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by

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ABSTRACT

Based on 22 years of tornado statistics for South Carolina and Georgia, the probability of a tornado of Class F3 or greater striking a point at the Savannah River Plant is calculated to be approximately 14×10^{-5} per year. These statistics show that Class F3 tornados (0.56-psi pressure drop and winds of 158 to 206 mph), are the most frequently occurring but causes only 23% of the damage compared with all classes of tornadoes. F4 tornadoes (1.10-psi pressure drop and winds of 207 to 260 mph) constitute only 20% of the total, but cause 63% of the damage.

A Gaussian diffusion model is used to calculate the ground level concentration (ratio of concentration to source mass χ/Q) as a function of distance downwind should a tornado strike a point within the Savannah River Plant (SRP). The particles released to the atmosphere are assumed to be 1- 3-μm diameter. For the calculations, two cases of possible small particle pickup are considered. In Case I a unit source of small particles is assumed to be injected into the tornado core and transported into the thunderstorm. In Case II, the cluster of particles is assumed to exit the side of the tornado core below the thunderstorm cloud. Several different stabilization heights within the thunderstorm, different horizontal wind speeds, and different turbulence dissipation rates are assumed for the calculations.

CONTENTS

DISPERSION OF SMALL PARTICLES IN A TORNADO

INTRODUCTION

Tornadoes are violently rotating winds normally attributed to localized storms during the spring and summer months. Although they occur predominately in the North American continent, tornadoes have been known to strike nearly every country in the world. The effects of tornadic winds are apparent from visual observations and photographs of the ground damage after tornado disasters. Although tornadoes have been studied and their motions analyzed for a number of years, little progress has been made in an effort to completely understand and estimate tornadic air motions. Of particular interest is the possible behavior of radioactive particulates during a tornado strike, i.e., material pulled into the tornado vortex and dispersed into the atmosphere following a strike at a nuclear facility.

Lack of a definite model of tornados and accompanying weather conditions prevents an exact prediction of radioactive dispersion. However, the general nature of tornado-borne materials can be estimated based on available knowledge. The general dispersal of radioactive debris can be described, but at most only crude approximations or untested hypotheses are available because of the violent, random nature of tornado activity. Consequently dispersal of radioactive particulates in the thunderstorm accompanying a tornado can only be estimated from empirical information and observation.

The purpose of this report is:

- To discuss the general nature of tornado behavior and suggest a design basis tornado model for the southeast region
- To review the probability of a tornado strike at the Savannah River Plant
- To analyze the trajectories of a cluster of small particles and deposition patterns for these ground level concentrations after a tornado strike, assuming various heights at which this cluster begins to undergo diffusion.

TORNADO DYNAMICS

Although the births of tornadoes have been observed during local severe storms, the exact mechanism of tornado formation is still unknown. The tornado and associated cloud system are an extremely complex and variable phenomenon.

Figure 1 shows a tornado as it develops from the base of a cumulonimbus cloud.[1] Funnels always appear to spiral down from a rotating bell-shaped mother cloud, but do not always touch the ground. When the funnel does touch the ground, the funnel becomes a tornado. Conditions favorable for tornadoes normally occur when cold recirculating air comes into contact with a warm humid surface layer. A strong unstable atmosphere is created which produces large buoyancy effects that cause upward motions. Further interaction coupled with large wind shears and updrafts lead to tornadic development.

From the standpoint of fluid dynamics, certain fundamental features are common to all tornadoes:[2]

- A tornado is a large vortex column with a low pressure core. Circulation of the vortex core is maintained by the rotating mother cloud.

- Air spirals inwardly at the foot of the vortex core because the warm humid air is of lower density near the ground. The strong turbulent updraft may extend several kilometers into the tropopause. Figure 2 shows the spiraling path of air as it moves upward to the mother cloud. Property damage normally occurs inside the ground layer (usually 30-m thick) near the vortex.

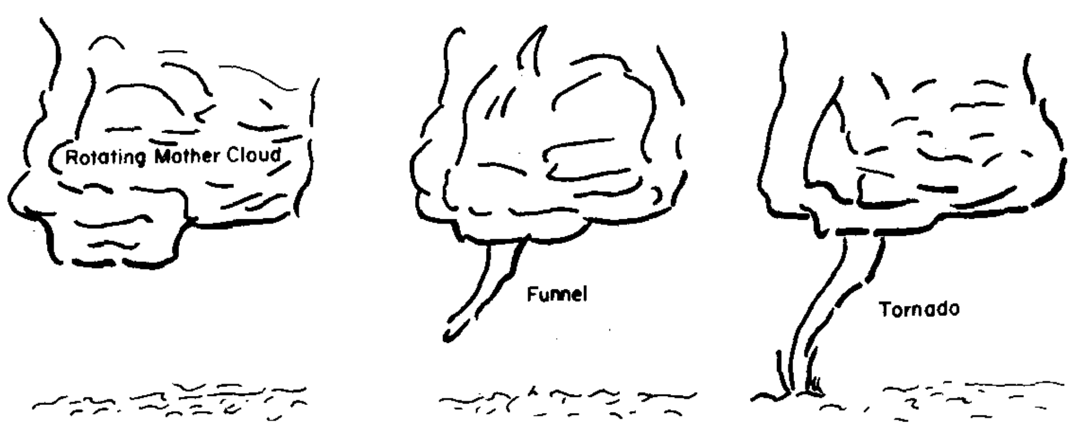

FIGURE 1. Development of a Tornado

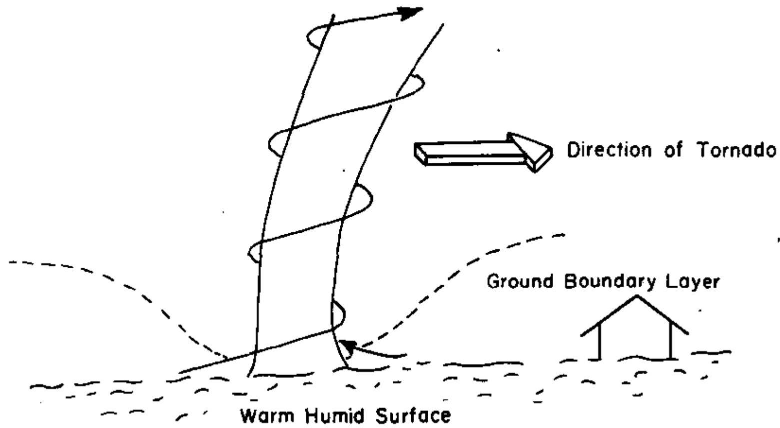

FIGURE 2. Spiraling of Air Toward the Vortex

- Friction arrests the rotary motion of the tornado at the ground. This frictional retardation of the tangential motion causes the radial pressure gradient to push the air toward the center of the vortex, creating large radial velocities near the surface and large vertical velocities just inside the core. This strong inward flow near the surface causes a slight downward flow outside the vortex. Velocity profiles as well as particulate trajectories are shown in Figure 3.

- In the turbulent ground boundary layer surrounding the vortex, pressure is nearly constant vertically except near the vortex core where the pressure decreases with a decrease in radial distance from the core.

- The tangential wind velocity, V_θ, increases with radial distance, R, from the core of the tornado with V_θ/R = constant when the flow is rotational. The flow is rotational out to a critical radius where the tangential wind velocity reaches a maximum. Beyond the critical radius, the flow is irrotational such that $V_\theta R$ = constant, and the tangential velocity subsequently decreases with increasing radial distance.

- The prevailing wind, usually mid-tropospheric, steers the rotating mother cloud, which in turn pulls the vortex column and causes it to tilt forward.

Various tornado characteristics are given in Table 1.

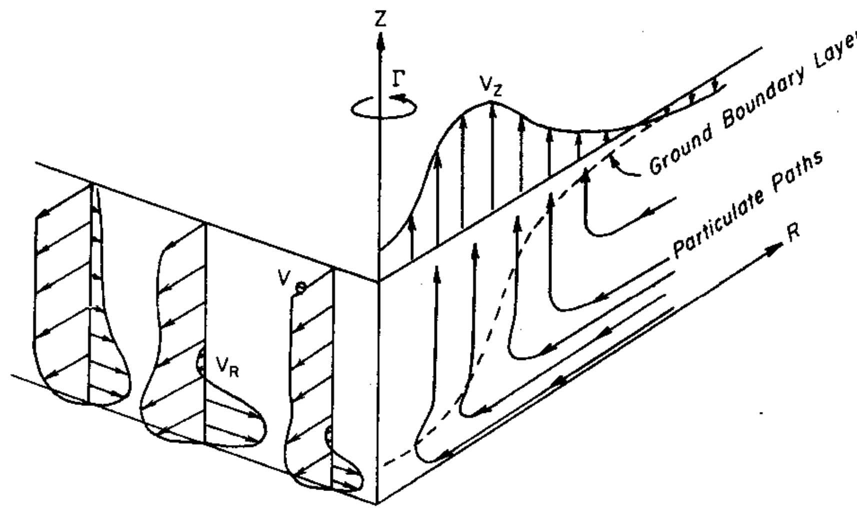

FIGURE 3. Velocity Distribution and Particulate Trajectories Near the Surface of the Ground Boundary Region (From Data in Reference 1)

TABLE 1[a]

Tornado Characteristics

Characteristics	*Reported Range*	*Weighted Average*
V_θ (km/hr)	160-800	480
V_Z (km/hr)[b]	32-320	160
V_{TRANS} (km/hr)[c]	0-120	48
ΔP at core (atm)	.02-.3+	.075
Damage width (m)	15-1500	180
Lifetime	min-hr	20 min
Damage Range (km)	0-100+	16
Visual Height below Cloud Base (m)	150-3000	900
No. of Concurrent Tornadoes	1-6	1
Circulation (m^2/sec)	(.1-10) x 10^4	3 x 10^4
Sense of Rotation	Usually cyclonic	Cyclonic
Tilting Angle with Ground (°)	5-40	15

a. Tornado Characteristics Obtained from Reference 1.
b. Vertical speed.
c. Translational Speed.

PROBABILITY OF A TORNADO STRIKE AT SRP

Based on the work of Thom[3] and Cooper,* the probability of a tornado striking the Savannah River Plant is calculated from

$$P_p = 1 - \left(1 - \frac{a}{S}\right)^{\bar{m}t} \qquad (1)$$

where a is the damage area, S is the area over which the tornado statistics are analyzed, $\bar{m}$ is the average number of tornadoes expected in region S per year, and t is the time in years. Based on statistics given by Cooper,* a tornado of the F3 class on the Fujita scale[4] (Figure 4) has the greatest probability of striking the Savannah River Plant (SRP). For the SRP area a = 300 square miles, S = 89,931 square miles, (Georgia and South Carolina) m = 9.64, and t = 1 year, and the probability of a tornado of the F3 category striking SRP is given as

$$P_p = 1 - \left(1 - \frac{300}{89,931}\right)^{9.64}$$

$$P_p = 0.0317$$

This value is obtained from statistics compiled over a 22-year period for tornadoes occurring in Georgia and South Carolina. It corresponds to a tornado of at least the F3 class striking some location in the SRP area every 32 years ($1/P_p$ = recurrence). Cumulative probability of all classes of tornadoes striking SRP is 0.079 per year, or once every 12.7 years.

Computed probabilities depend on size of damage area chosen for the computation as well as frequency of observations. Using statistics assembled by Cooper* the greatest threat from a tornado striking a particular point at SRP is from the F4 class. The probability is calculated as:

$$P_p = 1 - (1 - \frac{2.12}{89931})^{4.18}$$

$$P_p = 9.86 \times 10^{-5}$$

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*R. E. Cooper, Savannah River Laboratory, personal communication (1973).

where a = 2.12 square miles, the damage area of recorded F4 tornadoes in the two-state region. The point probabilities for all classes of tornadoes hitting a building are shown in Figure 4 for the SRP region. Combination of appropriate probabilities cited in Figure 4 yields a probability of 14×10^{-5} for a tornado of Class F3 or greater, striking a point at SRP. Although the frequency of tornadoes of the F3 class are greater than those of the F4 class, the damage area is approximately 7 times greater for the F4 class than the F3 class. No tornadoes of the F5 or F6 category have been observed during this 22-year period in Georgia and South Carolina. The determination of a Design Basis Tornado (DBT) for the Southeast by the Energy Research and Development Administration is based on Regulatory Guide 1.76, which states that a nuclear facility should be able to withstand tornadic loadings associated with tangential wind speeds of 290 mph and translational velocities of 70 mph. These velocities correspond to a tornado of the F6 category.

Figure 5 shows damage scenes associated with tornadoes ranging from the F1 to the F5 class. F0 damage is not included since the damage is very slight. These pictures were taken by Fujita[4] after a tornado strike on May 11, 1970, in a suburban residential area of Lubbock, Texas.

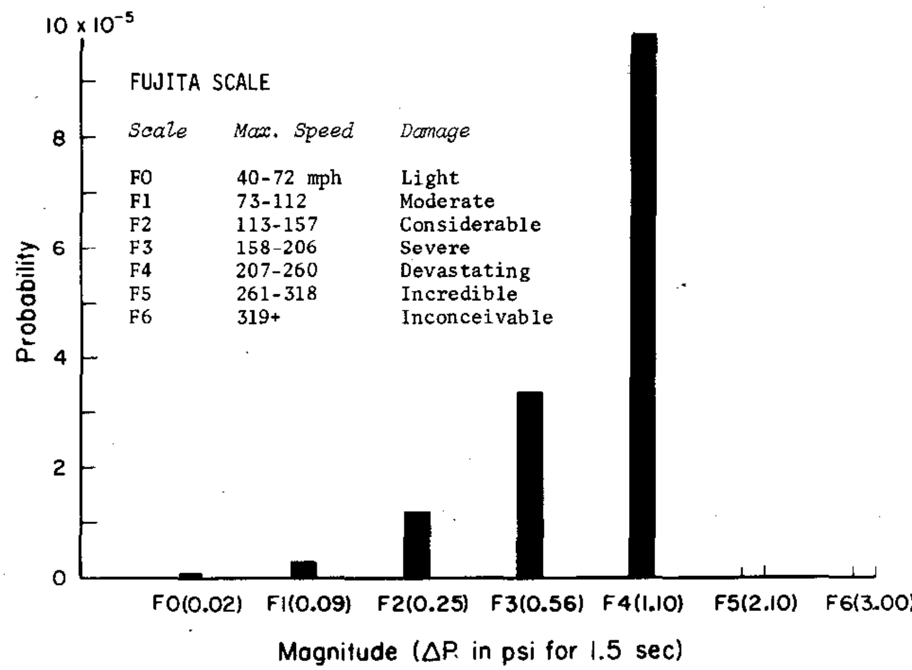
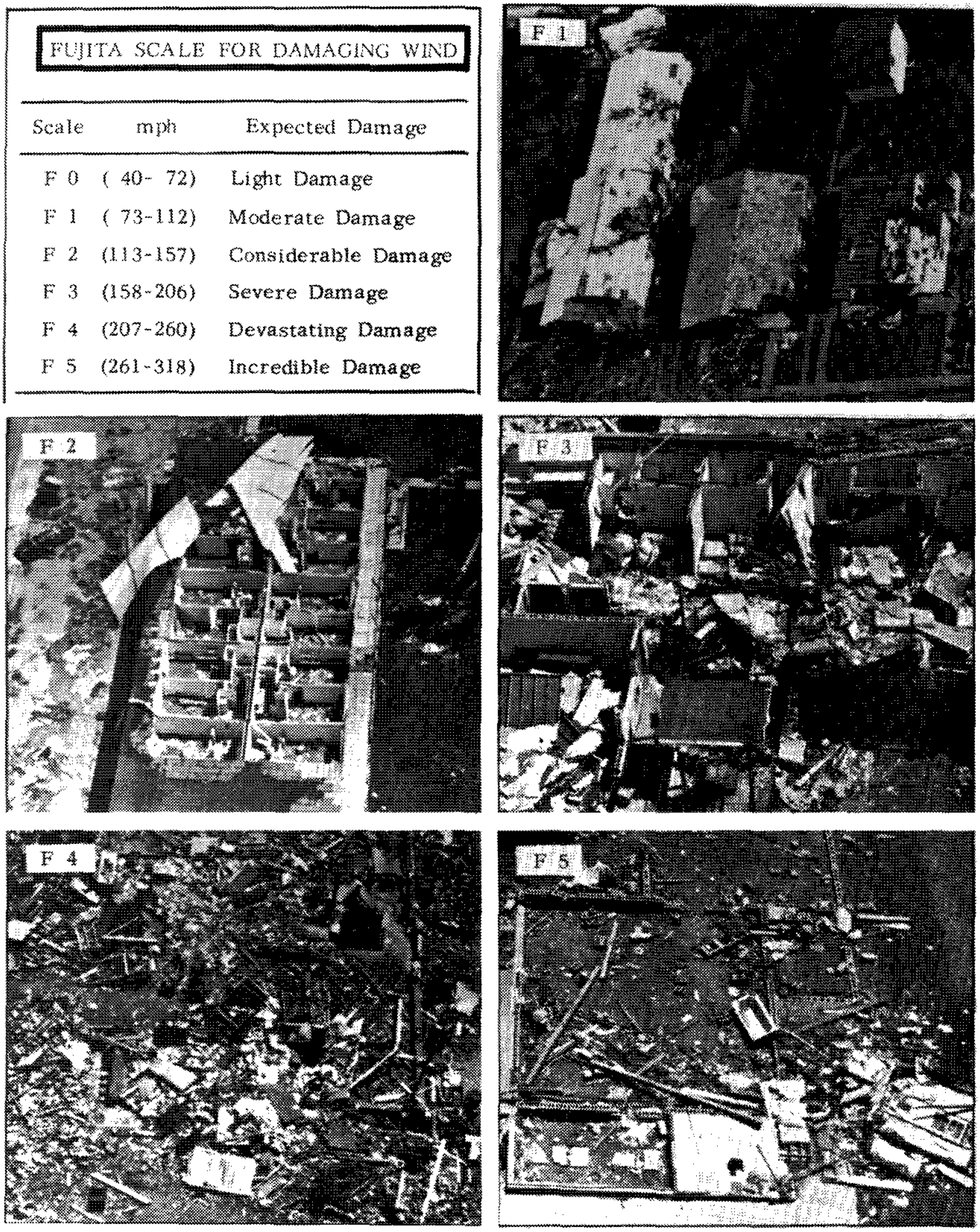


FIGURE 4. Probabilities and Associated Pressure Drops for All Classes of Tornadoes Striking a Point Within SRP. Based on Statistics for Georgia and South Carolina During 1950-1972.



FUJITA SCALE FOR DAMAGING WIND

Scale	mph	Expected Damage
F 0	(40- 72)	Light Damage
F 1	(73-112)	Moderate Damage
F 2	(113-157)	Considerable Damage
F 3	(158-206)	Severe Damage
F 4	(207-260)	Devastating Damage
F 5	(261-318)	Incredible Damage

FIGURE 5. F-Scale Damage Chart for New Suburban Structures (from Ref 4)

DEBRIS AND POLLUTANT DISPERSAL

Structural damage of a building normally occurs from explosive failure due to the rapid decrease in pressure and from airborne missiles. Atmospheric pressure in the building cannot decrease fast enough to equalize with the drop in pressure created by the vortex; this causes windows and doors to be breached as well as walls to collapse and roofs to be raised in conventional buildings (Figure 5). Pressure changes based on the cyclostrophic equation* for tornadoes of all categories undergoing a 1.5 second[5] pressure drop from atmospheric conditions are shown in Figure 4. Duration of the damaging winds from tornadoes have been known to range from 1 to 22 seconds,[4] based on the strength of the tornado.

Loose material is not subject to extreme lateral mixing in the core of a tornado until it reaches the mother cloud (thunderstorm cell). Once inside the mother cloud, the material disperses very rapidly due to the high degree of turbulence as well as the convective nature of the thunderstorm cloud. Material outside the core is assumed to move in a distorted spiral, moving upward and inward toward the vortex center. Injection of the material into the tropopause is possible after it enters the storm cell. Small particulates may be lifted to a specific height following the tornado vortex, then dispersed as if originating from that height as a cloud (puff) of pollutant. Pollutants may also be dispersed about the base of the vortex, and objects may roll and tumble on the ground.

There is an 80% chance of rain and hail accompanying a tornado. This rainfall usually occurs to the north and east of the tornado path,[6] with the tornado normally appearing in the right rear quadrant of the thunderstorm cell.

Should a tornado cause severe damage to a building at a nuclear facility, the resulting release of material of immediate consequence to people is likely to be of the order of 1-3 μm or less in diameter; large particles (>10 μm) are not inhaled into the lungs. Particles of the 1-3 μm or less are not easily scavenged by falling raindrops but are more effectively scavenged by acting as condensation nuclei.**

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*$\partial P/\partial R = \rho V^2/R$, where R is the radial distance from the axis of the tornado, V is the tangential plus translational wind speed, P is the pressure, and ρ is the density of air.

**T. V. Crawford, Savannah River Laboratory, personal communication (1974).

Scavenging of condensation nuclei is an efficient process, but the nuclei must participate in the cloud formation process. For the tornado situation discussed here, scavenging is most likely to take place in a new thunderstorm cell formed after the tornado strikes a building. Because thunderstorm cell lifetimes are about 30 minutes at the minimum, debris wouldn't be deposited by rain until 30 minutes or later after injection of the powder into the cloud. This would result in deposition some distance downwind but most likely to the north and east.

Should such deposition take place, exposure paths to man would be through inhalation as a result of resuspension and ingestion with food. Injestion would not occur on the date of deposition, permitting time for monitoring of soil and rainwater to be followed, as required, by cleanup measures.*

SIMULATION OF PARTICULATE DISPERSAL

The following assumptions were made with regard to a tornado strike at SRP:

- The tornado is at least of the F3 category.
- Direction of the tornado is toward the northeast; direction of pollutant dispersal is to the north and east of the strike path.
- A facility containing small particles is assumed to be breached, and the particles are assumed to escape into the atmosphere.
- The cluster of small particles is initially lifted as a small puff and dispersed in either of two ways:

  Case I. The cluster of small particles diffuses in the mother cloud for the lifetime of the thunderstorm cell; subsequent diffusion occurs outside the thunderstorm cell.

  Case II. The cluster of small particles is lifted following passage of the tornado vortex at specific heights above the ground outside the tornado core, then is assumed to diffuse into the atmosphere.

* T. V. Crawford, Savannah River Laboratory, Personal communication (1974).

- The particle dispersal locations are shown in Figure 6 where I and II correspond to Cases I and II above.

- Rolling and tumbling of debris are negligible.

- Washout scavenging by rainfall associated with the mother cloud is negligible.

To effectively simulate the distribution of particles in a tornadic thunderstorm, the rate of energy dissipation per unit mass, ε, is set equal to 1 m^2/sec^3 in accordance with estimates obtained from Slade[7] and MacCready[8] for cyclonic storms. Standard deviations are calculated from the general expression[9]

$$\sigma_i^2\ (t) = \left[\sigma_{o_i}^{2/3} + \frac{2}{3} C \varepsilon^{1/3} t \right]^3 \tag{2}$$

where σ_{o_i} is the original standard deviation of the source in

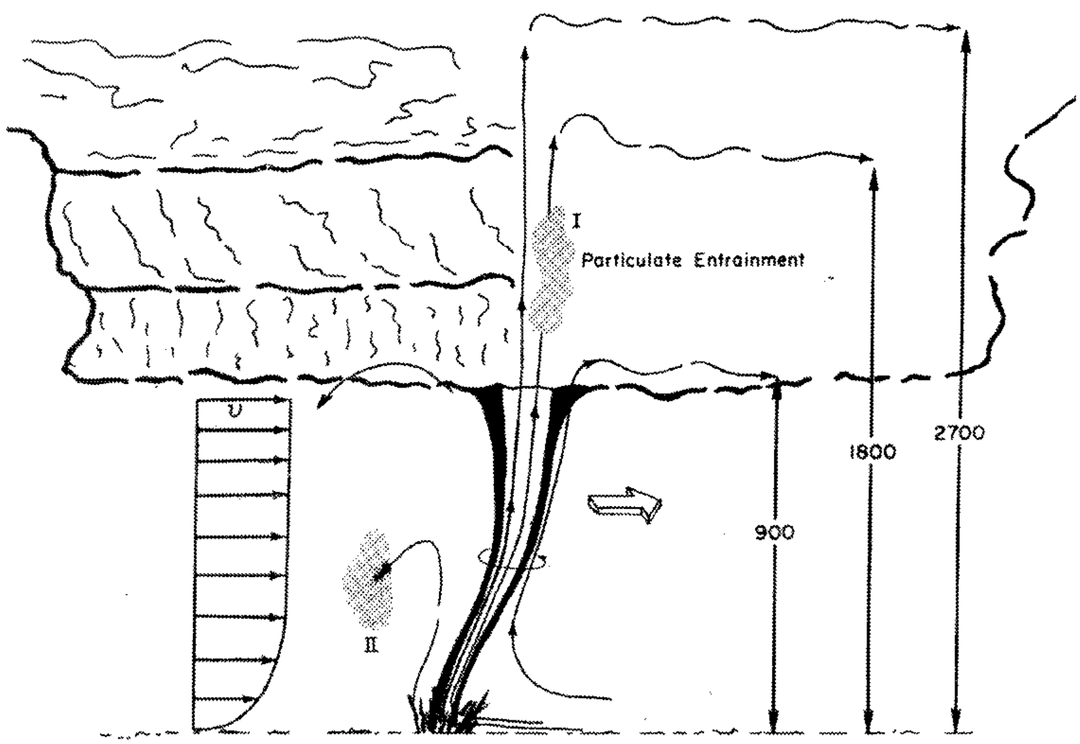

FIGURE 6. Radioactive Particulate Dispersal in a Tornado

direction i, C is a constant normally equal to 1, and t is time. With i = 1 as the horizontal direction (x), i = 2 as the lateral direction (y), and i = 3 as the vertical direction (z), initial values for the original standard deviations are set equal to

$$\sigma_{o_x} = 10 \text{ m}$$
$$\sigma_{o_y} = 10 \text{ m} \qquad (3)$$
$$\sigma_{o_z} = 20 \text{ m}$$

Instantaneous particulate concentrations, χ, are calculated from the Gaussian diffusion model given by Slade[7] as

$$\chi(x,y,z,H) = \frac{2Q}{(2\pi)^{3/2}\sigma_x(t)\sigma_y(t)\sigma_x(t)}$$

$$\exp\left[-\left(\frac{(x-Ut)^2}{2\sigma_x(t)^2} + \frac{y^2}{2\sigma_y(t)^2} + \frac{(z-H)^2}{2\sigma_z(t)^2}\right)\right] \qquad (4)$$

where Equation 4 has been multiplied by 2 to account for ground reflection, U is the mean horizontal velocity in m/sec, H is the height of the initial center of the concentration in m, Q is the source strength in g, and $\sigma_x(t)$, $\sigma_y(t)$, and $\sigma_z(t)$ are calculated from Equation 2. Sedimentation of radioactive powder is considered to be negligible due to the size of the particles. Ground level concentrations for distribution at the center of the pollutant cloud are calculated from Equation 4 by letting x = Ut, y = 0, and z = 0 such that

$$\chi(x,o,o,H) = \frac{Q}{2^{1/2}\pi^{3/2}\sigma_x(t)\sigma_y(t)\sigma_z(t)} \exp\left[\frac{-H^2}{2\sigma_z(t)^2}\right] \qquad (5)$$

Lateral ground level concentrations are calculated from

$$\chi(x,y,o,H) = \frac{Q}{2^{1/2}\pi^{3/2}\sigma_x(t)\sigma_y(t)\sigma_z(t)} \exp\left[-\left(\frac{Y^2}{2\sigma_y(t)^2} + \frac{H^2}{2\sigma_z(t)^2}\right)\right] \qquad (6)$$

In order to keep the diffusion from proceeding at an unrealistic rate, i.e., expanding rapidly to sizes larger than the thunderstorm cell, values for the standard deviations, $\sigma_i(t)$, are calculated from the expression[9]

$$\sigma_i(t) = \frac{\sigma_{i_{max}} \; \sigma_i(t)}{\sigma i_{max} + \sigma_i(t)} \qquad (7)$$

using previous values for $\sigma_i(t)$ obtained from Equation 2. Values for $\sigma_{i_{max}}$ are given as

$$\sigma_{y_{max}} = 2000 \text{ m}$$
$$\sigma_{z_{max}} = 2000 \text{ m} \qquad (8)$$

for diffusion occurring within the thunderstorm cell and

$$\sigma_{y_{max}} = 2 \times 10^6 \text{ m}$$
$$\sigma_{z_{max}} = 5000 \text{ m} \qquad (9)$$

for diffusion occurring outside the thunderstorm cell.

Centerline ground concentrations are plotted in Figures 7, 8, and 9 for three Case I simulations as a function of horizontal distance, x. Concentrations are expressed as m^{-3} (χ/Q ratio which is equivalent to assuming unit releases for Q). Wind speed was assumed to vary from 7.5 to 22.5 m/sec; these values are compatible with translational velocities associated with thunderstorms. The pollutant is pulled up to heights of 900, 1800, and 2700 m above the ground. Many combinations of these heights and wind speeds in the 7.5 to 22.5 m/sec. range were simulated. Although the particles would most likely be transported to the upper regions of the cloud, i.e., the tropopause, the cluster of particles is assumed to reach a height no greater than 2700 m. On reaching a prescribed height, χ/Q is calculated according to Equation 5, with $\varepsilon = 1 \; m^2/sec^3$ during the first 30 min within the thunderstorm cell and, $\varepsilon = 0.0005 \; m^2/sec^3$ after 30 min.

Concentrations are plotted in Figures 10 and 11 for two Case II simulations with $\varepsilon = 0.0005 \; m^2/sec^3$ as a constant throughout the calculations. The powder is assumed to be initially lifted by the tornado vortex but then dispersed at heights of 75, 400, and 800 m with wind speed varying from 7.5 to 22.5 m/sec.

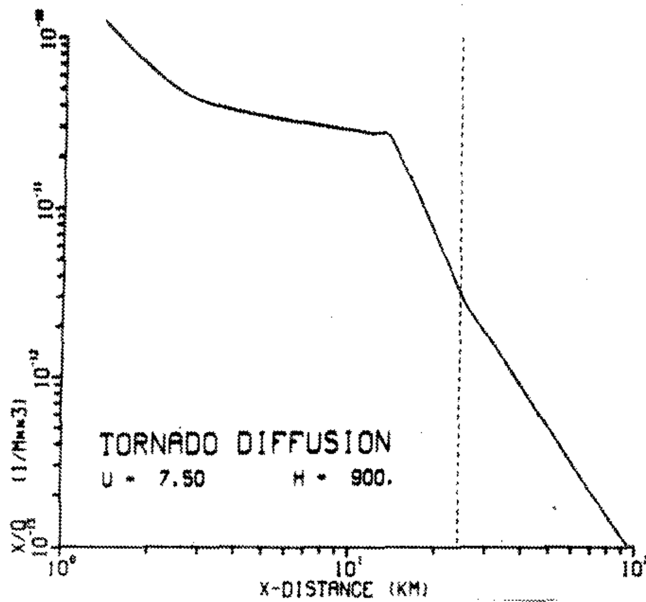

FIGURE 7. χ/Q Ratio as a Function of Distance for Case I, where average horizontal speed = 7.5 m/sec and release height = 900 m. Dotted vertical line is the SRP boundary from a point within SRP.

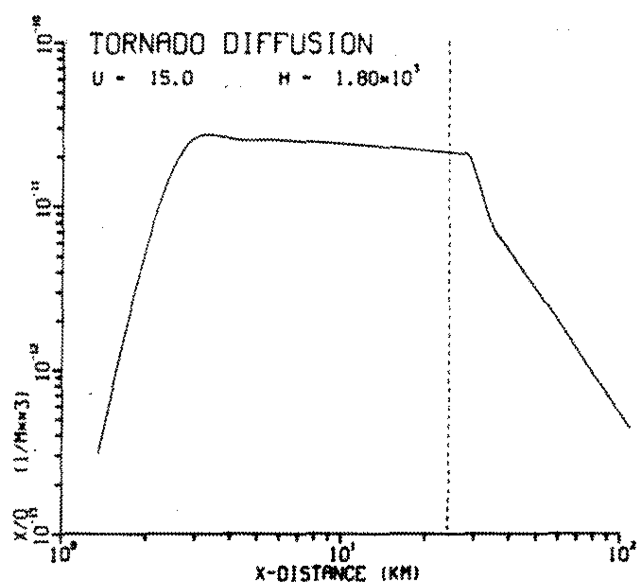

FIGURE 8. χ/Q Ratio as a Function of Distance for Case I, where average horizontal speed = 15 m/sec and release height = 1800 m. Dotted vertical line is the SRP boundary from a point within SRP.

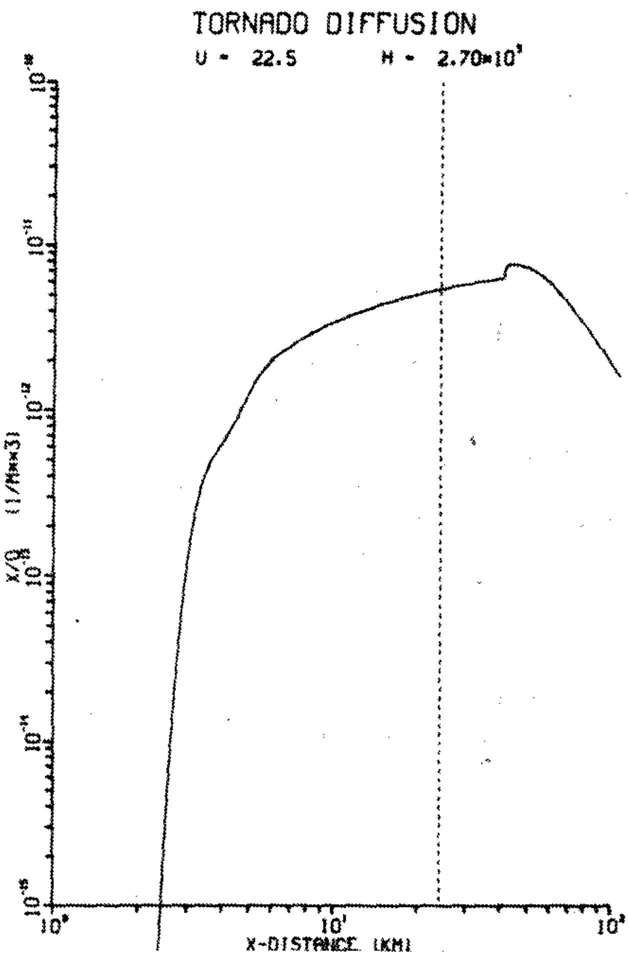

FIGURE 9. χ/Q Ratio as a Function of Distance for Case I, where average horizontal speed = 22.5 m/sec and release height = 2700 m. Dotted vertical line is the SRP boundary from a point within SRP.

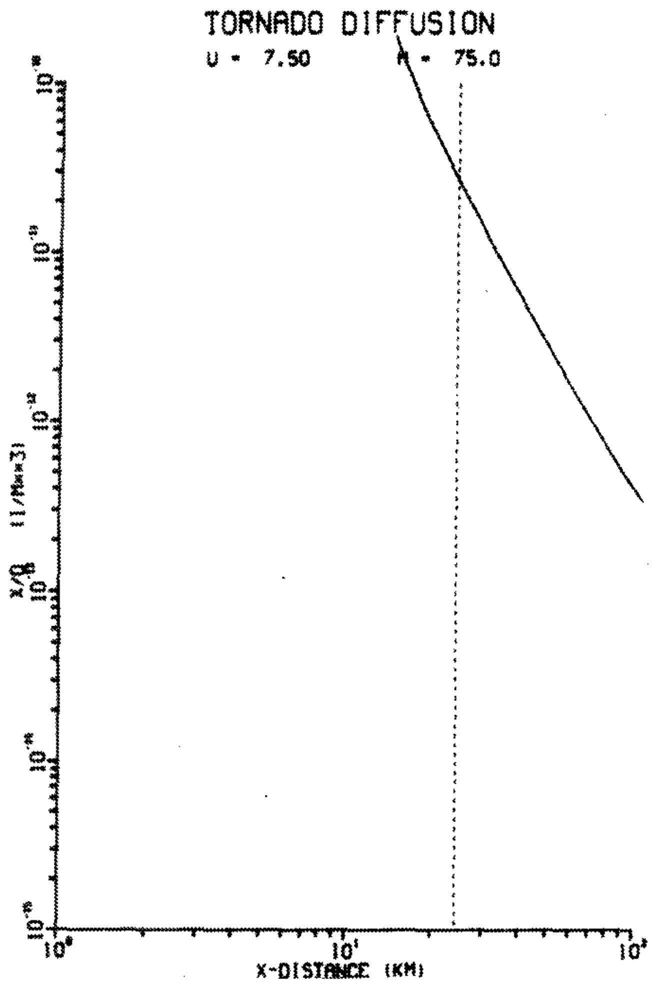

FIGURE 10. χ/Q Ratio as a Function of Distance for Case II, where average horizontal speed = 7.5 m/sec and release height = 75 m. Dotted vertical line is the SRP boundary from a point within SRP.

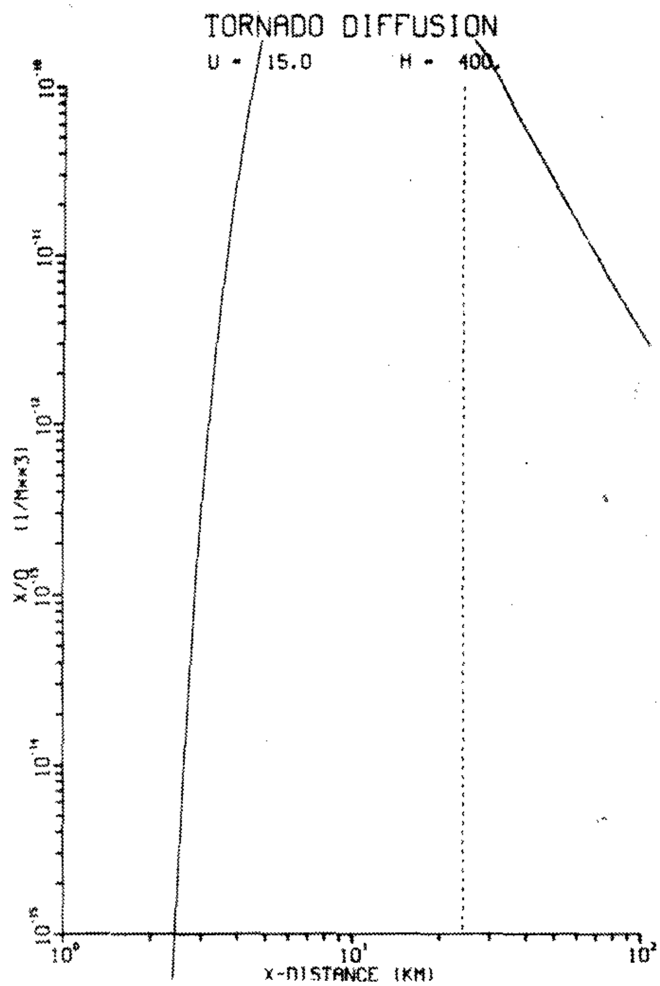

FIGURE 11. χ/Q Ratio as a Function of Distance for Case II, where average horizontal speed = 15 m/sec and release height = 400 m. Dotted vertical line is the SRP boundary from a point within SRP.

Lateral spreading of the concentration for a hypothetical location of a tornado strike at plant center is shown in Figure 12 for Case I and Case II simulations. The debris width is plotted at $y = \pm 2\sigma_y$, and σ_y is calculated from Equations 2 and 7. This corresponds to 95% of the concentration lying between $-2\sigma_y < y < 2\sigma_y$.

Initial spreading of the debris for Case I takes place inside the thunderstorm cell where the rate of energy dissipation, ε, is large; this causes the size of the debris spread, i.e., the standard deviations, σ_y and σ_z, to increase rapidly. On leaving the thunderstorm cell, spreading of the debris proceeds at a much slower rate due to the small value of ε. Consequently, the debris is more predominantly advected toward the northwest by the wind than dispersed.

Spreading of the debris occurs at a much slower rate in the Case II simulation. ε approximately equals energy dissipation rates associated with an unstable atmosphere and does not reflect the large amount of turbulence within the thunderstorm.

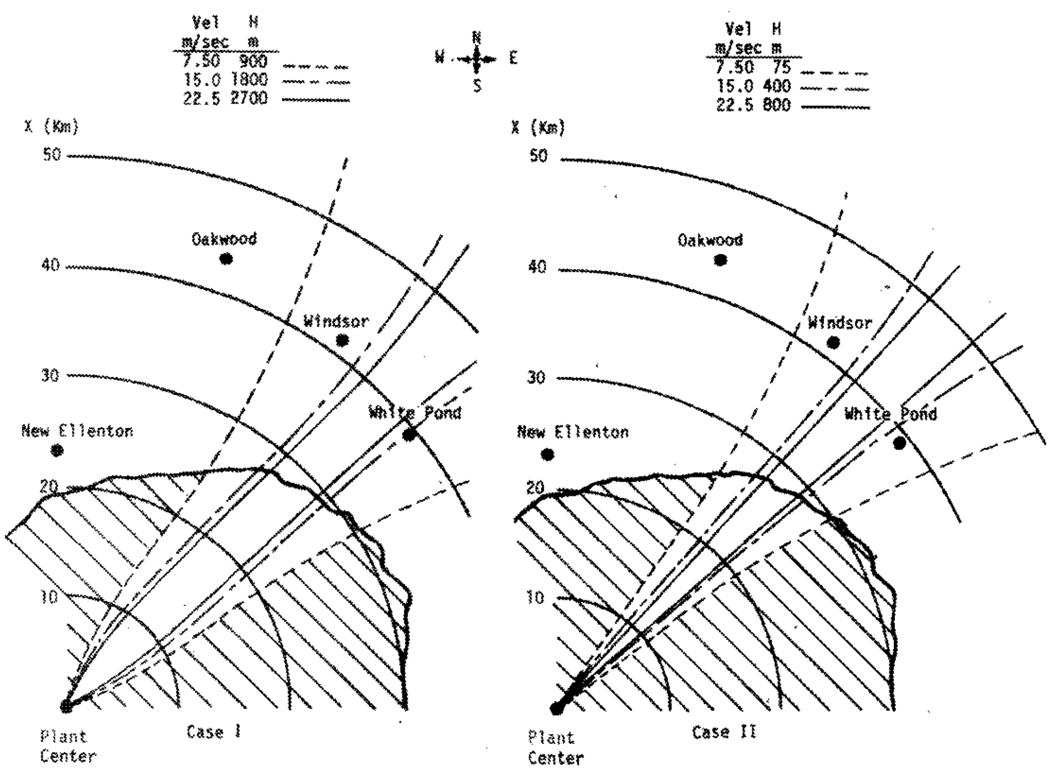

FIGURE 12. Cloud Width Profiles for $-2\sigma_y < y < +2\sigma_y$ in Case I and Case II Simulations

CONCLUSIONS

The following conclusions are made with regard to a hypothetical tornado strike at SRP:

- The probability of a tornado of the F3 class or greater striking a point at SRP is approximately 14 x 10^{-5} per year. Existing statistics reveal no data on F5 or F6 tornadoes in South Carolina and Georgia. The DBT model used by ERDA for the Southeast is of the F6 category: ERDA Regulatory Guide 1.76 indicates that a nuclear facility should be able to withstand tornadic winds corresponding to 360 mph. A more realistic DBT model is one based on a maximum tornado of the F4 category for the Southeast.

- Ground level centerline concentrations (χ/Q) at the site boundary northeast of the center of the SRP site (approximately 25 km) vary in the Case I simulations from 2.25 x 10^{-12} to 5.90 x 10^{-11} m^{-3}. Translational velocity of the storm was allowed to vary from 7.50 to 22.50 m/sec and height of initial dispersion from 900 to 2700 m above the ground. Ground level maximums occur between 40 and 60 km from the location of the tornado strike (outside the site boundaries) although they still lie within the above range.

- In Case II simulations, χ/Q values at the site boundary vary from 1.44 to 10^{-11} to 1.72 x 10^{-9} m^{-3}. In all but one test case, maximum levels occur inside the site boundaries; for U = 22.5 m/sec at H = 800 m, the maximum value occurs approximately 30 km from the location of the tornado strike.

- Spreading of the debris begins very rapidly in the lateral direction inside the thunderstorm cell for Case I simulations. This is due to the large value of the energy dissipation rate, ε, during the lifetime of the thunderstorm cell. Lateral spreading of the debris in the Case II simulation occurs at a slower rate because ε approximately equals the energy dissipation rates usually found in unstable atmospheres, i.e., ε does not reflect the influence of extreme turbulence in the thunderstorm cell.

- Ground level centerline concentrations are lower in Case I than in Case II; heights in Case I calculations are significantly higher in Case II calculations.

- Velocities and initially assumed heights are typical of values associated with tornadic thunderstorm activities. Energy dissipation rates are reasonable approximations of the actual phenomena.

- A more complete understanding of tornado dynamics has yet to be attained. Numerical simulations of dispersion are severely limited by the limited knowledge available on thunderstorm activity and tornado characteristics.

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