From: Mark Blumberg
To: Internet:koc@nei.org
Date: Wed, Jan 10, 2001 10:27 AM
Subject: Transmittal of Draft Research Document

The attached draft research study is being provided to the NEI Control Room Analysis subgroup to stimulate discussions concerning the modification of the ARCON code. The attachment is in WordPerfect format. Since this format may not be easily converted to Word format, a fax of the attachment is also being sent to 202-533-0112. If you have any questions concerning the report please feel free to contact me at 301-415-1083.

January 4, 2001

POTENTIAL MODIFICATIONS TO ARCON96 TO TREAT HIGH-VELOCITY VENT RELEASES

Disclaimer note: The following is an initial draft effort. As such it does not imply what the ultimate outcome may be and it may contain errors. Many issues require resolution. Decisions related to these and/or other issues that may be identified could result in significantly different results than may be implied below, including a decision that there is not an adequate basis for revising the ARCON methodology. Further testing, verification, resolution of some apparent inconsistencies, etc., are needed.

BACKGROUND

The ARCON computer code (Ramsdell and Simonen 1997) was developed as an alternative to the Murphy-Campe (Murphy and Campe 1974) method of calculating atmospheric dispersion factors (X/Q) for control room habitability assessments. The code calculates relative concentration values (X/Qs) for ground-level and stack releases using standard Gaussian equations. It has a third release option, vent releases. In the vent release option, X/Qs for vent releases are calculated by averaging the X/Qs for ground-level and stack release using the procedure described in Regulatory Guide 1.111 (NRC 1977). That procedure was developed to estimate X/Qs at the EAB and LPZ for releases from vents with low to moderate vertical velocities (10 to 15 m/s).

The ARCON code makes several significant departures from the Murphy-Campe procedure. It calculates X/Qs from hourly meteorological data and averages the hourly X/Qs, accounting for changes in meteorological conditions, to get X/Qs for periods ranging from one to 720 hours in duration. It includes corrections to the dispersion factors to account for dispersion under low wind speed conditions and in building wakes. It considers stack releases explicitly, and it has the vent release option.

Following release of the ARCON code, problems have arisen in two related areas of code application. The first problem area has been the use of the ARCON code for control room habitability assessments for stack releases. In these applications, the distance from the stack to the control room intake is generally small compared to the stack height. Therefore, the stack effluent does not have time to disperse down to intake level before being transported beyond the intake. As a result, the dispersion factors calculated by ARCON are typically essentially zero ($<<10^{-10}$ s/m^3). The second problem area is the use of ARCON for calculation of dispersion factors for vents with high velocity releases, for example, for releases from main steam safety valves (MSSVs) and atmospheric dump valves (ADVs). These releases have significant plume rise that carries the effluents well above control room intake level for almost all meteorological conditions. Again the dispersion factors calculated by ARCON are typically essentially zero.

Atmospheric dispersion factors of zero pose problems from a regulatory standpoint if there are physical mechanisms that can carry contaminated effluent from a stack or vent to the control room intake. Two such mechanisms can be postulated. The first is dispersion under calm conditions (mean wind velocity = 0.0), and the other involves wind direction meander including wind direction reversals. These mechanisms are not represented in ARCON or other computer

codes that rely on straight-line Gaussian dispersion models. However, ARCON can be modified to represent either or both mechanisms. Frenkiel derived a model that can be used to compute X/Q for any wind speed, including zero, and the standard straight-line Gaussian model can be used for meandering conditions and wind reversal if the distance is interpreted as distance traveled before arriving at the intake rather than the straight-line distance from the release point to the intake. In either case, the key to estimating X/Q is determining plume rise.

LOW WIND SPEED DISPERSION MODELS

In ARCON, ground-level X/Qs for stack releases are calculated using the standard straight-line Gaussian plume model

$$\chi / Q = \frac{1}{\pi \sigma_y \sigma_z U} \exp\left[-0.5 \left(\frac{h_s + \Delta h}{\sigma_z} \right)^2 \right] \qquad \textbf{(1)}$$

where σ_y and σ_z are atmospheric dispersion parameters that are a function of atmospheric stability and distance. For all stability classes, X/Q is zero directly beneath the release point because the exponential term is zero. As the distance increases, the dispersion parameters increase. Near the release point, the exponential term increases faster than the remainder of the term on the right side of Equation (1) decreases. The exponential term asymptotically approaches a value of 1.0, and as a result there is a distance at which the ground-level concentration reaches a maximum; as the distance continues to increase, the concentration decreases. This model can be used for low wind speeds, but not for calm winds because the equation becomes undefined if the wind speed is zero. As a practical matter, the equation should not be used for wind speeds less than about 1 m/s.

Atmospheric dispersion does not cease when the wind is apparently calm. Equation (1) becomes undefined in calm winds because it is only a partial solution of the governing equations. A portion of the complete solution for the governing equations is eliminated by the assumptions leading to Equation (1). Frenkiel (1953) used a different set of assumptions in solving the governing equations and arrived at a solution that remains defined for calm winds.

FRENKIEL'S MODEL

Frenkiel's model is well behaved in low wind speed conditions and gives finite X/Q values for calm wind (mean wind velocity = 0). As wind speed increases, X/Qs increase to a maximum value for a wind speed in the 1 to 2 m/s range and then decrease as the wind speed continues to increase. The model is (ASPP 1984, Eq 6.260 following correction)

$$\chi/Q = \frac{\sigma_u \exp\left(-\frac{U^2}{2\sigma_u^2} \right)}{(2\pi)^{3/2} \sigma_v \sigma_w r^2} \left[1 + (\frac{\pi}{2})^{1/2} \frac{Ux}{\sigma_u r} \exp\left(\frac{U^2 x^2}{2\sigma_u^2 r^2} \right) \mathrm{erfc}\left(-\frac{1}{2^{1/2}} \frac{Ux}{\sigma_u r} \right) \right] \qquad \textbf{(2)}$$

where σ_u, σ_v, and σ_w are along wind, cross wind, and vertical turbulence measures, respectively (m/s) and r is a pseudo-diagonal distance from a point directly above the release point to the intake. For calm winds Equation (2) has a simple form that is similar to the standard Gaussian puff model. It is

$$\chi / Q = \frac{\sigma_u}{(2\pi)^{3/2}\sigma_v\sigma_w r^2} \quad \mathbf{(3)}$$

The definition of r is

$$r^2 = x^2 + \left(\frac{\sigma_u}{\sigma_v}\right)^2 y^2 + \left(\frac{\sigma_u}{\sigma_w}\right)^2 z^2 \quad \mathbf{(4)}$$

for positions under the center line of a plume, y = 0.0, and z = h_s+Δh, thus

$$r^2 = x^2 + \left(\frac{\sigma_u}{\sigma_w}\right)^2 (h_s + \Delta h)^2 \quad \mathbf{(5)}$$

Values of σ_u and σ_w may be estimated from the wind speed and, perhaps, stability. Published data on low wind turbulence and data collected during dispersion experiments suggest that reasonable estimates of the turbulence parameters required by the Frenkiel's model can be made. A cursory review of atmospheric turbulence data indicates that an equation of the form

$$\sigma = (a^2 + b^2 U^2)^{1/2} \quad \mathbf{(6)}$$

can be used to estimate both σ_u and σ_w, providing appropriate values are selected for a and b. However, this approach has not been peer reviewed or published.

At moderate and high wind speeds, the X/Qs predicted by Frenkiel's model decrease proportional to about $u^{-3/2}$ (not including the effect of wind speed on plume rise). This decrease is more rapid than other models. In the common straight-line Gaussian models, X/Q decreases proportional to u^{-1}. Consequently, it would seem appropriate to limit application of the model to calm and near calm conditions.

RECIRCULATION MODEL

The recirculation model is basically the straight-line Gaussian model given by Equation (1) except that the distance used to determine model parameters (σ_y, σ_z, and Δh) is no longer the downwind distance. Instead, the wind direction is sufficiently variable that effluent returns to the vicinity of the release point, and the distance traveled is assumed to be equal to the distance to the maximum of the X/Q vs distance curve for the standard straight-line model. The distance to the maximum in the X/Q vs distance curve depends on initial release height, plume rise, and

atmospheric stability. In addition, the maximum may be reached before or after the plume reaches its equilibrium height. Therefore, it is necessary to search for the maximum X/Q.

The assumption that the plume returns to the vicinity of the release point is reasonable for calm and nearly calm winds. As the wind speed increases, the assumption becomes less tenable. As with the Frenkiel model, there is wind speed above which the model should not be used. Selection of the limiting wind speed is likely to be highly subjective.

PLUME RISE

Both Frenkiel's model and the recirculation model require plume rise estimates. Briggs (1984) provides useful equations for limiting plume rise in stable (PG stability classes E through F) and neutral atmospheric conditions (PG stability class D). However, the equation he provides for use in unstable conditions (PG stability classes A through C) requires information not readily available from licensee's meteorological systems.

The rise of plumes from MSSVs and ADVs does not appear to be specifically addressed in the literature. However, the plume rise equations of Briggs are derived from a combination of theoretical bases and experimental data that should be reasonably applicable to rise of plumes from these vents provided that the vents are at roof-top level and that the vent is uncapped and directed upward.

Near the source, Briggs gives following equation (Briggs 1984, Eq. 8.57) for plume rise near the source

$$\Delta h = \left(\frac{3}{\beta_1{}^2} \frac{F_m}{U^2} x + \frac{3}{2\beta_2{}^2} \frac{F_b}{U^3} x^2 \right)^{1/3} \quad \textbf{(7)}$$

where
Δh = plume rise (m)
F_m = momentum flux parameter (m^4/s^2)
Δ_1 = dimensionless entrainment constant related to momentum
U = wind speed at release height
x = distance from the release point (m)
F_b = buoyancy flux parameter (m^4/s^3)
Δ_2 = dimensionless entrainment constant related to buoyancy.

Briggs uses a value of 0.6 for Δ_1 and calculates Δ_2 as (Briggs 1984, Eq. 8.46)

$$\beta_2 = 0.4 + 1.2 \frac{U}{w_0} \quad \textbf{(8)}$$

where w_0 is the effluent exit velocity. The momentum flux parameter, F_m, is the momentum flux of the effluent at the vent divided by $\Delta\Delta_a$ where Δ_a is the density of air (kg/m^3). Thus, F_m is

$$F_m = \frac{\rho_o V_o}{\pi \rho_a} w_o \qquad \textbf{(9)}$$

where Δ_o = effluent density after expansion to atmospheric pressure (kg/m^3)
V_o = volumetric release rate (m^3/s)
w_o = effluent vertical velocity (m/s).

Similarly, the buoyancy flux parameter is the buoyant flux divided by $\Delta\Delta_a$. It is

$$F_b = g \frac{(\rho_a - \rho_o) V_o}{\pi \rho_a} \qquad \textbf{(10)}$$

Although plume rise estimated by Eq. 10 continues indefinitely, Briggs provides equations to estimate maximum plume rise for rise into a stable layer and rise limited by ambient turbulence.

For stable atmospheric conditions, the rise of buoyancy dominated plumes is limited (Briggs 1984, Eq. 8.71) to

$$\Delta h_{max} = 2.6 \left(\frac{F_b}{Us^2} \right)^{1/3} \qquad \textbf{(11)}$$

where s is the Brunt-Väisälä frequency, given by

$$s = \frac{g}{\theta_a} \frac{\partial \theta_a}{\partial z} \qquad \textbf{(12)}$$

where g is gravitational acceleration, 9.8 m/s^2, and Δ_a is the potential temperature of the air and z is the height above ground. Typical values of s are 0.00049 s^{-2} for E stability, 0.0013 s^{-2} for F stability, and 0.002 s^{-2} for G stability. Buoyant plume rise in neutral conditions is limited by ambient turbulence to (Briggs 1984, Eq. 8.97)

$$\Delta h_{max} = 1.2 \left(\frac{F_b}{Uu*^2} \right)^{3/5} (h_s + \Delta h)^{2/5} \qquad \textbf{(13)}$$

where u* is a scaling velocity related to atmospheric turbulence. For most purposes, u* is proportional to the wind speed and surface roughness with a constant of proportionality that is a function of surface roughness and height above ground. Typical values of the constant for

nuclear power plant sites range from about 10 to 20. Buoyant rise in unstable conditions should be greater than the rise in neutral conditions.

According to Briggs, even moderately warm plumes should ultimately be buoyancy dominated. Nevertheless, the following equations that can be used to estimate the maximum rise of momentum-dominated plumes are given for completeness. For stable atmospheric conditions, the rise of a momentum-dominated plume is limited to (Briggs 1984, Eq. 8.66)

$$\Delta h_{max} = 2.44\left(\frac{F_m}{s}\right)^{1/4} \quad \textbf{(14)}$$

For momentum-dominated plumes in neutral conditions, plume rise is limited to (Briggs 1984, Eqs. 8.87 and 8.96)

$$\Delta h_{max} = \beta_2^{-6/7}\left(\frac{F_m}{U}\right)^{3/7}\left[\frac{0.6(h_s + \Delta h)}{u*^3}\right]^{1/7} \quad \textbf{(15)}$$

Equations (13) and (15) both involve plume rise in a manner that precludes a general closed form solution. Approximate solutions are readily obtainable if $h_s << \Delta h$ or $h_s >> \Delta h$. In the case of high temperature, high velocity vent releases neither approximation is appropriate. However, when the equations are solved iteratively, the solutions converge rapidly.

Neither Ray Hosker (NOAA Atmospheric Transport and Dispersion Division) nor David Wilson (Univ. of Alberta) finds fault with the basic notion of using Briggs plume rise equations for releases from main steam system isolation valves or atmospheric dump valves. However, they expressed uneasiness with using the full plume rise calculated by Briggs equations for vents adjacent to or on the sides of buildings. Wilson suggested that some adjustment could be made to the entrainment constants in the equations to account for building effects. Neither Hosker nor Wilson is aware of anything in recent literature that addresses these issues.

VENT RELEASE PARAMETERS

The plume rise equations contain a buoyance flux parameter (F_b) and a momentum flux parameter (F_m). For most releases, these parameters are easily calculated from the air temperature, and the effluent temperature, stack flow, and stack radius. For high-temperature steam releases from the vents under consideration, the vent acts as a throttle. As the steam enters the air it expands to atmospheric pressure. Steam tables are needed to estimate the temperature and density of the effluent after expansion. It will be necessary to either require users to calculate F_b and F_m and enter them with other data or program steam tables into ARCON.

Precise estimates of the density of the steam will require air temperature and pressure. Neither air temperature or pressure is included in ARCON meteorological data sets. Temperature is included in the standard NRC meteorological data format, but pressure isn't.

PRELIMINARY COMPUTATIONAL INSIGHTS

Industry[a] provided NRC with a characterization of the thermodynamic conditions, mass flow rates, and velocities for steam discharges from ADVs, PORVs, and MSSVs for design-basis steam generator tube rupture events for three reactor types. These reactors were a 1973 vintage Two-Loop Westinghouse Plant, a 1973 vintage B&W plant, and the ABB-CE System 80+ ALWR. The System 80+ discharges were characterized at three stages of the SGTR event. Some additional information was provided that indicated that characteristics of potential discharges from a mid-1970s vintage ABB/CE plant are similar to those from a B&W plant. The discharge characteristics are summarized in Table 1.

Table 1. Test Case Steam Discharge Characteristics for SGTR Events

Reactor	Rel. Ht. (m)	Intake Ht. (m)	Intake Dist. (m)	Cont. Ht. (m)	Cont. Dist. (m)	Vert. Vel. (m/s)	F_b (m^4/s^3)	F_m (m^4/s^2)
Westinghouse	29.0	25.3	7.6	61.9	19.8	456	101	3,110
B&W	11.2	19	40	39.3	21	67.5	6.75	57.8
ABB/CE	17.2	10.7	62.4	39.3	21	67.5	6.75	57.8
ALWR Stage 1	13.7	22.5	35.0	53.0	24	457	432	46,300
ALWR Stage 2	13.7	22.5	35.0	53.0	24	131	181	5,680
ALWR Stage 3	13.7	22.5	35.0	53.0	24	12	16.5	47.4

The release height, intake height, and containment heights listed in Table 1 are all above grade. When the intake height is less than the release height, the difference in heights increases the effective release height. When the intake height is greater than the release height, the difference decreases the effective release height. In each case in Table 1, the release height is well below the height of the containment building. The difference between the containment height and the release height is related to the plume rise required for vent releases to clear the building and building wake. This factor has not been included in modeling of atmospheric dilution factors, but it is likely to be a significant factor if it can be incorporated appropriately. Plume rise less than this difference in release and containment building heights indicates the plume is likely to mix within the building wake and impact the intake even though the plume may initially rise above the intake. Plumes with rise less than a factor of 2 greater than the difference are likely to be entrained within the building wake on occasion. The intake distance is the horizontal distance between the release point and intake. It is a straight-line distance that does not include the effects of intervening structures. The containment distance is the distance of the release point from the containment building. It may be a significant factor in determining plume rise, but has not been incorporated in plume rise modeling.

PLUME RISE

[a] K.O. Cozens, Nuclear Energy Institute, email to J. J. Hayes, NRC, June 8, 2000.

Briggs plume rise equations (ASPP 1984, Eq 8.71 and 8.97) were used to estimate a maximum plume rise for each discharge characterization for Pasquill-Gifford Stability Classes A through G and wind speeds from 0.5 m/s to 10 m/s. The results of these calculations are presented in Table 2. The following assumptions were made in making the calculations:

1) maximum plume rise is limited to 1,000 m
2) maximum plume rise for neutral conditions may be used for unstable conditions
3) during stable conditions, plume rise is limited to the smaller of the rises calculated for neutral and stable conditions
4) the characteristic wind speed (u*) may be estimated as U/12.

These assumptions are reasonable, but by no means the only assumptions that might have been made. In addition, the values of F_b and F_m provided by industry were used without full verification. These values appear reasonable.

The computational results shown in Table 2 indicate that there are likely to be conditions in which the discharge steam clears the structures in the vicinity of the release point and that there are other conditions in which the discharge steam may not clear the structures. For example, the test case ALWR Stage 1 discharges are likely to clear structures for almost all conditions, but CE, B&W, and stage 3 ALWR vent releases may not clear structures in moderate to high winds. The bold numbers in Table 2 indicate maximum plume rise less than twice the difference in release point and containment building heights, and the numbers in bold italics indicate maximum plume rise less than the difference in heights.

Table 2. Maximum Plume Rise as a Function of Reactor Type, Wind Speed, and Stability

Reactor	Stability Class	Wind Speed (m/s) 0.5	1.0	2.0	4.0	7.0	10.0
Westinghouse	A-D	1000.0	1000.0	1000.0	483.6	102.6	**42.3**
	E	171.2	135.9	107.8	85.6	71.0	**42.3**
	F	123.7	98.1	77.9	**61.8**	**51.3**	**42.3**
	G	107.1	85.0	67.5	**53.6**	**44.4**	**39.5**
CE and B&W	A-D	1000.0	1000.0	255.8	**37.1**	***9.7***	***4.6***
	E	69.5	**55.1**	**43.8**	**34.7**	***9.7***	***4.6***
	F	**50.2**	**39.8**	***31.6***	***25.1***	***9.7***	***4.6***
	G	**43.5**	**34.5**	***27.4***	***21.7***	***9.7***	***4.6***
ALWR Stage 1	A-D	1000.0	1000.0	1000.0	1000.0	372.0	132.8
	E	275.9	219.0	173.8	138.0	114.5	101.7
	F	199.3	158.2	125.6	99.7	82.7	**73.4**
	G	172.7	137.0	108.8	86.3	**71.6**	**63.6**
ALWR Stage 2	A-D	1000.0	1000.0	1000.0	840.4	164.2	**61.1**
	E	207.9	165.0	131.0	104.0	86.3	**61.1**

	F	150.2	119.2	94.6	**75.1**	**62.3**	**55.3**
	G	130.1	103.3	82.0	**65.1**	**54.0**	**47.9**
ALWR Stage 3	A-D	1000.0	1000.0	615.7	84.0	***20.1***	***9.0***
	E	93.6	**74.3**	**58.9**	**46.8**	***20.1***	***9.0***
	F	**67.6**	**53.7**	**42.6**	***33.8***	***20.1***	***9.0***
	G	**58.6**	**46.5**	***36.9***	***29.3***	***20.1***	***9.0***

The computational results shown in Table 2 do not take into account any potential effects of buildings on plume rise. In moderate and high winds, buildings may increase atmospheric turbulence and thereby reduce plume rise. Similarly, the results do not consider locations of vents other than on the top of the highest structure in the building complex. In particular, there is no assurance that the plume-rise estimates in Table 2 are reasonable for vents located on the sides of buildings well below the roof line.

ATMOSPHERIC DILUTION FACTORS

Control room atmospheric dilution factors were calculated for a range of wind speed and atmospheric stability classes to examine the variation of the dilution factors with these important meteorological parameters. The atmospheric dilution factors calculated by the Frenkiel model are listed in Table 3, and those calculated using the recirculation model are listed in Table 4.

Table 3. Atmospheric Dilution Factors Calculated by the Frenkiel Model

		Wind Speed (m/s)					
	Stability Class	0.5	1.0	2.0	4.0	7.0	10.0
Westinghouse	A-D	1.57E-07	5.11E-08	8.34E-09	8.84E-09	8.99E-08	3.42E-07
	E	5.22E-06	2.71E-06	7.04E-07	2.78E-07	1.86E-07	3.42E-07
	F	9.90E-06	5.14E-06	1.34E-06	5.28E-07	3.53E-07	3.42E-07
	G	1.31E-05	6.82E-06	1.78E-06	7.01E-07	4.68E-07	3.91E-07
B&W	A-D	8.01E-07	2.70E-07	7.78E-07	2.72E-05	2.19E-02	7.49E-03
	E	2.48E-04	1.71E-04	6.13E-05	3.39E-05	2.19E-02	7.49E-03
	F	5.62E-04	4.27E-04	1.73E-04	1.14E-04	2.19E-02	7.49E-03
	G	8.23E-04	6.58E-04	2.87E-04	2.17E-04	2.19E-02	7.49E-03
ABB/CE	A-D	1.22E-06	4.12E-07	1.10E-06	1.71E-05	1.41E-04	3.95E-04
	E	2.64E-04	1.66E-04	5.15E-05	2.28E-05	1.41E-04	3.95E-04
	F	5.04E-04	3.27E-04	1.04E-04	4.66E-05	1.41E-04	3.95E-04
	G	6.68E-04	4.38E-04	1.40E-04	6.39E-05	1.41E-04	3.95E-04
ALWR Stage 1	A-D	7.03E-07	2.36E-07	3.90E-08	9.74E-09	3.53E-08	2.31E-07
	E	9.98E-06	5.63E-06	1.59E-06	6.85E-07	4.97E-07	4.40E-07
	F	1.99E-05	1.15E-05	3.36E-06	1.50E-06	1.12E-06	1.01E-06
	G	2.72E-05	1.60E-05	4.74E-06	2.15E-06	1.63E-06	1.49E-06
ALWR Stage 2	A-D	7.03E-07	2.36E-07	3.90E-08	1.39E-08	2.13E-07	1.67E-06
	E	1.82E-05	1.05E-05	3.05E-06	1.35E-06	1.00E-06	1.67E-06

	F	3.69E-05	2.20E-05	6.65E-06	3.08E-06	2.38E-06	2.21E-06
	G	5.08E-05	3.08E-05	9.54E-06	4.52E-06	3.57E-06	3.37E-06
ALWR Stage 3	A-D	7.03E-07	2.36E-07	1.06E-07	2.30E-06	1.55E-04	2.76E-02
	E	1.08E-04	6.91E-05	2.28E-05	1.16E-05	1.55E-04	2.76E-02
	F	2.36E-04	1.63E-04	5.89E-05	3.33E-04	1.55E-04	2.76E-02
	G	3.38E-04	2.43E-04	9.28E-05	5.62E-05	1.55E-04	2.76E-02

Table 4. Atmospheric Dilution Factors Calculated by the Recirculation Model

		Wind Speed (m/s)					
	Stability Class	0.5	1.0	2.0	4.0	7.0	10.0
Westinghouse	A	1.52E-06	9.07E-07	1.78E-06	3.08E-06	4.30E-06	7.68E-06
	B	5.00E-07	2.50E-07	1.00E-07	7.10E-07	2.17E-06	7.10E-06
	C	0.00E-00	1.36E-07	6.78E-08	7.36E-08	1.69E-06	6.30E-06
	D	0.00E-00	0.00E-00	2.63E-38	1.31E-14	9.16E-07	4.63E-06
	E	1.88E-06	1.91E-06	1.87E-06	1.78E-06	1.66E-06	3.98E-06
	F	1.87E-06	2.26E-06	2.46E-06	2.52E-06	2.47E-06	2.90E-06
	G	3.45E-07	1.02E-06	1.59E-06	1.78E-06	1.85E-06	1.86E-06
B&W	A	3.13E-06	8.07E-06	5.70E-05	7.80E-04	7.26E-04	4.45E-04
	B	5.13E-07	6.53E-07	1.47E-05	9.58E-04	1.24E-03	6.69E-04
	C	2.78E-07	1.39E-07	1.56E-06	7.51E-04	2.30E-03	1.02E-03
	D	0.00E-00	4.54E-24	1.18E-09	3.06E-05	4.98E-03	1.07E-03
	E	3.84E-05	3.71E-05	3.51E-05	3.36E-05	8.58E-03	8.18E-04
	F	7.27E-05	7.54E-05	7.59E-05	7.59E-05	1.54E-02	1.08E-03
	G	6.80E-05	7.92E-05	8.69E-05	9.97E-05	4.14E-03	9.43E-04
ABB/CE	A	2.97E-06	6.82E-06	1.51E-05	3.71E-05	5.98E-05	1.00E-04
	B	4.98E-07	5.63E-07	4.89E-06	2.31E-05	6.73E-05	9.79E-05
	C	2.70E-07	1.35E-07	7.44E-07	1.57E-05	6.21E-05	9.51E-05
	D	0.00E-00	1.68E-25	1.47E-10	1.15E-05	5.29E-05	8.34E-05
	E	2.22E-05	1.92E-05	1.60E-05	1.28E-05	5.07E-05	8.35E-05
	F	3.15E-05	2.84E-05	2.42E-05	1.95E-05	4.27E-05	7.03E-05
	G	2.28E-05	2.20E-05	1.98E-05	1.69E-05	3.41E-05	5.84E-05
ALWR Stage 1	A	1.54E-06	7.72E-07	5.15E-07	7.73E-07	1.02E-06	1.64E-06
	B	5.13E-07	2.57E-07	1.28E-07	7.76E-08	2.27E-07	1.15E-07
	C	0.00E-00	0.00E-00	6.95E-08	3.48E-08	1.46E-07	8.73E-07
	D	0.00E-00	0.00E-00	0.00E-00	9.81E-13	3.69E-08	4.38E-07
	E	2.82E-07	4.95E-07	5.66E-07	6.04E-07	6.27E-07	6.35E-07
	F	1.01E-07	3.85E-07	6.79E-07	8.48E-07	9.77E-07	1.05E-06
	G	0.00E-00	0.00E-00	2.17E-07	5.42E-07	7.26E-07	8.30E-07
ALWR Stage 2	A	1.54E-06	7.72E-07	1.27E-06	2.51E-06	4.31E-06	6.69E-06
	B	5.13E-07	2.57E-07	1.28E-07	4.17E-07	1.67E-06	5.59E-06
	C	0.00E-00	0.00E-00	6.95E-08	2.51E-08	7.95E-07	4.86E-06
	D	0.00E-00	0.00E-00	0.00E-00	7.66E-18	3.54E-07	3.46E-06
	E	1.22E-06	1.34E-06	1.43E-06	1.48E-06	1.50E-06	2.90E-06
	F	1.08E-06	1.68E-06	2.07E-06	2.43E-06	2.67E-06	2.81E-06
	G	0.00E+00	6.69E-07	1.41E-06	1.89E-06	2.29E-06	2.55E-06
ALWR Stage 3	A	1.67E-06	4.06E-06	1.30E-05	1.34E-03	8.80E-04	4.95E-04
	B	5.13E-07	2.57E-07	2.57E-06	2.02E-03	1.45E-03	7.04E-04
	C	2.78E-07	1.39E-07	1.55E-07	2.70E-03	2.45E-03	8.12E-04
	D	0.00E-00	1.56E-39	2.28E-13	3.72E-06	3.99E-03	4.13E-04
	E	1.64E-05	1.65E-05	1.61E-05	1.55E-05	5.00E-03	1.39E-04
	F	2.82E-05	3.11E-05	3.30E-05	3.40E-05	1.10E-04	2.83E-06
	G	2.32E-05	2.87E-05	3.43E-05	4.00E-05	9.10E-05	9.03E-03

For the Frenkiel model, the effective release height was assumed to be equal to the maximum plume rise plus the release height minus the intake height. The effective release height for the Westinghouse vent releases is approximately 4 m greater than the maximum plume rise, and the effective release height for the ABB/CE vent release is about 8 m greater than the plume rise. For the remaining vents releases, the effective release height is 8 or 9 m lower than the maximum plume rise. In some cases (B&W at 7 and 10 m/s, and ALWR Stage 3 at 10 m/s) the effective release height is near zero. The atmospheric dilution factors in these cases are much larger than the atmospheric dilution factors at lower wind speeds. As the wind speed increases above the speed at which the effective release height becomes zero, the atmospheric dilution factor decreases as if the release were a ground-level release. Note that the Frenkiel model may be used at all wind speeds, not just low wind speeds.

The effective release heights for the recirculation model calculations were also the maximum plume rise (Equation 13, 14, or 15, as appropriate) plus the release height minus the intake height. For each vent type in low-wind speed, neutral stability (D) conditions, the effective release height was sufficient that the maximum in the X/Q vs distance curve was not reached within 20 km of the release point. Similarly for ALWR stage 1 and stage 2 releases, the vertical dispersion under extremely stable (G) conditions at low wind speeds (0.5 m/s) is sufficiently small that the X/Q maximum was not reached. In all of these cases, the atmospheric dilution factors at 20 km, which are zero or near zero, are listed in Table 4. For the remaining cases, the table lists the maximum dilution factor in the X/Q vs distance curve unless the maximum occurs at a distance less than the distance between the release point and the intake. If the maximum in the X/Q vs distance curve occurs between the release point and the intake, the X/Q is calculated at the distance to the intake.

For wind speeds above about 4 m/s for unstable (A, B, C) conditions and about 5 or 6 m/s for neutral (D) and stable (E, F, G) conditions, the atmospheric dilution factors are about the same as atmospheric dilution factors for ground-level releases. However, these wind speeds are probably greater that the maximum wind speed for which a recirculation model is appropriate.

95TH PERCENTILE ATMOSPHERIC DILUTION FACTORS

Tables 3 and 4 present atmospheric dilution factors calculated by the Frenkiel and recirculation models without considering the frequencies of various combinations of atmospheric conditions. A copy of the of the ARCON96 source code was modified to use the Frenkiel and recirculation models for vent and elevation releases to permit evaluation of these models in a regulatory setting. The modified code has undergone limited testing, but the testing has not been sufficient to ensure that the results are correct.

In the initial set of modifications, the Frenkiel and recirculation models were added to ARCON. The Frenkiel model was used for wind speeds less than U_f, and the recirculation model was used for wind speeds greater than U_f but less than U_r. The existing elevated plume model was used for wind speeds above U_r. Using 1.0 m/s for U_f and 3.0 m/s for U_r, the modified code was run with five different sets of meteorological data for each of set of vent characteristics and vent/intake geometry. The results of these calculations are summarized in Table 5.

Table 5. ARCON00x Estimate of 95th Percentile X/Q Using A Combination of the Frenkiel and Recirculation Models

					System 80+ ALWR		
Meteor. Data	Year	West.	B&W	CE	Stage 1	Stage 2	Stage 3
Site A	1991	2.42E-06	2.93E-03	6.92E-05	8.16E-07	2.28E-06	4.17E-03
Site B	1988	1.86E-06	7.03E-04	5.06E-05	6.45E-07	1.97E-06	8.45E-04
Site C	1993	2.35E-06	4.41E-03	1.75E-03	4.39E-05	7.89E-05	6.32E-04
Site D	1995	7.22E-06	4.27E-03	1.41E-03	3.29E-05	6.27E-05	5.36E-04
Site E	1996	2.33E-06	4.54E-04	4.98E-05	6.67E-07	2.06E-06	1.19E-03

As expected, the 95th percentile X/Qs are sensitive to the vent release characteristics and release point-intake geometry. The sensitivity to vent release characteristics is seen in the variation of X/Qs for the ALWR releases. The geometry for these releases is the same. Sensitivity to release point/intake geometry is seen by comparing the X/Qs for the B&W and CE vent releases. These releases have the same characteristics, only the geometry is different.

The variation of 95th percentile X/Qs with meteorological data sets is not consistent. The Site C and Site D data sets give significantly larger X/Q for the B&W, CE and ALWR Stage 1 and 2 vent releases than the other three data sets. In contrast, the Site C and Site D data sets give lower X/Qs for the ALWR Stage 3 releases than the other three data sets. This inconsistency needs to be investigated.

A second modification was made to ARCON to permit the code to be using only the recirculation model. The results of running the code in this manner are presented in Table 6. The recirculation model was used when the wind speed was less than 3.0 m/s and a wind speed of 1.0 m/s was assumed for all hours with wind speeds less than 1.0 m/s. In general, the 95th percentile X/Qs are of same order of magnitude as those calculated with a combination of the Frenkiel and recirculation models, but slightly smaller. However in several cases (primarily with the Site C and Site D data sets), the elimination of the Frenkiel model reduced 95th percentile X/Qs by more than an order of magnitude. In no case did a 95th percentile X/Q increase.

Elimination of the Frenkiel model significantly reduced the variability of 95th percentile X/Qs associated with changes in meteorological data sets. However, it should be noted that there is still considerable variability in the X/Qs for the B&W and ALWR Stage 3 vent releases. This variability may be associated with the release point/intake geometry. In both cases, the release point is below the intake and F_b and F_m are relatively small. The F_b and F_m for the CE releases are the same as for the B&W releases, but the CE release point is above the intake. The X/Qs for these releases show much less variability than the X/Qs for the B&W releases.

Table 6. ARCON00x Estimate of 95th Percentile X/Q Using Only the Recirculation Model

					System 80+ ALWR		
Meteor. Data	Year	West.	B&W	CE	Stage 1	Stage 2	Stage 3
Site A	1991	2.27E-06	1.64E-03	5.34E-05	6.48E-07	1.98E-06	4.17E-03
Site B	1988	1.85E-06	3.49E-04	4.95E-05	6.10E-07	1.66E-06	8.45E-04
Site C	1993	2.27E-06	2.97E-04	5.76E-05	5.72E-07	1.78E-06	3.43E-04
Site D	1995	2.38E-06	2.91E-04	5.97E-05	5.75E-07	1.74E-06	3.24E-05
Site E	1996	2.33E-06	3.54E-04	4.96E-05	6.51E-07	1.99E-06	1.19E-03

One more modification was made to the ARCON code. In this modification, the smaller of the transition plume rise (Equation 7) and the maximum plume rise was used in calculating the effective release height. The results of calculations with this version of the code are listed in Table 7. The 95th percentile X/Qs are the same as or slightly larger than those listed in Table 6. The largest increase is less than a factor of 2.

Table 7. ARCON00x Estimate of 95th Percentile X/Q Recirculation Model with Transition Plume Rise

					System 80+ ALWR		
Meteor. Data	Year	West.	B&W	CE	Stage 1	Stage 2	Stage 3
Site A	1991	2.32E-06	1.64E-03	5.34E-05	6.60E-07	1.98E-06	4.17E-03
Site B	1988	2.01E-06	4.85E-04	4.95E-05	6.20E-07	1.73E-06	8.45E-04
Site C	1993	2.33E-06	4.19E-04	5.76E-05	6.12E-07	1.81E-06	6.33E-04
Site D	1995	2.42E-06	4.07E-04	5.97E-05	6.12E-07	1.78E-06	4.44E-04
Site E	1996	2.33E-06	3.55E-04	4.96E-05	6.51E-07	1.99E-06	1.19E-03

MODEL SENSITIVITY TO MINIMUM WIND SPEED AND MAXIMUM WIND SPEED FOR RECIRCULATION

The ARCON version using the recirculation without transition plume rise was run for CE vent releases with the Site D data set to test the sensitivity of the 95th percentile X/Qs to variations in the minimum wind speed and the maximum wind speed for recirculation. The results of these calculations, which are summarized in Table 8, show limited sensitivity to variation of the minimum wind speed. They show almost no sensitivity to variation in the maximum speed for use of the recirculation model.

Table 8. Sensitivity of 95th Percentile X/Qs for CE Vent Releases to Variation of Minimum Wind Speed and Maximum Recirculation Wind Speed

	Maximum Recirculation Wind Speed (m/s)				
Minimum Wind Speed (m/s)	2.0	2.5	3.0	3.5	4.0
0.5	6.54E-05		6.54E-05		6.54E-05
1.0	5.97E-05	5.97E-05	5.97E-05	5.97E-05	5.99E-05
1.5	5.53E-05		5.53E-05		5.55E-05

A second set of calculations was run for B&W vent releases using the Site B data set. The results of these calculations, which are presented in Table 9, are the reverse of the calculations for the CE releases made with the Site D data set. There is a small variation of the 95th percentile X/Qs associated with variation of the maximum wind speed for use of the recirculation model and no change associated with variation of the minimum wind speed.

Table 9. Sensitivity of 95th Percentile X/Qs for B&W Vent Releases to Variation of Minimum Wind Speed and Maximum Recirculation Wind Speed.

	Maximum Recirculation Wind Speed (m/s)				
Minimum Wind Speed (m/s)	2.0	2.5	3.0	3.5	4.0
0.5	3.95E-04		3.49E-04		3.61E-04
1.0	3.95E-04	3.90E-04	3.49E-04	3.45E-04	3.61E-04
1.5	3.95E-04		3.49E-04		3.61E-04

The reasons for the different outcomes of these two sets of calculations need to be explored. However, it is clear that the model sensitivity to these two parameters is not great.

ISSUES TO BE RESOLVED

The preliminary evaluation of potential modifications of ARCON96 to enable the code to adequately handle high-velocity vent releases clearly indicates that such modifications are possible. It also indicates that there are a number of technical and regulatory issues that should be resolved before a new version of ARCON is produced. The following list contains the issues that come to mind at this time; there may be other issues that arise in time.

- Is it reasonable to use the recirculation model for all wind speeds below the upper limit for application of the model? If so, what wind speed should be used as a default in

place of calm and nearly calm winds? (A default speed of 0.5 m/s seems reasonable.) Wind direction is not an issue for either this model or the Frenkiel model because the models maybe applied independent of direction.

- What is the appropriate upper wind speed for use of the recirculation model? (A speed in the 2-3 m/s range seems reasonable.)

- If the Frenkiel model is used, what is the appropriate upper wind speed for use of the Frenkiel model? (A speed in the 1-2 m/s range seems reasonable.)

- Because the recirculation model involves a search for the maximum X/Q, several questions arise related to the search. How precise should the estimate of the maximum X/Q be? Can the search be stopped when the maximum is bracketed and the probable error in X/Q is less than 1% or 5% of the highest calculated value? How far downwind should the search for the maximum value proceed? Can the search be terminated at 10 or 20 km if the peak hasn't been reached? If the search is terminated on the basis of distance, should the X/Q at the maximum distance be used?

- Is it reasonable to assume that plume rise for unstable conditions is at least as great as the rise in neutral conditions?

- Under some combinations of release and meteorological conditions, the limiting plume rise for stable conditions is slightly larger than the limiting rise for neutral conditions. In stable conditions, should the limiting rise for the neutral conditions be compared with the limiting rise for the stable condition, and the smaller rise be considered limiting?

- Is the use of transition plume rise in combination with maximum plume rise warranted? Or is the maximum plume rise sufficient?

- It sure would be nice to have some observational data on plume rise from MSSVs and ADVs for a variety of plants and meteorological conditions.

- How far above the highest building does the plume have to rise to be considered an elevated plume?

- If plume rise is calculated for MSSVs and ADVs, should it be routinely allowed for stack releases and other vents (low velocity)?

- Should an approximation to steam tables be included in ARCON, or is it appropriate to require ARCON users to enter the temperature and density of the steam after expansion to atmospheric pressure? Temperature is not included in the ARCON meteorological data set. It is in the NRC standard data format, but I don't recall seeing it very often. Is it acceptable to use an average air temperature and density in plume rise calculations?

- How should releases below intakes be treated if transition plume rise is included in the code? Should the recirculation model be used at all if the plume rise at the distance

from the release point to the intake plus 3 (4, 5,6,...?) sigma z is less than the intake height minus the release height?

- Would it be appropriate to subject the approach to an external peer review before completion of the model and code development? If so, would it be appropriate to include industry representatives on the peer review panel?

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