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A PUFF-PLUME ATMOSPHERIC DEPOSITION MODEL FOR USE AT SRP IN EMERGENCY RESPONSE SITUATIONS

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ABSTRACT

An atmospheric transport and diffusion model developed for real-time calculation of the location and concentration of toxic or radioactive materials during an accidental release was improved by including deposition calculations.

CONTENTS

A PUFF-PLUME ATMOSPHERIC DEPOSITON MODEL FOR USE AT SRP IN EMERGENCY RESPONSE SITUATIONS

INTRODUCTION

The potential exists at the Savannah River Plant for releases of either toxic gases or radionuclides. To provide realtime information on the trajectory and concentration of an accidental release, an automated system was developed. The system consists of meteorological towers, a minicomputer, and a network of terminals. This system is called the Weather Information and Display (WIND) System.[1] The primary code for emergency response is the PUFF-PLUME (PFPL) code, which simulates either instantaneous (puff) or continuous (plume) releases. The original version of PFPL is described in Reference 2. This report describes the updated version of PFPL now in operational use.

THE ATMOSPHERIC MODEL

Figure 1 illustrates the conceptual framework of the PFPL model. The diffusion process is separated into two phases. In Phase I, the Gaussian cloud grows as a function of wind speed and stability class. Near the ground, the vertical concentration becomes logarithmic. Phase II begins when the vertical standard deviation, σ_z, reaches a value of 0.8H, where H is the depth of the atmosphere's turbulent layer. At the horizontal distance from the source, where $\sigma_z \approx 0.8H$, the material remaining in the cloud is redistributed to a uniform vertical concentration throughout the mixed-layer. The logarithmic surface layer remains.

The basic theory of the model assumes that the dry deposition rate is limited not only by surface deposition processes, which are parameterized and combined into a single deposition velocity, but also by the rate at which turbulence can bring pollutants down to the surface (deposition) layer. The net effect of the two transfer rates determines the cloud depletion rate and surface concentrations. Mathematically, the region above the logarithmic surface layer is treated as a reservoir from which pollutants are drawn at a rate dependent on turbulence intensity and concentration gradient. The surface layer receives pollutants from above and deposits them on the ground. Depletion of the cloud by rain and/or radioactive decay is treated as an independent process.

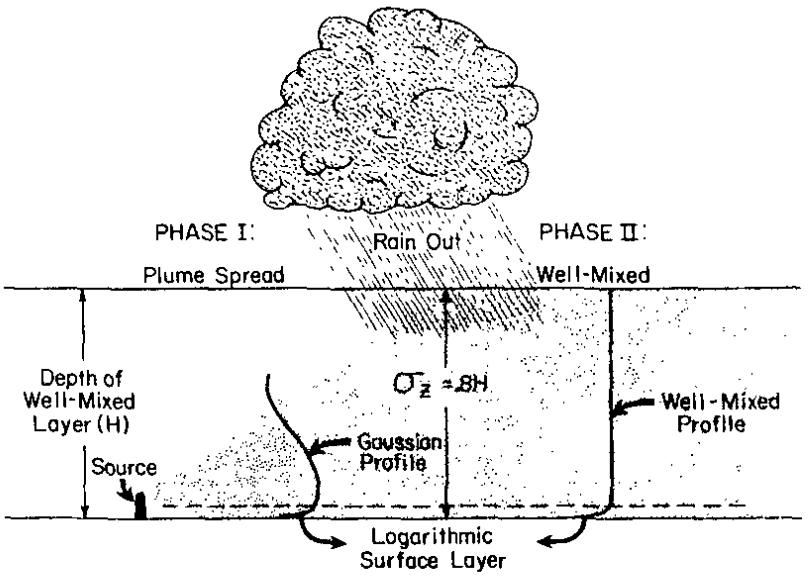

Figure 1. PFPL Model

DERIVATION OF THE MODEL

TRANSPORT AND DIFFUSION EQUATIONS

The fundamental equation to be solved is the general advection-diffusion equation, including gravitational settling, rainout, and radioactive decay:

$$\frac{\partial X}{\partial t} + u\frac{\partial X}{\partial x} - v_s\frac{\partial X}{\partial z} = -\Lambda_R X - kX - \overline{\frac{\partial u'X'}{\partial x}} - \overline{\frac{\partial v'X'}{\partial y}} - \overline{\frac{\partial w'X}{\partial z}} \qquad (1)$$

where X is concentration (g/m^3 or Ci/m^3), t is time, u is mean wind speed (directed along x-axis, m/sec), v_s is gravitational settling velocity (always >0, m/sec), z is vertical axis, Λ_R is the rainout coefficient (sec^{-1}), k is the decay constant for radionuclides, and $\overline{u'X'}$, $\overline{v'X'}$, $\overline{w'X'}$ are turbulent flux terms along the x, y, and z axes, respectively.

General analytical solutions to Equation 1 are intractable. However, if the turbulence flux terms are replaced by the eddy viscosity hypothesis of homogeneity, and Λ_R, k, v_s, and u are treated as constants over suitably small intervals of time and space, a Gaussian solution satisfies (Equation 1). Because the earth's surface limits downward diffusion and scavenges material from a pollutant cloud, boundary effects must also be modeled. The correct boundary condition was that proposed by Calder:[3]

$$\left[K_z\frac{\partial X}{\partial z} + v_s X\right]_{z\to 0} = v_d X(z\to 0) \qquad (2)$$

where v_d is the deposition velocity, and K_z is the vertical eddy viscosity. When applied to Equation 1, Equation 2 does not allow retention of the Gaussian model, and numerical solutions are required.

To avoid time-consuming numerical methods as much as possible, operationally oriented modelers have resorted to heuristic alterations of a basic reflecting Gaussian model. Two of the better-known attempts are those by Van der Hoven[4] and Horst.[5] The Horst model is considered to be better because deposition depletes the cloud at the surface, rather than instantaneously throughout the entire cloud. However, the disadvantage of the Horst model is that it requires more numerical integration than the Van der Hoven source depletion model. The Horst model also does not consider basic planetary boundary layer

features, such as the surface layer and the mixed-layer depth, which are relevant to the diffusion-deposition problem. The analytic model presented next considers these features and retains the basic improvement of the Horst model, i.e., depletion from the surface layer.

A simpler form of Equation 1 without rainout, radioactive decay, and settling, and in a coordinate system moving with the horizontal velocity, U, is:

$$\frac{dX}{dt} = -\overline{\frac{\partial(u'X')}{\partial x}} - \frac{\partial}{\partial y}(\overline{v'X'}) - \frac{\partial(\overline{w'X'})}{\partial z} \qquad (3)$$

Equation 3 can be further simplified by assuming that a Gaussian distribution in the x, y plane is adequate, and that concentrations away from cloud center are reduced according to a Gaussian distribution. Next, consider a point in the atmospheric surface layer, where deposition has steepened the vertical gradient of X. At that point, X varies according to the divergence of fluxes of material coming down from the cloud above, and going into the ground and vegetation.

Rewrite $(\overline{w'X'})$ as:

$$(\overline{w'X'}) \approx -(w^*X - v_dX) \qquad (4)$$

where w* is a velocity scale for the turbulence of the well-mixed layer above the surface layer. Substituting into Equation 3 (and ignoring horizontal diffusion for now):

$$\frac{dX}{dt} = \overbrace{+\frac{\partial w^*X}{\partial z}}^{\text{flux divergence at top of surface layer}} \quad \overbrace{-\frac{\partial v_dX}{\partial z}}^{\text{flux divergence near ground}} \qquad (5)$$

The first term on the right hand side of Equation 5 is simplified to

$$\frac{\partial w^*X}{\partial z} \approx \frac{d\sigma_z}{dt}\,\frac{(\overline{X} - X_R)}{\sigma_z} \qquad (6)$$

where $d\sigma_z/dt$ (the cloud growth rate) replaces w*, and $\overline{X}$ and X_R are the mean mixed-layer concentration and a reference concentration in the surface layer. In the surface layer, Slinn[6] suggests that $X \sim \ell n\,(z/z_o)$ is a reasonable assumption, where z_o is comparable to roughness length. This implies

$$X = cX_R \ell n(z/z_o) \qquad (7)$$

The constant c is evaluated at $z = z_R$, where z_R is an estimate of surface layer depth. With these assumptions Equation 5 can be written as

$$\frac{dX_R}{dt} = \frac{(\overline{X} - X_R)}{T} - \frac{v_d X_R}{z_R \ell n(z_R/z_o)} \tag{8}$$

where $T = \sigma_z \, (d\sigma_z/dt)^{-1}$. Physically, T is the time scale for cloud growth. If $\sigma_z > 0.8H$, where H is mixed-layer depth, then $T = H(d\sigma_z/dt)^{-1}$. Because H and z_R are both stability-dependent, the two variables should be related. Pielke[7] suggests the relationship $z_R = 0.04H$, which is used in this model.

A mass flux entering the surface layer must be balanced by a loss of mass from the well-mixed layer, so that

$$\frac{d\overline{X}}{dt} = \frac{(X_R - \overline{X})}{T} \tag{9}$$

Now define $\Lambda = \Lambda_R + k$, where Λ_R is the decay coefficient for rainout, and k is the radioactive decay constant. The settling term in Equation 1, $v_s \frac{\partial X}{\partial z}$, can be simplified similarly to the turbulent flux term:

$$v_s \frac{\partial X}{\partial z} \approx \frac{v_s \overline{X}}{L} \tag{10}$$

where $L = \sigma_z$ if $\sigma_z < 0.8H$, and $L = H$ if $\sigma_z \geq 0.8H$. Adding these sink terms to Equation 8 and 9:

$$\frac{d\overline{X}}{dt} = \frac{\left(X_R - \overline{X}\right)}{T} - \Lambda\overline{X} - \frac{v_s \overline{X}}{L} \tag{11}$$

$$\frac{dX_R}{dt} = \frac{\left(\overline{X} - X_R\right)}{T} - \frac{v_d X_R}{z_R \ell n(z_R/z_o)} - \Lambda X_R \tag{12}$$

The modified settling term appears only in Equation 11 because the settling flux coming into the shallow surface layer from above is balanced by an equal flux depositing on the canopy and earth. Following Slinn,[6] the deposition velocity in Equation 12 includes the settling velocity because particles brought into the surface layer by turbulence are still subject to settling. Equations 11 and 12 can be combined into a single expression for $\overline{X}$:

$$\frac{d^2\overline{X}}{dt^2} + \phi\frac{d\overline{X}}{dt} + \gamma\overline{X} = 0 \tag{13}$$

where,

$$\phi = \frac{2}{T} + \Lambda + A + \frac{v_s}{L}$$

$$\gamma = A\left(\Lambda + \frac{1}{T} + \frac{\Lambda}{AT} + \frac{v_s}{L} + \frac{v_s}{ALT}\right)$$

$$A = \frac{v_d}{z_R \ell n(z_R/z_o)} + \Lambda$$

Because Equation 13 is an ordinary, homogeneous, second-order differential equation, its solution is straightforward. The assumptions that led to Equation 13 are assumed to hold over 1 to 10 minute timesteps. Thus, for each timestep from t^i to t^{i+1}, the following initial conditions are imposed:

$$\overline{X} = \overline{X^i}$$

$$\frac{d\overline{X}}{dt} = \left.\frac{d\overline{X}}{dt}\right|^i$$

Solutions to Equation 13 can be real and unequal, real and equal, or complex.

Real and unequal roots:

$$\overline{X}^{\,i+1} = c_1 \exp\{r_1 \Delta t\} + c_2 \exp\{r_2 \Delta t\} \qquad (14)$$

where

$$r_1,\ r_2 = \frac{-\phi \pm \sqrt{\phi^2 - 4\gamma}}{2}$$

and

$$c_2 = \frac{\left.\frac{d\overline{X}}{dt}\right|^i - r_1 \overline{X}^i}{(r_2 - r_1)}, \qquad c_1 = \overline{X}^i - c_2, \text{ and } \Delta t \text{ is the timestep.}$$

and

$$X_R^{i+1} = X_R^i \, e^{-A\Delta t} - \frac{c_1(r_2 + \frac{Vs}{L} + \Lambda)}{(A + r2)} \left\{ e^{-r_2 \Delta t} - e^{-A\Delta t} \right\} \qquad (15)$$

Real and equal roots:

$$\bar{X}^{i+1} = c_1 \exp(-\phi\Delta t/2) + c_2 t \exp(-\phi\Delta t/2) \tag{16}$$

where

$$c_1 = \bar{X}^i, \quad c_2 = \left.\frac{d\bar{X}}{dt}\right|^i + c_1 \frac{\phi}{2}$$

and

$$X_R^{i+1} = X_R^i e^{-A\Delta t} + \frac{K_2}{\left(A-\frac{\phi}{2}\right)^2}\left\{ e^{-\frac{\phi}{2}\Delta t}\left[\left(A-\frac{\phi}{2}\right)\Delta t - 1\right] + e^{-A\Delta t}\right\} + \frac{K_1\left(e^{-\frac{\phi}{2}\Delta t} - e^{-A\Delta t}\right)}{(A - \phi/2)} \tag{17}$$

where $K_1 = c_1 \frac{\phi}{2} - c_2 - \left(\Lambda + \frac{v_s}{L}\right)c_1$

and

$$K_2 = c_2 \frac{\phi}{2} - \left(\Lambda + \frac{v_s}{L}\right)c_2$$

The solution for real and equal roots is used only when $|\phi^2-4\gamma|<10^{-20}$

Complex roots:

$$\bar{X}^{i+1} = \exp(-\phi\Delta t/2)\left\{ c_1 \cos\left(\frac{\sqrt{48-\phi^2}}{2}\Delta t\right) + c_2 \sin\left(\frac{\sqrt{48-\phi^2}}{2}\Delta t\right)\right\} \tag{18}$$

where

$$c_1 = \bar{X}^i, \quad c_2 = \frac{2\left.\frac{d\bar{X}}{dt}\right|^i + \phi\bar{X}^i}{\sqrt{48-\phi^2}}$$

and

$$X_R^{i+1} = \frac{-A\Delta t}{e}\left\{X_R^i + \frac{B_4B_1-B_3B_2 - \frac{B_1\Delta t}{e}\left[(B_1B_3 + B_2B_4)\sin(B_2\Delta t) + (B_1B_4 - B_2B_3)\cos(B_2\Delta t)\right]}{B_1^2 + B_2^2}\right\} \quad (19)$$

where

$$B_1 = A - \frac{\phi}{2},\ B_2 = \frac{\sqrt{4\gamma-\phi^2}}{2},\ B_3 = c_2(A + \frac{v_s}{L} - \frac{\phi}{2}) - c_1\frac{\sqrt{4\gamma-\phi^2}}{2}$$

$$B_4 = c_1(A + \frac{Vs}{L} - \frac{\phi}{2}) + c_2\frac{\sqrt{4\gamma-\phi^2}}{2}$$

At the time of release, the apportionment of the pollutant cloud to the surface and well-mixed layers is determined from a vertically integrated Gaussian distribution.

$$\text{If } z_R \geq h \quad \overline{Q}^1 = \frac{Q}{2}\left[1 - \text{erf}\left(\frac{z_R - h}{\sqrt{2}\sigma_{zo}}\right)\right]$$

$$\text{If } z_R < h \quad \overline{Q}^1 = \frac{Q}{2}\left[1 + \text{erf}\left(\frac{h - z_R}{\sqrt{2}\sigma_{zo}}\right)\right]$$

where σ_{zo} is σ_z at $t = 0$, and h is release height. Also, $Q_R{}^1 = Q - \overline{Q}^1$.

In practice, $\overline{Q}^{i+1}$, the total material left in the well-mixed layer at timestep t^{i+1}, and $Q_R{}^{i+1}$, the corresponding amount left in the surface-layer, are calculated, rather than X^{i+1} and $X_R{}^{i+1}$. This is a simpler procedure, since Gaussian distributions are assumed in the horizontal plane. Given $\overline{Q}^{i+1}$ and $Q_R{}^{i+1}$, the surface centerline concentrations for an instantaneous puff and a continuous plume are <u>defined</u> to be:

Puff

$$X^{i+1} = \frac{2Q^{i+1}}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{h}{\sigma_z}\right)^2\right] \quad (20)$$

where

$$Q^{i+1} = \overline{Q}^{i+1} + Q_R{}^{i+1}$$

Plume

$$X^{i+1} = \frac{2Q^{i+1}}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{h}{\sigma_z}\right)^2\right] \quad (21)$$

and, for σ_z >0.8H:

PUFF

$$X^{i+1} = \frac{Q^{i+1}}{2\pi\sigma_x\sigma_y H} \tag{22}$$

PLUME

$$X^{i+1} = \frac{Q^{i+1}}{\sqrt{2\pi}\ \sigma_y u H} \tag{23}$$

The definitions Equations 20 through 23 ignore the logarithmic surface layer, and thus give estimates of surface concentrations and doses that are more conservative than they would otherwise be. Equations 20 through 23 become simple reflecting Gaussian models when there is no deposition, rainout, or radioactive decay. Deposition at timestep i+1 is defined to be

$$D^{i+1} = \frac{(Q^i - Q^{i+1})}{\sqrt{2\pi}\ u\sigma_y \Delta t} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \tag{24}$$

i.e., the material is deposited evenly along the cloud track and according to the Gaussian distribution along the lateral axis. Plume deposition is assumed to last one hour unless otherwise specified. Radioactive decay does not contribute to $(Q^i - Q^{i+1})$ in Equation 24.

During the phase when σ_z <0.8H, an elevated release will not interact fully with the surface layer (see Figure 1). This will be an extended period during stable conditions. To simulate an elevated release, the pollutant cloud and surface layer are separated by increasing the time scale for cloud growth, T, in inverse proportion to the amount of the cloud in contact with the surface layer.

$$T = \frac{\sigma_z}{(d\sigma_z/dt)} \left\{1 - \text{erf}\left[(h-v_s t-z_R)/\sigma_z\right]\right\}^{-1} \tag{25}$$

If the release is so high that $(h-v_s t-z_R)/\sigma_z$ >5.0, then no interaction is allowed, and the cloud is depleted only by rain and/or radioactive decay.

DIFFUSION PARAMETERS

For a puff release, σ_y and σ_z are calculated from the expressions developed by F. B. Smith and documented by Pasquill:[8]

$$\sigma_y = 0.22\sigma_a x \tag{26a}$$

$$\sigma_z = 0.22\sigma_e x \tag{26b}$$

where σ_a and σ_e are the standard deviations, in radians, of the horizontal and vertical wind fluctuations, respectively, and x is downwind distance.

For a plume release, σ_y is calculated from the expression derived by Pasquill:[9]

$$\sigma_y = \sigma_a x f(x) \tag{27}$$

where x is in kilometers, $f(x) = 0.33\left(\frac{10}{x}\right)^{0.5}$ for x>10 km, and

$$f(x) = \frac{x^{-0.2}}{1.67 + 0.3\left(\frac{|1 - x^{-0.2}|}{0.48}\right)^{0.5}} \tag{28}$$

for x≤10 km.

Equation 28 is an interpolating formula derived from values of f(x) given by Pasquill.[9]

At present, σ_z for a plume release is calculated from Briggs.[10] A separate expression is given for each stability class (Table 1).

Table 1

Vertical Standard Deviations

Stability Class	σ_z	
A	$0.20x$	(29a)
B	$0.12x$	(29b)
C	$0.08x(1+2*10^{-4}x)^{-1/2}$	(29c)
D	$0.06x(1+1.5*10^{-3}x)^{-1/2}$	(29d)
E	$0.03x(1+3*10^{-4}x)^{-1}$	(29e)
F	$0.02x(1+3*10^{-4}x)^{-1}$	(29f)

In all calculations, puff estimates of σ_y and σ_z from Equation 26 are constrained to be no larger than the plume estimates from Equations 27-29.

Stability classes in Equation 29 are determined from observed σ_a and σ_e according to Table 2.

Table 2

Classification of Atmospheric Stability

Pasquill Category	σ_a	σ_e
A	>25°	>17.5
B	20° to 25°	14 to 17.5
C	15° to 20°	10.5 to 14
D	10° to 15°	7 to 10.5
E	5° to 10°	3.5 to 7
F	<5°	<3.5

The observed values of σ_a and σ_e are computed from instantaneous (every 2 seconds) observations of wind direction taken from SRP meteorological towers as follows:

$$\sigma_a = \left[\frac{1}{N} \sum_{i=1}^{N} \left(\theta_i^2 - \overline{\theta}^2 \right) \right]^{1/2} \qquad (30)$$

where θ_i is the i^{th} instantaneous value of N wind direction observations, and $\overline{\theta}$ is the average for all N values. Running totals of θ_i^2 are stored in the SRL PDP 11/40 computer rather than individual values because of core limitations.

Running totals can cause values of σ_a computed from Equation 30 to be spuriously large when the wind direction is close to north (360°). This problem is corrected by allowing θ to vary from 0° to 720°. The first observation in a 15-minute averaging interval is always less than 450°, and subsequent observations are referenced to that initial value. For example, an initial observation of 300° remains 300°, but an initial value of 20° becomes 380°.

Values of σ_e are computed with a relation similar to Equation 30. The averaging problems caused by running totals of σ_a are not encountered in σ_e calculations because the evaluation angle is unlikely to stray beyond ±45°.

Average wind direction, $\overline{\theta}$, is computed with Equation 31 from averaged running totals of the u and v (horizontal) wind components

$$\overline{\theta} = \tan^{-1}\left(\frac{\overline{v}}{\overline{u}}\right) \tag{31}$$

where $\overline{u}$ and $\overline{v}$ are the averaged components. The average wind speed, U, is defined by

$$U = \left(\overline{u}^2 + \overline{v}^2\right)^{1/2} \tag{32}$$

The SRL Emergency Response Code uses one-hour averages (four successive 15 minute intervals) of U, $\overline{\theta}$, σ_a, and σ_e.

DRY DEPOSITION

Dry deposition processes can roughly be divided into two categories: gaseous and particulate. The distinction between the two is not absolute because some isotopes, such as ^{131}I, apparently are released from reactors as vapors, but are absorbed by aerosols and behave like particles later.[4] However, pollutant behavior can usually be specified to be either like a gas or like a particle. Table 3 shows the radionuclides and chemical compounds of concern to SRP and their mode of treatment.

Table 3

Significant Nuclides and Compounds at SRP

Pollutant	Form
^{238}Pu	particle
^{239}Pu	particle
^{252}Cf	particle
^{244}Cm	particle
^{60}Co	particle
FP (Fission Products)	particle
HTO, HT	gas
Cl_2	gas
H_2S	gas
SO_2	gas
^{131}I	indeterminate (specified deposition velocity)
Noble Gases	gas (total reflection, no deposition)

Particle Deposition

Modeling particle deposition requires knowledge of a particle size distribution function and the processes that remove significant amounts of the particles in each sector of the distribution function. Removal processes are combined into a single deposition velocity, which is calculated by the "resistance analogue" method (Reference 10, p. 65).

Resistance Function

The rate at which particles with no appreciable fall velocities are deposited is governed by three deposition processes, or resistances: The atmospheric or aerodynamic resistance above the vegetation canopy, the "in-canopy" resistance, and the needle or leaf boundary layer resistance. These resistances are additive, as shown in Figure 2.

χ_P is set equal to zero (no resuspension is assumed). By definition, the flux into the canopy, F_R, is:

$$F_R = \frac{\chi_R}{r_a + r_b + r_i} = v_d \chi_R \tag{33a}$$

$$\text{so } v_d = \frac{1}{r_a + r_b + r_i} + v_s \tag{33b}$$

where v_s, the settling velocity, has been included as a separate, additional deposition process, following Slinn.[6]

Deposition of particles on the ground is not modeled explicitly because the Savannah River Plant is heavily forested, and the ground is either covered by fallen leaves, pine needles, or grass. The leaf area index (see next section on gas deposition) is thus much larger than one, and so deposition on bare ground is neglected.

The atmospheric resistance is modeled similarly to the other resistances: a momentum concentration gradient divided by a momentum flux.

$$r_a = \frac{\rho |u_1 - u_2|}{\tau} \tag{34}$$

where u_1 and u_2 are the wind velocities above and within the canopy, τ is the momentum flux into the canopy, and ρ is atmospheric density. By definition;

$\tau/\rho = u^{*2}$, so,

$$r_a = \frac{|u_1 - u_2|}{u^{*2}} \tag{35}$$

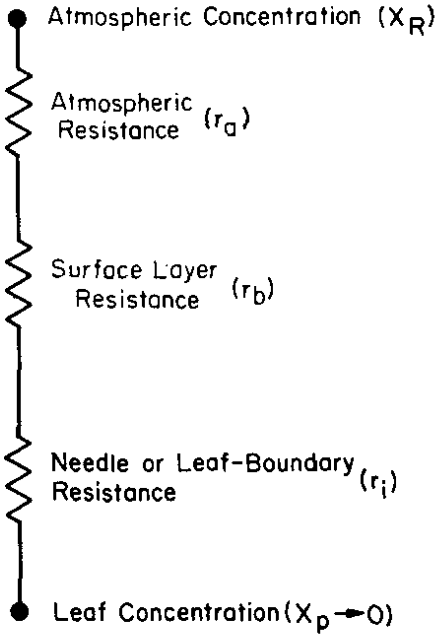

Figure 2. Deposition Processes for Particles

At present, u* is computed from the logarithmic velocity profile

$$u_1 = \frac{u^*}{k} \ln\{\frac{z-d}{z_o}\} \tag{36}$$

with z_o, the roughness length (10 cm) and d, a displacement length (10m). The in-canopy velocity, u_2, is approximated by

$$u_2 = (0.5u_1)^{1/2} \tag{37}$$

The surface layer resistance, r_b, is the ratio of the largest turbulent length scale within the canopy to the eddy diffusivity. Application of the logarithmic velocity profile produces

$$r_b = (ku^*)^{-1} \tag{38}$$

The needle boundary layer resistance, r_i, represents only the effect of Brownian motion on small particles. Molecular collisions move particles that are sufficiently small through the laminar boundary layer adjacent to the needle surface (Reference 10, p. 170). The transfer processes are modeled by Equations 39 and 40.

$$r_i = r_h \left(\frac{D_h}{D_i}\right)^{2/3} A_L^{-1} \tag{39}$$

$$r_h = \frac{\rho c_p D}{(0.32 + 0.51\ R_e^{0.52})K} \tag{40}$$

where r_h is the corresponding resistance to heat transfer, D_h is thermal diffusivity (0.257 cm^2/sec), D_i is the effective Brownian diffusivity, c_p is the specific heat of air at constant pressure, D is needle diameter, K is thermal conductivity, A_L is leaf area index, and R_e is the needle Reynolds number, defined by

$$R_e = \frac{u_2 D}{\nu} \tag{41}$$

where ν is molecular viscosity (0.15 cm^2/sec). The effective Brownian diffusivity, D_i, is defined by

$$D_i = k_B T P \tag{42}$$

where k_B is the Boltzmann constant (1.38×10^{-16} erg/K), T is absolute temperature (K), and P is an interpolation formula (Reference 11, p. 27, 191).

$$P = \{1 + \frac{0.864\ell}{r} + \frac{0.29\ell}{r} \exp\left(-\frac{1.25r}{\ell}\right)\}/6\pi\eta r \qquad (43)$$

where ℓ is the molecular mean free path (0.942×10^{-5} cm), r is particle (equivalent sphere) radius (cm), and $\eta = \nu\rho$. When P is calculated from Equation 43, Equation 42 is valid within 10% accuracy for particles between 10^{-7} and 10^{-3} cm.

The needle boundary layer resistance, r_i, should include the effects of impaction as well as Brownian diffusion. However, according to Monteith (Reference 10, p. 164), the theoretical work on impaction[11] is of little practical interest because the theory assumes a sticky surface. In reality, many of the particles bounce off, and the bounce-off rate is a complex function of particle size and composition, and needle size and wetness. Furthermore, Monteith (Reference 10, p. 176) presents empirical curves of deposition velocity and particle sizes which are close to model-generated curves for which impaction was not considered. So impaction processes have not been explicitly included in this model.

The settling velocity, v_s, required by Equation 33b, is calculated from Stokes' Law for particle diameters of less than 70 microns.

$$v_s = \frac{D_p^2 g \rho_p}{18\nu\rho} \qquad (44)$$

where D_p is particle diameter, g is acceleration due to gravity, ρ_p is particle density, and other variables are as previously defined. Particle fall velocities that are outside the Stokes range are estimated with interpolation formulae taken from Reference 12, p. 441. For particles between 70 and 1000 microns,

$$v_s = 70 + 0.45\ (D_p - 200) \qquad (45)$$

where v_s is in cm/sec. For $D_p > 1000$ microns,

$$v_s = 7.8\ D_p^{0.57} \qquad (46)$$

Equations 45 and 46 are not used much because, as the next section shows, most of the particle size distribution function lies within the Stokes range.

Distribution Function

Measurements by Gay[13] at SRP of ^{238}Pu, ^{239}Pu, and ^{240}Pu bearing particles about 400 m from reactor stacks show that the particle sizes are lognormally distributed. If P_D is particle diameter, and $Y = \ell n\ P_D$, then the cumulative distribution function for Y is

$$\phi(Y) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{(Y-\overline{Y})/S_y} \exp(-t^2/2)dt \qquad (47)$$

where S_y is the standard deviation of Y. Data show $\overline{Y}$ to be -0.274, and S_y to be 2.37.

The particle spectrum described by Equation 47 is split into 8 size classes, each of which is treated separately by the atmospheric transport model (page 6). Each sector has a width of S_y. Sector boundaries, representative particle sizes, and the proportion of the total distribution in each sector are given below.

Table 4

Sector Boundaries							
-3Sy	-2Sy	-Sy	0	Sy	2Sy	3Sy	4Sy
Median Particle Size, microns							
1.9×10^{-4}	2.0×10^{-3}	2.0×10^{-2}	2.2×10^{-1}	2.5	27	280	3000
Percent of Distribution							
0.5	2.5	12.3	34.7	34.7	12.3	2.5	0.5
Settling Velocity, sec/cm							
10^{-10}	10^{-8}	10^{-5}	1.7×10^{-4}	0.019	2.2	108	755

All particles listed in Table 3 are assumed to have the same size distribution described by Equation 47.

Gas Deposition

The calculation method for gas deposition rate is based on atmospheric, soil, and plant physiological resistances. Figure 3 illustrates the components of the system and their relations:

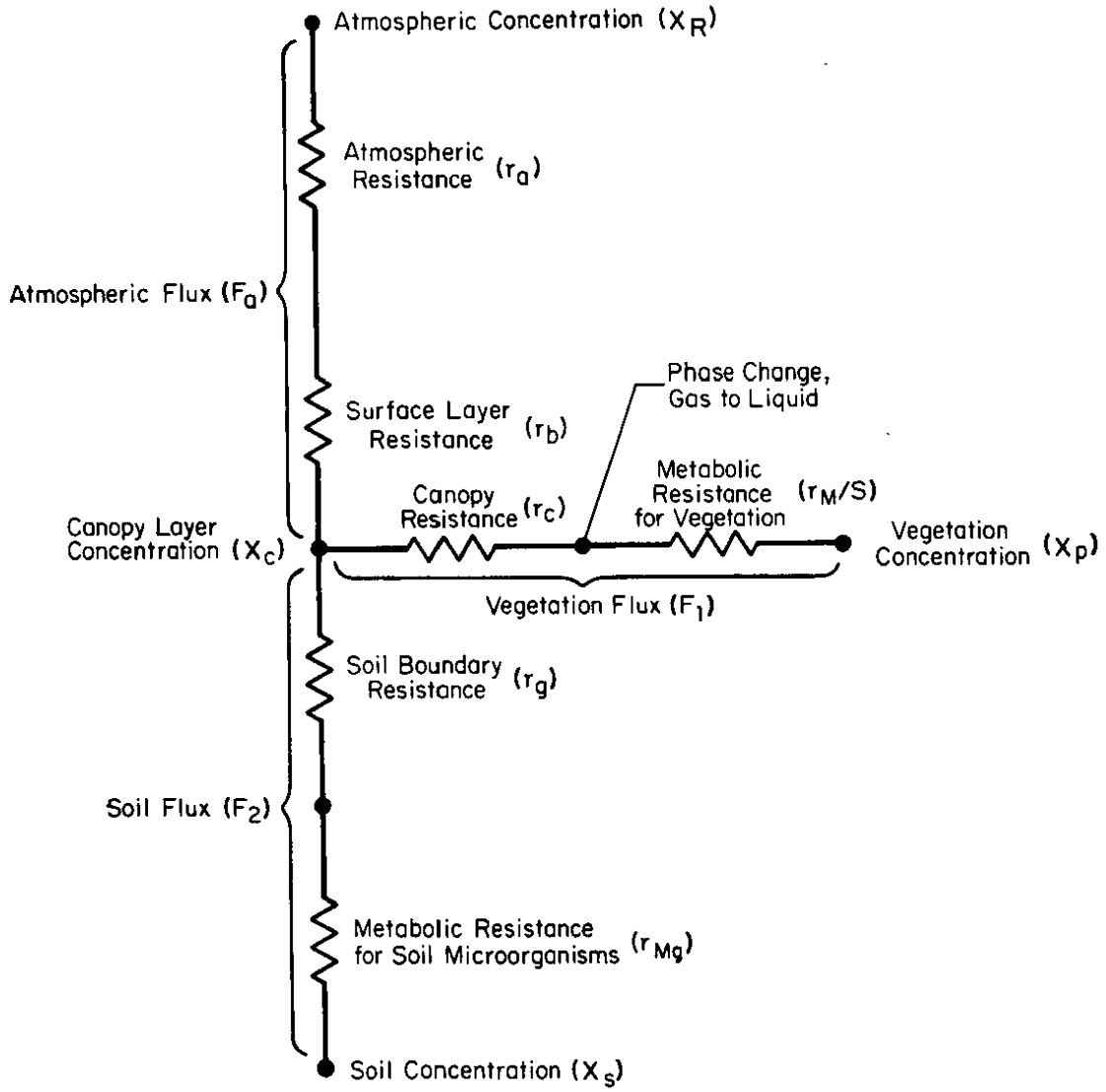

Figure 3. Deposition Processes for Gases

r_b contains an extra term, which accounts for the excess resistance, or additional resistance to transfer of heat or gases, relative to momentum.

$$r_b = (ku^*)^{-1} + 0.94\ (0.5u_1)^{1/2}A_L^{-1} \tag{48}$$

In Equation 48, A_L is the leaf area index, a dimensionless quantity defined as the average area of all leaves (upper sides only) at all levels within a unit area of a stand of vegetation. At present, our expression for A_L is from Reference 14:

$$A_L = A_{Lmin}\ \{[1 + \exp\ (3.90 - 7.09X_N)]^{-1} + 1 - [1 + \exp\ (4.66 - 9.35X_O)]^{-1}\} \tag{49}$$

where $A_{Lmin} = 4.0$, and

$$X_N = \frac{D-G}{F-G} \tag{49a}$$

$$X_O = \frac{D-G}{366} \tag{49b}$$

and D = Julian day of year, G = beginning of growth period (Day 81), and F = date leaf fall starts (Day 275). Also, if $D < G$, then $D = D + 366$.

Canopy resistance (r_c) is a function of light intensity, humidity, temperature, and soil moisture. A model that included all of these effects would be large and complicated, so simple expressions are used:

$$r_c = 7.0/A_L \text{ during day}$$
$$r_c = 35.0/A_L \text{ at night} \tag{50}$$

This relationship accounted for about 60% of the variation seen in loblolly pines at SRP.[15] Sunrise and sunset are computed with standard formulae. r_M is a metabolic resistance for vegetation. Estimates are:

$$T_2 = 2.0 \text{ sec/cm} \qquad Cl_2 = 10^5 \text{ sec/cm}$$
$$HTO = 0.0 \qquad H_2S = 10^5 \text{ sec/cm}$$
$$SO_2 = 100 \text{ sec/cm} \tag{51}$$

Based on experimental evidence presented by Hill and Chamberlain[16] and summarized by Braunstein (Reference 17, pp. 8-18, 8-42), the r_M for Cl_2, H_2S, and SO_2 is set equal to zero for

surface concentrations below 1 ppm. The expression for Cl_2 and H_2S in Equation 51 crudely models the closing of stomata as a reaction to toxic gases above 1 ppm. S is solubility of the gas: for T_2 ~0.666, HTO = 1.0, $Cl_2 \approx 2.3$, $H_2S \approx 2.1$, $SO_2 \approx 39.4$.

The soil boundary layer resistance (r_g) is estimated by

$$r_g = 5u^{*-1} + 2.0 \qquad (52)$$

r_{Mg} is an additional soil resistance which models metabolic resistances of soil microorganisms. Estimates are

$$\begin{aligned} T_2 &= 1.0 \text{ sec/cm} & Cl_2 &= 10^5 \text{ sec/cm} \\ HTO &= 0.0 & H_2S &= 10^5 \text{ sec/cm} \\ SO_2 &= 10^5 \text{ sec/cm} \end{aligned} \qquad (53)$$

(The tritium estimates are based on field work at SRP.[18])

In the resistance diagram, fluxes and concentrations in the atmosphere, vegetation, and soil are represented by F_a and χ_R, F_1 and χ_P, and F_2 and χ_S, respectively. Concentration in the air of the canopy layer is χ_c. Final sink concentrations in the soil and vegetation are assumed to be zero (no back-gassing to atmosphere). Because all resistances are defined by a concentration difference divided by a flux, then (with χ_p and χ_s both set equal to zero):

$$F_1 = \frac{\chi_c}{r_c + r_M/S}, \qquad F_2 = \frac{\chi_c}{r_g + r_{Mg}} \qquad (54)$$

and $F_a = F_1 + F_2$

so

$$F_a = \chi_c \frac{r_g + r_{Mg} + r_c + r_M/S}{(r_c + r_M/S)(r_g + r_{Mg})} \equiv \chi_c \alpha \qquad (55)$$

Because deposition velocity, v_d, is defined by F_a/χ_R, and also,

$$r_a + r_b = (\chi_R - \chi_c)/F_a \qquad (56)$$

then, solving for v_d:

$$v_d = \frac{\alpha}{1+(r_a + r_b)\alpha} \qquad (57)$$

WET DEPOSITION

Although rain can be an effective scavenger of particles and gases, the depletion rate is a complex function of rainfall rate, solubility or particle size, and drop size. In an operational situation, none of this information will be available. At best, the only available information will be whether the rain is heavy or light, and whether it is widespread or localized. Accordingly, the pollutant cloud is simply assumed to be scavenged at a rate proportional to pollutant concentration:

$$\frac{dQ}{dt} = -\Lambda_R Q \tag{58}$$

where Λ_R is the scavenging coefficient. Garland[19] gives an order-of-magnitude estimate of Λ_R for SO_2 of 10^{-5} sec^{-1}, which is the same value given by Dana[20] for HTO. The same rate is used here for H_2S and Cl_2. For ^{131}I, Brenk and Vogt[21] give

$$\Lambda_R = 8 \times 10^{-5} R^{0.6}$$

where R is the rainfall rate in mm/hr. If the ^{131}I is in aerosol form, then

$$\Lambda_R = 1.2 \times 10^{-4} R^{0.5}$$

Noble gases and HT are not scavenged by rain ($\Lambda_R = 0$).

Λ_R varies with particle size and rainfall rate because small particles lack inertia and are swept around large drops. The following expressions for Λ_R approximate theoretically derived curves by Chamberlain.[22]

For "light rain" (1 mm/hr):

$$\Lambda_R = 3.9(1-e^{-\sqrt{v_s}})10^{-4} \tag{59}$$

for "heavy rain" (5 mm/hr):

$$\Lambda_R = 14.2(1-e^{-\sqrt{v_s}})10^{-4} \tag{60}$$

where v_s is settling velocity.

RADIOACTIVE DECAY AND DOSE FACTORS

Radioactive decay rates and dose factors for radionuclides of concern at SRP are given in Table 5.

Table 5

Half Lives and Dose Factors

	Half-Life	Dose Factor, rem/curie sec per m^3
Plutonium-238	87.8 years	7.6×10^4
Plutonium-239	2.44×10^4 years	7.3×10^4
Californium-252	2.63 years	7.6×10^5
Curium-244	17.9 years	2.3×10^4
Cobalt-60	5.27 years	2.60×10^2
Fission Products	1 hour to 10 days	3.92×10^2
Tritium	12.33 years	4.3×10^{-6}
Tritiated Water	12.33 years	1.43×10^{-1}
Iodine-131	8.04 days	5.24×10^2
Noble Gases (Xe, Kr)	variable	(function of total reactor inventory and cloud size)

NOBLE GASES

The atmospheric model described on page 6 is not appropriate for releases of the noble gases (Kr, Xe), which are inert, and therefore nondepositing. Furthermore, the whole-body dose from exposure to noble gases is a function of the gamma flux integrated over the entire radioactive cloud. So concentrations at ground level are not relevant to the noble gas dose calculation.

The method for calculating gamma doses from a noble gas release is described in Appendix A. The numerical integrations required in the calculations are time-consuming, even though they are performed efficiently.

The code as originally developed by Cooper takes about 30 minutes to run on a PDP 11/40 minicomputer (72 time steps). Because the essence of an emergency response code is rapid turnaround, the following interpolation formula was devised. Given two points along a cloud trajectory where the numerical integrations have been performed, (D_1,x_1) and (D_2,x_2), the interpolated dose (D) at point x is

$$D(x) = \frac{(D_1-D_2)}{x\left[\frac{1}{x_1} - \frac{1}{x_2}\right]} - \frac{(D_1-D_2)}{\frac{x_1}{(1-x_2)}} + D_1 \qquad (61)$$

Equation 61 is based on the assumption that the dose will decrease in proportion to the inverse of the distance from the release.

At present, the numerical integration is performed every 12 timesteps, and Equation 61 estimates doses at the intervening timesteps; estimates are always conservative (high), but not by more than about 50%.

The document by Cooper that describes the noble gas gamma dose calculations is reproduced as Appendix A of this report.

SAMPLE CALCULATIONS

Representative calculations for gas and particle releases are presented in this section. This first series of calculations compares results from the model developed (SRL model) to results from the Horst[5] surface depletion model and the Van der Hoven[4] source depletion model. A constant deposition velocity of 2 cm/sec and wind speed of 2 m/sec were chosen to make the ratio of $v_d/u = 0.01$, as in the Horst model.

The SRL model results for stable conditions (Figure 4) are generally similar to those for the Horst model (Figure 5). The only significant difference between the Horst and SRL suspension ratio calculations appears at large distances downwind, where the rate of depletion for the SRL model tapers off. The tapering off was caused by the Briggs σ_z formula for stable conditions, which predicts cessation of plume growth at large downwind distances.

In neutral conditions (Figures 6 and 7), results are again similar for the Horst and SRL models. The SRL 10-m and 2-m suspension ratios were nearly identical, so only the 10-m suspension ratios are plotted. For a 10-m release, the SRL model predicts slightly more rapid depletion of the cloud at large downwind distances than the Horst model, but the depletion is still less than that predicted by the Van der Hoven model.

The SRL model differs most from the Horst and Van der Hoven models in unstable conditions (Figure 8 and 9). The SRL model predicts much more depletion at large downwind distances than either the Horst or Van der Hoven models. This increased deposition is entirely caused by the constraint of a maximum mixing depth in the SRL model. A 1500-m mixing depth (typical for a sunny afternoon) was used for the computations plotted in Figure 8. Deposition models need to include the best possible estimates of mixed-layer depths because pollutants recycle through the mixed-layer and are repeatedly exposed to surface deposition processes in the surface layer. The recycling time is approximately

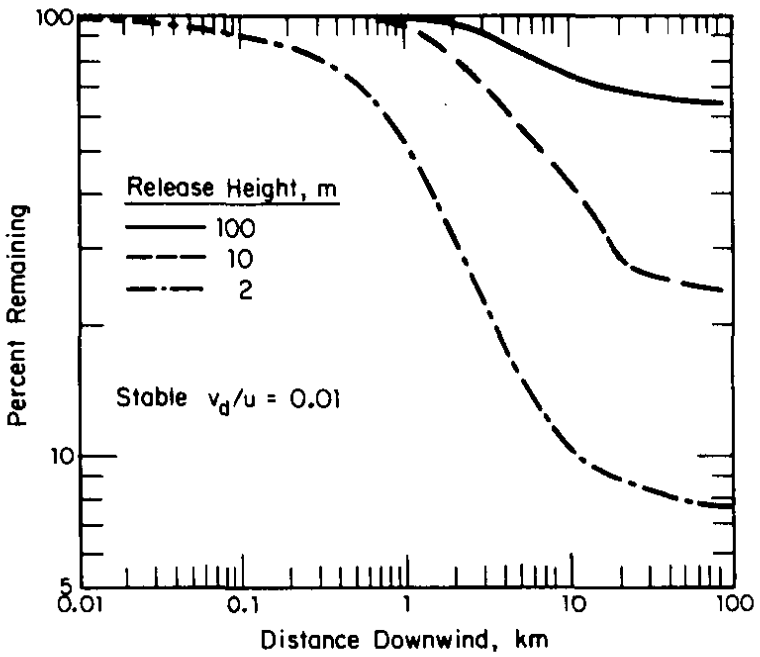

Figure 4. Calculations for Stable Conditions - SRL Model

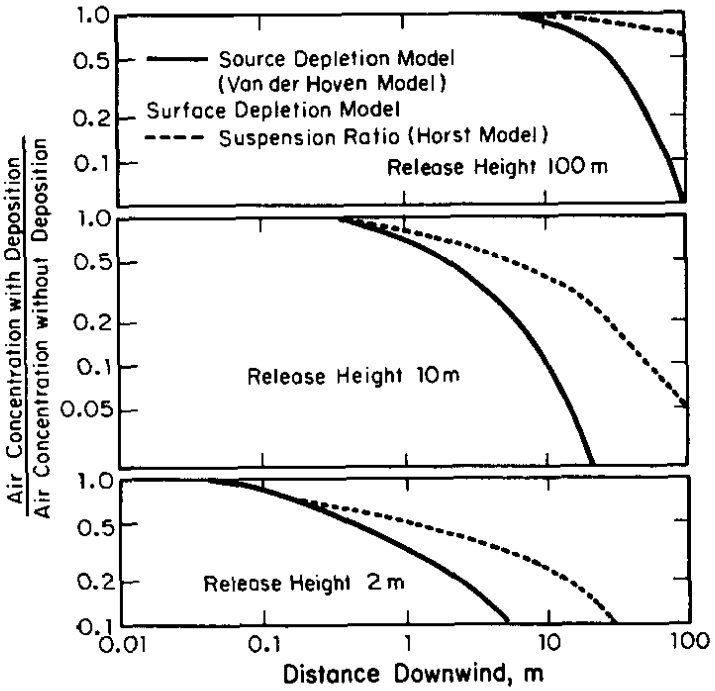

Figure 5. Calculations for Stable Conditions - Horst and Van der Hoven Models

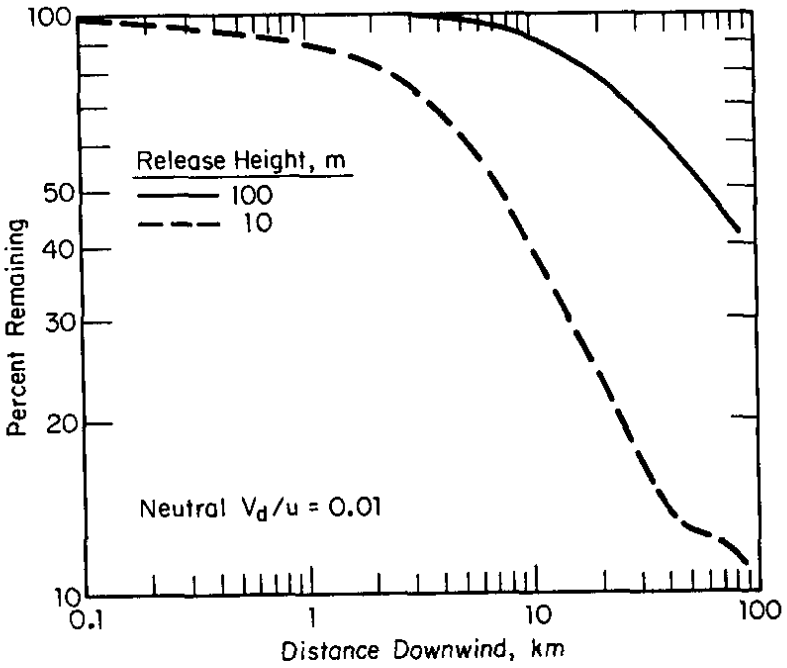

Figure 6. Calculations for Neutral Conditions - SRL Model

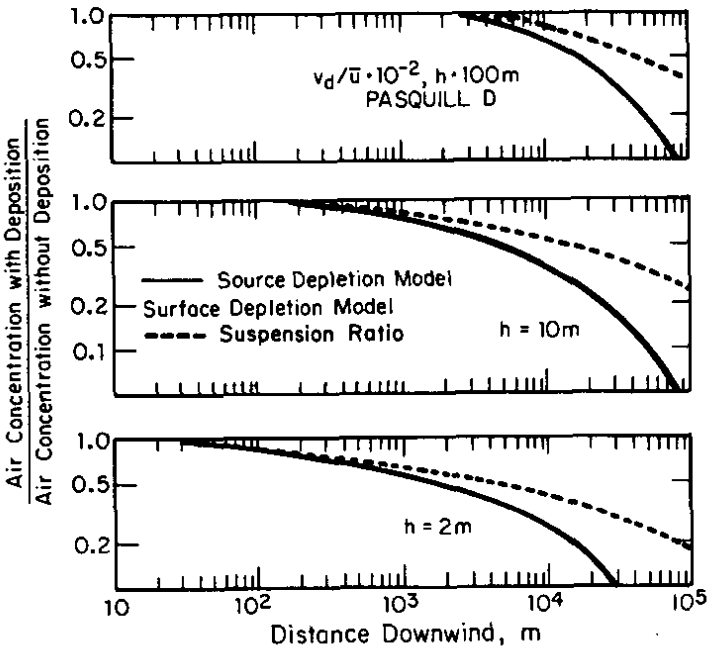

Figure 7. Calculations for Neutral Conditions - Horst and Van der Hoven Models

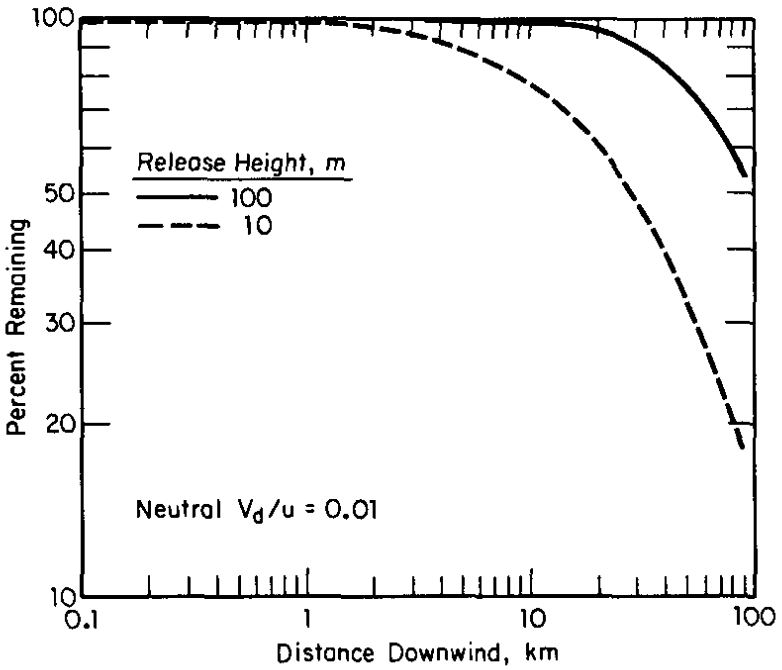

Figure 8. Calculations for Unstable Conditions - SRL Model

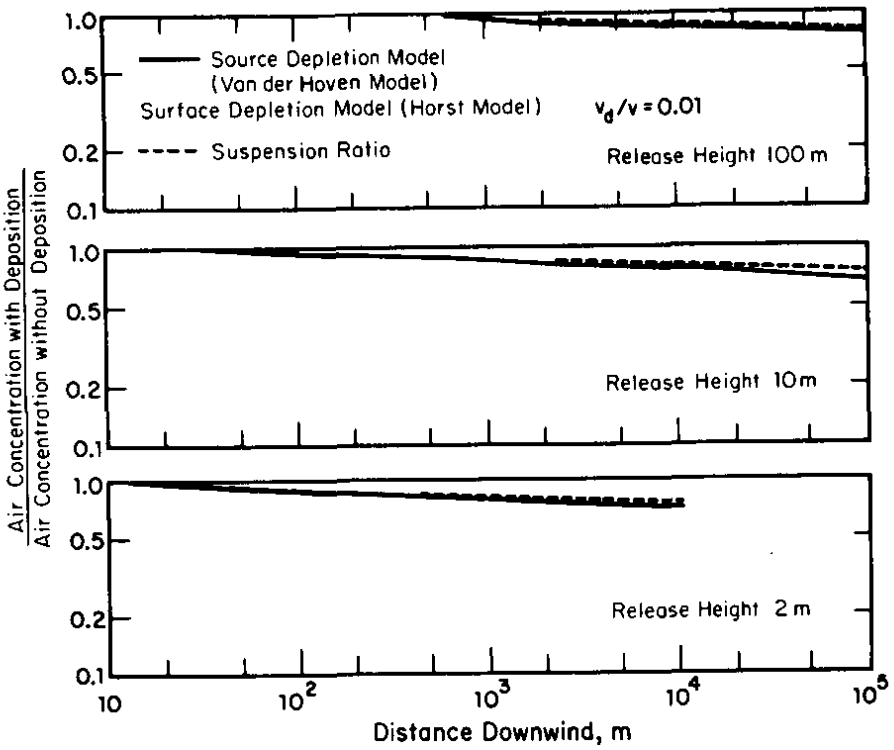

Figure 9. Calculations for Unstable Conditions - Horst and Van der Hoven Models

H/w*, where H is mixed-layer depth, and w* is the convective velocity scale. On a sunny afternoon, H and w* are on the order of 1000 m, and 1 m/sec, respectively, so the recycling time is only about 15 minutes. Therefore, a parcel of polluted air will be exposed to surface deposition processes dozens of times on a sunny, unstable day.

As a further illustration of the importance of mixed-layer depth to deposition, note in Figure 10 that the results for an unrealistic 10,000-m depth are almost identical to those for the Horst and Van der Hoven models (Figure 9). The very rapid deposition for the 500-m mixed-layer depth is probably excessive because Pasquill A stability should be associated with deep mixed-layers. In summary, models that allow unlimited vertical diffusion appear to underpredict surface deposition in unstable conditions.

Figure 11 presents results for a simulated ^{238}Pu release with a release height of 61 m (stack height at SRP). Cloud depletion is relatively slow for all stability classes for particle releases because neither gravitational settling nor Brownian diffusion is effective in the "gap" region around 1 micron, which contains most of the mass of the particle spectrum. However, rain increases ^{238}Pu deposition rates significantly because it is a fairly efficient scavenger of micron-sized particles. Figure 11 shows results for rainfall of 5 mm/hr in neutral conditions. When the ^{238}Pu data are divided into particle-size categories (Figure 12), the increased efficiency of scavenging because of Brownian diffusion under neutral to unstable conditions is seen to partially offset the decrease in deposition of 1- to 10-micron particles. The decrease is caused by the more intense turbulence, which is better able to keep moderate-sized particles suspended against the force of gravity.

Centerline deposition and surface concentration curves for the simulated ^{238}Pu release have maxima at different points downwind because gravitational settling deposits the largest particles almost immediately, before the main body of the cloud has reached the ground (Figures 13 and 14). The concentration maximum is closest to the source in unstable conditions because the downward diffusion of the cloud is more rapid. Lateral diffusion is also more rapid under unstable conditions, but less time is available to reduce concentrations before cloud touchdown.

The deposition of toxic gases is heavily dependent on surface concentration (Figure 15). The simulated chlorine gas releases in Figure 15 show the expected uptake by soil and vegetation for 1 g/sec and 10^4 g/sec release rates under slightly unstable conditions. Both releases experienced no loss by deposition until the centerline surface concentration dropped below 1 ppm. Because concentrations dropped below 1 ppm earlier for the smaller release,

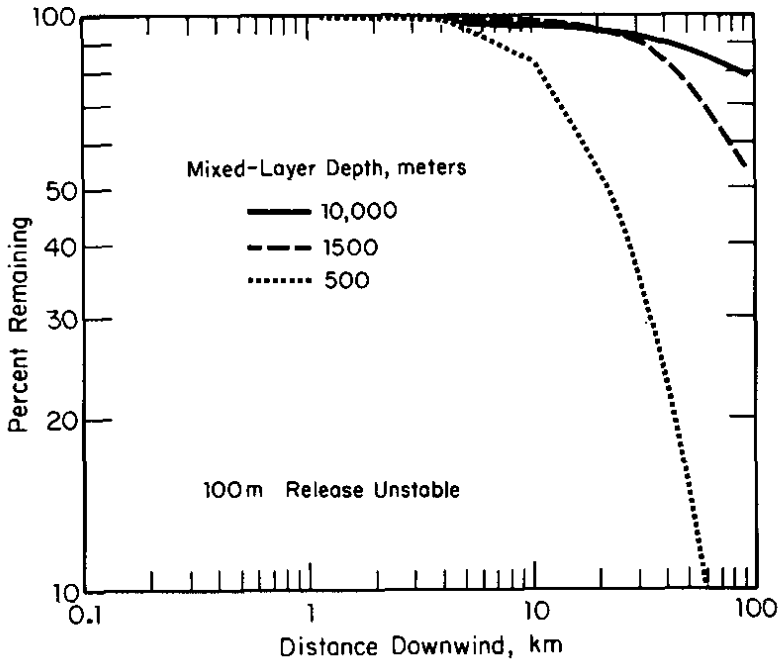

Figure 10. Deposition Calculations for Unstable Conditions with Different Mixed-Layer Depths - SRL Model

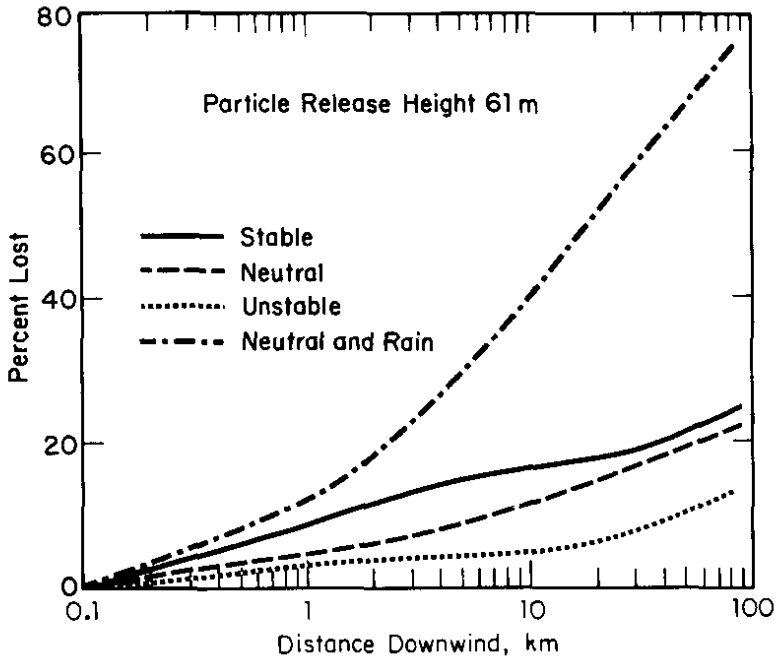

Figure 11. Particle-Deposition Calculation as a Function of Stability Class and Rain

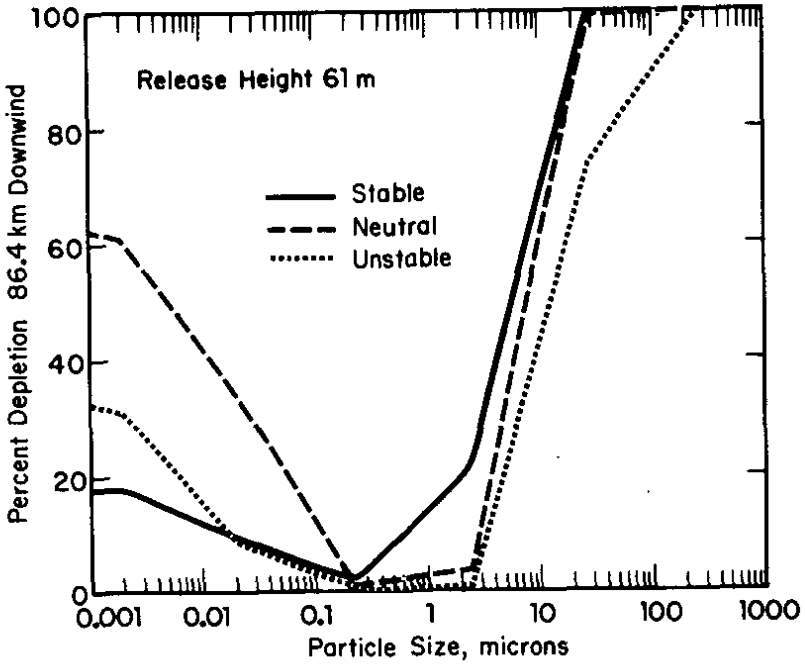

Figure 12. Effect of Particle Size on Deposition

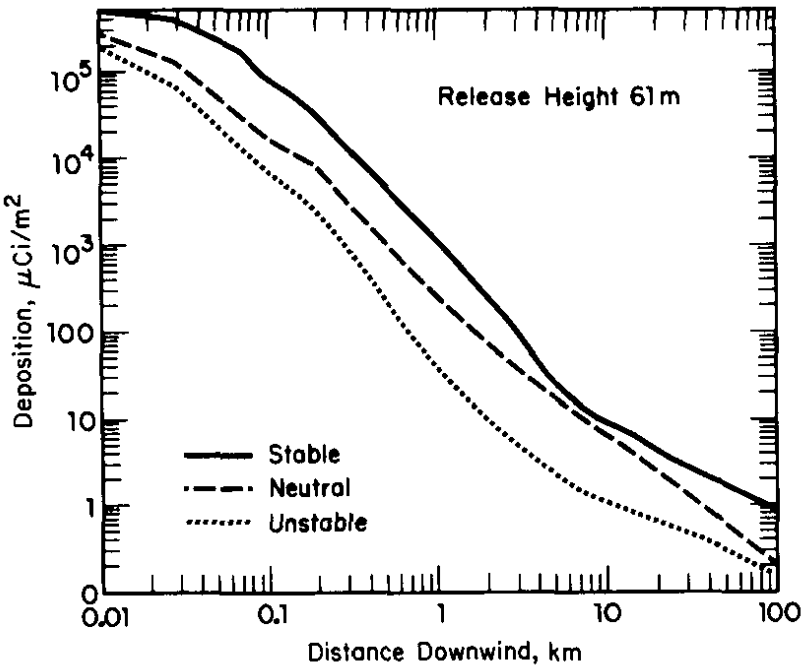

Figure 13. Effect of Downwind Distance on Deposition

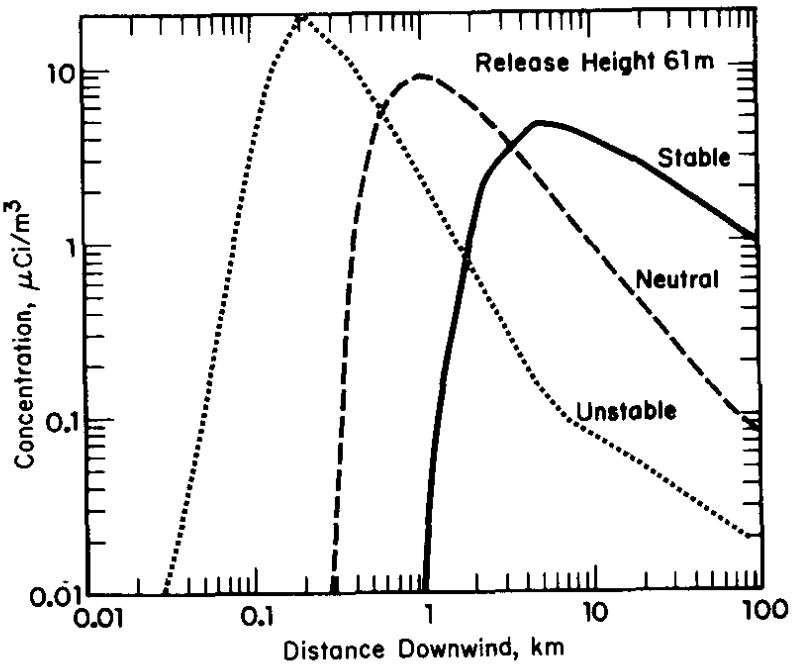

Figure 14. Effect of Downwind Distance on Atmospheric Concentration

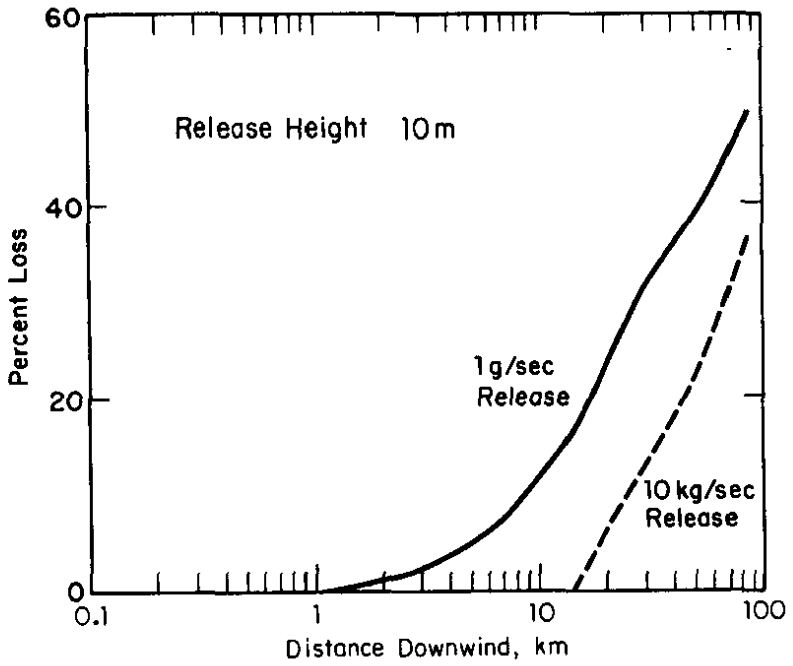

Figure 15. Gas Deposition Calculations

deposition also started earlier. The 1-ppm criterion crudely simulates the closing of leaf stoma as a reaction to high concentrations of toxic gases (see pages 23-24). This variable reaction to chemical pollutant concentrations means that predictions for a given set of meteorological conditions, release height, and release rate cannot be simply scaled up or down to fit another release rate.

FUTURE WORK

The equations for PFPL diffusion parameters will continue to be updated as new information is acquired through field measurements and theoretical studies. In particular, the effects of vertical wind shear on cloud growth will be included. Field measurements of the deposition of plutonium-bearing particles out to distances 25 km will be compared to model predictions. The methods for calculating deposition velocities will be updated as new information becomes available. For example, recent measurements[23] show that much of the SO_2 emitted from power plants rapidly converts to sulfate particles which settle out or are scavenged at the surface.

Additional emergency response codes are being added to the WIND System. An operational code now exists for prediction of the transport and dispersion of pollutants in a river. A research code is available for simulation of the initial slumping behavior of a liquified heavy gas release, before it evaporates and mixes thoroughly with the atmosphere.

PFPL now uses forecast winds provided by the Techniques Development Laboratory of the National Oceanic and Atmospheric Administration. These forecasts will be compared to forecasts from a one-dimensional boundary-layer code which will predict winds up to 12 hours in advance. A code for prediction of low-level, nocturnal, drainage winds is also under development. Pollutant concentrations stay high in drainage flows long after the release time because turbulence mixing is weak, and confined to a shallow layer near the ground.

COMPUTER PROGRAM DESCRIPTION*

The PFPL program is started by the user with Menu Option 6 of the WIND System. It is a highly modified version of an earlier program for computing and plotting atmospheric dispersion of pollutants released from any of the seven active plant areas at SRP or from other locations throughout the southeastern U. S. The original code had been modified by so many different programmers that it required almost 32K of PDP 11/40 memory to execute and had no structure.

---

* Written by J. H. Carswell, Computer Systems Division, Savannah River Laboratory.

The new version is divided into several subroutines and overlaid to produce a code that executes in about 17K of memory (Figure 16). The program is structured so that a moderately experienced programmer can follow the flow and make additions or changes. This is, however, not a complete rewrite of the earlier code, but rather a modification in which the earlier program was divided into subroutines. Thus, the structure of the code is still not optimal, either for efficiency or speed. Comment statements are supplied in places where the logic may be confusing.

OVERLAY STRUCTURE AND SUBROUTINES

The actual overlay structure is described in the file used in building the task. The contents of this file are shown below:

```
        .PSECT   TEKLET,RW,D,GBL,REL,OVR
        .PSECT   TKSTUF,RW,D,GBL,REL,OVR
        .PSECT   TKTRNX,RW,D,GBL,REL,OVR
        .ROOT    MAIN-*(MAIN1,MAIN2,MAIN3,MAIN4)
MAIN:   .FCTR    PFPL-TEKLET-TKSTUF-TKTRNX-[1,1]TEKTRO-ATTDET
MAIN1:  .FCTR    PFPLOT-PAGE-[140,140]DYDIFF-[140,140]TIMCVT
MAIN2:  .FCTR    PFPLIN-TWOOPT-(LVL1,LVL2,LVL3,LVL4,LVL5,LVL6,LVL7,LVL8)
MAIN3:  .FCTR    PFPLCM-PFFLX-PFFL2-ERGM-BESK-[140,140]DYDIFF-[140,140]TIMCVT
MAIN4:  .FCTR    PFPLWT-PAGE-TITLE1-TITLE2-[140,140]DYDIFF-[140,140]TIMCVT
LVL1:   .FCTR    OFSITE
LVL2:   .FCTR    ONSITE
LVL3:   .FCTR    [140,140]TIMCVT-[140,140]DYDIFF
LVL4:   .FCTR    TIMZUL-[140,140]DYDIFF
LVL5:   .FCTR    PRCWND-[140,140]ITIME-(SBLV5A,SBLV5B,SBLV5C,SBLV5D,SBLV5E)
SBLV5A: .FCTR    TVSVRD-[140,140]ARCGET-([140,140]AZMADJ,[140,140]INXCLC)
SBLV5B: .FCTR    LATWND
SBLV5C: .FCTR    CANWND
SBLV5D: .FCTR    MANWND
SBLV5E: .FCTR    FORWND-SBLV5F,SRLV5G,SBLV5H)
SBLV5F: .FCTR    JULIAN-WEIGHT-[30,30]UNLOCK-FORMIX
SBLV5G: .FCTR    [140,140]HRAGET-[140,140]HIXCLC-[140,140]INXCLC
SBLV5H: .FCTR    [140,140]ARCGET-([140,140]AZMADJ,[140,140]INXCLC)
LVL6:   .FCTR    RADACT
LVL7:   .FCTR    CHEMCL
LVL8:   .FCTR    PFINIT
        .END
```

The PSECT's describe COMMON areas used by the TEKTRONIX graphics package. PFPL.ODL is the name asigned to this file. It is stored under UIC = [6,1] on DP0. This file is called up at TASKBUILD time by the command file PFPL.CMD, also stored under UIC = [6,1] on DP0. The contents of the command file is shown below:

```
PFPL,PFPL/-SP=PFPL/MP
LIBR=CORLIB:RO
MAXBUF=3072
ACTFIL=3
ASG=MD:1
ASG=TI:5
ASG=LP:6
//
```

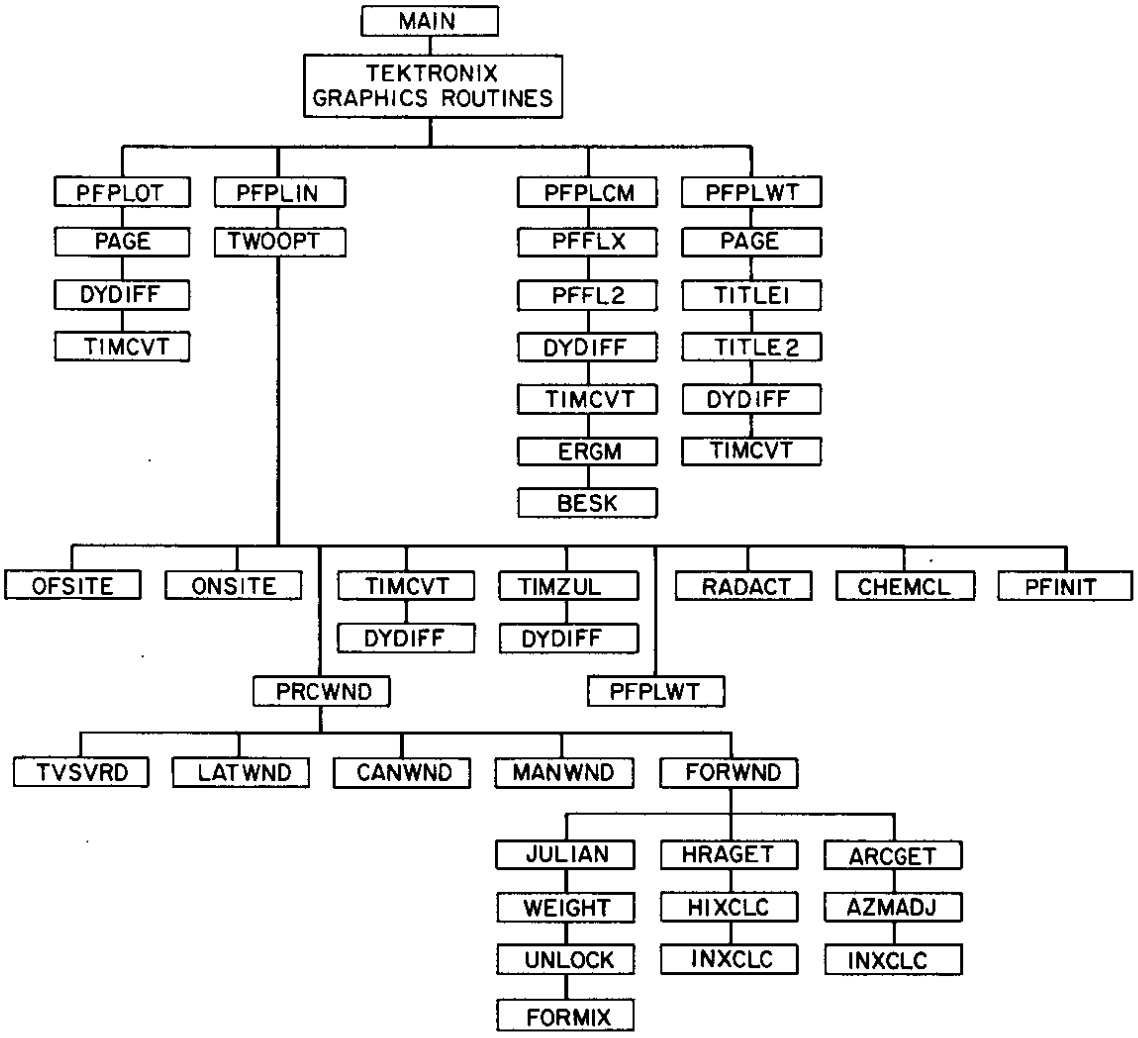

Figure 16. PFPL Subroutine Structure

Each of the subroutines used in PFPL is described briefly of below. Lists are included of input and output arguments, and the name of the source file for the subroutine stored under UIC [6,1] on DP0.

MAIN

Source file name: PFPL.FTN

Input arguments: None

Output arguments: None

This is the driver routine for the task. It calls each of the four sub-levels of the task. It also attaches and detaches the graphics terminal and requests the mapping task appropriate to the terminal being used (such as tasks PFPM01, PFPM06 for terminals TT01, TT06).

ATTACH and DETACH

Source file name: ATTDET.FTN

Input arguments: LUN The LUN for the terminal in question

Output arguments: ISTAT Status of operation
1 - complete
3 - directive error
n - actual I/O status

These subroutines attach or detach the I/O device specified by LUN.

PFPLIN

Source file name: PFPLIN.FTN

Input arguments: None

Output arguments: IINERR Error flag
0 - Successful
1 - Unsuccessful

This routine processes most of the user input options, sets up the flags, and calls the appropriate subroutines for getting the data corresponding to a given option. In addition to the multiple

choice options provided the user by this routine, it also allows the user to enter a date and time, or, by entering nothing, to default to the current date and time. This date and time will be used for the start of the release. The relation of this time to the current time becomes important if the user chooses automatic wind data. The error flag is set if there is an I/O device error, if an error occurs while trying to read the internal clock, or if invalid data is discovered in one of the lower level processing routines.

TWOOPT

Source file name: TWOOPT.FTN

Input arguments:	IANS	Answer to be checked
	IOPT1	Possible value of option
	IOPT2	Possible value of option
Output arguments:	IRES	Option flag - 0 - if IANS = IOPT1 or blank 1 - if IANS = IOPT2
	IERR	Error flag 0 - No error 1 - IANS ≠IOPT1,IOPT2, or blank

This routine compares a user-entered answer (IANS) against three possible values (IOPT1, IOPT2, and ' ') and sets a return flag (IRES) accordingly.

TIMCVT

Source file name: TIMCVT.FTN

Input arguments:	IMO-ISEC	Zulu time and date
Output arguments:	JMO-JSEC	Local time and date
	IAMPM	'AM' or 'PM'
	IDLSTD	'DT' or 'ST' for daylight or standard time
	IERR	= 1 if any invalid data

This subroutine, written by Jim Froggatt of the Engineering Services Division, DuPont-Wilmington, calculates eastern daylight or standard time given Zulu time. It is designed to work between the years 1979 and 2050. If an error is found in any of the input parameters, the error flag is set and returned.

TIMZUL

Source file name: TIMZUL.FTN

Input arguments:	IMO-ISEC	Local time and date
	IAMPM	'AM' or 'PM'
	IDLSTD	'DT' or 'ST' for daylight or standard time
Output arguments:	JMO-JSEC	Zulu time and date
		= 1 if any invalid data

This subroutine is the inverse of TIMCVT. It calculates Zulu time, given eastern daylight or standard time. Note that the input time is on a 12-hour scale using AM and PM, and not a 24-hour scale.

DYDIFF

Source file name: DYDIFF.FTN

Input arguments:	IFCTN	Function indicator (0 or 1)
	IMO-IYR	Date
	JMO-JYR	Date (input only if IFCTN = 0)
	ISPAN	Number of days between "I" and "J" Dates (input only if IFCTN = 1)
Output arguments:	JMO-JYR	Date (output only if IFCTN = 1)
	ISPAN	Number of days between "I" and "J" Dates (output only if IFCTN = 0)
	IERR	= 1 if any invalid data

If IFCTN = 0, this subroutine calculates the number of days between the "I" and "J" dates supplied to it. If IFCTN = 1, the subroutine calculates the "J" date given the "I" date and the span of days.

PFPLOT

Source file name: PFPLOT.FTN

Input arguments: None

Output arguments: IERR = 1 if an error is detected in any of the lower level routines

This subroutine is responsible for writing the input summary to the terminal and for copying it for the user if he has so opted. First it completes the wind data arrays if they were not filled automatically or by the user. It also computes and fills the displacement, travel time, and mean velocity arrays.

PFPLCM

Source file name: PFPLCM.FTM

Input arguments: None

Output arguments: IERR = 1 if an error is detected in any of the lower level routines

This subroutine performs the major portion of the calculations. It determines downwind concentrations and doses for chemicals and specific radioactive isotopes other than noble gases for which no particulate deposition is to be considered. Separate subroutines are called for the noble gases and for deposition calculations.

PFFLX

Source file name: PFFLX.FTN

Input arguments:

NWND	Index of time interval
NWND1	Index indicating hours since start
SIGY	Standard deviation of lateral cloud width
SIGZ	Bounded standard deviation of cloud depth
SZ	Unbounded standard deviation of cloud depth

Output arguments:

DEP	Material deposited each time step
BET	% of cloud removed by all depletion processes
PLU	Plume concentration
PUF	Puff concentration
GLCPC	Concentration of material released
IERR	= 1 if an error is detected in any of the lower level routines

This is the major subroutine used in computing the percent deposition of the release material as a function of distance from the source, as described on page 16.

PFFL2

Source file name: PFFL2.FTN

Input arguments: ICALL 0 - Indicates whether radioactive isotopes other than tritium and I-131 if 0, or
1 - chemical, tritium or I-131 if 1.

	NWND	Index of time interval
	HINV	Mixed-layer depth
	DEL	Radioactive decay constant
	DELR	Rain washout coefficient
	DELT	Time interval in seconds
	TAU	Cloud recirculation time, sec
	ZREF	Surface layer depth, m
	DV	Deposition velocity, m/sec
	VF	Fall velocity, m/sec
	DQTDT	Time rate of change of cloud mass above surface layer
	QT	Portion of cloud mass above surface layer
	QR	Portion of cloud mass in surface layer
	CUT	Width of particle size sector for ICALL = 0
	BUNG	Cloud surface-layer interaction factor
	BORC	1.0 - ERF (BUNG)
	T	Cloud travel time
	SZ	Unbounded standard deviation of cloud depth
	SIGY	Standard deviation of lateral cloud width
	SIGZ	Bounded standard deviation of lateral cloud width
	U	Wind speed, m/sec
Output Arguments:	PLU	Plume concentration
	PUF	Puff concentration
	FPLU	Gaussian/well-mixed plume transition factor
	FPUF	Gaussian/well-mixed puff transition factor
	BET	% of cloud removed by all depletive processes
	BET1	BET from previous time step
	DPL	Material deposited
	DQT1	Amount of pollutant left above the top of the descending mixed layer
	DQT2	Value of DQT1 for previous time step

This is the secondary subroutine used in computing the depletion and deposition of a cloud. It is called by PFFLX, and the arguments have different significance for chemical and radioactive releases.

ERGM

Source file name: ERGM.FTN

Input arguments:	HL	Mixed-layer depth, m
	NX	Index of time interval
	HS	Stack height, m

	SIGZ	Bounded standard deviation of cloud depth
	SIGY	Standard deviation of lateral cloud width
	UBAR	Mean wind speed of time interval
	BAR1	Displacement from source, m
Output arguments:	BAR2	Dose along centerline, rem
	BAR3	Dose at 2*SIGY, rem
	RXFAC	Reactor power fraction relative to 1000 MW
	FRIOD	Fraction of iodine released
	Q	Source term diminished by radioactive decay
	IRK	If 0, compute dose integrals and depleted source; If 1, compute depleted source only

This subroutine computes distributed total doses for material Gaussian integration in both Y and Z directions, with mixing height specified. It is used here for noble gas releases (Appendix A).

BESK

Source file name: BESK.FTN

Input arguments:	X	All arguments are parameters used in the numerical integration over Gaussian clouds
Output arguments:	BKO	
	BK1	
	BKI1	

This is a secondary routine called by ERGM to perform the actual numerical integrations of the Gaussian distribution. See Appendix A.

PFPLWT

Source file name: PFPLWT.FTN

Input arguments: None

Output arguments:	IERR	= 1 if an error is detected in any of the lower level routines

This subroutine writes to the terminal the concentration, the dose for a radioactive release, and the percent deposition of the cloud, if applicable, for each time step. It also writes the concentration and displacement to the disk file DPO:[167,167]PFPT.DAT for use in the mapping task.

PAGE

Source file name: PAGE.FTN

Input arguments: None

Output arguments: None

This subroutine increments the page number for the hardcopy output, gets the current date and time, and writes title, date, time, and page number on each new page of output.

TITLE1

Source file name: TITLE1.FTN

Input arguments:	NAME1	Release type - radioactive (0) or chemical (1)
	NAME3	limits type - English (0) or metric (1)

Output arguments: None

This subroutine writes appropriate headings for each column of data on a page of output.

TITLE2

Source file name: TITLE2.FTN

Input arguments:	METRIC	limits types - English (0) or metric (1)
	IOPT	Release type - radioactive (0) or chemical (1)
	IFLAG	Cloud type - plume (0) or puff (1)
	IBAG	Noble gas indicator - No (0); yes (1)

Output arguments: None

This subroutine writes information defining concentrations and doses at the bottom of each page.

ONSITE

Source file name: ONSITE.FTN

Input arguments: None

Output arguments: IERR Error flag for I/O error at terminal

This subroutine determines, for an onsite release, the plant area where the release occurred. Longitude and latitude, are stored in COMMON.

OFSITE

Source file name: OFSITE.FTN

Input arguments: None

Output arguments: IERR Error flag for I/O error at terminal

This subroutine allows the user to choose an offplant release site from a list of sites, or to specify another site by entering the longitude and latitude of that site. If another site is specified, the screen coordinates of the site are computed. Regardless of the choice, longitude, latitude, and screen coordinates are stored in COMMON.

PRCWND

Source file name: PRCWND.FTN

Input arguments: None

Output arguments: IERR Flags I/O error from disk.

This subroutine initializes arrays in the WINDS COMMON, gets the latest tower data, and directs control to the subroutine appropriate for the type of wind data the user requested.

TVSVRD

Source file name: TVSVRD.FTN

Input arguments: None

Output arguments: IERR Flags error condition in reading disk

This subroutine gets the latest hourly-averaged seven-tower data for an onsite location from the system archive files. For the offsite locations in the immediate vicinity of the plant, it reads SAM data for the area from the disk file

DPO: [7,2] TVSVDT.DAT

The data arrays are stored in the TOWERS COMMON.

LATWND

Source file name: LATWND.FTN

Input arguments: None

Output arguments: None

This subroutine stores the latest wind data, read in TVSVRD, in the first positions of the arrays in the WINDS COMMON.

MANWND

Source file name: MANWND.FTN

Input argument: None

Output arguments: KKZ Number of sets of data entered
IABORT Flags last set of data entered

This subroutine allows the user to enter his own values for wind speed, direction, etc. These values are entered in the appropriate arrays in the WINDS COMMON. These data may be saved for later reuse as canned data.

CANWND

Source file name: CANWND.FTN

Input arguments: None

Output arguments: IERR Flags I/O error on disk and invalid data

This subroutine allows the user to choose from a list of canned wind characteristics. The list and the data are both stored in the disk file

DPO: [7,2] CANNED.DAT

The data chosen are stored in the appropriate arrays in the WINDS COMMON.

FORWND

Source file name: FORWND.DAT

Input arguments: None

Output arguments: None

This subroutine reads forecast winds stored on the disk file

DPO: [7,2] MOSOUT.DAT,

and, if necessary, links it with observed wind stored in the archive files. For onsite location, the observed data are read from the 15-minute seven-tower archive files; for offsite locations adjacent to the plant, the WJBF SAM hourly data archive files are used. When observed data must be linked to forecast data, the latest observed "u" and "v" components of the velocity are allowed to "persist" for four hours before a "cosmetic" adjustment is made with the remaining forecast values. A weighted-average adjustment is made to the forecast values of σ_a and σ_e, with no persistance allowed. The resulting winds are stored in the appropriate arrays in the WINDS COMMON.

HRAGET

Source file name: HRAGET.FTN

Input arguments:

IMO-ISEC	A given time and date
ISTART	A flag to indicate number of hours before or after given time first record should be read
IREC	Number of one hour records to retrieve

Output arguments:	JMO-JSEC	Not used in this task
	IFILE	Not used in this task
	ILAST	Not used in this task
	INTHRA (11,48)	Not used in this task
	RELHRS (7,48K)	Real results array
	SEC	Not used in this task
	IFULL	Not used in this task
	ISTAT	Read status
	IERR	Error flag

(For a more comprehensive description of the arguments, refer to the subroutine listing.)

This subroutine supplies the calling routine with up to 48 hours of hourly-averaged data. The data are read from either of the two archive files;

DPO: [7,2]HRAIX1.DAT or
DPO: [7,2]HRAIX2.DAT.

HIXCLC

Source file name: HIXCLC.FTN

Input arguments:	IMO-ISEC	A given date and time
Output arguments:	INEXT	Next record to read from archive file
	IFILE	Index of archive file to be read
	IWKDAY	Not used in this task
	IERR	Error flag

For a given date and time, this subroutine determines the index of the archive file containing data for that time and the number of the appropriate record within the file.

INXCLC

Source file name: INXCLC.FTN

Input arguments:	IFLTYP	File type, always 'LONG' for this task
	IMO-ISEC	A given date and time
Output arguments:	INEXT	Index of next record to read from archive file
	IFILE	Index of archive file to be read
	IERR	Error flag

This subroutine is used together with HIXCLC to determine the correct file index and record number from which to read data for a given date and time.

ITIME

Source file name: ITIME.FTN

Input arguments: None

Output arguments:

IHR	
IMIN	Current time of day (Zulu)
ISEC	

This routine reads the current time of day from the internal system clock.

ARCGET

Source file name: ARCGET.FIN

Input arguments:

ISET	Quality assurance flag
IMO-ISEC	A given time and date
ISTART	A flag to indicate number of 15-minute intervals before or after given time first record should be read
IREC	Number of 15-minute records to retrieve

Output arguments:

JMO-JSEC	Ending time and date of last 15-minute interval read
IFILE	Not used in this task
ILAST	Not used in this task
TVDATA(32,5)	Result array - WJBF TV Tower
SVDATA(24,5)	Result array - Seven Towers
APDATA(10,3)	Not used in this task
LTVFLG(36,6)	Not used in this task
LSVFLG(36,6)	Not used in this task
SEC	Not used in this task
IFULL	Not used in this task
ISTAT	Read status
IERR	Error Flag

(For a more comprehensive description of the arguments, refer to the subroutine listing.)

This subroutine supplies the calling routine with up to 12 hours of 15-minute averaged TV and SEVEN TOWER DATA. These data are read from one of the following files:

DPO: [177,177]ARCIX1.DAT,
DPO: [177,177]ARCIX2.DAT, or
DPO: [177,177]ARCIX3.DAT

AZMADJ

Source file name: AZMADJ.FTN

Input arguments:	ITVSV	Flag TV or SEVEN TOWER DATA
	PREVNO	Number of points accumulated prior to current 15-minute interval
	POINTS	Number of points in current 15-minute interval for determining a weighted average
	ICHAN	Channel number of reading
	AZM	Mean AZIMUTH reading for the channel for the 15-minute record being processed
Output arguments:	AZM	Adjusted AZIMUTH reading for the channel for the 15-minute record being processed
	IERR	Error flag

This subroutine supplies a corrected AZIMUTH for either TV or SEVEN TOWER DATA.

FORMIX

Source file name: FORMIX.FTN

Input arguments:	JNOW	Internal index representing current time
	JCALS	Internal index representing time of start of calculation
	JFORS	Internal index representing time of first available forecast
Output arguments:	IERR	Error flags

This subroutine determines the values of mixed-layer depth to be used throughout the calculation. The larger of the prescribed climatological value and the wind shear value will be used. In the future, the larger of the wind shear value and the convective value will be used, but currently we do not have the ability to automatically get a forecast reading of the convective mixed-layer depth.

COMMON AREAS

The contents of the several COMMON areas used by PFPL are listed below with a definition of these variables. Excluded are the COMMON areas needed to support the TEKTRONIX graphics routines. Refer to the TEKTRONIX documentation for information regarding these areas.

COMMON Name: INPUT

Contents:

Variable Name	Type	Definition
XLAT	R*4	Latitude of release site
XLON	R*4	Longitude of release site
AREANM	R*4	Name of area for on-site calculation
HSTK	R*4	Stack height
HTLID	R*4	Mixed-layer depth
STOPE	R*4	Isotope name for radioactive release
HAFLFE	R*4	Halflife of isotope for radioactive release
DOSECV	R*4	Dose factor of isotope for radioactive release
RXFAC	R*4	For noble gases, reactor power fraction relative to 1000 MW
FRIOD	R*4	For noble gases, iodine release fraction
Q	R*4	Release rate or total release in metric units
QCR	R*4	Release rate for plume calculation in units entered by user
GASS	R*4	Name of gaseous substance released for a chemical release
GASMWT	R*4	Molecular weight of gas for chemical release
GASTMP	R*4	Temperature of gas for a chemical release
SIGY0	R*4	Horizontal size of cloud at time zero
SIGZ0	R*4	Vertical size of cloud at time zero
DELTAT	R*4	Time interval in seconds
PLMTM	R*4	For a plume calculation, length of time of release
XJNAM(6)	R*4	Optional job title for page headings
ICOPY	I*2	0 - Make a hardcopy of output 1 - Do not make a hardocpy of output

Variable Name	Type	Definition
IEOM	I*2	0 - English units 1 - Metric units
ILOC	I*2	0 - Onsite release 1 - Offsite release
ICRD	I*2	0 - Offsite coordinates are catalogued for easy use 1 - Offsite coordinates are not catalogued; user will enter his own
IWND	I*2	1 - Use current wind data 2 - Use canned wind data 3 - Use manually entered wind data 4 - Use forecast/observed wind data
IPFPL	I*2	0 - Plume calculation 1 - Puff calculation
IRLSE	I*2	0 - Radioactive release 1 - Chemical release
IMO-ISEC	I*2	Date and time (Zulu) of release start
JMO-JSEC	I*2	Date and time (Eastern) of release start
IAMPM	I*2	'AM' or 'PM' for Eastern time
IDLSTD	I*2	'ST' or 'DT' for Eastern Standard or daylight time
NAREA	I*2	Index of onsite area (1-12)
NWNDX	I*2	Number of hours of calculation
NZT	I*2	Number of hours of input wind data
IDC	I*2	Time interval for output for last eleven hours of calculation
IDEP	I*2	0 - Include deposition calculation 1 - Ignore deposition
IRAIN	I*2	0 - No rainfall 1 - Light rainfall 2 - Heavy rainfall
IPAGE	I*2	Page number of output
IJNAM	I*2	0 - No optional job title entered 1 - Optional job title will be used
IFCT	I*2	Number of time steps per hour

COMMON Name: WINDS

Contents

Variable Name	Type	Definition
UVEL(24)	R*4	Array containing "u" component of velocity by time interval
VVEL(24)	R*4	Array containing "v" component of velocity by time interval
SIGA(24)	R*4	Array containing standard deviation of horizontal wind direction by time interval
SIGE(24)	R*4	Array containing standard deviation of vertical wind direction by time interval
ADIR(24)	R*4	Array for temporarily storing wind direction by time interval
X(72)	R*4	X-coordinate of distance from site in meters by time interval
Y(72)	R*4	Y-coordinate of distance from site in meters by time interval
R(72)	R*4	Total displacement from site in meters by time interval
TRVTME(72)	R*4	Total time of travel by time interval
UMEAN(72)	R*4	Mean velocity by time interval
SIGYA(72)	R*4	Array for temporarily storing standard deviation of lateral cloud width by time interval
GAMC(72)	R*4	Gamma dose by time interval along the centerline, rem
GAM2C(72)	R*4	Gamma dose by time interval at a distance of $2\sigma_y$ from centerline, rem
CPC(72)	R*4	Centerline concentration by time interval, measured in parts per million for a chemical release and picoCuries per cubic meter for a radioactive release
C2SY(72)	R*4	Concentration by time interval at a distance of $2\sigma_y$ from the centerline, measured in parts per million for a chemical release and picocuries per cubic meter for a radioactive release
DEP(72)	R*4	The amount of pollutant by time interval deposited along the centerline, measured in grams per square meter for a chemical release and disintegrations per minute per square meter for a radioactive release
DEPV(72)	R*4	The percent of the cloud gone due to deposition and radioactive decay, by time interval
HTIN(72)	R*4	Mixed-layer depth in meters by time interval

COMMON Name: TOWERS

Contents:

Variable Name	Type	Definition
TVBUF (32,5)	R*4	Wind data read from the WJBF TV tower
SVBUF (24,5)	R*4	Wind data read from the seven towers
UX	R*4	Fifteen-minute averaged "u" component of wind velocity
VY	R*4	Fifteen-minute averaged "v" component of wind velocity
SIGAZ	R*4	Fifteen-minute averaged horizontal standard deviation of wind direction in degrees
SIGEL	R*4	Fifteen-minute averaged vertical standard deviation of wind direction in degrees

SAMPLE RUN OF PFPL

An example of INPUT/OUTPUT for a simulated release (Figure 17) shows requests for information by the PFPL code and the answers that the operator keyed in. Note that all questions can be answered simply by hitting the return key, which causes the code to use the stored or default values.

The operator first decides whether he wants paper copy of the results, next metric or English units, then the release location (either onsite or offsite), the site release point, and release height. In the case of an offsite release, the operator only has to specify a site number (see Figure 18) if the site name and location are stored in the computer. Otherwise, the operator must specify the site latitude and longitude.

Next, the time of release is entered, which can be in the past, present, or future. The computational timestep follows, which allows coarse or fine resolution in time (and space) for the predicted concentrations and deposition. The wind type option allows a choice of latest observed winds, canned (archived) winds for testing and demonstration, manual input, or automatic winds. The automatic option combines observations from previous hours, latest observations, plus forecast winds into one continuous series. The forecast winds are adjusted toward a persistence forecast for 2 to 4 hours after the present, depending on the discrepancy between the forecast and observed winds over the past few hours. (See Reference 24 for a complete discussion of the source of the forecast winds and their adjustment.)

Following the wind option are several questions dealing with the nature of the release. First, the operator must decide if the release is to be treated as an instantaneous (puff) or continuous (plume) release. The appropriate mathematical approximation depends on the duration of the release and the wind speed. The critical release duration time is calculated and displayed by the code.

Radioactive and chemical releases can be simulated; in this case, the radioactive option was chosen. The total release in curies is next, followed by initial cloud size.

```
TO ABORT PROGRAM DURING INPUT, HIT CTRL-Z.
TO CANCEL LINE OF INPUT BEFORE ENTRY, HIT CTRL-U.

HARD COPY?  YES OR NO.  DEFAULT IS YES.


ENTER JOB NAME OF UP TO 24 CHARACTERS, TO BE USED AS A PAGE HEADER.
 DEFAULT PAGE HEADER GIVES RELEASE TYPE AND GAS OR ISOTOPE NAME.
DEMONSTRATION
 (M)ETRIC OR (E)NGLISH UNITS?  DEFAULT IS ENGLISH.
M
 RELEASE LOCATION AT SRP?  TYPE YES OR NO.  DEFAULT IS YES.

 RELEASE LOCATION 'AA' (FOR A AREA), 'CC', 'DD', 'FF', 'HH', 'KK', 'PP'
 ARE AVAILABLE.  DEFAULT IS 'KK'.
FF


 ENTER STACK HEIGHT IN METERS.  DEFAULT IS 61.0 M.
36
 ENTER TIME AND DATE OF RELEASE, FOR EXAMPLE:
 0915 AM 120379  (HRMN AM MODAYR); DEFAULT IS PRESENT' HOUR
 REMEMBER, NOON IS 0000 PM, AND MIDNIGHT IS 0000 AM
0200 PM 042081

 ENTER TIME STEP IN MINUTES (1-6 OR 10) TO BE USED IN CALCULATIONS.
 DEFAULT IS 10 MINUTES

 INDICATE TYPE OF WINDS---(L)ATEST, (C)ANNED, (M)ANUAL, (A)UTOMATIC.
 DEFAULT IS 'L'.
A

  TYPE 'PF' FOR PUFF OR 'PL' FOR PLUME.  DEFAULT IS 'PF'.
 NOTE:  IF RELEASE IS LONGER THAN   2.6 MIN. USE PLUME.
 PF
  RADIOACTIVE RELEASE ?  YES OR NO.  DEFAULT IS YES.

  ENTER ISOTOPE FOR DOSE FACTORS:
       TYPE PU 8 FOR PLUTONIUM-238
       TYPE PU 9 FOR PLUTONIUM-239
       TYPE CF52 FOR CALIFORNIUM-252
       TYPE CM44 FOR CURIUM-244
       TYPE I131 FOR IODINE-131
       TYPE C060 FOR COBALT-60
       TYPE HTO  FOR TRITIUM
       TYPE FP   FOR FISSION PRODUCT (RU)
       TYPE GASN FOR NOBLE GASES
       OR HIT RETURN FOR NO ISOTOPE.
  PU 8

  ENTER TOTAL RELEASE IN CI.  DEFAULT IS 1 CI
  .0001
  ENTER INITIAL HORIZONTAL SIZE OF CLOUD IN METERS
       (DEFAULT IS 1 M)

  ENTER INITIAL VERTICAL SIZE OF CLOUD IN METERS
       (DEFAULT IS 1 M)

  DO YOU WANT TO COMPUTE % DEPOSITION?  YES OR NO.  DEFAULT IS YES.

   ENTER AMOUNT OF RAINFALL:  0-NONE; 1-LIGHT; 2-HEAVY
  1

   OUTPUT EVERY TIME STEP FOR FIRST SIX TIME STEPS.
   ENTER DESIRED FREQUENCY IN TIME STEPS FOR REMAINING OUTPUT
   MAX IS 10; DEFAULT IS 3
  2
```

Figure 17. Input/Output for a Simulated Release

```
LOC NO.   LOCATION            LATITUDE   LONGITUDE

   1      704U                33D 17M    81D 43M
   2      MEMPHIS,TENN.       35D  7M    90D  3M
   3      LACOMBE, LA         30D 18M    89D 56M
   5      BELLEFONTE          34D 43M    85D 55M
  10      BROWNS FERRY        34D 42M    87D  7M
  15      BRUNSWICK           33D 58M    78D  1M
  20      CATAWBA             35D  3M    81D  4M
  25      CHEROKEE            35D  2M    81D 32M
  30      CRYSTAL RIVER       28D 57M    82D 42M
  35      FARLEY              31D 13M    85D  6M
  40      GENERAL ELECTRIC    34D 19M    78D  5M
  45      HATCH               31D 56M    82D 21M
  50      MCQUIRE             35D 26M    80D 57M
  55      OCONEE              34D 47M    82D 53M
  60      PERKINS             35D 51M    80D 27M
  65      HB ROBINSON         34D 24M    80D 10M
  70      ST. LUCIE           27D 21M    80D 15M
  75      SHERRON HARRIS      35D 38M    78D 57M
  80      SUMMER              34D 18M    81D 19M
  85      TURKEY POINT        25D 26M    80D 20M
  90      VOGTLE              33D  9M    81D 46M
  95      WESTINGHOUSE        33D 53M    80D 55M
  99      CONTINENTAL CAN     33D 20M    81D 57M
 ENTER DESIRED LOCATION NO. (HIT RETURN TO ENTER MANUAL COORDINATES)
25
```

Figure 18. Offsite Locations Stored in Computer Memory

Deposition calculations are optional; if they are not used, the code uses a simple reflecting Gaussian model. The rainfall option allows the operator to roughly approximate the additional removal of gaseous or particulate pollutants by rain. Finally, the output interval allows the operator to vary the printout interval after the first six timesteps.

The input information supplied by the operator is printed out by the PFPL code, along with other relevant information (Figure 19). The meteorological data that are used in the computations follow. In the data columns, wind speeds are either m/sec or miles per hour, and wind direction is in degrees from true north. Siga and sige refer to the standard deviations of the short term wind fluctuations in the horizontal and vertical planes, respectively. The mixing depths in meters or feet are printed in the final column, under HTINV. Short-term forecasts of mixed-layer depths over SRP are made by a separate code, which was based on research by Garrett.[25]

The actual calculations (Figure 20) are presented as a function of distance from the release point and time after release. The approximate cloud width is presented in terms of the distance needed for a $2\sigma_y$ decrease in concentration to 13.5% of the centerline value, based on a Gaussian profile. Cloud centerline doses (in rems) and concentrations at ground level (pCi/m^3) are calculated next. The dose at the edge of the cloud ($2\sigma_y$) is listed next, followed by computed centerline deposition at the ground. Deposition is expressed in terms of disintegrations per minute, for the convenience of field verification crews. Finally, the percentage of the original release that has been removed from the atmosphere by surface deposition, rain, and radioactive decay is listed. This final column gives the operator a quick impression of the net efficiency of all removal processes.

Figure 21 presents cloud widths and trajectories on successively larger grids. The plotted cloud width is $4\sigma_y$, and thus encompasses about 95% of a Gaussian cloud. Clouds are plotted at locations corresponding to one-hour travel intervals, except for the first graph, which plots at 20 minute intervals. The plots represent puff trajectories which are calculated with winds averaged only over SRP. Because only SRP winds are used, the trajectory will often be in error at large distances from the release point. For a continuous (plume) release that lasts for more than about an hour, the plotted trajectory and cloud width will not give an accurate impression of the area actually covered by the pollutant. For a 12-hour release during a period of shifting winds, 12 separate trajectories would be needed to show the total area covered by the plume.

DEMONSTRATION 4/20/81 2:42 PM ST PAGE 1

THE FOLLOWING DATA DETERMINE GROUND LEVEL DOSES AND CONCENTRATIONS AT CLOUD CENTERLINE AS A FUNCTION OF TIME AND TRAVEL DISTANCE. ALSO PRESENTED IS THE DOSE FOR RADIOACTIVE RELEASES OR THE CONCENTRATION FOR CHEMICAL RELEASES AT A DISTANCE EQUAL TO 2-SIGY FROM THE PUFF CENTERLINE. THE INPUT DATA CONSISTS OF HOURLY AVERAGED WIND DATA. A MAXIMUM OF TWELVE HOURS OF DATA IS INPUT, BUT OUTPUT CAN BE COMPUTED EVERY TIME STEP.

START TIME OF RELEASE IS 2: 0 PM ST 4/20/81

PUFF RELEASE.

TIME INTERVAL FOR CALCULATION IS 10 MINUTES

THIS IS A DEPOSITION CALCULATION WITH LIGHT RAIN.

RADIOACTIVE RELEASE--ISOTOPE IS PU 8
HALFLIFE IS 7.556E 05 HOURS.
SOURCE TERM IS 1.000E-04 CI

STACK HEIGHT IS 36.0 M

RELEASE LOCATION AT SRP, F AREA.

DEMONSTRATION 4/20/81 2:42 PM ST PAGE 2

TIME	W-SPD (MPS)	W-DIR	SIGA	SIGE	HTINV (M)
2: 0 PM ST	7.04	276.35	13.65	10.84	1000.0
3: 0 PM ST	7.04	276.35	12.79	10.92	1000.0
4: 0 PM ST	7.04	276.35	13.38	11.42	900.00
5: 0 PM ST	6.01	280.77	14.67	11.64	800.00
6: 0 PM ST	3.34	309.88	15.71	11.78	700.00
7: 0 PM ST	2.72	333.48	16.47	11.84	600.00
8: 0 PM ST	2.60	339.27	15.87	11.63	500.00
9: 0 PM ST	2.50	345.68	15.00	11.33	400.00
10: 0 PM ST	2.40	352.57	14.00	11.00	300.00
11: 0 PM ST	2.50	15.30	14.67	10.33	312.50
0: 0 AM ST	2.60	32.80	15.33	9.67	325.00
1: 0 AM ST	2.70	44.60	16.00	9.00	337.50

Figure 19. Input Printout from PFPL

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DISTANCE (KM)	ETA HR:MIN	2-SIGY (KM)	CNTR-LINE DOSE	CNTR-LINE CONC	2-SIGY DOSE	CNTR-LINE DEP	PERCENT GONE
4.22	2:10 PM ST	0.44	5.69E-06	9.45E-01	7.70E-07	6.67E 00	7.1
8.45	2:20 PM ST	0.89	1.67E-06	1.39E-01	2.26E-07	1.78E 00	10.9
12.67	2:30 PM ST	1.33	8.21E-07	4.56E-02	1.11E-07	1.00E 00	14.0
16.89	2:40 PM ST	1.77	4.98E-07	2.08E-02	6.74E-08	6.52E-01	16.8
21.12	2:50 PM ST	2.21	3.38E-07	1.13E-02	4.58E-08	4.59E-01	19.2
25.34	3: 0 PM ST	2.63	2.77E-07	7.78E-03	3.75E-08	3.43E-01	21.4
33.78	3:20 PM ST	3.33	2.09E-07	4.62E-03	2.82E-08	2.23E-01	25.1
42.23	3:39 PM ST	3.95	1.68E-07	3.15E-03	2.28E-08	1.59E-01	28.2
50.68	4: 0 PM ST	4.52	1.42E-07	2.32E-03	1.92E-08	1.22E-01	30.9
59.12	4:19 PM ST	5.06	1.22E-07	1.78E-03	1.65E-08	9.80E-02	33.2
67.57	4:40 PM ST	5.57	1.07E-07	1.42E-03	1.45E-08	8.24E-02	35.5
76.02	5: 0 PM ST	6.05	9.57E-08	1.17E-03	1.30E-08	6.98E-02	37.5
83.23	5:19 PM ST	6.48	1.02E-07	9.89E-04	1.37E-08	6.96E-02	39.4
90.44	5:40 PM ST	6.89	9.28E-08	8.50E-04	1.26E-08	6.12E-02	41.2
97.65	6: 0 PM ST	7.28	8.53E-08	7.39E-04	1.15E-08	5.44E-02	42.8
101.65	6:20 PM ST	7.51	1.45E-07	6.77E-04	1.96E-08	8.39E-02	44.2
105.66	6:39 PM ST	7.73	1.38E-07	6.23E-04	1.86E-08	7.71E-02	45.6
109.66	7: 0 PM ST	7.95	1.31E-07	5.75E-04	1.77E-08	7.12E-02	46.9
112.93	7:20 PM ST	8.14	1.53E-07	5.36E-04	2.07E-08	7.94E-02	48.1
116.19	7:39 PM ST	8.32	1.46E-07	5.02E-04	1.98E-08	7.39E-02	49.3
119.46	8: 0 PM ST	8.50	1.40E-07	4.70E-04	1.89E-08	6.90E-02	50.4
122.58	8:20 PM ST	8.66	1.41E-07	4.43E-04	1.90E-08	6.73E-02	51.4
125.70	8:39 PM ST	8.82	1.35E-07	4.19E-04	1.83E-08	6.30E-02	52.4
128.82	9: 0 PM ST	8.98	1.30E-07	3.96E-04	1.76E-08	5.92E-02	53.3
131.82	9:20 PM ST	9.13	1.31E-07	3.76E-04	1.77E-08	5.77E-02	54.3
134.82	9:39 PM ST	9.27	1.26E-07	3.58E-04	1.71E-08	5.43E-02	55.1
137.82	10: 0 PM ST	9.41	1.22E-07	3.41E-04	1.65E-08	5.13E-02	55.9
140.70	10:19 PM ST	9.53	1.23E-07	3.26E-04	1.67E-08	5.03E-02	56.7

ALL CONCS AT GROUND LEVEL IN PICO CI/M**3, DEPOSITION IN D/M PER SQ-M
ALL DOSES ARE GROUND LEVEL 70-YR DOSE COMMITTMENT IN REM

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DISTANCE (KM)	ETA HR:MIN	2-SIGY (KM)	CNTR-LINE DOSE	CNTR-LINE CONC	2-SIGY DOSE	CNTR-LINE DEP	PERCENT GONE
143.58	10:40 PM ST	9.65	1.20E-07	3.12E-04	1.62E-08	4.76E-02	57.5
146.46	11: 0 PM ST	9.78	1.16E-07	2.99E-04	1.57E-08	4.51E-02	58.2
149.46	11:19 PM ST	9.91	1.08E-07	2.87E-04	1.46E-08	4.12E-02	58.9
152.46	11:40 PM ST	10.04	1.05E-07	2.75E-04	1.42E-08	3.91E-02	59.6
155.46	0: 0 AM ST	10.17	1.02E-07	2.63E-04	1.38E-08	3.71E-02	60.2
158.58	0:19 AM ST	10.30	9.53E-08	2.52E-04	1.29E-08	3.40E-02	60.9
161.70	0:40 AM ST	10.44	9.26E-08	2.42E-04	1.25E-08	3.23E-02	61.5
164.82	1: 0 AM ST	10.58	9.00E-08	2.32E-04	1.22E-08	3.07E-02	62.0
168.06	1:19 AM ST	10.72	8.43E-08	2.23E-04	1.14E-08	2.82E-02	62.6
171.30	1:40 AM ST	10.87	8.19E-08	2.14E-04	1.11E-08	2.69E-02	63.1
174.54	2: 0 AM ST	11.01	7.97E-08	2.05E-04	1.08E-08	2.56E-02	63.7

ALL CONCS AT GROUND LEVEL IN PICO CI/M**3, DEPOSITION IN D/M PER SQ-M
ALL DOSES ARE GROUND LEVEL 70-YR DOSE COMMITTMENT IN REM

Figure 20. Release Calculations

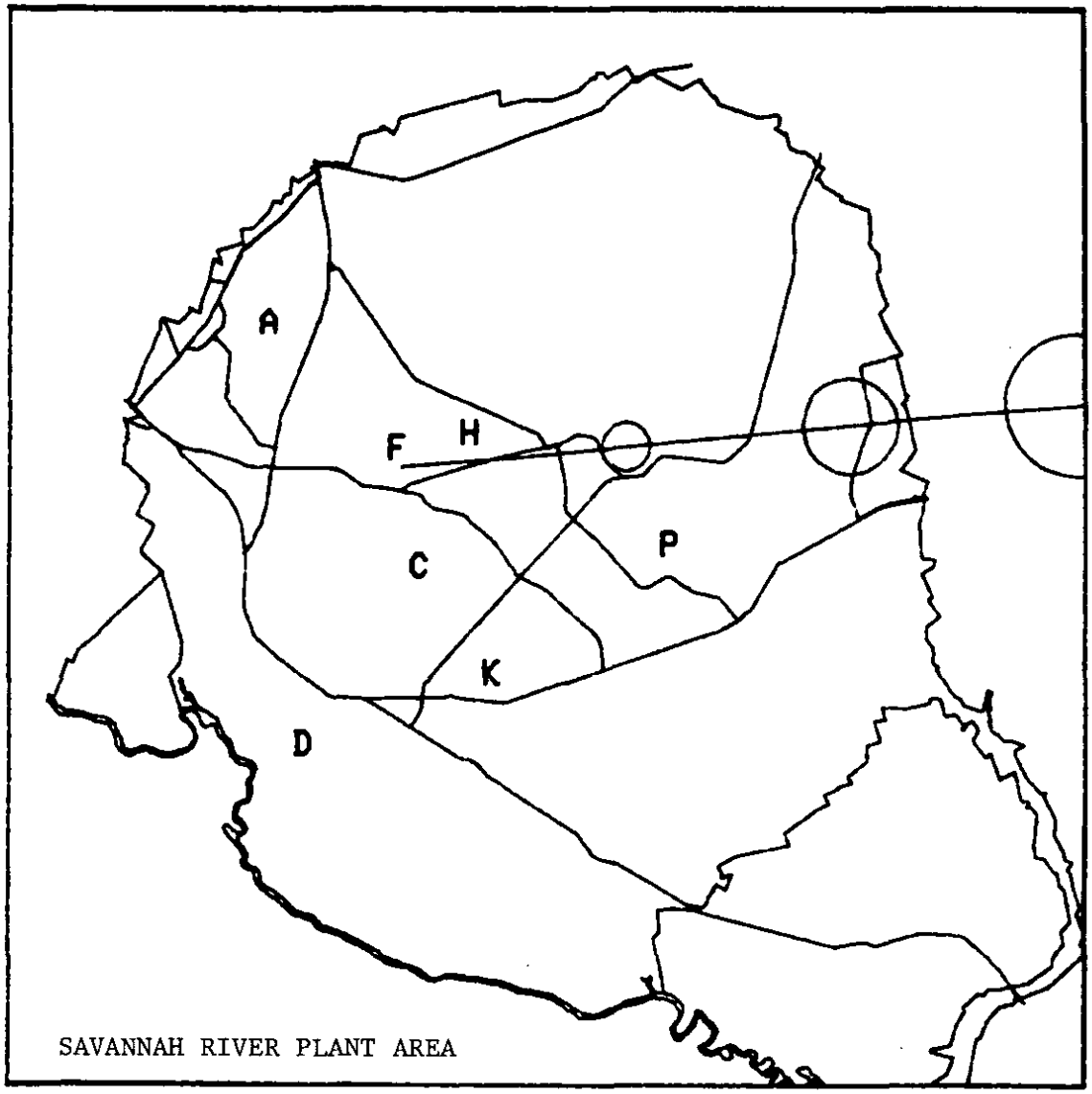

Figure 21. Trajectories and Cloud Widths

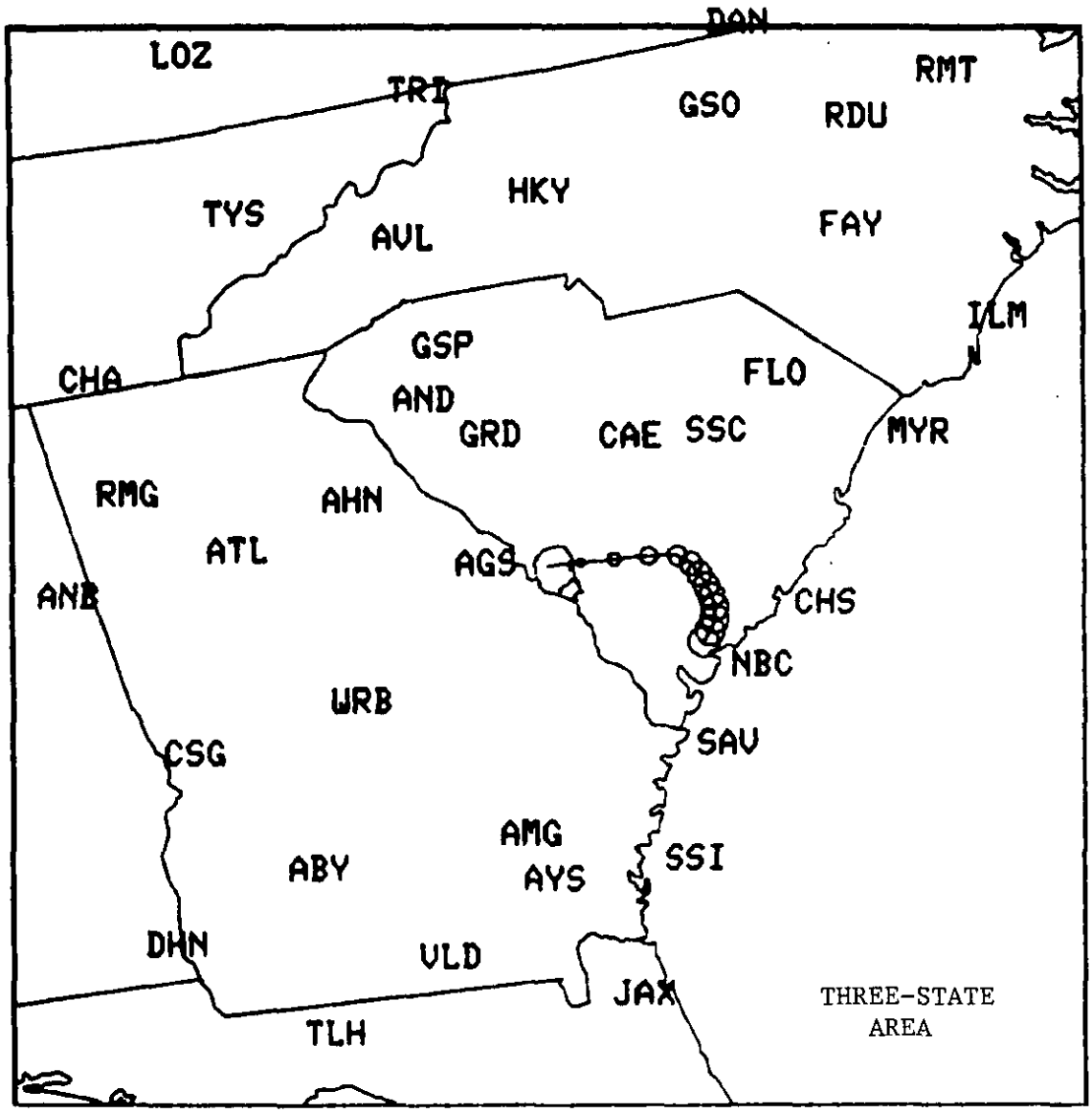

Figure 21. (Continued)

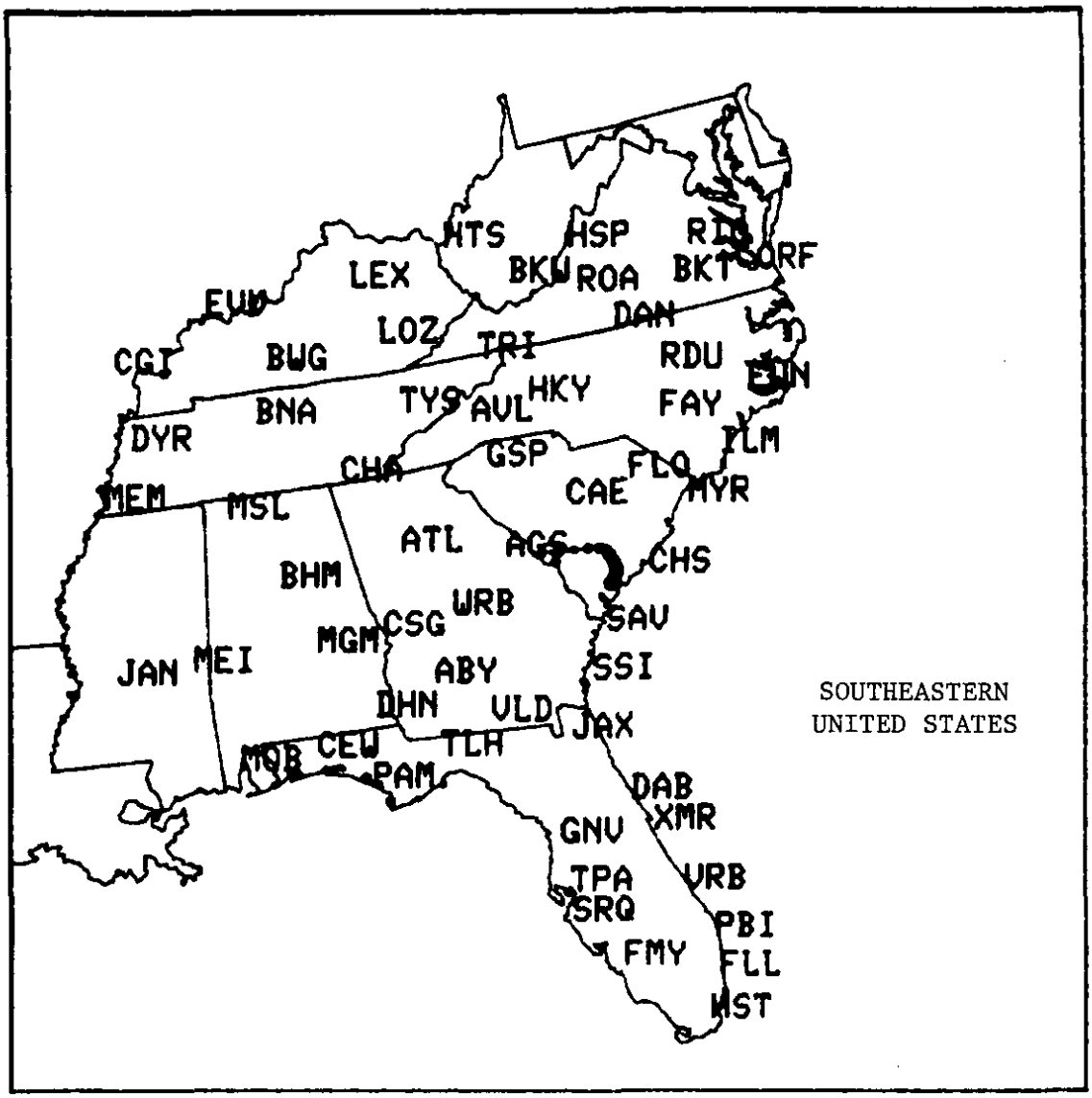

Figure 21. (Continued)

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APPENDIX A

ERGAM - AN EMERGENCY RESPONSE CODE TO ESTIMATE WHOLE BODY GAMMA DOSE*

The Savannah River Plant has several large reactors in routine operation for the production of various isotopes. There is a remote possibility that radioactivity could be released to the environs in the event of an an accident. Because these reactors have a confinement system designed to remove more than 99% of the fission-product iodine from the effluent stream, the initial release to the atmosphere under accident conditions would consist primarily of noble gases. Therefore, the most significant radiological consequences would be whole body dose from exposure to gamma radiation. Because of the long mean-free path of the gamma photons, the dose uptake from a passing cloud of gamma emitters is not related to air concentrations at the receptor point. Emergency response capabilities are required as part of the SRL responsibility for the assessment of the possible consequences of accidental releases of radioactive and toxic materials to the environs. To properly estimate the whole body gamma dose, the gamma flux must be integrated with respect to a receptor point, resulting from total spatial distribution of gamma emitters. The code ERGAM was written to accomplish this efficiently in terms of input requirements necessary to initiate the job on the IBM 360/195 and in terms of the computer time required to execute the job. Computer requirements are less than 0.1 second per dose estimate. Thus, ERGAM represents an extension of the capabilities already in effect to implement emergency response in accident situations.

Statement of the Problem

It is postulated that in any reactor accident involving fuel melting the halogen and noble gas fission products would be released to the atmosphere via the reactor confinement system. The amount released would be a function of operating history and the amount of fuel melted. As previously stated, the initial hazard to personnel would be gamma radiation from the noble gases. The computational problem is to provide an estimate of whole body gamma dose to an individual at ground level. An adequate estimate must take into account the total spatial distribution of the emitting material by integrating over space and time.

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* Written by R. E. Cooper, Savannah River Laboratory

The Mathematical Model

The mathematical model used in ERGAM is a modification of that developed in EGAD* where the modification is to account for Gaussian dispersion in the crosswind direction instead of being confined within sector boundaries. Two basic assumptions in this model greatly facilitate computations. The first assumption is that the material is released instantaneously. The material actually may be released over a period of several minutes, but the average wind direction probably will not change significantly over this period resulting in little or no error in this assumption. Stated more explicitly, the integral exposure at a downwind receptor point is essentially the same for instantaneous and short-term release if the wind direction persists over the release period. Secondly, the cloud size is assumed to be constant during the period over which a dose is accumulated at a downwind receptor point. Thus, the total exposure at the receptor point may be considered as having occurred in unit time (one second) from line sources extended to infinity in the upwind and downwind direction parallel to the direction of plume travel. A development of the line source concept is given by L. M. Arnett.** The intensity of each source with respect to a ground-level receptor depends on its position relative to the plume axis, total release inventory, and perpendicular distance from the receptor. The dose to a receptor from a line source is determined to be

$$D(a) = \frac{\nu dS}{2\pi\sigma a} \int_{o}^{\pi/2} B \exp \left[- \mu a \sec \phi \right] d \phi \qquad (1)$$

where a = perpendicular distance from line source to receptor, m

B = gamma photon buildup factor in air, which is a function of gamma energy

dS = line source intensity determined from the Gaussian source distribution function, photons/sec.

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* R. E. Cooper. EGAD - A Computer Program to Compute Dose Integrals from External Gamma Emitters. USAEC Report DP-1304 E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, SC.

** L. M. Arnett. "Calculation of Radiation Dose from a Cloud of Radioactive Gases." Nucl. Appl. 3, 217 (1967).

μ = air attenuation coefficient for gamma photons, also a function of energy, m^{-1}

ν = dose conversion factor as a function of energy, (rem/sec)/(photons/m^2-sec)

ϕ = the angle between the perpendicular from receptor to the line source and the vector from receptor to any point on the line

$\bar{u}$ = effective wind speed, m/sec

When B takes the form

$$B = \sum_{i=1}^{3} \alpha_1(\mu_1 a^i) \tag{2}$$

where the α_i are polynomial fitting coefficients as documented in DP-1304, then

$$G(\mu a) = \int_0^{\pi/2} B \exp\left[-\mu a \sec\phi\right] d\phi =$$

$$K_{i1}(\mu a) + \left[\alpha_i(\mu a) + \alpha_3(\mu a)^3\right] K_o(\mu a) +$$

$$(\alpha_2 + \alpha_3)(\mu a)^2 K_i(\mu a) \tag{3}$$

where the K_n are Bessel functions, and K_{i1} is the Bickley-Naylor function of order 1. The analytically integrated function $G(\mu a)$ thus represents a time integration and $\pm x$ (upwind and downwind) integration for a line source. The resulting expression is

$$D(a) = \frac{\nu dS\ G(\mu a)}{2\pi\bar{u}a} \tag{4}$$

It is now necessary to account for the spatial distribution and intensity of individual line sources through the y-z plane. For a Gaussian distribution with finite mixing height,

$$dS = f(y,z) = \frac{S_o \nu}{2\pi\sigma_y\sigma_z\bar{u}} \left\{ \exp -\left[\frac{y^2}{2\sigma_y^2} + \frac{(Z-H)^2}{2\sigma_z^2}\right] + \right.$$

$$\left. \sum_{i=1}^{\infty} \exp\left[-\frac{1}{2}\left\{\left(\left[(i-1) - M\right] L - H + (-1)^i Z\right)^2 + \frac{y^2}{\sigma_y^2}\right\}\right] + \right.$$

$$\sum_{i=1}^{\infty} \exp\left[-\frac{1}{2}\left\{\left(\left[(i-1) + M\right] L + H + (-1)^{i+1} z\right)^2 + \frac{y^2}{\sigma_y 2}\right\}\right] \quad (5)$$

where H = release height, m

L = mixing height, m

σ_y, σ_z = standard deviation of the activity distribution in the y (crosswind) and z (vertical) directions, respectively, m

S_o = total gamma source term, MeV/sec

M = (i+1) modulo 2 which can only take on the values 0 and 1.

and the total dose may be expressed as

$$D = \frac{S_o \nu}{4\pi^2 \sigma_y \sigma_z \bar{u}} \int_{-\infty}^{\infty} \int_{o}^{L} f(y,z) \frac{G(\mu a)}{a} \, dzdy \quad (6)$$

and $a^2 = y^2 + z^2$. S_o is total inventory, MeV/sec.

Equation 6 is evaluated for a receptor point at a downwind distance x by Gaussian quadratures and imposing practical limits on the integrations. The actual integration scheme employed resulted from attempts to obtain maximum utilization of the guadrature points by integration only over areas that provide a significant contribution to dose. The integration scheme was also structured to avoid inflection points over any interval of integration. This is a prerequisite for accuracy especially when estimating dose to a receptor at ground level which is displaced laterally from the plume centerline.