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REVIEW OF ATMOSPHERIC TRANSPORT AND DISPERSION MODELS USED FOR DOSE ASSESSMENT

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The New York State Department of Environmental Conservation's 6 NYCRR Part 380 regulations, *"Rules and Regulations for Prevention and Control of Environmental Pollution by Radioactive Materials,"* apply to the release of radioactive materials into the environment. Certain categories of radioactive emissions require a Part 380 Radiation Control Permit. When you apply for a permit, you must be able to demonstrate that the emissions you propose will comply with the 100 mrem public dose limit and the 10 mrem dose constraint. This guidance describes how **facilities applying for a permit to discharge radioactive materials to the air** can make that demonstration, when using atmospheric transport and dispersion models, utilizing the methodology outlined in Paragraph 380-5.2(b)(1). This method is referred to as *Method 2*, and is a dose assessment. This methodology is required when radioactive emissions exceed the effluent concentrations in the tables (Column 1, Table II of Section 380-11.7). This Review is a supplement to the Department's *Demonstrating Compliance with the Public Dose Limits in Part 380*, and expands discussion on how to use Method 2 to calculate radionuclide concentration in the effluent at the nearest location potentially occupied by a public receptor. Once the radionuclide concentration has been calculated, the committed effective dose equivalent (CEDE) can then be calculated (producing the dose assessment) and compared to public dose limits.

DOSE ASSESSMENTS

Assessments of potential public dose from radioactive emissions can be broken down into a number of simple elements:

- determination of annual radionuclide activities emitted to air on an annual basis
- dispersion modeling to calculate average annual concentrations at the nearest potential public receptor
- calculating CEDE using appropriate dose conversion factors and assumptions about Reference Man

Atmospheric transport and dispersion models. Dispersion models are used to calculate the concentrations of pollutants downstream from their release point, once release concentration is known from direct measurement or estimation. The basic Gaussian plume models generally used in this capacity for regulatory purposes will be those appropriate for long-term releases from point sources, to receptors located on generally flat terrain; when using continuous release models, the time frame over which exposure is usually considered is yearly. There are other models than pure Gaussian that may be encountered, but these tend to be complex, rely heavily upon accurate terrain and micro-meteorological input, and are more frequently utilized for short-term release situations. This brief review outlines some of the more common methods, issues and caveats that exist in regard to dose modeling; it is not to be considered in any way authoritative or all-inclusive.

The models presented herein are not appropriate for modeling short-term releases, which are typical of emergency response. Care needs to be exerted when utilizing models that do not account for radioactive decay, as in the case of many models more intended for non-radiological effluents; nevertheless, plume depletion by precipitation scavenging or deposition is obviously not a consideration for facilities that do not produce particulates, and facilities emitting only short-half-life radionuclides will not be concerned with buildup of soil or surface water contamination, or food chain buildup. Finally, complex topography, or the presence nearby of buildings or structures of significant height, can alter potential dose to a public receptor significantly.

MANUAL CALCULATION OF CONCENTRATION

Concentration at stack exit point[1]

The simplest, and generally least applicable, model assumes that the effluent concentration C at the receptor will be the same as that at the stack exit:

$$C = \frac{fQ}{V} \tag{1}$$

where

C = average annual concentration (Bq/m^3)
f = fraction of time wind blows toward receptor
Q = effluent release rate (Bq/s)
V = flow rate at exit (m^3/s)

Concentration using a basic Gaussian plume model[2,3]

The Gaussian distribution is a type of relationship from statistics that describes the frequency of occurrence of many types of physical or statistical events. This distribution (also called the normal distribution or bell curve) describes such things as the way height or IQ vary in large populations, or the way errors tend to occur in random observations. It is found that concentration along the horizontal extent of a gaseous pollutant in air can be described (under perfect circumstances) using Gaussian mathematics, given that you know some facts about the situation (such as the rate at which the pollutant is entering the atmosphere, how fast the air parcel is traveling at the exit point, the direction in which the wind is blowing, etc.).

The equations presented here are each suitable to calculate the concentration of a radionuclide under a particular set of circumstances; initial conditions are extremely important for determining which equation to use. Note that all of these equations are best estimates, not to be considered accurate for any particular circumstance; they are simply convenient *conservative* modeling tools, that if used appropriately provide *reasonable upper bounds* on nuclide concentrations at receptors, and therefore proportional to acquired dose. If there is any uncertainty about which equation is appropriate in a particular case, or how to apply them, consult a modeling expert. Hand application of the most general (and, therefore, most complex) Gaussian concentration equation presented here is not often needed for dose modeling, but familiarity with it and how it works is important; see the references for this section or other dispersion texts for more detailed information. One of the basic forms of the Gaussian dispersion model (there are many others, given the variables involved) is

$$C = \frac{fQ}{\pi u \sigma_y \sigma_z} \exp\left[\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2 \right] \quad (2)$$

where one may generally take σ_y and σ_z as

$$\sigma_y = \frac{0.08x}{\sqrt{1+0.0001x}}$$

$$\sigma_z = \frac{0.06x}{\sqrt{1+0.0015x}}$$

for neutral (and therefore most general) atmospheric stability conditions. Here:

u = mean wind speed (m/s)
H = height of release point (m)
x = horizontal distance from release to receptor
σ_y, σ_x = the horizontal and vertical turbulent diffusion (Pasquill-Gifford) parameters respectively (in units of m), which are functions of the atmospheric stability and distance to receptor

This equation is used to calculate concentration for receptors at ground level, directly below the plume centerline. The Pasquill-Gifford parameters presented here are applicable to rural, unobstructed conditions, and can be determined for various stability conditions of the atmosphere. Stability is rated from A (unstable) through F (very stable); neutral conditions are D class. Plots and equations for these parameters are available in Turner, along with detailed limitations on their usage,[3] as well as in many other sources. Choice of stability parameters should, of course, be made with local microclimate in mind. Continuous emissions and steady-state conditions are presumed, as are conservation of mass (no settling, reactions, decay, etc.), wind always in x direction, and, of course, that Gaussian conditions prevail for dispersion. This equation may be grossly inaccurate at extreme distances (tens of kilometers), with upstream or downstream structures nearby, or under extreme (or even not-so-extreme) atmospheric conditions.

Source and receptor located on same building surface[4]

If the source and the receptor are on the same building surface (roof or side of building) and $x \leq$ 3 times the diameter of the stack, it should be presumed that the receptor is breathing undiluted exhaust and Eq. 1 should be used. If $x > 3d$ then

$$C = \frac{30Q}{ux^2} \tag{3}$$

where u = the average wind speed (m/s) at roof level measured far enough away that the Bernoulli wind-increasing effect over the building will not affect the result. This equation accounts for buildup of concentration along a vertical wall due to the building wake effect.

Source and receptor not on same building surface (wake effects)[5]

In this case one desires to find concentration when a receptor is not on the source building, but stands close by on the ground or in a courtyard. Consider the source building: it will present a certain surface area perpendicular to the direction of airflow. This cross-sectional area is called the *projected frontal area* and is represented by A_{cross} (see Fig. 2). When $x \leq (A_{cross})^{1/2}$ or $x \leq 100$ m, we may use the following equation:

$$C = \frac{fQ}{\pi uhk} \tag{4}$$

where k = 1 m and h is the *smaller* value of the height of the building h_b or the cross-sectional length h_{cross}.

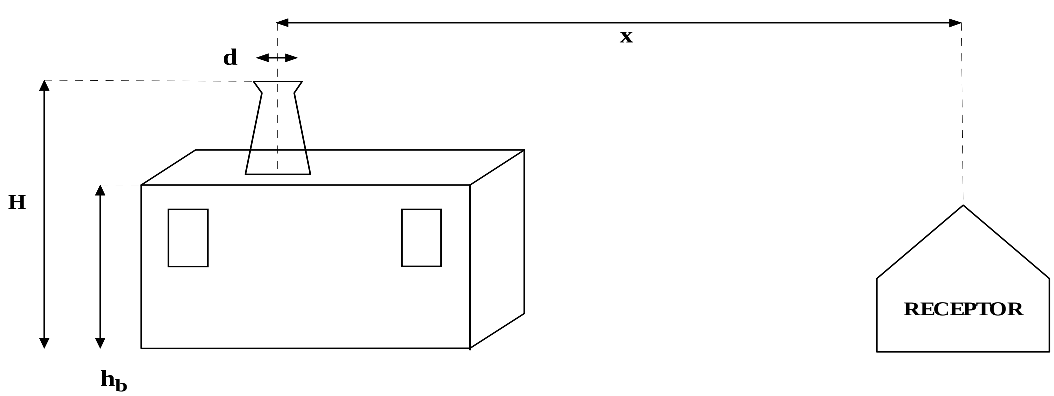

Figure 1. Parameters for dispersion calculations

For the condition where x > 100 m, and it is thought that airflow is still affected by building wakes, calculational decisions will need to be made. Air concentrations and concomitant dose for filterable nuclides from cyclotrons may well have already reached their maximum somewhere before x = 100 m, or it may be possible to demonstrate that dose will remain below regulatory limits at all distances, in which case the methods described will probably suffice. If not, one can resort to the use of somewhat more complicated calculations to describe the situation which occurs in urban areas or those with increased mechanical and/or buoyant turbulence.

Studies have found the following general rules of thumb[6]:

- Stacks should not be located near building edges or fresh air intakes
- Intakes should not be placed on the leeward wall of a building
- A lower adjacent building upwind of an emitting building will tend to increase dilution on the emitting building roof
- In the case of a higher upwind building, increasing exhaust velocity is more beneficial than increasing stack height.

See NCRP Report 123 I or Turner for generally applicable procedures; more complicated approaches are available, but are too complex to be covered in this guide.

Momentum rise

Often overlooked when performing dose calculations is the fact that the exhaust airstream may rise considerable distances above the stack exit before effective dispersion begins. In this situation it may be considered that the height of the release stack has effectively been increased, and this fact may be taken advantage of when performing dispersion calculations. Emission height may be affected by two factors. The one generally encountered is known as *momentum rise*, and is the extra height an exhaust stream will attain because of the momentum of the airstream coming out of the stack. This may or may not be considerable, depending upon site parameters and whether or not a strobic fan is used to increase momentum rise. Note also that maximum rise stated by fan manufacturers is often not the average rise actually encountered under actual conditions; for instance, airspeed has a major effect upon this parameter, and cannot be ignored. The other factor to consider is whether the exiting airstream is heated above the temperature of the surrounding air parcel; if it is, the exit stream will rise because of its buoyancy. Note that, if effluents are not at temperatures significantly higher than ambient, *buoyancy rise* need not be considered.

Exit velocity will vary greatly depending upon exhaust system design. For routinely encountered retail production systems, where linear exit velocity (commonly measured in ft/min) may be modest, say, something of the order of 200-300 ft/min (roughly 1.0-1.5 m/s), momentum rise will not be very significant, and can effectively be ignored for conservatism. In crowded urban areas with many large buildings downstream, use of a strobic fan can maximally add 70 m or more to the stack exit height, and is an effective and relatively inexpensive means by which to increase this factor. The liberal use of strobic fans, which also reduce pollutant concentrations via entrainment of outside air into the exhaust stream, is highly encouraged.

To calculate momentum rise, we use equations for rise under both stable, and stable-neutral, conditions and then use the lesser value as the presumed rise[7]:

$$\text{stable rise:} \qquad \Delta H = 1.5 s^{-1/6}\left[\frac{\left(v^2 d^2 T\right)}{4T_s u}\right]^{1/3}$$

$$\text{unstable-neutral rise:} \qquad \Delta H = \frac{3dv}{u} \tag{5}$$

Here

ΔH = change in effective stack height (m)
u = wind speed at stack exit point (m/s)
v = stack gas exit velocity (m/s)
d = stack exit diameter (m)
T = ambient temperature (K)
T_s = stack gas temperature (K)

The parameter s is called the *stability parameter* and can be calculated by

$$s = \frac{g}{T}\left(\frac{dT}{dz} + \Gamma\right) \tag{6}$$

where g = acceleration of gravity (9.8 m/s^2) and Γ = adiabatic lapse rate (0.0098 K/m).

Stack-tip downwash[8]

There is another adjustment that can be made to stack height because of an effect called *stack-tip downwash*. This is a fluid-dynamical effect that is the result of vortex formation in the downwind direction. When the ratio v/u < 1.5, the emitted stack gas may be pulled down somewhat because of eddy formation. If h is the height of the stack, to calculate the revised height of emission h′, we use the equation[9]

$$h' = h + 2\left(\frac{v}{u} - 1.5\right) \tag{7}$$

The maximum correction factor is 3*d; in many cases this effect is therefore negligible, not only because of this factor, but because the ratio of exit exhaust velocity to wind velocity will often exceed 1.5. If utilized, the final effective height will thus be the height of the stack, plus the momentum rise, minus the stack-tip downwash for most calculations.

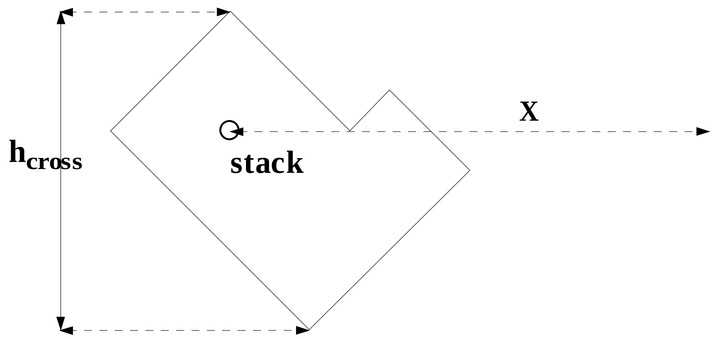

Figure 2. Cross-sectional area

Annual intake via inhalation. When calculating dose manually, the concentration to annual dose to the nearest potential receptor is performed by considering annual radionuclide concentrations at the receptor for each nuclide. Annual dose is then the summation of doses due to contributions from each nuclide.

This approach is most feasible for areas expected to have uniform concentrations, or at a physically predetermined location; for instance, on a facility roof at the nearest air intake, or at the base of a building with a stack on the roof. It becomes problematic for other situations, where the location of highest dose is not predetermined and therefore unknown; use of a computer program that determines maximum dose over a range of distances downwind is therefore highly recommended for convenience. Otherwise, numerous calculations may need to be performed to determine a greatest upper bound on dose.

Dose conversion factors. After choosing and applying the appropriate atmospheric dispersion modeling methodologies, the average annual nuclide concentrations obtained at nearby receptors can be estimated. The calculated concentrations at the receptor sites are then used to calculate potential dose through the use of dose conversion factors obtainable through EPA's Federal Guidance Report No. 11 or NCRP Report No. 123 II through a simple multiplication, as dose is linearly proportional to concentration.

COMPUTER MODELING PROGRAMS FOR PERFORMING DOSE ASSESSMENT

A number of relatively simple IBM PC-compatible programs exist for the calculation of concentration and concomitant dose to the nearest receptor and/or population. Two of these have been created by federal agencies for use by health physicists for dose modeling, and are free for use: CAP88 PC and COMPLY (refs. 10, 11). Both programs have firm limitations of applicability; these limitations must be fully understood. The user guides must be read before application, and the programs and their results should only be used or evaluated by health physicists experienced in dose assessment and confident of proper application. It is imperative that **all** input variables are clearly presented and documented in the Part 380 permit application, as Department staff will perform confirmatory dose calculations as part of the permit application review process. Applications without such information will be determined to be incomplete.

A very brief overview of modeling program functionality is presented below. In this regard some caveats are necessary: the few salient facts presented about these programs below are abbreviated, incomplete, and presented for convenience only, may change, and are not intended to replace program documentation or experience in use.

It is important to note that both programs are intended only for modeling low-level chronic exposures, and that they are based on the Gaussian plume model of dispersion with its associated limitations. Presumably these programs will be used only to model dose to the nearest receptor in order to determine compliance with public dose limits; features related to population dose and risk are not considered below.

There are numerous other programs than those listed that have been developed for dose modeling; unfortunately, these tend to be complex, and intended for short-term release modeling, or proprietary, complex, and expensive. Accordingly, we expect that the two programs listed below (CAP-88PC and COMPLY) will remain a mainstay of simple modeling efforts for some time.

CAP88-PC. This USEPA program can perform dose assessments for collective populations and maximally exposed individuals. It is a more refined model than COMPLY, and requires more detailed, site specific input data; properly validated inputs provide more realistic model outputs. A convenient feature is the presence within the program of meteorological data for many National Weather Service stations; data files include direction, frequency and stability information. CAP-88PC calculates momentum and buoyancy rise, and also calculates radionuclide plume depletion and some food chain parameters; it does not calculate stack-tip downwash, or building wake situations where the receptor is located on or near the source building. (One can account for stack-tip downwash by setting stack height to zero; this method has obvious drawbacks in some situations.) Note that multiple sources are considered to be co-located. Also note that the dispersion coefficients used are for open country, not urban or suburban areas or those of irregular topology, and results must be considered in this light. The effective dose equivalent for the maximally-exposed individual is tabulated in mrem/yr for a 50 year exposure. Reference 10 contains the World-Wide Web universal resource locator for downloading this resource.

COMPLY is a simple screening model, to conservatively estimate dose. COMPLY was developed by the USEPA to demonstrate compliance with National Emission Standards for Hazardous Air Pollutants (NESHAPs) in 40 CFR 61. It is a Gaussian plume model similar to CAP88-PC, and most of the above comments for that program apply to the use of this program as well. Notable differences are that COMPLY does not have a built-in database of wind direction frequencies (although this information may be utilized if provided by the user), but does consider building wake effects (while not considering stack-tip downwash). COMPLY is no longer maintained by the EPA; it has retained its popularity as it calculates dose for a wide variety of radionuclides and is easy to use. Reference 11 contains the World-Wide Web universal resource locator for downloading this resource and for further information. Note that COMPLY generally produces extremely conservative dose estimates.

SUMMARY

Always call the Radiation Control Permit Section with questions before expending the considerable effort required to produce dose modeling that may not be appropriate for the situation at hand. We will not perform the modeling for you, but are happy to offer guidance as to the applicability of models to particular situations.

REFERENCES

Federal Guidance Report No. 11, Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion, USEPA, 9/88.

1. Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground—Work Sheets, NCRP Report No. 123 I, Sec. 2.1. National Council on Radiation Protection and Measurements, Bethesda, MD, 1996.

2. Ibid., Section 2.2.

3. Turner, D. Bruce, Workbook of Atmospheric Dispersion Estimates, Second Ed., Eq. 2.3. Lewis Publishers, Boca Raton, FL, 1994.

4. Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground—Work Sheets, NCRP Report No. 123 I, Sec. 2.2.3. National Council on Radiation Protection and Measurements, Bethesda, MD, 1996.

5. *Ibid*., Section 2.2.4.

6. Schulman LL, Scire JS. The effect of stack height, exhaust speed, and wind direction on concentrations from a rooftop stack. ASHRAE Transactions 1991; 97(2):573–582.

7. Turner, D. Bruce, Workbook of Atmospheric Dispersion Estimates, Second Ed., Section 3.4.2. Lewis Publishers, Boca Raton, FL, 1994.

8. *Ibid*., Section 3.1.

9. Eckerman, Keith F. et al., Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion, Federal Guidance Report No. 11. Office of Radiation Programs, U.S. EPA, Washington, DC 20460, 1988.

10. CAP-88PC. Clean Air Act Assessment Package-1988, officially distributed by DOE EH-232 and the Oak Ridge Radiation Shielding Information Center, currently by US EPA. Homepage for CAP88-PC: http://www.epa.gov/rpdweb00/assessment/CAP88/ [accessed 6 May 2013]. Current version: CAP-88 V.4 (V.4.1 scheduled for release 2018).

11. COMPLY. http://www.epa.gov/radiation/assessment/comply.html [accessed 6 May 2013]. Current version: COMPLY V1.7.1 released October 2016