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Transport of Breeder Reactor-Fire-Generated Sodium Oxide Aerosols for Building-Wake-Dominated Meteorology

D. E. Fields
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HEALTH AND SAFETY RESEARCH DIVISION

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TRANSPORT OF BREEDER REACTOR-FIRE-GENERATED SODIUM OXIDE AEROSOLS FOR BUILDING-WAKE-DOMINATED METEOROLOGY

D. E. Fields, A. C. Cooper, and C. W. Miller

ABSTRACT

This report describes the methodology used and results obtained in efforts to estimate the sodium aerosol concentrations at air intake ports of a liquid-metal cooled, fast-breeder nuclear reactor. An earlier version of this methodology has been previously discussed (Fields and Miller, 1985). A range of wind speeds from 2-10 m/s is assumed, and an effort is made to include building wake effects which, in many cases, dominate the dispersal of aerosols near buildings. For relatively small release rates, on the order of 1-10 kg/s, the plume rise is small and estimates of aerosol concentrations are derived using the methodology of Wilson and Britter (1982), which describes releases from surface vents. For release rates on the order of 100 kg/s. much higher release velocities are expected, and plume rise is considered. An effective increase in release height is computed using the Split-H methodology with a parameterization suggested by Ramsdell (1983), and the release source strength is transformed to rooftop level. Evaluation of the acute release aerosol concentration is then based on the methodology for releases from a surface release of this transformed source strength. For a horizontal release, a methodology is developed to chart the plume path as a function of release and site meteorology parameters.

Results described herein must be regarded as maximum aerosol concentrations, based on models derived from generic wind tunnel studies. More accurate and site-specific results may be obtained through wind tunnel simulations and through simulating emissions from release points other than those assumed here.

1. INTRODUCTION

Liquid-metal cooled nuclear reactors often use large quantities of liquid sodium or sodium-potassium alloy, and evaluation of the possible consequences of a liquid metal fire, henceforth referred to as a sodium fire, is an important consideration of the design process. One facet of this evaluation is to determine the sodium aerosol concentration at the air intake ports. These ports are used for heat exchanger cooling, and

blockage of a critical number of ports would lead to a significant cooling problem. To provide an added safety margin, extra cooling ports are included in the reactor design.

This report describes the methodology used and the results obtained in estimating the sodium aerosol concentrations at selected air intake ports of a liquid metal-cooled fast breeder nuclear reactor under medium wind-speed conditions during sodium aerosol fires. This methodology is based on an approach described previously (Fields and Miller, 1985). The methodology has been extended to include horizontally-emitted jets, and is here applied to a different power pak configuration than that considered in the early report. These calculations are important because they suggest that reactor cooling at safe levels may be possible even in the event of such fires. Building wake effects, which in many cases dominate the dispersal of aerosols near buildings, are included in these calculations. A proprietary reactor design was obtained from Rockwell International, and the site was parameterized using architectural blueprints. These site parameters here serve as inputs for a methodology based on work by Wilson and Britter (1982), Briggs (1971, 1974, 1975), and Ramsdell (1983), which was used to determine the aerosol concentration values. Values were generated for a range of wind speeds from 2-10 m/s. Results described herein must be regarded as maximum aerosol concentrations, based on models derived from generic wind tunnel studies. More accurate and site-specific results may be obtained through wind tunnel simulations and through simulating emissions from release points other than those assumed here.

Our conclusions include the following points. First, our results show that the concentration of sodium aerosols at reactor cooling ports are very much a function of the design of emission ports. For example, the choice of rain cap design for a stack has a significant impact on the path of the aerosol cloud released from the stack, and on the ultimate concentration of aerosol at intake ports. Similarly, application of the methodology developed in this report demonstrates that allowing horizontal emission of aerosols may lead to aerosol concentrations that are significantly above what would be expected from vertical aerosol emissions.

A second important conclusion, that follows from consideration of the behavior of aerosol clouds under low-speed conditions, and that is supported by the uncertainty analysis presented here, is that there is a definite need for further consideration of sodium aerosol transport following liquid metal fires in breeder reactor complexes. Low wind-speed conditions (calms) are inadequately treated in present methodologies, including those developed here. A separate methodology, not derived from considerations of releases from surface vents and stacks for wind speeds greater than 2 m/s, should be developed to consider transport under conditions where the wind speed lies between 0 and 2 m/s.

We have pointed out the need for such a methodology to Rockwell International staff, and have discussed the considerable uncertainty in model predictions that is generated by omitting from consideration wind speeds below 2 m/s.

2. METHODOLOGY FOR SLOW-SPEED AND FOR VERTICAL EMISSIONS

It is generally agreed that wind tunnel experiments are the most reliable laboratory-scale methods for predicting aerosol dispersion and aerosol concentrations in regions where building wake effects are dominant. In view of the complexity and expense of site-specific wind tunnel studies, generic wind tunnel studies have been performed that provide scaling factors and empirical coefficients that allow the prediction of maximum aerosol concentrations for general cases. Wilson and Britter, (1982) summarize some of these studies for aerosol releases from surface and roof vents.

The ratio of the aerosol concentration CS (kg/m^3) at a building surface exhaust vent to the upper bound of the concentration C (kg/m^3) at a receptor point is shown (Wilson and Britter, 1982) to be

$$\frac{CS}{C} = \frac{KE\ R^2}{D\ A}, \tag{1}$$

where

KE = (CS U A)/Q,

R = shortest distance between source and receptor, measured along building (m),

D = empirical constant of magnitude 9.0 for roof vents,

A = projected building frontal area (m^2),

U = windspeed at roof level far upwind of building (m/s),

Q = source intensity (kg/s).

Equation (1) and the expression for KE may be rearranged to yield

$$C = \frac{D\ Q}{UR^2}. \tag{2}$$

It is unlikely (except for very low wind speeds) that a significant fraction of aerosol particles will be transported against the prevailing wind. Although flow separation at roof and wall edge may occur in strong winds (Hosker, private communication), identification of the situations where this mechanism might lead to heightened inlet-port concentrations must be based on wind tunnel studies.

If plume rise is to be accounted for, it is necessary to compute an "effective" source strength normalized to the roof height and to use this normalized source strength in Eq. (2) to determine a concentration at points downwind. The sector average roof level concentration CC (kg/m^3) (for a downwind 22.5-degree sector) is given by the equation (Fields and Miller, 1980)

$$CC = \frac{2.032\ Q}{xU\sigma_z}\left[\exp\left(-\ \frac{h^2}{2\sigma_z^2}\right)\right], \tag{3}$$

where

x = source emission point to roof-edge distance (m),

σ_z = vertical dispersion coefficient (m),

h = plume rise (m), above the emission point. The height above the receptor point is determined from the receptor point elevation.

The effective roof source strength QR for this concentration may be approximated by multiplying the concentration in Eq. (3) by the downwind plume area cross section and the wind velocity. For the 22.5-degree sector plume, this correction yields

$$QR = 0.842\ Q\left[\exp\left(-\ \frac{h^2}{2\sigma_z^2}\right)\right]. \tag{4}$$

The value of the vertical dispersion coefficient σ_z in Eq. (4) is dependent on building roof wake effects. It may be approximated (Wilson and Britter, 1982) by

$$\sigma_z = 0.21\ RF^{0.25}x^{0.75}\ . \tag{5}$$

The scaling factor RF for wake-dominated air flow and diffusion (Wilson and Britter, 1982) is calculated for a given wind direction, based on DS, the smallest building dimension perpendicular to the wind vector,

and DL, the largest building dimension perpendicular to the wind vector. In a conservative calculation, wind direction must be chosen such that transport is greatest for the emission and receptor points of interest, and with consideration of the influence of DS and DL on the aerosol concentration. Its value is given by

$$RF = DS^{0.67} DL^{0.33} \quad . \tag{6}$$

The amount of momentum-driven plume rise h above the emission point may be predicted (Ramsdell, 1983) from the exhaust port exit diameter D, the windspeed U, and the exhaust velocity W by the equation

$$h = 3 \; D \; W/U \quad . \tag{7}$$

There exist, in addition to momentum-driven plume rise which results from the initial upward plume velocity, other mechanisms that increase the effective aerosol release-height. These other mechanisms, which are driven by density differences between the plume and the ambient air, result in a more gradual lofting of the plume in comparison to momentum plume rise. These density differences result from (1) temperature differences, (2) molecular weight differences, and (3) water droplet evaporation after plume emission. The plume water content is assumed zero for this application. Briggs (1974) presents methods for estimating the plume rise from these effects.

Briggs' (1974) computes density-driven plume rise based on the parameter Δ_D, where Δ_D is defined by

$$\Delta_D = \Delta_T + \Delta_m + \Delta_w \quad , \tag{8}$$

where

Δ_T = the temperature contribution to the relative density difference,

Δ_m = the molecular weight contribution, and

Δ_w = the liquid water contribution.

These contributions to Δ_D are evaluated as follows:

$$\Delta_T = -(c_{po}/c_p)\ (\Delta T/T)\ , \tag{9}$$

where

c_{po} = the specific heat capacity at constant pressure of the effluent,

c_p = the specific heat capacity of the ambient air (c_p = 0.24 cal/gm - °K),

ΔT = the difference between the effluent and ambient temperatures, and

T = the ambient absolute temperature;

$$\Delta_m = (1-28.9/m_o)\ , \tag{10}$$

where m_o is the reciprocal of the mean of the inverse molecular weight of the effluent; and

$$\Delta_w = 8\ Q_w/Q_o\ , \tag{11}$$

where Q_w is the estimated mass flux of liquid water in the effluent and Q_o is the mass flux of the effluent.

Once parameter Δ_D is found, Briggs suggests that parameter F be computed using the equation

$$F = -2.6\ \Delta_D Q_o\ , \tag{12}$$

and from this the density-driven plume rise Δh is given, for daytime conditions with the wind speed U greater than 3.5 m/s,

$$\Delta h = 21\ F^{2/3}\ U\ , \tag{13}$$

and for nighttime conditions when the wind speed U is less than 3.5 m/s,

$$\Delta h = 19\ F^{1/3}\ . \tag{14}$$

In summary, maximum aerosol concentrations expected on building surfaces from low speed and vertical building surface releases with no plume rise may be determined using Eq. (2). If plume rise is expected, then Eqs. (4)-(7) may be used to estimate an effective source strength QR evaluated at the roof edge. This effective roof edge source strength may then be substituted into Eq. (2), where R in Eq. (2) becomes the receptor-to-roof edge distance. Eqs. (8)-(14) may be used to evaluate the magnitude of density-driven plume rise.

3. METHODOLOGY FOR HORIZONTAL RELEASES

In order to estimate the aerosol concentration at receptor points on building surfaces from horizontal emissions for the conservative situation where the plume is injected directly into the wind, we develop a methodology that predicts the point above the emission point that the plume, being blown back toward the building by the wind, impinges on either the building or the vertical projection of the building wall. This point is the location of an effective source of aerosols. This effective aerosol source may be used to predict aerosol concentrations at receptor points (intake ports) using the equations from Chapter 2.

To develop the path the horizontally emitted plume follows in space, we use the generalized Briggs (Briggs, 1971 and Briggs, 1975) plume-rise equations. These equations are formulated to predict vertical plume rise. In these equations, the effect on entrainment due to the relative velocity between the plume and ambient air is parameterized in the jet entrainment coefficient B_j, while the effect on entrainment due to the temperature difference between the plume and ambient air is parameterized by the adiabatic entrainment coefficient B_1. This parameterization of B_1 is valid so long as the vertical potential temperature gradient is less than or equal to zero (considered a default value for Pasquill stability classes A, B, C, or D). For a horizontally emitted plume, the temperature gradient may be assumed zero. The vertical flux terms due to initial momentum and due to buoyancy are also separated. This separation of the effects of different mechanisms makes the Briggs equations a particularly attractive starting point for decoupling vertical and horizontal motion. The subset of the generalized Briggs equations that applies for zero potential temperature gradient (Bowers et al., 1979) predict that the plume rise $\Delta h_N\{x\}$ at a downwind distance x is given by

$$\Delta h_N(x) = \left[\frac{3F_m x'}{B_j^2 u^2} + \frac{3F x'^2}{2B_1^2 u^3} \right]^{1/3} \qquad (15)$$

where F_m = momentum flux term;

F = buoyancy flux term;

B_j = jet entrainment coefficient;

B_1 = adiabatic entrainment coefficient;

u = mean wind speed (m/sec).

Parameter B_j may be calculated from the exit velocity V_s and the mean wind speed u using the equation

$$B_j = \left(1/3 + \frac{u}{V_s}\right) \tag{16}$$

Parameter x' in Eqn. (15) is defined as follows:

$$x' = \begin{cases} x & ; x < 3.5\, x^* \text{ and } F > 0 \\ x & ; x < \dfrac{4d\left(V_s + 3u\right)^2}{V_s u} \text{ and } F = 0 \\ 3.5\, x^* & ; x \geq 3.5\, x^* \text{ and } F > 0 \\ \dfrac{4d\left(V_s + 3u\right)^2}{V_s u} & ; x \geq \dfrac{4d\left(V_s + 3u\right)^2}{V_s u} \text{ and } F = 0 \end{cases} \tag{17}$$

where

$$x^* = \begin{cases} 14\, F^{5/8}; & F \leq 55\ m^4/sec^3 \\ 34\, F^{2/5}; & F > 55\ m^4/sec^3 \end{cases}$$

Parameter F may be obtained using the following equations:

$$F_m = \left(T_a/T_s\right) V_s^2 d^2/4 \tag{19}$$

$$F = \begin{cases} F' = \dfrac{g V_s d^2}{4} \left(1 - T_a/T_s\right) & ; F' > F_c \\ 0 & ; F' \leq F_c \end{cases} \tag{20}$$

$$F_c = \begin{cases} 0.0727 \ (V_s d)^{4/3} & ; \ F' \leq 55 \ m^4/sec^3 \\ 0.0141 \ (V_s d)^{5/3} & ; \ F' > 55 \ m^4/sec^3 \end{cases} \tag{21}$$

where

T_a = ambient air temperature (°K);

T_s = stack exit temperature = (°K), input as zero for a pure momentum source;

F_c = buoyancy flux below which plume rise is due momentum only;

d = stack inner diameter (m); and

g = acceleration due to gravity (9.8 m/sec^2).

Equations analogous to equations 15-21 must be formulated to predict the motion and dispersion of a horizontally-emitted plume. For a vertically-emitted plume described by Eqn. (15), the effect of the initial upward momentum on plume rise is contained in the first term, while the effect of buoyancy on plume rise is contained in the second term. For a horizontally-emitted plume directed into a high wind, only the first (momentum) term is needed to compute the horizontal distance that a single puff would move into still air before its horizontal velocity would fall to zero. Entrainment of ambient air would be driven by both jet and adiabatic mechanisms, however, so the entrainment coefficient should be made up of both the jet and adiabatic coefficients; viz.,

$$B = \sqrt{B_j^2 + B_a^2} \tag{22}$$

The value of B_j is given by Eqn. 16, while a reasonable default value for B_a is 0.6 (Briggs, 1975). The time-dependence of the height of a parcel of a vertically-emitted plume varies for heights that are less than the maximum value according to x'/u in the first term of Eqn. 15, and this time dependence may be made explicit by replacing the quotient by the time since emission, t_e. If the horizontally-emitted plume is directed into a wind field of horizontal velocity component u, then the horizontal coordinate of any parcel of the plume will vary with t_e, according to the following equation:

$$x_H = \left(\frac{3F_m t_e}{B^2 u}\right)^{1/3} - ut_e \tag{23}$$

This equation describes the time-dependent horizontal component of the position of a particle of the plume as a function of time since emission. As one would expect, once the plume becomes mixed with the ambient air, it moves with the wind at a velocity $-ut_e$. The second term actually dominates the first for two reasons: the first reason follows from the functional dependence on t_e in the two terms, while the second reason is that we can replace x' by x only until the plume loses its initial momentum. The transition values for x' are given in Eqn. 17.

We may evaluate Eqn. 23 to obtain solutions for $x_H = 0.0$. The first solution, $x_H = 0.0$, corresponds to the initial position of the plume. The second solution for $x_H = 0.0$ corresponds to time since emission t_{e0} at which the plume returns either to the building wall surface from which it was emitted, or to the vertical extension of that surface. This solution is expressed by

$$t_{eo} = \left(\frac{3F_m}{B^2 u^4}\right)^{1/2} \tag{24}$$

Knowing the time as given in Eqn. 24 between emission of a parcel of the plume and its return to the plane of the vertical building surface allows us to compute the vertical distance between the point of emission and the point of return to the vertical plane. The height above its

emission point that a vertically-emitted plume would reach if it were subject only to buoyancy considerations is same as the height above its emission point that a horizontally-emitted plume would reach. For a horizontally-emitted plume, we may account for the effect of buoyancy by choosing the second term in Eqn. 15 to obtain an expression for the the vertical position of the plume, Δh_H:

$$\Delta h_H = \left(\frac{3Fx'^2}{2B^2u^3} \right)^{1/3} \tag{25}$$

In this equation, we have once again included the combined effects of jet and adiabatic entrainment by using the combined entrainment coefficient B as defined by Eqn. 22. In order to calculate the vertical position of the plume when it returns to the vertical plane from which it was emitted, we must include variable t_e in Eqn. 25, and evaluate at the. particular time t_{e0} from Eqn. 24. We use $t = x/u$, where x is related to x' according to Eqn. 17. Incorporation of the criteria defined in Eqn. 17 yields

$$\Delta h_H = \left[\begin{array}{ll} \left(\frac{3F\, t_{eo}^2}{2B^2u} \right)^{1/3} & ; \quad x < 3.5x^* \text{ and } F > 0 \\ \left(\frac{3Ft_{eo}}{2B^2u} \right)^{1/3} & ; \quad x < \frac{4d\,(V_s + 3u)^2}{V_s u} \text{ and } F = 0 \\ \left(\frac{3}{2} \frac{F}{B^2u^3} (3.5x^*)^2 \right)^{1/3} & ; \quad x \geq 3.5x^* \text{ and } F > 0 \\ \left(\frac{3}{2} \frac{F}{B^2u^3} \left(\frac{4d(V_s + 3u)^2}{V_s u} \right)^2 \right)^{1/3} & ; \quad x \geq \frac{4d\,(V_s + 3u)^2}{V_s u} \text{ and } F = 0 \end{array} \right]. \tag{26}$$

In summary, for horizontally-emitted plumes injected into a wind field, one may determine the vertical position that the plume impinges either on the wall from which it was emitted or the extension of that wall, by using Eqn. 26. The elapsed time between emission of a parcel of that plume, and its return to the vertical plane is given by Eqn. 24.

4. APPLICATION OF METHODOLOGY

4.1 SAFR Power Pak Architectural Configuration

We will apply the methodology described in Chapters 2 and 3 to compute potential aerosol concentrations at air intake ports from emissions on the building structure of one of the Sodium Advanced Fast Reactor (SAFR) (Lancet, 1985) power paks. Modules of this nuclear power system are sodium-cooled, and are designed to be economic and inherently safe.

Figure 1 presents the configuration of a SAFR power pak and identifies potential emission points (E1 through E4) and air intake ports (I1 and I2) that will be referred to in subsequent sections of this chapter. Certain aspects of the design are proprietary, so this figure is not drawn precisely to scale.

Building dimensions and geometrical parameters were obtained from Rockwell architectural drawings SK-P-21, -25, -27, and -28, and these drawings will be mentioned in the discussion.

4.2 Meteorological and Source Parameters

Wind speeds were assumed to vary from 2 to 10 m/s, with 2 m/s intervals. The methodology outlined in Chapter 2 is not considered to apply to wind speeds below 2 m/s. Two different sources were considered. The first, to be referred to as a "slow speed release", had an aerosol emission rate of 1.9 kg/s. The second type of source, to be referred to as a "high speed release", had an aerosol emission rate of 97 kg/s and an exhaust velocity of 21.9 m/s. A nominal exhaust port diameter of 3.72 m was assumed for exhaust ports other than the stack, and exhaust port diameters were varied to demonstrate the effect of this parameter on aerosol concentrations and to quantify one source of variability in the results.

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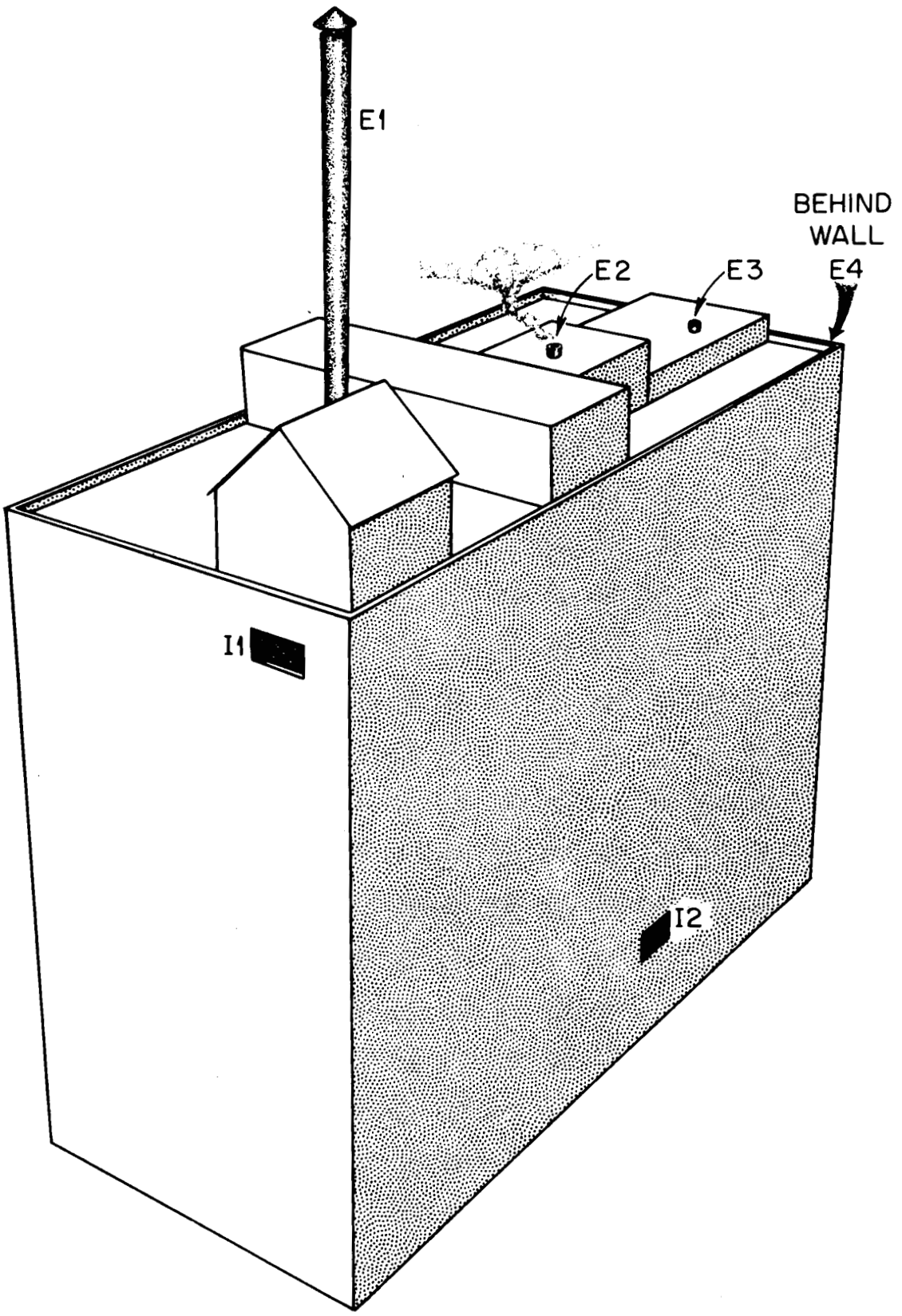

Figure 1. Generalized architectural configuration for SAFR power pak.

4.3 Slow Speed Releases

Aerosol releases at low speed are assumed to be described by the methodology presented in Chapter 2 for both horizontal and vertical releases. Measurements for parameter R were taken from SK-P-28 and -21.

Aerosol concentrations at air intake ports I1 and I2 resulting from emissions at potential exhaust points E1-E4 were calculated using code NA1.F4, the listing for which is included in Appendix A.

Results from calculations of aerosol concentrations are presented in Table 1. From the results presented in Table 1, one observes that the primary effect of wind speed on aerosol concentration is to dilute the emitted aerosols. At wind speeds below 2 m/s, for which the methodology is inapplicable, one would expect the aerosol concentrations to rise above values calculated here.

4.4 High Speed Releases: Exhaust Port E1

Exhaust port E1 is a stack that extends 29.2 m above the building surface. Measurements of architectural parameters were taken from drawings SK-P-21 and -28. Aerosol releases at high speed are assumed to be described by the methodology presented in Chapter 2 for both horizontal and vertical releases. As shown on architectural drawings, this stack is equipped with a rain deflector cap that may result in high speed releases from this port being directed downward, with a resulting increased aerosol concentration at air intake ports. The effect of rain cap design was investigated by assuming the initial momentum of the exhaust to be directed either vertically downward, vertically upward, or horizontally, and by calculating the resulting concentrations at input ports consistent with these assumptions.

Aerosol concentrations at air intake ports I1 and I2 resulting from emissions at the outlet of stack (emission point E1) were calculated using code IN1FS.F4, the listing for which is included in Appendix B.

Results from calculations of aerosol concentrations are presented in Table 2. In this table, the effects of rain deflection cap design are indicated in the choice of plume dynamics as defined in the table notes; e.g., type A plume dynamics indicates that the aerosol plume is

Table 1. Sodium aerosol concentrations (kg/m^3) for slow speed releases and an emission rate of 6.9 kg/s.

Exhaust Port	Input Port	Wind Speed (m/s)				
		2	4	6	8	10
E1	I1	.64E-02	.32E-02	.21E-02	.16E-02	.13E-02
E2		.49E-02	.24E-02	.16E-02	.12E-02	.98E-03
E3		.36E-02	.18E-02	.12E-02	.89E-03	.71E-03
E4		.31E-02	.15E-02	.10E-02	.77E-03	.61E-03
E1	I2	.29E-02	.15E-02	.98E-03	.74E-03	.59E-03
E2		.41E-02	.21E-02	.14E-02	.10E-02	.83E-03
E3		.57E-02	.29E-02	.19E-02	.14E-02	.11E-02
E4		.50E-02	.25E-02	.17E-02	.13E-02	.10E-02

Table 2. Sodium aerosol concentrations (kg/m^3) for high speed releases. (Exhaust Port diameter = 3.72 m.)

Exhaust Port	Input Port	Plume Dynamics[a]	Wind Speed (m/s) 2	4	6	8	10
E1	I1	A	.79E+01	.40E+01	.26E+01	.20E+01	.44E+00
		B	.00E+00	.00E+00	.00E+00	.00E+00	.00E+00
		C	.77E-20	.39E-20	.26E-20	.19E-20	.15E-20
	I2	A	.11E+01	.56E+00	.37E+00	.28E+00	.18E+00
		B	.00E+00	.79E-36	.12E-21	.57E-16	.50E-13
		C	.20E-03	.10E-03	.67E-04	.50E-04	.40E-04
E2	I1	D	.00E+00	.00E+00	.00E+00	.00E+00	.37E-27
		E	.00E+00	.23E-13	.59E-07	.153-04	.23E-03
	I2	D	.003+00	.14E-25	.75E-13	.29E-19	.79E-11
		E	.00E+00	.14E-25	.75E-13	.33E-08	.56E-06
E4	I1	D	.51E-01	.11E+00	.58E-01	.44E-01	.35E-01
		E	.53E+01	-	-	-	-
	I2	D	.54E-02	.16E+00	.95E-01	.73E-01	.59E-01
		E	.41E+00	-	-	-	-

[a]NOTES:

A. Aerosol plume is assumed directed vertically downward by rain deflection cap on stack. Stack height recalculated and set equal to 29.2-3DW/U meters.

B. Aerosol plume is assumed directed vertically upward by rain deflection cap on stack. Stack height recalculated and set equal to 29.2 + 3DW/U meters.

C. Aerosol plume is assumed emitted horizontally from stack. Stack height set equal to 29.2 meters.

D. Aerosol plume is assumed to intersect the downwind roof edge that is closest to the aerosol emission point.

E. Aerosol plume is assumed to intersect the downwind roof edge that is beyond that edge closest to the aerosol emission point.

initially directed vertically downward.

The influence of varying wind speed is seen from Table 2 to be more complex for high speed than for slow speed releases: for high speed releases, a greater wind speed not only results in greater dilution of the aerosol plume thus lowering the aerosol concentration, but it also causes greater dispersion of the plume, which can return emitted aerosols to building surfaces that they would have missed under lower wind speed conditions.

4.5 High Speed Releases: Exhaust Ports E2 and E3

Measurements of architectural parameters were taken from drawings SK-P-21, -27, and -28. Aerosol releases at high speed are assumed to be described by the methodology presented in Chapter 2 for vertical releases.

Computer code BEACH.F4 was used to calculate aerosol concentrations from emissions at ports E2 and E3. A listing of this code is included in Appendix C.

Results of these calculations are presented in Table 2. Notes D and E indicate whether either the building edge closest to the aerosol emission point, or the building edge just beyond the closest edge, is the edge used for the computation of aerosol concentration at air intake ports. The largest concentration value should be chosen, but both values are included in the table to provide an indication of the importance of considering plume behavior under varying conditions.

4.6 High Speed Releases: Exhaust Port E4

Measurements of architectural parameters were taken from drawings SK-P-21, -27, and -28. Aerosol releases at high speed are assumed to be described by the methodology presented in Chapters 2 and 3 for horizontal releases. Exhaust port E4 is expected to emit aerosols in a horizontal direction. If these aerosols are emitted in the direction toward the wind is blowing, there should be no impact on an isolated power pak. The influence of adjacent buildings is not considered here. A worst case situation would occur if these aerosols are emitted in the

direction from which the wind is blowing. If the wind speed were quite low in this case, the plume would be expected to be blown away and lofted whereas if the wind speed were somewhat higher the plume would be expected to be blown back toward the building, possibly even impinging on the building surface.

In order to quantify the plume behavior under varying wind speeds and aerosol emission parameters, Eqs. 16-26 from Chapter 3 that predict where the plume intersects the vertical plane of the building wall from which it is emitted were coded and implemented as program ZIG.FOR. A listing of this program is included as Appendix D.

Results from execution of program ZIG.FOR indicate that the aerosol plume from emission point E4 would be bent back and its centerline would impinge on the side of the building for wind velocities 4, 6, 8, and 10 m/s. For a wind velocity of 2 m/s, the center line of the plume would miss the building edge.

Results of the aerosol concentration calculations for emission point E4 are included in Table 2. Results for wind speeds of 4, 6, 8, and 10 m/s are calculated as for slow speed building surface releases, with the emission position determined from the output of program ZIG.FOR, and using program NA1.F4 (see Appendix A), with a source strength of 97 kg/s.

Results for wind speeds of 2 m/s are calculated using the methodology described in Chapter 2. The calculations were done using program IN1SP2.F4, which is included in Appendix E. Since the centerline of the returning plume misses the building surface, aerosol concentrations at air intake ports are computed by separately considering the effects of the dispersed plume encountering two of the building edges, as was done for emission points E2 and E3. There are therefore two concentration values presented for a wind speed of 2 m/s, and the higher value should be conservatively chosen.

It is apparent from Table 2 that modifications to minimize the impact of aerosols emitted from point E4 would be desirable. These modifications might include increasing the exhaust velocity by using exhaust fans, directing the emitted aerosols vertically using a deflector, locating the exhaust port on the roof rather than the wall, or providing alternate exhaust ports on other walls to insure that the aerosols would not be emitted directly upwind.

5. SENSITIVITY OF RESULTS TO VARIATIONS IN MODEL INPUT

Predicted aerosol concentrations at air intake ports vary according to simple formulae for slow releases. Aerosol concentrations may be predicted using Eqs. 1 and 2, as implemented in program NA1.F4 given in Appendix A. The sensitivity of results presented in Section 4.3 to source strength is a direct relationship, while the concentration varies inversely as wind speed, and as the square of the distance from the release point to the intake port.

For high speed releases, for which the aerosols are emitted as a plume that is projected from the building surface as a function of its initial momentum and of its density, several additional variables are involved. Examination of the variation of predicted aerosol concentration with changes in meteorological and architectural parameters is of value in exposing the robustness of results and in suggesting how these results may scale where other conditions are found. Of course, more quantitative results may be found for any specific situation simply by applying the methodology, so long as the assumptions made in formulating the methodology are valid, and the caveats associated with the methodology are considered.

The effects of wind speed on aerosol concentrations at intake ports I2 and I2 are summarized in Table 2. Results presented here were calculated using a nominal port diameter of 3.72 m. Since port diameter, or stack diameter, may be in most cases chosen by the facility designer, we have explored the effect of exhaust port diameter on aerosol concentrations. Table 3 presents the predicted sodium aerosol concentrations at intake ports I1 and I2 resulting from high-speed emissions from points E1, E2, and E3 for an exhaust port diameter of 1.86 m. Increasing the exhaust port diameter to 2.34 m yields the results presented in Table 4. These results may be compared to those presented in Table 2, for which the exhaust port diameter was a (larger) nominal value of 3.72m. Table 5 presents the results of an analogous set of calculations, for which the exhaust port diameter was assumed still larger, having a diameter of 5.58 m.

Table 3. Sodium aerosol concentrations (kg/m^3) for high speed releases. (Exhaust Port diameter = 1.86 m.)

Exhaust Port	Input Port	Plume Dynamics[a]	Wind Speed (m/s) 2	4	6	8	10
E1	I1	A	.79E+01	.40E+01	.32E-01	.33E-04	.12E-06
		B	.003+00	.00E+00	.00E+00	.00E+00	.00E+00
		C	.77E-20	.39E-20	.26E-20	.19E-20	.15E-20
	I2	A	.11E+01	.56E+00	.17E+00	.39E-01	.12E-01
		B	.16E-35	.11E-15	.49E-11	.56E-09	.64E-08
		C	.20E-03	.10E-03	.67E-04	.50E-04	.40E-04
E2	I1	D	.00E+00	.00E+00	.61E-19	.40E-11	.15E-07
		E	.46E-13	.30E-04	.21E-02	.11E-01	.23E-01
	I2	D	.94E-38	.63E-10	.68E-05	.34E-03	.19E-02
		E	.12E-25	.26E-09	.85E-06	.20E-04	.10E-03
E3	I1	D	.27E-30	.46E-06	.19E-02	.17E-01	.33E-01
		E	.19E-07	.84E-02	.96E-01	.21E+00	.30E+00
	I2	D	.00E+00	.58E-19	.22E-06	.68E-03	.11E-01
		E	.29E-25	.66E-08	.20E-04	.38E-03	.16E-02

[a]NOTES:

A. Aerosol plume is assumed directed vertically downward by rain deflection cap on stack. Stack height recalculated and set equal to 29.2-3DW/U meters.

B. Aerosol plume is assumed directed vertically upward by rain deflection cap on stack. Stack height recalculated and set equal to 29.2 + 3DW/U meters.

C. Aerosol plume is assumed emitted horizontally from stack. Stack height set equal to 29.2 meters.

D. Aerosol plume is assumed to intersect the downwind roof edge that is closest to the aerosol emission point.

E. Aerosol plume is assumed to intersect the downwind roof edge that is beyond that edge closest to the aerosol emission point.

Table 4. Sodium aerosol concentrations (kg/m^3)
for high speed releases.
(Exhaust Port diameter = 2.34 m.)

Exhaust Port	Input Port	Plume Dynamics[a]	Wind Speed (m/s) 2	4	6	8	10
E1	I1	A	.79E+01	.40E+01	.13E+01	.70E-02	.31E-04
		B	.00E+00	.00E+00	.00E+00	.00E+00	.00E+00
		C	.77E-20	.39E-20	.26E-20	.19E-20	.15E-20
E1	I2	A	.11E+01	.56E+00	.33E+00	.10E+00	.32E-01
		B	.00E+00	.43E-20	.23E-13	.14E-10	.41E-09
		C	.20E-03	.10E-03	.67E-04	.50E-04	.40E-04
E2	I1	D	.00E+00	.00E+00	.16E-04	.50E-04	.40E-04
		E	.15E-19	.37E-06	.22E-03	.25E-02	.82E-02
	I2	D	.00E+00	.22E-15	.25E-07	.15E-04	.25E-02
		E	.18E-37	.83E-13	.14E-07	.15E-05	.15E-04
E3	I1	D	.00E+00	.16E-10	.39E-04	.28E-02	.13E-01
		E	.74E-12	.52E-03	.25E-01	.94E-01	.17E+00
	I2	D	.00E+00	.70E-34	.48E-12	.16E-05	.48E-03
		E	.26E-38	.17E-11	.36E-06	.33E-04	.29E-03

[a]NOTES:

A. Aerosol plume is assumed directed vertically downward by rain deflection cap on stack. Stack height recalculated and set equal to 29.2-3DW/U meters.

B. Aerosol plume is assumed directed vertically upward by rain deflection cap on stack. Stack height recalculated and set equal to 29.2 + 3DW/U meters.

C. Aerosol plume is assumed emitted horizontally from stack. Stack height set equal to 29.2 meters.

D. Aerosol plume is assumed to intersect the downwind roof edge that is closest to the aerosol emission point.

E. Aerosol plume is assumed to intersect the downwind roof edge that is beyond that edge closest to the aerosol emission point.

Table 5. Sodium aerosol concentrations (kg/m^3) for high speed releases. (Exhaust Port diameter = 5.58 m.)

Exhaust Port	Input Port	Plume Dynamics[a]	Wind Speed (m/s) 2	4	6	8	10
E1	I1	A	.79E+01	.40E+01	.26E+01	.20E+01	.16E+01
		B	.00E+00	.00E+00	.00E+00	.00E+00	.00E+00
		C	.77E-20	.39E-20	.26E-20	.19E-20	.15E-20
	I2	A	.11E+01	.56E+00	.37E+00	.28E+00	.22E+00
		B	.00E+00	.00E+00	.53E-36	.50E-04	.40E-04
		C	.20E-03	.10E-03	.67E-04	.50E-04	.40E-04
E2	I1	D	.00E+00	.00E+00	.00E+00	.00E+00	.00E+00
		E	.00E+00	.48E-27	.15E-13	.16E-08	.42E-06
	I2	D	.00E+00	.00E+00	.31E-38	.60E-22	.19E-14
		E	.00E+00	.00E+00	.41E-26	.69E-17	.23E-12
E3	I1	D	.00E+00	.00E+00	.90E-31	.36E-15	.86E-10
		E	.00E+00	.42E-17	.62E-08	.12E-04	.41E-03
	I2	D	.00E+00	.00E+00	.00E+00	.00E+00	.15E-30
		E	.00E+00	.00E+00	.96E-26	.89E-16	.50E-11

[a]NOTES:

A. Aerosol plume is assumed directed vertically downward by rain deflection cap on stack. Stack height recalculated and set equal to 29.2-3DW/U meters.

B. Aerosol plume is assumed directed vertically upward by rain deflection cap on stack. Stack height recalculated and set equal to 29.2 + 3DW/U meters.

C. Aerosol plume is assumed emitted horizontally from stack. Stack height set equal to 29.2 meters.

D. Aerosol plume is assumed to intersect the downwind roof edge that is closest to the aerosol emission point.

E. Aerosol plume is assumed to intersect the downwind roof edge that is beyond that edge closest to the aerosol emission point.

Examination of the results presented in Tables 2, 3, 4, and 5 again shows the complex dependence on wind speed demonstrated in Chapter 4. Higher wind speeds results in greater dispersion of the aerosol plume. This dispersion is reflected in lower aerosol concentrations within the plume (thus tending to cause lower aerosol concentrations at air intake ports) but the plume dispersion causes the plume to spread and impinge on building edges that it might have otherwise missed (thus tending to increase aerosol concentrations at air intake ports). Except for plumes emitted vertically downward, increasing port diameter while maintaining plume composition and exhaust velocity results in greater lofting of the plume, which leads to lower aerosol concentrations at air intake ports. The functional form of this dependence is complex. The variation of exhaust velocity with changes in port diameter was not available to us; therefore, no attempt was made to consider the combined effects of changes of exhaust velocity and port diameter.

Sensitivity of computed aerosol concentrations to variations in the design of the rain cap on the stack designated emission point E4 has been discussed in Section 4.4. Consideration of different rain cap designs has been included in generation of the results presented in Tables 3, 4, and 5, and these Tables support the conclusion that the rain cap designs that direct the plume vertically downward, should be avoided in preference to designs that direct the emitted plume either vertically upward, or horizontally.

Suggestions have been made in Section 4.6 for modifications that might be made as to the design and/or location of emission point E4. To reiterate, design changes might include increasing the exhaust velocity by using exhaust fans, directing the emitted aerosols vertically using a deflector, locating the exhaust port on the roof rather than the wall, or providing alternate exhaust ports on other walls to insure that the aerosols would not be emitted directly upwind.

In order to examine the effect of changing the port size of emission point E4, a series of runs of program ZIG.FOR, included in Appendix D, were made. These results are summarized in Table 6, which shows the effect of wind speed and of port diameter on the vertical distance between the elevation of release of a horizontal aerosol plume directed upwind, and the elevation of the centerline of the return plume

Table 6. Vertical distance between emission height of a horizontal aerosol plume directed upwind, and the elevation of the centerline of the return plume to the vertical plume directly above the emission point.

Windspeed	D = .98	D = 1.95	D = 2.93
2	.96E+01	.24E+02	.41E+02
4	.29E+01	.72E+01	.12E+02
6	.14E+01	.35E+01	.59E+01
8	.80E+00	.20E+01	.34E+01
10	.51E+00	.13E+01	.21E+01

to the vertical plume directly above the emission point. Examination of the results shown in Table 6 shows that larger port diameters and smaller wind velocities results in increased plume altitude at the return point of the plume. As explained above for other emission points, the effects of port diameter on exhaust velocity were not incorporated in these calculations.

6. UNCERTAINTIES FUNDAMENTAL TO THE METHODOLOGY

The only way to determine the accuracy of any model is to compare predictions made by that model with measurements made in the field under conditions identical to those assumed by the model. None of the models used in this methodology have reportedly been field validated in this manner. Furthermore, the SAFR site will likely be so complex that no generic field validation will be able to insure adequate validation of any methodology used.

In the absence of field validation, wind tunnel studies can be performed to test predictive methodologies. For example, a scale model SAFR site could be constructed and tested in an appropriate wind tunnel facility. However, the extrapolation of wind tunnel results to the real world is not always readily accepted, and field validation studies would likely be needed to firmly establish the predictive accuracy of any methodology used.

6.1 Building-Wake Effects

The basic building wake effect model used in this report, Eqn. 1, is based on a number of wind tunnel studies for buildings of simple, block design. Roof, side, and rear receptors for roof vent releases were considered in deriving the empirical dilution constant D. Wilson and Britter (1982) summarize the measurements used in deriving the value of D = 9 used in this report. This value was chosen by Wilson and Britter so that all measured concentrations would be equal to or less than the predicted concentration. In some individual cases, a measured air concentration one order or magnitude or more lower than the value predicted based on Eqn. 1 was found. Wilson and Britter (1982) emphasize that they are attempting to predict maximum air concentrations. In the absence of field testing, however, it is impossible to exactly determine how these wind tunnel results correlate with real conditions.

6.2 Plume Rise Effects

Ramsdell (1983) also does not present any field testing results for his Split-H plume rise consideration methodology. Briggs (1984) presents limited results from field validation studies which indicate that it is possible to predict plume rise within a factor of 2 or better. However, the results of only a very few studies were cited, and it does not appear that any of the cited studies considered site conditions as complex as those considered in this report. Overall, it appears that the basic conservatism of the overall methodology used in this report was not compromised by the plume rise considerations.

7. DISCUSSION AND RECOMMENDATIONS

The methodology and analyses described in this report might be extended in several ways. First, other wind speeds might be considered. Investigation should be made of the effects on the aerosol concentration at air intake ports of choosing other emission points and other emission vent diameters. As an indication of the value of such a calculation, one might consider restricting the emission vent diameter to achieve a higher exit velocity and greater plume rise. This consideration requires knowledge of the effects of changing port diameter on aerosol exhaust velocity and composition.

It might be useful to consider the effects of sodium aerosol particle growth and agglomeration (Miller, Fields, and Wiseman, 1982). While it is unlikely that predicted concentrations would be greatly changed by considering the production of larger particles with greater fall velocities, any conclusions drawn about the expected intake port concentrations for low wind speeds would be much more defensible.

Low wind-speed conditions (calms) are inadequately treated in present methodologies, including that developed in this report. We have pointed out this fact to Rockwell International staff, and have discussed the considerable uncertainty in model predictions that is generated by omitting from consideration wind speeds below 2 m/s.

We have proposed to construct a methodology that is capable of treating aerosol transport under low wind-speed conditions. This methodology might be applied to simulate aerosol conditions from release and receptor ports and for the low and high intensity fire conditions considered in this report. It should allow development of the time-dependent shape and concentration of an aerosol cloud under low wind-speed conditions. Our current thinking about the appropriate approach suggests that a superimposed puff model should yield acceptable results. A particle-in-cell model would also work, but the model complexity and expense would be considerably greater.

Suggestions have been made in Section 4.6 and in Chapter 5 for modifications that might be made as to the design and/or location of emission point E4. Design changes might include increasing the exhaust velocity by using exhaust fans, directing the emitted aerosols

vertically using a deflector, locating the exhaust port on the roof rather than the wall, or providing alternate exhaust ports on other walls to insure that the aerosols would not be emitted directly upwind.

Changes that might be considered in the design of the rain cap on the stack designated emission point E1 are discussed in detail in Section 4.4. It is apparent from this discussion that incorporation of a rain cap that would direct the exhaust plume either vertically upward or horizontally would result in significantly lower aerosol concentrations at air intake ports I1 and I2 than selection of a design that would direct the aerosol plume vertically downward.

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APPENDIX A: CODE NA1.F4

Application of this program is described in Section 4.3.

```
C       THIS PROGRAM IS USED TO DETERMINE AERSOL CONCENTRATIONS AT
C       INPUT PORTS 1-2.  THE SLOW SPEED RELEASES ARE EMITTED FROM
C       EXHAUST PORTS 1-4 WITH A WIND SPEED (U) VARYING FROM 2 M/S
C       TO 10 M/S.  THE SOURCE STRENGTH (QE) IS 1.9 KG/S.
C
C
        DIMENSION R(4,2),U(5),C(5)
C
        DATA R/ 36.6,41.83,48.93,52.8,
     &          53.9,45.51,38.71,41.34/
C
        DATA B/9.0/, QE/1.9/
C
        DATA U/ 2., 4., 6., 8., 10./
C
C
3000    FORMAT('INPUT PORTEXHAUST PORTAEROSOL CONCENTRAIONS')
        WRITE(6,3000)
C
C       J---LOOP THROUGH INPUT PORTS
        DO 500 J=1,2
C
C       I---LOOP THROUGH EXHAUST PORTS
        DO 400 I=1,4
C
C       L---LOOP THROUGH WIND SPEEDS
        DO 300 L=1,5
C
        C(L)=B*QE/(U(L)*R(I,J)*R(I,J))
300     CONTINUE
        WRITE(6,3100)J,I,(C(L),L=1,5)
3100    FORMAT(I2,':',I2,':',5(E8.2,':'))
400     CONTINUE
500     CONTINUE
        STOP
        END
```

APPENDIX B: CODE IN1FS.F4

Application of this program is described in Section 4.4.

```
C       THIS PROGRAM IS USED TO DETERMINE AEROSOL CONCENTRAIONS AT
C       INPUT PORTS 1-2.  THE RELEASES, FAST SPEED, ARE EMITTED
C       FROM EXHAUST PORT #1 WITH A WIND SPEED (U) VARYING FROM
C       2 M/S TO 10 M/S.  THE PARAMETERS USED IN THE FOLLOWING
C       EQUATIONS ARE DEFINED AS FOLLOWS:
C
C             B - EMPIRICAL CONSTANT OF MAGNITUDE
C             U - WINDSPEED
C             Q - SOURCE INTENSITY (KG/S)
C             X - SOURCE EMISSION POINT TO ROOF EDGE DISTANCE (M)
C             D - EXHAUST PORT EXIT DIAMETER
C             W - EXHAUST VELOCITY
C
        DIMENSION RROOF(2),U(5),C(5),RF(2,3),X(2),DS(2),DL(2)
C
C
        DATA B/9.0/, Q/97./, D/3.72/, W/21.9/
        DATA RROOF/ 6.8, 18.1/
        DATA X/6.0, 20.7/
        DATA DS/38.2, 29.1/
        DATA DL/68.0, 52.5/
C
        DATA U/ 2., 4., 6., 8., 10./
C
C
C
        WRITE(6,3000)
3000    FORMAT('INPUTPORT DELH AEROSOL CONCENTRATIONS')
C
C       J--LOOP THROUGH INPUT PORTS
        DO 500 J=1,2
C
C       I--LOOP THROUGH VARIATIONS IN DELH
        DO 400 I=1,3
C
        RF(I,J) = (DS(J)**0.67)*(DL(J)**0.33)
        SIG=.21*(RF(I,J)**.25)*(X(J)**.75)
C
C       L--LOOP THROUGH WINDSPEEDS
        DO 300 L=1,5
C
```

```
C       EXHAUST PORT #1 IS A TALL STACK WITH A VERTICAL HEIGHT OF
C       29.2 M. THE PRESENTS OF A STACK CAP COULD INFLUENCE THE
C       PLUME RISE.  THEREFORE THREE DIFFERENT CASES WERE TAKEN
C       INTO ACCOUNT:
C          1) STACK HEIGHT MINUS MOMENTUM DRIVEN PLUME RISE VALUE
C          2) STACK HEIGHT PLUS MOMEVTUM DRIVEN PLUME RISE VALUE
C          3) STACK HEIGHT
C
        IF (I .EQ. 1) DELH = 29.2 - (3.*D*W/U(L))
        IF (I .EQ. 2) DELH = 29.2 + (3.*D*W/U(L))
        IF (I .EQ. 3) DELH = 29.2
C
100     IF (DELH .LT. 0) DELH=0
        QROOF=.842*Q*EXP(-(DELH*.5/SIG)**2)
        C(L)=B*QROOF/(U(L)*RROOF(J)*RROOF(J))
300     CONTINUE
        WRITE(6,3400)RROOF(J),X(J),DS(J),DL(J)
3400    FORMAT(4(E8.2,':  '))
        WRITE(6,3100)J,I,(C(L),L=1,5)
3100    FORMAT(1H ,/I2,':',I2,':',5(E8.2,':'))
400     CONTINUE
500     CONTINUE
        STOP
        END
```

APPENDIX C: CODE BEACH.F4

Application of this program is described in Section 4.5.

```
C       THIS PROGRAM IS USED TO DETERMINE AEROSOL CONCENTRATIONS AT
C       INPUT PORTS 1-2.  THE FAST SPEED RELEASES ARE EMITTED FROM
C       EXHAUST PORTS #2 AND #3 WITH A WINDSPEED (U) VARYING FROM
C       2 M/S TO 10 M/S.  TWO SETS OF VALUES WERE CALCULATED FOR
C       EACH EXHAUST.  IN THE FIRST CALCULATION 'X' (SOURCE EMISSION
C       POINT TO ROOF EDGE DISTANCE) IS TAKEN FROM THE ROOF EDGE
C       CLOSEST TO THE EMISSION POINT.  THE SECOND CALCULATION OF 'X'
C       IS TAKEN FROM THE FURTHEST ROOF EDGE DISTANCE.  THE
C       PARAMETERS USED IN THE FOLLOWING EQUATIONS ARE DEFINED AS
C       FOLLOWS:
C           B - EMPIRICAL CONSTANT OF MAGNITUDE
C           U - WINDSPEED
C           Q - SOURCE INTENSITY (KG/S)
C           X - SOURCE EMISSION POINT TO ROOF EDGE DISTANCE (M)
C           D - EXHAUST PORT EXIT DIAMETER
C           W - EXHAUST VELOCITY
        DIMENSION RROOF(2,2,2),U(5),C(5),RF(2,2,2),X(2,2,2),DS(2,2),
     &  DL(2,2),HGT(2,2,2)
C
C
        DATA B/9.0/, Q/97./, D/3.72/, W/21.9/
        DATA RROOF/37.2, 6.8, 35.1, 18.1, 37.2, 6.8, 37.6, 18.1/
        DATA X/4.5, 30.8, 10.3, 17.7, 11.7, 37.8, 4.9, 17.2/
        DATA DS/28.3, 49.5, 27.4, 36.3/
        DATA DL/52.5, 68.0, 52.5, 52.5/
        DATA HGT/0.0, 15.2, 0.0, 15.2, -7.8, 7.8, -7.8, 7.8/
C
        DATA U/ 2., 4., 6., 8., 10./
C
C
C
        WRITE(6,3000)
3000    FORMAT('EXHAUSTPORT INPUTPORT EDGE AEROSOL CONCENTRATIONS')
C
C       J--LOOP THROUGH EXHAUST PORTS
        DO 500 J=1,2
C
C       I--LOOP THROUGH INPUT PORTS
        DO 400 I=1,2
C
C       K--LOOP THROUGH VARIATIONS ON 'X'
        DO 200 K=1,2
C
        RF(K,I,J) = (DS(I,J)**0.67)*(DL(I,J)**0.33)
        SIG=.21*(RF(K,I,J)**.25)*(X(K,I,J)**.75)
C
C       L--LOOP THROUGH WINDSPEEDS
        DO 300 L=1,5
C
```

```
        DELH=3.*D*W/U(L)+HGT(K,I,J)
        QROOF=.842*Q*EXP(-(DELH*.5/SIG)**2)
        C(L)=B*QROOF/(U(L)*RROOF(K,I,J)*RROOF(K,I,J))
300     CONTINUE
C       WRITE(6,3400)RROOF(K,I,J),X(K,I,J),DS(I,J),DL(I,J),HGT(K,I,J)
C3400   FORMAT(5(E8.2,':  '))
        WRITE(6,3100)J,I,K,(C(L),L=1,5)
3100    FORMAT(1H ,/I2,':',I2,':',I2,':',5(E8.2,':'))
200     CONTINUE
400     CONTINUE
500     CONTINUE
        STOP
        END
```

APPENDIX D: PROGRAM ZIG.FOR

Application of this program is described in Section 4.6.

```
TY ZIG.FOR
C       THIS PROGAM CALCULATES THE DYNAMICS FOR HORIZONTIALLY EMITTED
C       PLUMES.  THE PARAMETERS THAT ARE USED IN THE FOLLOWING
C       EQUATIONS ARE DEFINED AS FOLLOWS:
C
C               FM = MOMENTUM FLUX TERM
C               F  = BUOYANCY FLUX TERM
C               FC = BUOYANCY FLUX BELOW WHICH PLUME RISE IS DUE TO
C                    MOMENTUM ONLY
C               BJ = JET ENTRAINMENT COEFFICIENT
C               TA = AMBIENT AIR TEMPERATURE
C               TS = STACK EXIT TEMPERATURE, INPUT AS ZERO FOR A
C                    MOMENTUN SOURCE
C               VS = STACK EXIT VELOCITY, INPUT AS ZERO IF NO PLUME
C                    RISE IS TO BE CALULATED
C               D  = STACK INNER DIAMETER
C               G  = ACCELERATION DUE TO GRAVITY
C               U  = MEAN WIND SPEED AT EMISSION AT HEIGHT H
C               B  = ENTRAINMENT COEFFICIENT COEFFICIENT FOR HIGH-SPEED
C                    LONGITUDINALEMISSIONS
C               T  = TIME OF RETURN OF PLUME TO VERTICAL PLANE OF
C                    EMISSIONS
C               X  = DOWNWARD DISTANCE
C               S  = STABILITY PARAMETER
C               BA = ENTRAINMENT COEFFICIENT
C
C
C      THE CALCULATIONS FROM THIS PROGRAM WERE USED TO DETERMINE THE
C      PLUME RISE FROM THE HORIZONTAL EMISSIONS FROM EXHAUST PORT #4.
C
C
      DIMENSION DELH(5),U(5),D(3)
      DATA U/ 2., 4., 6., 8., 10./
      DATA TA/288./, TS/810./, VS/21.9/,
     &       BA/0.6/, G/9.8/
      DATA D/.98, 1.95, 2.93/
C
C
C     CALCULATE A DELTA H ('DELH' - PLUME RISE) FOR EACH
C     WINDSPEED ('U' - 2, 4, 6, 8, 10)
C
C
      DO 1300 I=1,3
      DO 100 J=1,5
C
C
      BJ=(1/3)+(U(J)/VS)
C
C
      B=SQRT((BJ**2)+(BA**2))
C
```

```
C
      FM=((TA/TS)*(VS**2)*((D(I)**2)/4))
C
C
      T=((3*FM)/((B**2)*(U(J)**4)))**.5
C
C
      WRITE(6,200)T
200   FORMAT (1H ,/'T = ',E8.2)
C
C
      FP=((G*VS*(D(I)**2))/4)*(1-(TA/TS))
C
C
      IF (FP .LE. 55) GOTO 300
      FC=(.0141*((VS*D(I))**1.67))
      GOTO 400
300   FC=(.0727*((VS*D(I))**1.33))
C
C
C     HIGH-DENSITY PLUME RISES ARE NOT CONSIDERED
C
400   IF (FP .GT. FC) GOTO 500
      WRITE(6,600)
600   FORMAT ('ERROR-----FP .LE. FC')
      STOP
C
C
500   F=FP
C
C
      IF (F .LE. 55) GOTO 900
      XS=34*(F**.4)
      GOTO 700
900   XS=14*(F**.625)
700   WRITE(6,800) XS
800   FORMAT (1H ,/' X* = ',E8.2)
C
C
      X=((3*FM*T)/((B**2)*U(J)))**.33
C
C
      IF (X .GE. (3.5*XS)) GOTO 1000
      DELH(J)=((3/2)*(F/(B**2))*((T**2)/U(J)))**.33
      GOTO 1100
1000  DELH(J)=((3/2)*(F/(B**2))*(((3.5*XS)**2)/(U(J)**3)))**.33
C
C
1100  WRITE(6,1200) I,J,DELH(J)
1200  FORMAT(1H ,/I2, '   DELH(',I2,') = ',E8.2)
100   CONTINUE
1300  CONTINUE
      STOP
      END
```

APPENDIX E: PROGRAM IN1SP2.F4

Application of this program is described in Section 4.6.

```
 TY IN1SP2.F4
C       PREVIOUS CALCULATIONS DETERMINED THAT THE SOURCE POINT FROM
C       THE HORIZONTAL FAST SPEED EMISSIONS FROM EXHAUST PORT #4 FOR
C       WINDSPEEDS 4, 6, 8, AND 10 M/S HIT A BLDG.        WINDSPEED
C       2 M/S DID NOT, SO IT WAS CONSIDERED SEPERATELY.  THIS
C       PROGRAM MEASURED THIS SPECIAL CASE.
C
C
        DIMENSION RROOF(2,2),U(1),RF(2,2),X(2,2),DS(2,2),
     &  DL(2,2),DELH(2,2)
C
C
        DATA B/9.0/, Q/97./, D/3.72/, W/21.9/
        DATA RROOF/37.2, 6.8, 37.6, 18.1/
        DATA X/16.6, 42.7, 8.8, 21.5/
        DATA DS/27.4, 27.4, 36.3, 36.3/
        DATA DL/52.5, 52.5, 52.5, 52.5/
        DATA DELH/10.7, 25.9, 10.7, 25.9/
C
        DATA U/ 2./
C
C
C
        WRITE(6,3000)
3000    FORMAT('EXHAUSTPORT INPUTPORT EDGE AEROSOL CONCENTRATIONS')
C
C       J--LOOP THROUGH INPUT PORTS
        DO 500 J=1,2
C
C       I--LOOP THROUGH VARIATIONS ON 'X'
        DO 400 I=1,2
C
        RF(I,J) = (DS(I,J)**0.67)*(DL(I,J)**0.33)
        SIG=.21*(RF(I,J)**.25)*(X(I,J)**.75)
        QROOF=.842*Q*EXP(-(DELH*.5/SIG)**2)
        C=B*QROOF/(U(1)*RROOF(I,J)*RROOF(I,J))
C       WRITE(6,3400)RROOF(I,J),X(I,J),DS(I,J),DL(I,J),DELH(I,J)
C3400    FORMAT(5(E8.2,':  '))
        WRITE(6,3100)J,I,C
3100    FORMAT(1H ,/I2,':',I2,':',E8.2,':')
400     CONTINUE
500     CONTINUE
        STOP
        END
```

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