^{-7}, \quad (10)$$

4. Beyond 300 km,

$$\rho = 2.2 \times 10^{-5} \text{ persons/m}^2. \quad (11)$$

FIG. 5. Population density vs distance from a hypothetical accident at a federal nuclear waste repository.

Note that the population of the FWR has been assumed virtually zero. It is expected that only a few guards would be on duty during normal circumstances. Figure 5 shows a graph of these equations out to 100 km with ρ in persons/km².

AREA INTEGRALS

If we obtain the integral of $(\chi/Q) \cdot A \cdot \rho$ (where A is the area under consideration), we need then only multiply by the appropriate dose conversion factor to obtain the total population dose (in person-rem) out to 1000 km over the swath of the plume or puff. Since the three quantities χ/Q , A , and ρ are interrelated with respect to distance or, equivalently, time, one must integrate their product over either distance or time to obtain the population dose factor*. Let this integral be denoted as Σ .

For a plume, Eq. (1) incorporates sector-averaging over a 22.5° sector. The integral is,

$$\Sigma = \int_{x_i}^{x_f} \bar{\frac{\chi}{Q}} \rho \, dA, \quad (12)$$

where the bar over χ indicates sector averaging, and $dA = (\pi/8)xdx$. Substitution of the appropriate χ/Q expression from Table 1 and the population-density equation from the previous section yields an integral equation with distance downwind as the sole variable. Numerical integration at various distances as far out as 10⁶ m results in the plume values shown in Table 2.

For a puff release, we do not sector-average since the puff passes a given distance downwind only once and no meandering occurs at that distance. The integral is

* The product of the population dose factor, the dose conversion factor, and the source term strength yields the population dose for each radionuclide and its pathway.

TABLE 2. Integrated values of $(X/Q) \rho \, dA$ for plumes and $(X/Q) \rho t \, dA$ for puffs at various distances and accident locations (10^{-11} person-y/m³).^a

Location	Upper limit of integration (m)							
	$10^{2.5}$	10^3	$10^{3.5}$	10^4	$10^{4.5}$	10^5	$10^{5.5}$	10^6
FRP								
Plume Avg.	.060	.15	.27	.93	3.3	4.8	6.9	10.
Worst	.29	.59	.88	2.0	5.0	6.3	8.5	10. ^a
Puff Avg.	.081	.19	.36	1.3	4.4	6.4	9.2	13.
Worst	.39	.82	1.3	3.3	9.5	13.	16.	20.
Transportation								
Rural								
Plume Avg.	.27	.64	1.2	1.9	3.0	4.5	6.6	9.5
Worst	1.3	2.6	3.9	5.2	6.5	7.8	9.1	10.
Puff Avg.	.35	.85	1.6	2.6	4.0	6.0	8.8	13.
Worst	1.7	3.6	5.7	8.1	11.	14.	17.	21.
Urban								
Plume Avg.	15.	37.	68.	110.	150.	160.	165.	170.
Worst	74.	150.	220.	290.	340.	350.	355.	360.
Puff Avg.	20.	49.	89.	140.	200.	210.	215.	220.
Worst	97.	210.	330.	460.	560.	570.	575.	580.
FWR								
Plume Avg.	<.001	<.001	<.001	<.001	.0023	.025	.92	3.9
Worst	<.001	<.001	<.001	<.001	.0026	.034	.92	3.9
Puff Avg.	<.001	<.001	<.001	<.001	.0030	.022	1.0	1.3
Worst	<.001	<.001	<.001	<.001	.0055	.050	1.3	5.1

^aThe worst case tabular values are calculated using either the average or worst case expressions in Table 1, whichever results in the highest value.

$$\Sigma = \int_{x_1}^{x_f} \frac{\bar{\chi}}{Q} \rho t \, dA, \quad (13)$$

where t is the time of puff passage. For the puff, $\bar{\chi}$ is the average concentration over the area of the puff (assumed to have a radius of $2\sigma_h$). The average value theorem yields χ/Q as a function of the concentration at the center of the puff, χ_c/Q ; the latter quantity can be expressed as a function of χ from Table 1. Further, if we relate dA to the area of an equivalent square with sides of length $2\sqrt{\pi}\sigma_h$, the quantity t becomes $2\sqrt{\pi}\sigma_h/u$. The horizontal standard deviation, σ_h , is obtained using a scale dependent diffusion equation.⁷ Now we can express the population dose factor integral for a puff of unit strength as

$$\Sigma = 1.61 \times 10^{-4} \, \epsilon/u^4 \int_{x_1}^{x_f} \frac{\chi_c}{Q} x^3 \rho \, dx, \quad (14)$$

where ϵ is the atmospheric dissipation rate.

Numerical integration of Eq. 12 for various distances out to 1000 km gives the puff values shown in Table 2.

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