6 TRANSPORT OF RADIONUCLIDES THROUGH THE AIR TO AN EXPOSURE LOCATION

Radioactive materials in the form of gases and particulates may be released into the air and transported by the wind to an exposure location. The radionuclide concentrations in air and deposited on ground surfaces at this exposure location depend on atmospheric transport, diffusion, and deposition processes that affect the transport of radionuclides from the point of release to the exposure location (Figure 6-1).

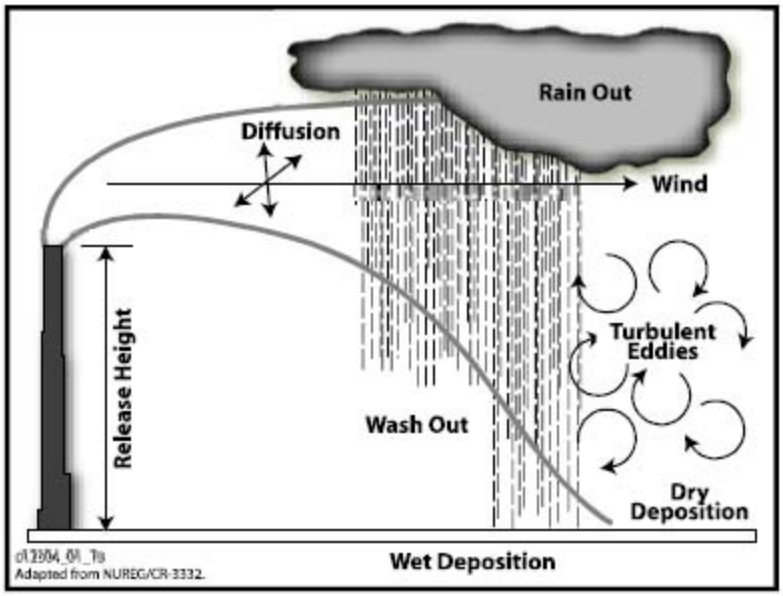

Figure 6-1 Atmospheric Dispersion and Removal Processes

Adapted from NUREG/CR-3332 (1)

6.1 Description of Atmospheric Processes

Some of the atmospheric processes and factors important for Phase III of the SRS Dose Reconstruction Project include dispersion, depletion, and release height.

Dispersion. As the contaminant plume is advected from the source (transported by the bulk motion of the wind), turbulent eddies diffuse the contaminant plume. These combined influences, sometimes called plume dispersion, cause the contaminants in the plume to disperse in the atmosphere as it travels away from the source (1). A concentration gradient exists in the contaminant plume, so that the contaminant concentrations in the center of the plume are larger than those toward the plume edges and the concentrations closer to the source are generally larger than those further downwind.

As the plume moves with the wind, diffusion continues in the upward vertical direction to the mixing height, generally ranging from about 200 to 2,000 meters above the surface of the earth (1). Within this atmospheric mixing layer,[1] turbulence is generated that mixes the contaminants. But the top of the mixing layer is marked by a decrease in turbulence. Above this "boundary," further vertical diffusion can be significantly reduced (1).

[1] Another name for the mixing layer is the planetary boundary layer (1).

There are two main causes of turbulence within the mixing layer: 1) mechanical turbulence, caused by ground surface effects, and 2) thermal turbulence, caused by buoyancy effects. Mechanical turbulence results from the frictional drag of the earth's surface. Turbulence increases in proportion to the wind speed and the roughness of the underlying surface.

Thermal turbulence depends on the stability of the atmosphere within the mixing layer. Atmospheric conditions within the mixing layer may be unstable, stable, or neutral depending on conditions that promote, retard, or have no effect on the vertical movement of air particles. Assuming that a parcel of air (and the particles within it) is set in motion so that it either rises or falls, further movement depends on the temperature of the parcel of air relative to that of the surrounding atmosphere into which it moves (1):

- *Unstable conditions.* If a parcel of air is incrementally displaced upward and is warmer in that location than the surrounding atmosphere, it is lighter and will continue to rise. If a parcel of air is incrementally displaced downward and is cooler in that location than the surrounding atmosphere, it is denser and will continue to sink. If the lapse rate (the change of temperature with height) of the surrounding atmosphere is less than the adiabatic lapse rate (dry adiabatic lapse rate is -9.8 ºC/1000 m), these unstable conditions will prevail and turbulence will be promoted.
- *Stable conditions.* If a parcel of air is incrementally displaced upward and is cooler in that location than the surrounding atmosphere, it is denser and sinks back toward its original location. If a parcel of air is incrementally displaced downward and is warmer in that location than the surrounding atmosphere, it is lighter and will rise back toward its original location. If the lapse rate of the surrounding atmosphere is greater than the adiabatic lapse rate, these stable conditions will prevail and turbulence will be suppressed.
- *Neutral conditions.* If a parcel of air is incrementally displaced, up or down, and at that location has the same temperature as the surrounding atmosphere, then the parcel of air will remain at its new location. If the lapse rate of the surrounding atmosphere is equal to the adiabatic lapse rate, these neutrally stable conditions will prevail and turbulence will be neither promoted nor suppressed.

Different atmospheric stability conditions can strongly affect the dispersion of contaminants. For example, under stable conditions and when winds are strong and in a constant direction, a plume from a stack can retain a narrow shape in the vertical direction for a long distance downwind. On the other hand, unstable conditions can result in a looping plume, and the contaminant released from a stack can contact the ground relatively close to the release point (2).

Depletion. Removal mechanisms that reduce contaminant concentrations within the plume include wet and dry deposition, radioactive decay, and chemical change.

Wet deposition processes include rainout and washout. Rainout is a process that occurs within clouds. Contaminants interact with precipitation formation processes and are removed from the clouds by rain. Washout occurs below the cloud layer. Falling rain contacts the contaminants, carrying it to earth. Dry deposition processes include removal of contaminants due to gravitational settling, or from contact with the ground, vegetation, or buildings.

Radioactive isotopes decay during transport to a downwind receptor. The significance of this removal process depends on the radionuclide half-life and the transport time.

The chemical forms of the radioactive isotopes affect their deposition rates and therefore their depletion from the plume. Factors to be considered include whether a radioactive isotope is being transported as a gas or a particle, and if the latter, its diameter and density.

Release Height. Almost all of the radionuclide activity that was released into the air from SRS was released from stacks rather than from ground level. Concentrations are essentially zero near the base of the stack, but rise quickly to a peak value at some distance downwind, and then decrease regularly thereafter. Concentrations are larger along the centerline of the plume than on the ground on either side (3). The higher the contaminant release point, the farther the contaminant usually travels before significant concentrations of contaminant reach ground level.

6.2 Gaussian Plume Model

One of the most widely used models for numerically describing the movement and dispersion of contaminant from a release point is the Gaussian plume model (1). Figure 6-2 shows a simplified depiction of a Gaussian plume model, depicting contaminants released from a stack. The model accounts for the downward movement as well as the vertical and horizontal dispersion of the released contaminants, and predicts contaminant concentrations on the ground and in the air. The figure depicts Gaussian (normal) distributions in the vertical and crosswind directions. Near the point of release, the concentration is high near the centerline and falls off rapidly toward the edges. But further downstream, the distribution of concentration spreads from the centerline (4).

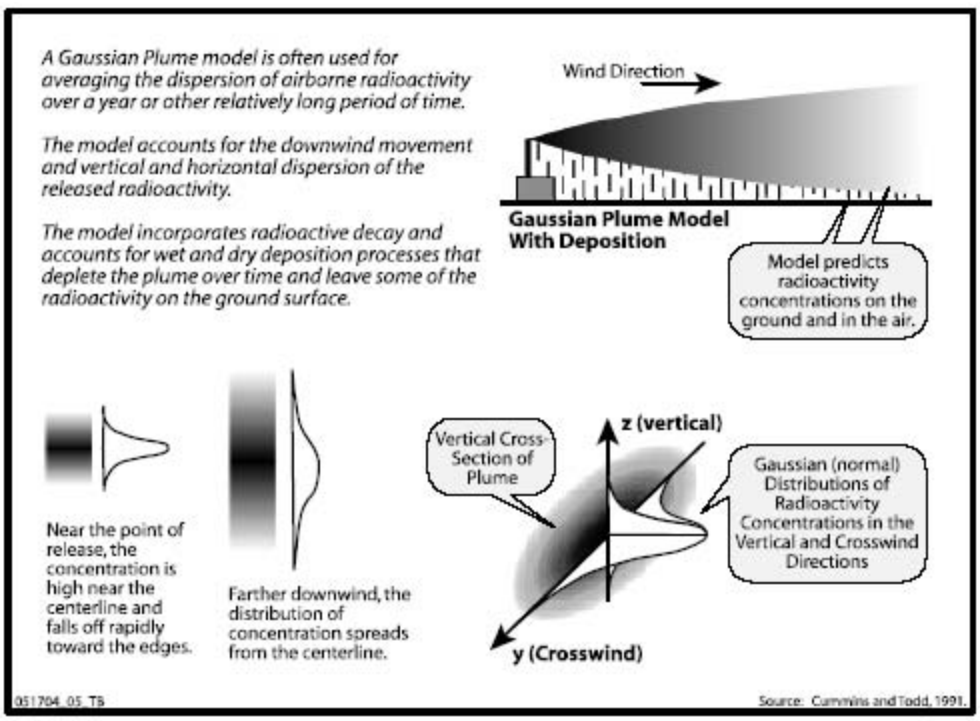

Figure 6-2 Illustration of Straight-Line Gaussian Plume Model (4)

The shapes of the concentration distributions are described in the Gaussian plume model by parameters known as diffusion coefficients.[2] Assuming that diffusion along the direction of the wind is small compared to transport by wind, the Gaussian plume model incorporates two diffusion coefficients, σ_y and

[2] Some references refer to σ_y and σ_z as diffusion coefficients; others as dispersion coefficients.

σ_z, that are the standard deviations of the Gaussian distributions in the crosswind (horizontal) (σ_y) and vertical (σ_z) directions.[3]

Many systems have been used to estimate diffusion coefficients. Most of the systems have been based on atmospheric stability classes and the distance from the source. These atmospheric classes are linked to the three atmospheric stability conditions (neutral, stable, and unstable) described in Section 6.1. A commonly used system is the Pasquill-Gifford system (1). It uses a set of equations that approximate a corresponding set of empirically determined curves. The curves provide σ_y and σ_z values as a function of the distance from a source for six stability classes.[4] This system was used for the Phase III study because it is well established and compatible with the data that was obtained for the SRS.

6.3 Sector Average Modification to Gaussian Plume Model

Wind normally does not blow from the same direction for prolonged periods. For chronic or long-duration releases, the basic Gaussian plume model is modified using a sector-average approximation:

- An imaginary circle is drawn around the contaminant release point, and the circle is divided into a series of pie-shaped wedges, called sectors.
- The quantity of contaminant discharged into each sector is determined by considering the frequency that the wind blows in the direction of the sector.
- In each sector, the average contaminant concentrations are determined as a function of distance from the release point by considering the wind speed and stability class, weighted by the frequency that these conditions occur in each sector.

For this analysis (and many others) the circumference around the release point has been divided into sixteen sectors corresponding to the sixteen major compass directions: N, NNE, NE, ENE, E, and so forth. Each sector is a pie-shaped wedge, consisting of two radii and a terminating arc with a 22.5^o angle (360° /16 sectors) between the radii. Radionuclide concentrations and deposition rates were calculated in each sector. At a given distance from the release point, the model considers the concentration to be constant across the sector. The actual concentration, in fact, would not be discontinuous, as this suggests, but because the model considers only sixteen directions, the numerical result is coarser. If smaller and smaller sectors were chosen for the analysis (i.e., one degree), then the magnitude of any discontinuities would become extremely small.

Appendix A has a more detailed description of the sector average modification and how it was employed in this study. The sector average approximation uses data averaged over a long time period (20 years for this study). Consequently, the simultaneous occurrence of unusual meteorological conditions and an acute release (potentially leading to a high dose in an unexpected location) cannot be modeled effectively. Chapter 13 contains a recommendation to attempt to estimate the importance of such occurrences.

6.4 Use of Joint Frequency Distribution Data

6.4.1 Definition

The joint frequency distribution (JFD) is a set of data for a specific location that represents a summary of meteorological conditions over a specified period of time such as a year. The joint frequency distribution

[3] By convention, the coordinate system used in Gaussian plume models defines the x-axis as the direction downwind of the source, the y-axis as the cross wind direction (lateral to the source), and the z-axis as the vertical direction.
[4] The six stability classes are: (A) extremely unstable, (B) moderately unstable, (C) slightly unstable, (D) neutral, (E) slightly stable, and (F) moderately stable (2).

is computed by compiling meteorological data, usually determined and recorded for each hour, over an appropriate time interval and computing the frequency of occurrence of each joint frequency category. Each joint frequency category represents a band (range) of wind speeds, directions, and stability conditions.

6.4.2 Data Available from SRS

To estimate airborne radionuclide transport from release points to exposure locations, a set of meteorological data were needed that reflected the conditions that existed between 1954 and 1992. The data were needed to establish the joint frequency distributions for input to the computer model.

The preference was to use SRS-specific meteorological data that spanned all 39 years of nuclear material production. Unfortunately, the onsite SRS meteorological program was established in the early 1970's, leaving a data gap of about 20 years. To approximate meteorological data for all 39 years, consideration was given to using data from the National Weather Stations (NWSs) located near Columbia, South Carolina, and near Augusta, Georgia. Even though these two NWSs were only about 90 km apart and reasonably close to SRS,[5] there were differences in topography and weather patterns, as well as limitations in the available meteorological data (5). A comparison of wind roses for the years 1992 -1996 between these NWSs and the SRS meteorological station showed clear differences in wind patterns (5). The data from these NWSs was considered not sufficiently representative of SRS meteorological conditions to warrant using these data for Phase III.

Therefore, the limited available data from the SRS meteorological station was used to represent all 39 years of nuclear material production. Because joint frequency distribution data from the SRS meteorological station was available for Phase III as five-year averages, four five-year JFD averages were combined to arrive at a twenty-year average. The combined JFD is presented in tabular form in Appendix U. This assumption appeared to be reasonable in light of the general practice used by the SRS for estimating environmental consequences. For example, the SRS Environmental Report for 1991 states that SRS used the meteorological measurements made over a five-year period (1982-1986) and that other time periods "show very little change in dispersion conditions" (6). Additional meteorological data, such as precipitation type and amount for various stability classes, is also shown in Appendix U.

6.5 Source and Exposure Locations

Figure 6-3 shows the locations of the four virtual sources considered for Phase III for release of radionuclides into the air. Also shown are the ten exposure locations where members of the hypothetical exposure scenarios were exposed to radionuclides that had been transported from the four virtual sources.

Exposure locations and the exposure scenarios are listed in Table 6-1. Members of some exposure scenarios (e.g., Migrant Worker Family) were exposed to radionuclides in air and deposited on the ground at only one exposure location, while members of other exposure scenarios (e.g., Delivery Person Family) were exposed to radionuclides in air and deposited on the ground at more than one exposure location.

[5] The Augusta NWS station is about 30 km west-northwest of the SRS meteorological station, while the Columbia NWS station is about 80 km northeast of the SRS meteorological station (5).

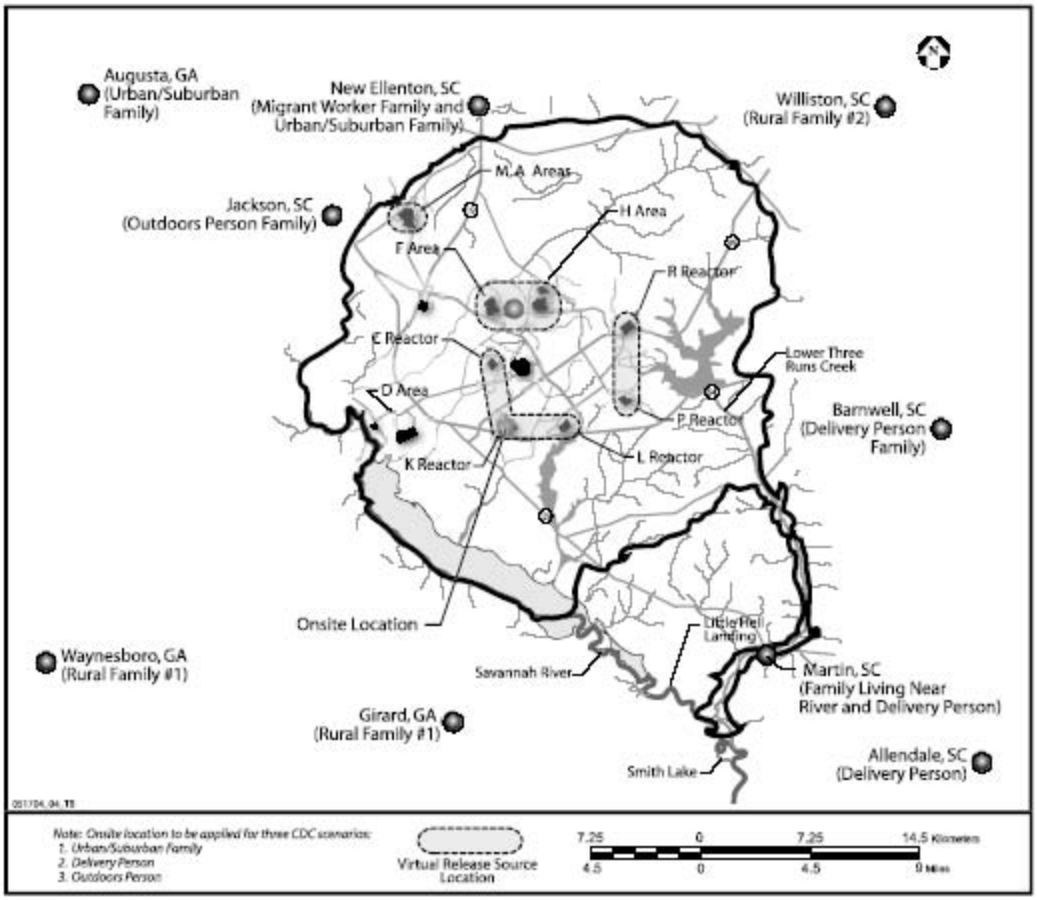

Figure 6-3 Virtual sources and Air Pathways Exposure Locations

Table 6-1 Exposure Locations and Exposure Scenarios

This Exposure Location	Is Considered for These Exposure Scenarios
1. Girard, GA	Rural Family One
2. Waynesboro, GA	Rural Family One
3. Augusta, GA	Urban/Suburban Family
4. Jackson, SC	Outdoors Person Family
5. New Ellenton, SC	Urban/Suburban Family, Migrant Worker Family
6. Barnwell, SC	Delivery Person Family
7. Martin, SC	Delivery Person Family, Near River Family
8. Allendale, SC	Delivery Person Family
9. Williston, SC	Rural Family Two
10. SRS near K-Reactor	Urban/Suburban Family, Delivery Person Family, Outdoors Person Family

The distances from each virtual source to each of the ten exposure locations are presented in Table 6-2 in order of increasing distances from each source.

Table 6-2 Distances (m) from Virtual Sources to Exposure Locations

A-Area, M-Area, SRL		F- and H-Area*		C-, K-, & L-Reactors, D-Area, CMX-TNX*		P- & R-Reactors*	
Distance	Exposure Location	Distance	Exposure Location	Distance	Exposure Location	Distance	Exposure Location
4,824	Jackson	8,666	On site	1,889	On site	8,881	On site
9,266	New Ellenton	12,392	Jackson	16,582	Jackson	20,648	Barnwell
16,226	On site	14,205	New Ellenton	21,092	New Ellenton	20,666	New Ellenton
24,196	Augusta	25,657	Williston	23,149	Girard	20,961	Jackson
30,065	Williston	28,585	Barnwell	23,629	Martin	21,880	Martin
36,789	Barnwell	29,293	Martin	27,743	Barnwell	22,354	Williston
37,477	Girard	30,033	Girard	29,256	Williston	25,800	Girard
38,309	Martin	33,397	Augusta	36,775	Waynesboro	36,775	Allendale
38,710	Waynesboro	39,858	Waynesboro	38,318	Augusta	41,940	Augusta
54,256	Allendale	45,038	Allendale	40,178	Allendale	44,286	Waynesboro

*Includes tritium evaporation from seepage basins.

6.6 Additional Parameters Used for Transport Analysis

In addition to basic meteorological data, values for several additional model parameters were specified. All four virtual sources are modeled as point sources having elevated release heights as listed in Table 6-3.

Table 6-3 Heights of Virtual Sources

Virtual Source Group	Height (m)	Actual Sources Represented
1	10	A-Area, M-Area, SRL
2	61	F-Canyon, H-Canyon, H-Area Tritium Stack (includes stacks and basin evaporation)
3	61	C-, K- and L-Reactors (includes stacks and basin evaporation), D-Area, CMX-TNX.
4	61	P- and R-Reactors (includes stacks and basin evaporation)

Values for other parameters used for the air transport assessment are provided in Appendix F. Plume rise due to momentum and buoyancy effects was conservatively assumed to be zero.

6.7 References

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