

**Technical Report for  
Calculations of Atmospheric Dispersion  
at Onsite Locations  
for Department of Energy Nuclear Facilities**



**Office of Nuclear Safety  
Office of Environment, Health, Safety and Security  
U.S. Department of Energy**

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## FOREWORD

This is the initial technical report released under the auspices of the Department of Energy's (DOE's) Nuclear Safety Research and Development (NSR&D) Program.

This technical document provides the results of an evaluation of the technical bases for the default atmospheric dispersion parameter known as  $\chi/Q$  used in the calculation of onsite radiological doses. The objective of the evaluation was to determine if the chosen default value is conservative and thus appropriate for use for both radiological dose and chemical exposure calculations. The report explains how the parameter is calculated and used, and includes sensitivity calculations using various computer models.

The NSR&D Program was established to strengthen DOE's regulatory structure, increase technical knowledge, and support continuous safety improvements in DOE's nuclear facilities. The program is managed by the Office of Nuclear Safety, within the Office of Environment, Health, Safety and Security. Guidance for the program is provided by Program Offices in DOE and in the National Nuclear Security Administration through their participation on the NSR&D Committee.

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## EXECUTIVE SUMMARY

The Department of Energy (DOE) has performed an evaluation of the technical bases for the default value for the atmospheric dispersion parameter  $\chi/Q$ . This parameter appears in the calculation of radiological dose at the onsite receptor location (co-located worker at 100 meters) in safety analysis of DOE nuclear facilities. The results of the calculation are then used to determine whether safety significant engineered controls should be established to prevent and/or mitigate the event causing the release of hazardous material. An evaluation of methods for calculation of the dispersion of potential chemical releases for the purpose of estimating the chemical exposure at the co-located worker location was also performed. The default  $\chi/Q$  dispersion value and methods for determining atmospheric dispersion are prescribed in Appendix A of DOE Standard (STD) 1189-2008, *Integrating Safety into the Design Process*:

*“For the purposes of this Standard, a  $\chi/Q$  value at 100 m of  $3.5E-3 \text{ sec/m}^3$  must be used for the dispersion calculation. This value is based upon NUREG-1140 (no buoyancy, F-stability, 1.0 m/sec wind speed at 100 m, small building size [10 m x 25 m ], and 1 cm/sec deposition velocity).”*

DOE’s evaluation consisted of: (a) a review of the regulatory basis for the default  $\chi/Q$  dispersion parameter; (b) an analysis of this parameter’s sensitivity to various factors that affect the dispersion of radioactive material; and (c) performance of additional independent calculations to assess the appropriate use of the default  $\chi/Q$  value. The evaluation also analyzed the appropriateness of the use of the default  $\chi/Q$  value when calculating the dispersion of chemical releases. The key conclusions from the evaluation were:

- Radiological dispersion: The default  $\chi/Q$  value provides a conservative estimate of dispersion for calculating exposure of the co-located worker where the release is subject to aerodynamic effects from the facility building (nominally a 10 m by 36 m building).
- Chemical dispersion: The default  $\chi/Q$  value provides a conservative estimate of dispersion for calculating exposure of the co-located worker where the release is subject to aerodynamic effects from the facility building (nominally a 10 m by 36 m building).
- Special Condition 1 – Dispersion from a small building or if there is no building: For uncommon situations where there is a release from a facility smaller than that assumed in this analysis, the default  $\chi/Q$  value may not provide a conservative estimate of dispersion.
- Special Condition 2 – Extreme wind and tornadic conditions: The default  $\chi/Q$  value will provide a conservative estimate of dispersion under these conditions.

An approach for determining an appropriate  $\chi/Q$  value under Special Condition 1 is provided.

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## 1. INTRODUCTION

### 1.1 Purpose

This purpose of the assessment documented in this report was to:

- Evaluate the technical basis for the default atmospheric dispersion parameter (i.e.,  $\chi/Q$ ) stated in Department of Energy (DOE) Standard (STD) 1189-2008, *Integrating Safety into the Design Process*, for assessing co-located worker exposures;
- Identify any exceptions or limitations to the use of the default  $\chi/Q$  value in accident analysis; and
- Evaluate whether, and under what conditions, the default  $\chi/Q$  value can be used to calculate co-located worker exposure due to chemical releases.

This assessment was performed by the Office of Nuclear Safety, within the Office of Environment, Health, Safety and Security, which is responsible for the development and maintenance of DOE's nuclear safety directives and technical standards.

The main body of this report provides an overview of the assessments performed and results. Details are provided in the Appendices.

### 1.2 Background

Appendices A and B of DOE-STD-1189-2008 (Ref. 1) provide criteria and guidance for the calculation of the radiological dose and chemical exposure of co-located workers from potential accidents at DOE's nuclear facilities. These calculations are used to determine whether safety-significant controls are warranted for the protection of co-located workers. Uniform use of key inputs and assumptions in these analyses, where justified, ensures overall consistency in DOE's design process.

Appendix A of DOE-STD-1189-2008, *Safety System Design Criteria*, addresses the design of structures, systems and components used to prevent or mitigate accidents involving radioactive materials. The appendix provides (a) inputs and parameters for atmospheric dispersion of releases, (b) sets a default value for  $\chi/Q$  ( $3.5 \times 10^{-3} \text{ s/m}^3$ ) to be applied to unmitigated accident releases, and (c) establishes 100 meters from the estimated release point as the distance for calculating dose to a co-located worker. Appendix B, *Chemical Hazard Evaluation*, provides guidance for calculating chemical exposure to co-located workers. A default  $\chi/Q$  value is not specified for chemical releases.

## **2. EVALUATION OF THE BASIS FOR AND USE OF THE DEFAULT $\chi/Q$ VALUE FOR RADIOLOGICAL RELEASES**

### **2.1 Regulatory Basis**

Appendix A of DOE-STD-1189-2008 cites the Nuclear Regulatory Commission's (NRC) NUREG-1140, *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licensees* (Ref. 2), as the source of the default  $\chi/Q$  value chosen by DOE for atmospheric dispersion analysis. NUREG-1140 was developed to assess whether NRC needed to impose additional emergency planning requirements on fuel cycle and other radioactive materials licensees. The conclusions reached in the NUREG were based upon calculations whose inputs and assumptions represent conservative release conditions (i.e., ground-level release, no plume rise, no plume meander); a wind speed and stability consistent with those traditionally used by NRC in radiological hazard evaluations, representing very adverse (i.e., minimum dispersion) meteorological conditions; a deposition velocity corresponding to a mix of meteorological conditions and particle size values; and a building wake value that defines the critical initial plume dimensions. Attachment A provides details on this regulatory basis.

The evaluation of the regulatory basis found that the  $\chi/Q$  value of  $3.5 \times 10^{-3} \text{ s/m}^3$  at 100 m, identified in DOE-STD-1189-2008, corresponds to a conservative value for this distance based on the NUREG-1140 methodology.

### **2.2 Sensitivity Analysis of $\chi/Q$ to Input Assumptions**

Although the default  $\chi/Q$  value is based on a number of conservative assumptions, it remains sensitive to specific choices in the initial parameters. To ensure confidence in establishing the appropriate range of use for the default value, the sensitivity of the result to initial plume dimensions, plume meander, extreme weather conditions, and deposition velocity was evaluated. Attachment B provides details on this sensitivity analysis.

This analysis found that dispersion calculations were most sensitive to variations in initial plume dimensions, a factor dependent on the building wake effect, and that this factor could result in the default  $\chi/Q$  value being nonconservative for some applications (i.e., when release is from a building less than a certain size). Other factors did not have as large of impact on the results that gave confidence that the default  $\chi/Q$  value is appropriate.

### 2.3 Confirmatory Calculations of Default $\chi/Q$ Value

As part of this evaluation,  $\chi/Q$  calculations were performed at 100 meters using three methods: (1) hand calculations; (2) the MACCS2 code, following guidance in *MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report* (Ref. 3); and (3) the ARCON96 atmospheric dispersion model endorsed by the NRC for calculation of more realistic  $\chi/Q$  values in the near-field (documented in Reference 4, *Atmospheric Relative Concentrations in Building Wakes*, NUREG/CR-6331, Revision 1). Attachments C and D discuss and provide details of these analyses.

The results of these confirmatory calculations showed that the default  $\chi/Q$  value of  $3.5 \times 10^{-3} \text{ s/m}^3$  is a conservative value for nearly all cases. As discussed in Section 2.2; in the situation where credit cannot be taken for the building wake effect or where a building is smaller than that assumed in NUREG-1140, the default  $\chi/Q$  value may not provide a conservative estimate of atmospheric dispersion.

### 2.4 Approach for Calculating A $\chi/Q$ Value for Conditions Where the Default Value May Not Be Conservative

As part of this evaluation, a simple approach for determining an appropriate  $\chi/Q$  value under the condition where the default value may not be conservative was developed. This approach is based a variation of the Gaussian plume equations in Regulatory Guide 1.145. Examples are provided to illustrate how it can be utilized. Attachment E provides details on this approach.

## 3. EVALUATION OF USE OF THE DEFAULT $\chi/Q$ VALUE FOR CHEMICAL RELEASES

An assessment was made of whether the default  $\chi/Q$  value would be appropriate to use in determining chemical exposure at the co-located worker location of 100 meters from a release point. This analysis considered different types of release mechanisms (e.g., buoyant and non-buoyant) and various chemicals. Calculations were performed using the EPIcode (Ref. 5) and ALOHA (Ref. 6). Attachment F discusses and provides details on the assessment and the calculations made.

This evaluation found that the release of neutrally-buoyant gases is a bounding event for all chemical release calculations at the co-located receptor location of 100 meters from the release point. This is because positively-buoyant releases have enhanced vertical dispersion, while negatively-buoyant releases (dense gases) have enhanced horizontal dispersion. Similar to calculations for the radiological releases, the chemical release calculations showed that the default  $\chi/Q$  value is conservative for chemical releases for nearly all cases, except the situations



where the building wake cannot be credited or where a building is smaller than that assumed in NUREG-1140. For these situations the default  $\chi/Q$  value may not provide a conservative estimate of dispersion.

#### 4. CONCLUSIONS

Based on the analyses and evaluations conducted for this technical report, the following four key conclusions were reached:

- Radiological dispersion: The default  $\chi/Q$  value provides a conservative estimate of dispersion for calculating exposure of the co-located worker where the release is subject to aerodynamic effects from the facility building (nominally a 10 m by 36 m building).
- Chemical dispersion: The default  $\chi/Q$  value provides a conservative estimate of dispersion for calculating exposure of the co-located worker where the release is subject to aerodynamic effects from the facility building (nominally a 10 m by 36 m building).
- Special Condition 1 – Dispersion from a small building or if there is no building: For uncommon situations where there is a radiological or chemical release from a facility smaller than that assumed in this analysis, the default  $\chi/Q$  value may not provide a conservative estimate of dispersion.
- Special Condition 2 – Extreme wind and tornadic conditions: The default  $\chi/Q$  value will provide a conservative estimate of dispersion for radiological and chemical releases under these conditions.

The attachments to this report provide detailed technical information supporting these conclusions.

#### 5. REFERENCES

1. *Integration of Safety into the Design Process*. [DOE-STD-1189-2008](#), U.S. Department of Energy, Washington, DC, March 2008.
2. S. A. McGuire, *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licenses*, [NUREG-1140](#), U.S. Nuclear Regulatory Commission, Washington, D.C., January 1988.
3. *MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report*, [DOE-EH-4.2.1.4](#), U.S. Department of Energy, Washington, DC, June 2004.
4. J.V. Ramsdell, Jr., and C.A. Simonen, *Atmospheric Relative Concentrations in Building Wakes*, [NUREG/CR-6331, Revision 1](#), U.S. Nuclear Regulatory Commission, Washington, D.C., May 1997.

5. *EPIcode Computer Code Application Guidance for Documented Safety Analysis Final Report*, [DOE-EH-4.2.1.3](#), U.S. Department of Energy, Washington, DC, June 2004.
6. *ALOHA Computer Code Application Guidance for Documented Safety Analysis Final Report*, [DOE-EH-4.2.1.3](#), U.S. Department of Energy, Washington, DC, June 2004.

## Attachment A: Technical Basis for the Default $\chi/Q$ Value

### A.1 Purpose

This attachment provides an overview of (a) the methodology used to calculate the atmospheric dispersion of radionuclide releases and (b) the technical basis of DOE's approach for calculating atmospheric dispersion and associated dose rates at nuclear facilities, including the use of a "default value" of the atmospheric dispersion parameter  $\chi/Q$  when calculating the dose to a co-located worker located 100 meters from the release point.

### A.2 Calculation of Atmospheric Dispersion

Atmospheric dispersion is usually expressed in terms of  $\chi/Q$ , where  $\chi$  is the concentration of the pollutant in air at some downwind ( $x, y, z$ ) location, using either the instantaneous concentration (units such as becquerel [Bq]/m<sup>3</sup> or g/m<sup>3</sup>) or the time-integrated concentration (units such as Bq-sec/m<sup>3</sup> or g-sec/m<sup>3</sup>).  $Q$  is either the constant rate of release (units such as Bq/sec or g/sec) of the pollutant or total source strength (units such as becquerels or grams) of the pollutant.  $\chi/Q$  represents the relative concentration of the plume as it travels downwind from a release point. The  $\chi/Q$  is a key factor in calculating the dose to an individual, which in turn determines the need for and type of safety controls.

As discussed in Chapter 2 of D.B. Turner's *Workbook of Atmospheric Dispersion Estimates* (Ref. 1), a Gaussian distribution equation is expressed as:

$$\frac{\chi(x, y, z, H)}{Q} = \frac{1}{2\pi\sigma_y\sigma_zU} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \left\{ e^{-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2} + e^{-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2} \right\} \quad (\text{Equation A.1})$$

Where:

- $\chi$  Concentration at location  $x, y, z$  (Bq/m<sup>3</sup>, g/m<sup>3</sup>, Bq-sec/m<sup>3</sup> or g-sec/m<sup>3</sup>)
- $Q$  Radionuclide or toxic chemical emission rate (Bq, g, Bq/sec or g/sec)
- $\sigma_y$  Standard deviation of concentration in the horizontal direction (m)
- $\sigma_z$  Standard deviation of concentration in the vertical direction (m)
- $U$  Wind speed diluting the plume (m/s)
- $x$  Downwind distance in the direction of the mean wind (m)
- $y$  Distance in the horizontal plane perpendicular to the  $x$ -axis (m)
- $z$  Height of the receptor (m)
- $H$  Effective release height of the plume centerline (m)

Equation A.1 determines the atmospheric dispersion based on atmospheric variables such as temperature, wind speed, and wind direction. The Gaussian distribution in the horizontal and vertical planes determines the size of the plume, which is dependent on the stability of the atmosphere and the dispersion of the plume in the horizontal and vertical directions downwind from the release point (see Figure A-1). Note that the downwind plume distance,  $x$ , does not appear explicitly in this equation. As implemented by D.B. Turner, values for  $\sigma_y$  and  $\sigma_z$  are estimated as a function of downwind distance,  $x$ , and the stability of the atmosphere.

Typically, radiological consequences are expressed as the total effective dose (TED) to the receptor at the highest exposure conditions. For most accident types with ground-level or near ground-level releases, this dose is evaluated at the co-located worker location or at, or near, the site boundary. The TED includes (a) the 50-year committed effective dose (CED) from inhalation both during plume passage and later from resuspension, (b) the cloud shine effective dose (ED), (c) the groundshine ED, and (d) the skin absorption ED. This TED calculation does not include the ingestion CED from consumption of contaminated water and foodstuffs as the dose to the receptor is from a short term exposure to the released material. The dose can be calculated as follows:

$$Dose = DCF * ST * \chi/Q * BR \quad \text{(Equation A.2)}$$

Where:

- DCF    Dose conversion factor(s) for unit activity uptake (rem/Ci or Sv/Bq)
- ST     Source term (Ci or Bq)
- $\chi/Q$     Relative concentration (s/m<sup>3</sup>)
- BR     Breathing rate of an individual exposed to the plume (m<sup>3</sup>/s)

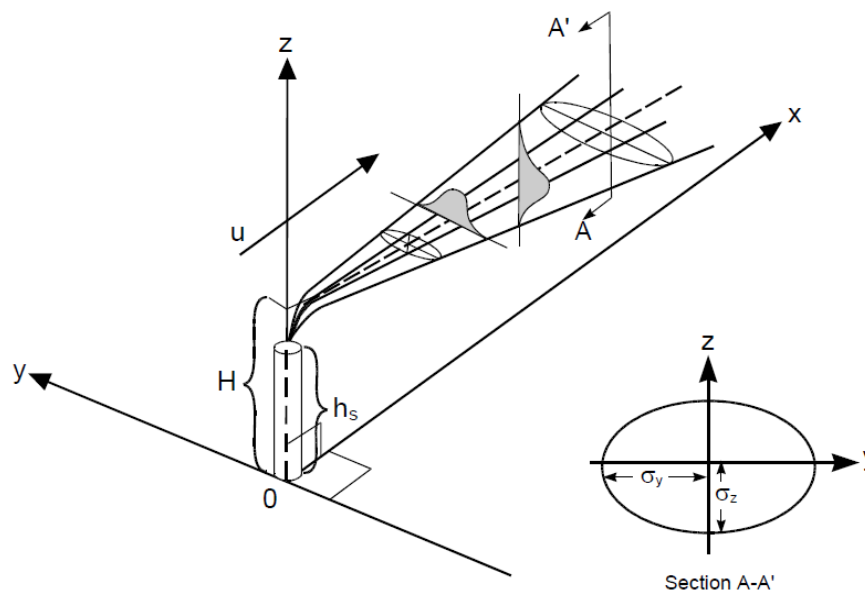


Figure A-1: Gaussian plume distribution and coordinate system

Source: [Environmental Protection Agency](#)

The following assumptions are made for use of a Gaussian model:

- The plume spread has a normal distribution in the horizontal and vertical directions;
- The radionuclide or toxic chemical emission rate ( $Q$ ) is constant and continuous;
- Wind speed and direction are uniform; and
- Total reflection of the plume takes place at the ground surface.

### A.3 Technical Basis for Use of a Default Value for $\chi/Q$

Appendix A of DOE STD-1189-2008, *Integration of Safety into the Design Process* (Ref. 2), discusses co-located worker protection and establishes a “conservatively calculated unmitigated dose of 100 rem ... as the threshold for designation” for classification of safety significant structures, systems, and components (SSCs). Appendix A requires that a  $\chi/Q$  value of  $3.5 \times 10^{-3}$  s/m<sup>3</sup> be applied for atmospheric dispersion calculations at a 100 meters distance from the release point to determine the classification of SSCs and also for use in determining the seismic design category for SSCs when applying radiological hazards to co-located worker thresholds. Appendix B of DOE-STD-1189-2008 provides general guidance on safety significant designation for SSCs with respect to toxic chemical hazards; however, it does not provide an analogous  $\chi/Q$  value for toxic chemical hazards.

The default value approach was adopted to provide some uniformity in calculations of co-located worker exposures at DOE facilities. The selected default value is also consistent with the long-standing practices of the NRC, as reflected in NUREG-1140, *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licensees* (Ref. 3). NUREG-1140 makes the following conservative assumptions:

1. Ground-level release;
2. No credit for plume buoyancy;
3. Poorly dispersive atmospheric conditions of F-stability class (moderately stable) and 1.0 m/s wind speed; usually representative of the 95% percentile, or very adverse (minimum dispersion) weather conditions;
4. 30-minute release duration for inhalation (which includes an 8-hour exposure for ground and cloud shine);
5. Building size of 10 m x 25 m for building wake and cavity determinations, resulting in an initial vertical and horizontal plume dimension of 4.7 m and 8.3 m, respectively<sup>1</sup>; and
6. 1 cm/s deposition velocity.

Figure A-2 illustrates the results of NRC's calculations based on these assumptions. The assumed maximum inhalable dose using the stated assumptions is reached at approximately 100 meters downwind of the release. This distance has been used by DOE to determine whether a co-located worker safety control should be designated as safety significant. The  $\chi/Q$  value selected in DOE-STD-1189-2008 corresponds to the uppermost curve in Figure A-2 at the 100-meter distance.<sup>2</sup>

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<sup>1</sup> CRAC2 calculated the initial horizontal plume dimension ( $\sigma_y$ ) by dividing the building width by 3 and the vertical plume dimension ( $\sigma_z$ ) by dividing the building height by 2.15. (See Equations E.1 and E.2 in Attachment C)

<sup>2</sup> There is a slight difference in  $\chi/Q$  values between NUREG-1140 ( $3.3E-3$  s/m<sup>3</sup>) and DOE-STD-1189 ( $3.5E-3$  s/m<sup>3</sup>). This difference is small relative to the uncertainties in Gaussian dispersion modeling.

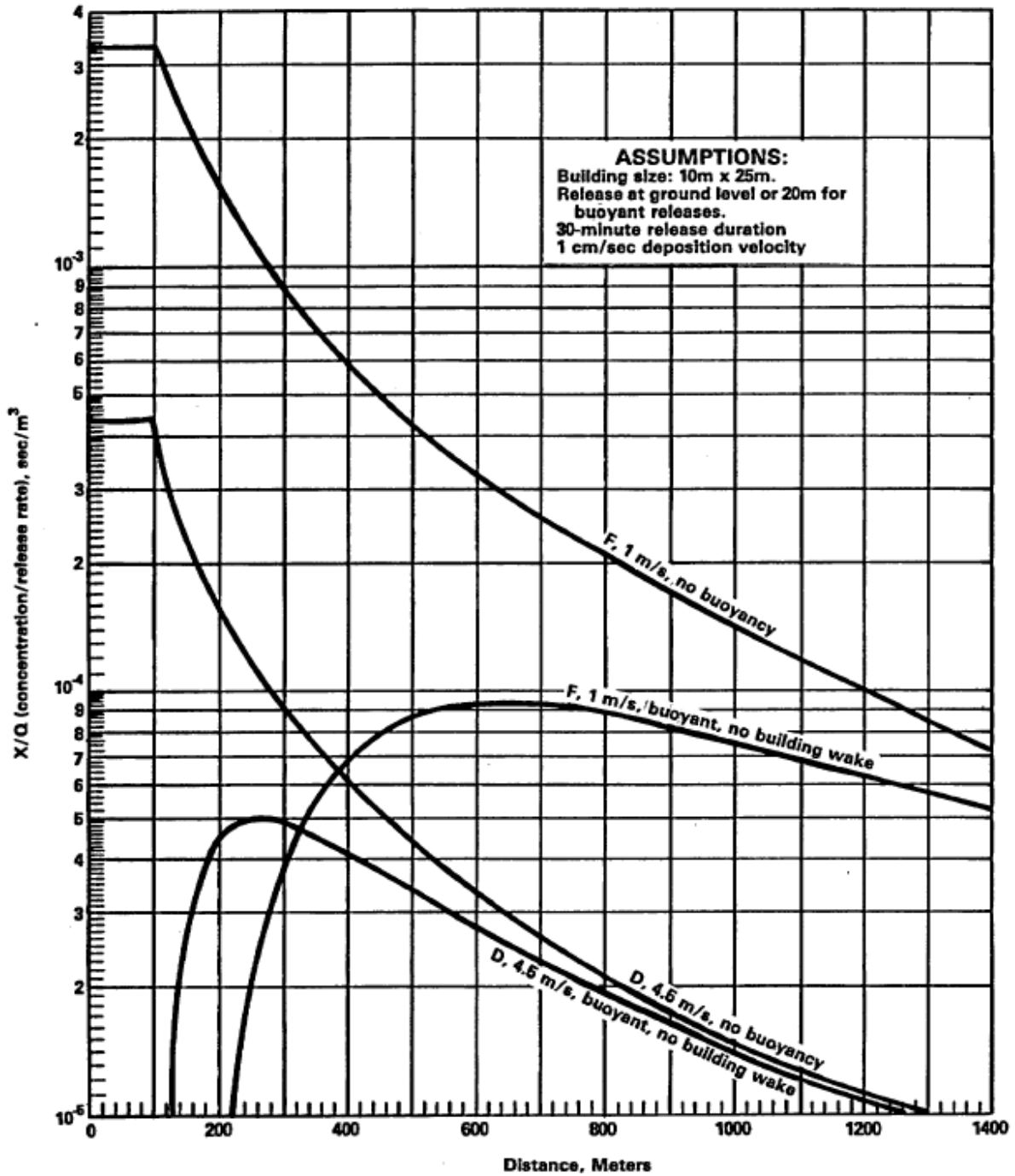


Figure A-2: From NUREG-1140 – Atmospheric dispersion ( $\chi/Q$ ) versus distance

#### A.4 References

1. D.B. Turner, *Workbook of Atmospheric Dispersion Estimates: An Introduction to Dispersion Modeling*, Second Edition, CRC Press, 1994.
2. *Integration of Safety into the Design Process*. [DOE-STD-1189-2008](#), U.S. Department of Energy, Washington, DC, March 2008.
3. S. A. McGuire. *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licenses*, [NUREG-1140](#), U.S. Nuclear Regulatory Commission, Washington, D.C., January 1988.



## **Attachment B: Sensitivity of the Default $\chi/Q$ Value to Initial Parameters for Radiological Releases**

### **B.1 Purpose**

While the default  $\chi/Q$  value in DOE-STD-1189-2008 (Ref. 1) is based on a number of conservative assumptions, the value is sensitive to specific choices in the initial parameters. In this attachment, the sensitivity of the default  $\chi/Q$  value to initial parameters such as building wake and initial plume dimensions, extreme high winds and tornadoes, averaging time, and deposition velocity is evaluated to determine its appropriate applicability. Section B.6 explores the uses and limitations of several atmospheric dispersion models to better understand their limitations.

### **B.2 Building Wake and Initial Plume Dimensions**

Despite known limitations at close distances from the release point, it has become accepted practice within DOE to use a steady-state Gaussian model to support conservative quantitative estimates of the dose to a hypothetical co-located worker at 100 m from a radiological release. The key concern with the use of the default  $\chi/Q$  value is that it assumes a specific initial plume dimension as a result of the building wake.<sup>1</sup> The limits of this assumption are discussed below.

If it is determined that a sufficiently-sized building is not proximate to the release, additional considerations can be applied to the nature of the release, an alternative analytical approach can be tried based on DOE-EH and Savannah River Site work reported in References 2 and 3. Reference 3 notes that to compensate for the building size limitation, it is possible to simulate the effects of a building wake via the MACCS2 code by treating the source of the release as an area rather than a point. While the building wake model/area source approach based on MACCS2 yields highly approximate results at short distances, these results will be more defensible than would be obtained by assuming a point source.<sup>2</sup> Using the same assumptions in MACCS2, but removing the building wake and applying the Eimutis-Konicek dispersion parameters (Ref. 4) recommended in Reference 3, results in a  $\chi/Q$  value of  $1.4 \times 10^{-2} \text{ sec/m}^3$ , or four times the default value of  $3.5 \times 10^{-3} \text{ sec/m}^3$ . Alternatively, employing the Gaussian plume equation (Equation A.1) and assuming that a building is not present, a plume centerline receptor and a ground-level release (i.e.,  $y = z = H = 0$ ) yields Equation B.1. Again using the dispersion coefficients derived

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<sup>1</sup> Note that due to differences in assumptions about the magnitude of the building wake, the initial plume dimensions from a 10 m x 25 m building in CRAC2 requires a 10 m x 36 m building in more modern atmospheric dispersion codes, such as MACCS2.

<sup>2</sup> The impact of an initial plume dimension from an area source is subsumed by the larger initial plume dimension from the aerodynamic effects of the building.

using the Eimutis-Konicek parameterization at 100 m, the calculated value of  $\chi/Q$  is  $3.1 \times 10^{-2}$   $\text{sec}/\text{m}^3$ ; 9 times the default value.

$$\frac{\chi}{Q}(x, 0, 0, 0) = \frac{1}{\pi * U * \sigma_y * \sigma_z} \quad (\text{Equation B.1})$$

Where:

- U      Wind speed diluting the plume (m/s);
- $\sigma_y$       Standard deviation of concentration in the horizontal direction (m); and
- $\sigma_z$       Standard deviation of concentration in the vertical direction (m).

In the case of a release which is in proximity to a building of sufficient size to match the dispersion characteristics of a 10 m x 36 m building (or larger), the use of the default  $\chi/Q$  value is conservative. Proximity to a building can be defined per EPA-450/4-80-023R, *Guideline for Determination of Good Engineering Practice Stack Height* (Ref. 5). For regulatory application, a building is considered sufficiently close to a stack to cause wake effects when the distance between the stack and the nearest part of the building is less than or equal to five times the lesser of the height or the projected width of the building. While the default  $\chi/Q$  value in DOE-STD-1189-2008 uses a defined building for calculation of the building wake effect, the actual building size can be used for determining the proximity of other buildings to the release (see Table C-1).

### B.3 Dispersion under Extreme High Winds and Tornadoes

Significant variations are potentially present in the dispersion of radiological releases. The default  $\chi/Q$  value assumes weather conditions that are conducive to minimizing dispersion (i.e., light winds in a stable atmosphere). Extreme straight-line winds and extreme high winds associated with tornadoes will greatly increase the dispersion of a release and may also influence the initial conditions, such as the integrity of buildings near the release point. The simultaneous assumption of a high wind or tornado accident scenario with minimal dispersion lends high confidence as to the conservatism of the final result. While the incident of extreme high winds has the potential to impact initial assumptions, such as the presence of the building and the associated building wake, the implications for initial release characteristics are also significant.

A study by Weber and Hunter (Ref. 6) provides a peer-reviewed technique examining downwind plume concentrations for releases in which a tornado breaches a primary confinement barrier. The study is illustrative of the considerations for the conditions resulting from a tornado and is relevant to the use of the default  $\chi/Q$  value. In the specific scenario studied, the tornado damages the structure and draws the released radionuclides into its vortex. In this case, the initial plume dimensions far exceed those of the default methodology. This scenario is

comparable to an accident characterized by an instantaneous release and a short exposure time. The default  $\chi/Q$  value in this case would clearly be a conservative assumption.

The study discusses another potential scenario resulting from a release as a result of extreme high winds, in which the immediate lifting of particles or dispersion of aerosols does not occur. In this case, it recommends the scenario be handled with standard Gaussian models using an appropriate wind speed. This would align, in this process, with using the default  $\chi/Q$  value. While there is potential that the scenario would result in the removal of an assumed building structure, and the resulting dispersion from the wake, the impact of this (i.e., increase in  $\chi/Q$ ) is of similar scale as the impact from wind speeds and a stability class<sup>3</sup> associated with the initial extreme high wind conditions.

The model results from MACCS2 and NRC Regulatory Guide 1.145, *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants* (Ref. 7), assuming no building wake are a factor of 4-9 greater than the  $\chi/Q$  value at 100 m established by NUREG-1140 (Ref. 8) assuming a building wake. An examination of Figure 1 of NUREG-1140 indicates that shifting from stable, light wind conditions (1 m/s and F stability class) to neutral stability and moderate winds (4.5 m/s and D stability class) results in about an order of magnitude reduction in the  $\chi/Q$  value. Given the similar scale of the impacts, the default  $\chi/Q$  value provides conservative results in scenarios associated with extreme high wind conditions, inclusive of tornados, without consideration of whether the building structure remains intact, to protect the assumptions of initial plume dimensions.

#### **B.4 Averaging time**

In NUREG-1140, the radiological  $\chi/Q$  value was stated to be based on a 30-minute release duration. An additional condition is that no credit for plume meander<sup>4</sup> is allowed at 100 m since the plume is considered to remain within the building wake. As specified in the EPA's *Risk Management Program for Offsite Consequence Analysis* (Ref. 9), the averaging time reflects the exposure time that is associated with the toxic chemical exposure guideline of interest and is generally equal to or less than the release duration. The supporting methods used to establish the appropriateness of the default  $\chi/Q$  value do not vary with changes in the averaging time, given the lack of variation in wind direction, wind speed, or plume meander. For the MACCS2 analysis, the lack of variation is also caused by setting to the same value for the release duration

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<sup>3</sup> Definitions for the seven stability classes (A thru F) can be found in Appendix A of *MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report*, [DOE-EH-4.2.1.4](#) (Ref. 2).

<sup>4</sup> Some dispersion codes, such as MACCS2, apply adjustments to  $\sigma_y$  to account for meander associated with longer exposure times. This should not be confused with release duration. The meander is accounted for by multiplying  $\sigma_y$  by a scaling factor, which is a ratio of the larger exposure time to the reference exposure duration (i.e., 600 seconds), raised to the 0.2 power.

and the exposure time. The dependence on release duration within CRAC2 (Ref. 10), the code used for development of NUREG-1140  $\chi/Q$  values, would only lead to minor increases in predicted impact associated with shorter exposure times.

Excluding plume meander from the atmospheric dispersion model is a conservative approach, as the meander would further diffuse the plume in cases of longer averaging times. Thus, the chosen default  $\chi/Q$  value is applicable to release durations shorter or longer than 30 minutes. Accordingly, no extra consideration for the length of exposure time is relevant to the application of the default  $\chi/Q$  value.

### **B.5 Impact of Deposition Velocity**

A 1 cm/sec deposition velocity was used in the calculation of the default  $\chi/Q$  value referenced in DOE-STD-1189-2008. A Gaussian plume model such as MACCS2 can be used to assess the importance of the assumed deposition velocity at 100 m. As further shown in Attachment D, changing the deposition velocity from 1 cm/sec to 0 cm/sec results in only a 15% increase<sup>5</sup> in the  $\chi/Q$  value at 100 m. The same release conditions, with a 1 km receptor more typically associated with an offsite impact, results in a doubling of the  $\chi/Q$  value when the effects of deposition are not accounted for. This is consistent and expected, given that the deposition occurs incrementally with time, and the longer distance of dispersion would therefore allow more time for deposition to impact the results. These model runs are discussed in Attachment D.

This modest impact on the co-located dose is in sharp contrast to the sensitivity of the analysis to the assumptions in initial plume dimensions.

### **B.6 Short-Distance Gaussian Plume Modeling**

DOE's Central Registry, or Toolbox, contains a number of computer codes compliant with software quality assurance requirements found in DOE Order (O) 414.1D, *Quality Assurance*, (Ref. 11). The three codes listed below are approved for use in atmospheric dispersion and radiological consequence calculations to support safety analysis.

- Generalized Environmental Radiation Dosimetry Software System - Hanford Dosimetry System (GENII) code (V2.10.1) developed and maintained by Pacific Northwest National Laboratory;
- HotSpot Health Physics Code (V2.07.1), developed and maintained by Lawrence Livermore National Laboratory; and

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<sup>5</sup> Guidance for deposition velocity is provided in Safety Bulletin No. 2011-02, *Accident Analysis Parameter Update*. The value in the Safety Bulletin is bounded by the use of 0 cm/s and would produce an increase less than 15% at a 100 m receptor. Further detail on the use of deposition velocity is also provided in Reference 17.

- MELCOR Accident Consequence Code System, Version 2, (MACCS2) (V1.13.1), developed for the NRC and maintained by Sandia National Laboratory.

All of these codes employ a steady-state Gaussian dispersion model and therefore are subject to similar limitations. DOE's code guidance documents for MACCS2 (Ref. 2) carries the following proviso:

*"The class of code also does not model dispersion close to the source (less than 100 meters from the source), especially where the influence of structures or other obstacles is still significant. Dispersion influenced by several, collocated facilities, within several hundred meters of each other should be modeled with care. Similarly, the MACCS2 class of codes should be applied with caution at distances greater than ten to fifteen miles, especially if meteorological conditions are likely to be different from those at the source of the release."*

The proviso is needed because a Gaussian plume model does not produce accurate results closer than 100 m to the source because in this region the influence of structures or other obstacles is still significant. DOE's code guidance documents note that dispersion influenced by several co-located facilities within several hundred meters of each other should be modeled with care.

Moreover, DOE's guidance for the GENII code, *GENII Computer Code Application Guidance for Documented Safety Analysis Final Report* (Ref. 12) prohibits the user from inputting receptor distances less than 100 meters. This guidance document explains that for distances less than about 100 m, dispersion coefficients generally do not provide a good fit to the observational data and the models are generally considered approximate. This is because the underlying steady state assumptions of Gaussian plume models do not perform well in the near-field. The MACCS2 Guidance Report (Ref. 2) specifies the limitations of the code at less than 100 m from the source. This is a slight divergence from the NRC's Code Manual for MACCS2, *Code Manual for MACCS2: Volume 1, User's Guide* (Ref. 13), which extends the area of uncertainty to 500 m, noting that the Gaussian plume dispersion parameterizations commonly available are likely to be of limited value at distances less than 0.5 km because of building wake effects. Such effects are seen on the sheltered side of a building or obstacle and are difficult to accurately configure into a Gaussian model. As stated previously, the Gaussian model accounts for these effects by creating additional virtual distance in the dispersion, but at these short distances, the virtual distance can actually be greater than the physical distance.

These same concerns about the fundamental limitations of Gaussian plume models apply to CRAC2 and NRC Regulatory Guide 1.145, Revision 1, as they rely on similar formulations and assumptions. These concerns, among others, led the NRC to investigate alternative methods for evaluating impacts at short distances. Results of those investigations, published in NUREG/CR-5055, *Atmospheric Diffusion for Control Room Habitability Assessments* (Ref. 14), indicated that

Gaussian plume models did not reliably predict, and typically overestimated, the concentrations in the vicinity of buildings.

Further work, presented in NUREG/CR-6331, Revision 1, *Atmospheric Relative Concentrations in Building Wakes* (Ref. 15), highlighted the development of models such as ARCON96. In Regulatory Guide 1.194, *Atmospheric Relative Concentrations for Control Room Radiological Habitability Assessments at Nuclear Power Plants* (Ref. 16), the NRC now recommends the use of ARCON96 for the assessment of control room habitability. However, DOE's approach is to utilize the Gaussian plume approach, which is conservative.

## B.7 References

1. *Integration of Safety into the Design Process*, [DOE-STD-1189-2008](#), U.S. Department of Energy, Washington, D.C., March 2008.
2. *MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report*, [DOE-EH-4.2.1.4](#), U.S. Department of Energy, Washington, D.C., June 2004.
3. Napier, B.A, Rishel, J.P., and N.E. Bixler. *Final Review of Safety Assessment Issues at Savannah River Site*, [PNNL-20990](#), published by Pacific Northwest National Laboratory, 2011.
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11. *Quality Assurance*, [DOE Order 414.1D](#), U.S. Department of Energy, Washington, D.C., 2011.
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14. *Atmospheric Diffusion for Control Room Habitability Assessments*, NUREG/CR-5055, U.S. Nuclear Regulatory Commission, Washington, D.C., May 1988.
15. *Atmospheric Relative Concentrations in Building Wakes*, [NUREG/CR-6331, Revision 1](#), U.S. Nuclear Regulatory Commission, Washington, D.C., May 1997.
16. *Atmospheric Relative Concentrations for Control Room Habitability Assessments at Nuclear Power Plants*, [Regulatory Guide 1.194](#), U.S. Nuclear Regulatory Commission, Washington, D.C., June 2003.
17. Sugiyama et al., *Deposition Velocity Methods for DOE Site Safety Analyses*, [LLNL-TR-654366](#), Lawrence Livermore National Laboratory, U.S. Department of Energy, 2014.

## Attachment C: Confirmatory Calculations Using MACCS2 for Radiological Dispersion

### C.1 Purpose and Summary

In order to validate the use of a of  $3.5 \times 10^{-3} \text{ s/m}^3$  value for  $\chi/Q$  in DOE-STD-1189-2008 (Ref. 1), a study was undertaken to compare modeling results generated by the MACCS2 and CRAC2 codes (Ref. 2 and 3, respectively). MACCS2 is one of the DOE Toolbox codes used for the calculation of radiological dose consequence. The older CRAC2 code was used for calculation of the NUREG-1140 (Ref. 4) results. This attachment reports study results.

### C.2 CRAC2

Section A.1 of DOE-STD-1189-2008 cites NUREG-1140 as the basis for the  $\chi/Q$  value used for atmospheric dispersion analysis:

*“This value is based upon NUREG-1140 (no buoyancy, F-stability, 1.0 m/sec wind speed at 100 m, small building size [10 m x 25 m], and 1 cm/sec deposition velocity).”*

Figure 1 of NUREG-1140 depicts atmospheric dispersion values versus distance (see Figure C-1 below). As can be seen from the figure, the default value in DOE-STD-1189-2008 is approximately<sup>1</sup> equal to the highest (i.e., most conservative) value at 100 m from the point of release.

NUREG-1140 used the CRAC2 code for  $\chi/Q$  calculations. CRAC2 did not use a Gaussian plume model, but rather replaced the Gaussian crosswind profile with a “top hat” function. The top hat function has a width of  $3\sigma_y$  and the amplitude is 0.836 of the Gaussian peak; however, the area under the top hat curve is identical to the area under the Gaussian curve. A comparison of the top hat function and a Gaussian curve is provided in Reference 3. The key input parameters for the CRAC2 calculations are building size, release duration, release height, and deposition velocity for particulates.

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<sup>1</sup> There is a slight difference in  $\chi/Q$  values between NUREG-1140 ( $3.3\text{E-}3 \text{ s/m}^3$ ) and DOE-STD-1189 ( $3.5\text{E-}3 \text{ s/m}^3$ ). This difference is small relative to the uncertainties in Gaussian dispersion modeling.



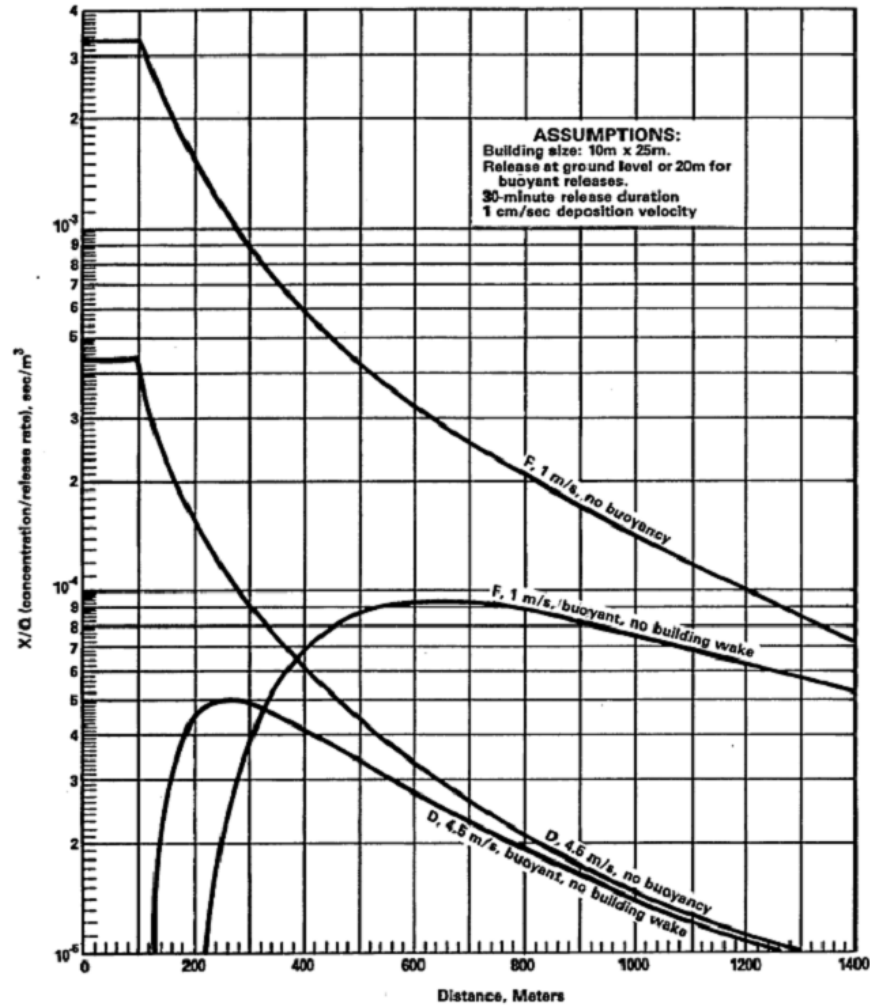


Figure C-1: From NUREG-1140 – Atmospheric dispersion versus distance

### C.3 MACCS2

MACCS2 is a Gaussian plume model for calculation of radiological atmospheric dispersion and consequences. Since the issuance of DOE-STD-3009-94 (Ref. 5), MACCS2 has been used for DOE applications primarily as a tool for deterministic consequence analysis. Code results have been used for safety control selection in nuclear facilities.

Page 2-1 of Reference 2 provides the following additional information:

*“MACCS2 predicts dispersion of radionuclides by the use of multiple, straight-line Gaussian plumes. The direction, duration, sensible heat, and initial radionuclide concentration may be varied from plume to plume. Crosswind dispersion is treated by a multi-step function and both wet and dry deposition features can be modeled as independent processes. For DSA applications, the MACCS2 user can apply either the*

*stratified random sampling mode or the Latin Hypercube Sampling (LHS) mode to process one year of site-specific meteorological data, with the former approach encouraged for current applications. Based on the meteorological sampling of site-specific data, and application of user-specified dose and/or health effects models, complementary cumulative distribution functions (CCDFs) are calculated for various measures of consequence. The average, median, 95th, and 99.5th percentile consequences are provided in the output”.*

## **C.4 Calculation of MACCS $\chi/Q$ for Co-located Workers**

### **C.4.1 Methodology and Assumptions**

MACCS2, Version 1.13.1, was used to perform a series of plume dispersion runs in order to compare  $\chi/Q$  results to results plotted in Figure 1 of NUREG-1140. Base case MACCS2 results were derived using assumptions consistent with those assumed in calculation of the default  $\chi/Q$  value, namely:

- Constant weather conditions of 1 m/s wind speed and F stability;
- Mixing layer height, 1000 m;
- Ground level release, non-buoyant plume scenario;
- 30 minute release duration (also accounts for plume meander);
- Building wake effects based on 10 m high by 25 m wide building as modeled in CRAC2 (Initial plume dimensions of 8.33 m by 4.65 m, for horizontal ( $\sigma_y$ ) and vertical ( $\sigma_z$ ), respectively);
- Dry deposition rate of 1 cm/sec;
- No wet deposition;
- Surface roughness of 10 cm; and
- Tadmor-Gur plume dispersion coefficients.

In addition, sensitivity runs were performed to determine the effect of varied modeling assumptions that might be applied in using MACCS2. For example, consistent with the recommendations in Reference 6, the dispersion coefficients were calculated using the Eimutis-Konicek method.  $\chi/Q$  was calculated using the MACCS2 building wake model, which varies from the CRAC2 building model in accounting for horizontal building wake such that the initial plume dimensions used would imply a building size of 10 m x 36 m rather than a building size of 10 m x 25 m. This adjustment is necessary to maintain consistency with the CRAC2 model. Sensitivity runs varying site surface roughness and dry deposition were also run to

simulate highly conservative conditions. The dry deposition assumptions are conservative relative to the guidance presented in Reference 7.

Modeling assumptions for the sensitivity runs included the following:

- Building wake effects based on a 10 m high by 25 m wide building utilizing the MACCS2 building wake model. This results in initial plume dimensions of 5.81 m by 4.65 m, for horizontal ( $\sigma_y$ ) and vertical ( $\sigma_z$ ), respectively;
- Eimutis-Konicek plume dispersion coefficients;
- 3 cm site surface roughness; and
- Dry deposition rate of 0 cm/s.

Table C-1 below describes the model runs undertaken.

**Table C-1: MACCS2 Run Descriptions**

Case	Case ID	Case Description
1	Base Case (To replicate results of NUREG-1140)	ATMOS cases run for the 100 meter worker case (T-G for < 5 km); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, CRAC2 building wake, 1 cm/s DV, surface roughness length 10 cm.
2	Base Case + 0 DV	ATMOS cases run for the 100 meter worker case (T-G for < 5 km); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, CRAC2 building wake, 0 cm/s DV, surface roughness length 10 cm.
3	Base Case + MACCS2 Bldg Wake	ATMOS cases run for the 100 meter worker case (T-G for < 5 km); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, MACCS2 building wake, 1 cm/s DV, surface roughness length 10 cm.
4	Base Case + E-K Coefficients	ATMOS cases run for the 100 meter worker case (Eimutus-Konicek); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, CRAC2 building wake, 1 cm/s DV, surface roughness length 10 cm.

5	Base Case + 3 cm	ATMOS cases run for the 100 meter worker case (T-G for < 5 km); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, CRAC2 building wake, 1 cm/s DV, surface roughness length 3 cm.
6	Base Case + E-K Coefficients + MACCS2 Bldg Wake	ATMOS cases run for the 100 meter worker case (Eimutus-Konicek); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, MACCS2 building wake, 1 cm/s DV, surface roughness length 10 cm.
7	Base Case + E-K Coefficients + No Bldg Wake	ATMOS cases run for the 100 meter worker case (Eimutus-Konicek); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, no building wake, 1 cm/s DV, surface roughness length 10 cm.
8	Base Case + No Bldg Wake	ATMOS cases run for the 100 meter worker case (T-G for < 5 km); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, no building wake, 1 cm/s DV, surface roughness length 10 cm.
9	Base Case + E-K Coefficients + 0 DV + No Bldg Wake	ATMOS cases run for the 100 meter worker case (Eimutus-Konicek); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, no building wake, 0 cm/s DV, surface roughness length 10 cm.
10	Base Case + E-K Coefficients + 0 DV	ATMOS cases run for the 100 meter worker case (Eimutus-Konicek); constant weather F-stability, 1 m/s wind speed; 1800s (30min) release, ground-level release, no sensible heat, no entrainment, no meander, CRAC2 building wake, 0 cm/s DV, surface roughness length 10 cm.

#### C.4.2 Results

Case 1 was an attempt to replicate, as closely as possible, the scenario in Figure 1 of NUREG-1140. The value obtained using the assumptions in Case 1 and Tadmor-Gur dispersion coefficients is  $3.47 \times 10^{-3} \text{ s/m}^3$  and is in good agreement with the  $3.3 \times 10^{-3} \text{ s/m}^3$  in NUREG-1140 and the  $3.5 \times 10^{-3} \text{ s/m}^3$  in DOE-STD-1189-2008. However, outside of 100 meters, the plots from NUREG-1140 diverged from the MACCS2 plots, with the MACCS2 plots showing slightly higher  $\chi/Q$  values for a given distance. Results are shown in Figure C-2.

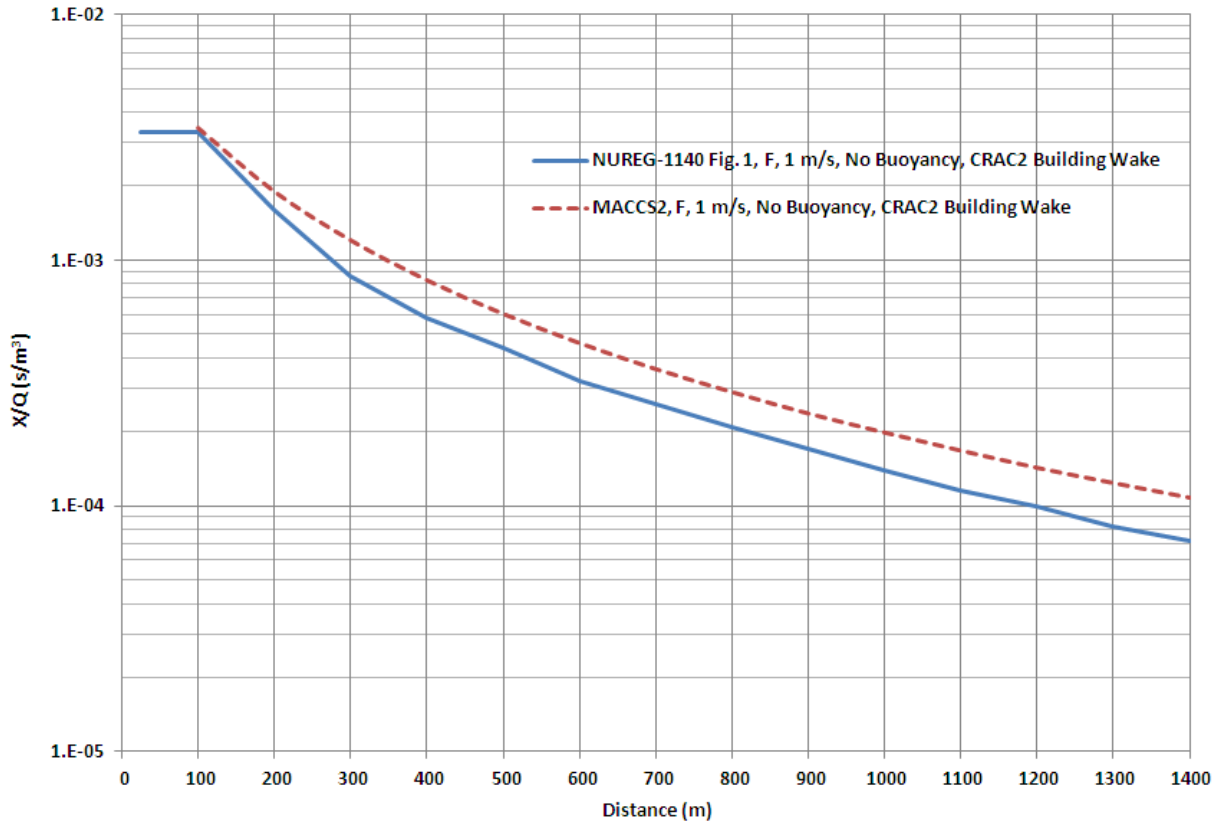


Figure C-2: Atmospheric dispersion versus distance for CRAC2 and MACCS2

For the 100 meter value, the results of all sensitivity scenarios are presented in Table C-2. Despite variations in modeling parameters such as dispersion coefficients, building wake model, deposition velocity, and surface roughness, the  $\chi/Q$  value remains reasonably consistent. The exceptions are Cases 7-9, where no building wake is modeled. In these cases,  $\chi/Q$  value increases by almost an order of magnitude. This discrepancy occurs because of the assumption of no building wake. MACCS2 removes the initial plume dimension from the building wake and assumes a point source release.

**Table C-2:  $\chi/Q$  Sensitivity Case Run Results at 100 m**

CASE	$\chi/Q$ Value (s/m3)
Nureg-1140	3.30E-03
CASE 1	3.47E-03
CASE 2	3.98E-03
CASE 3	4.33E-03
CASE 4	3.46E-03
CASE 5	3.78E-03
CASE 6	4.31E-03
CASE 7	1.35E-02
CASE 8	1.19E-02
CASE 9	2.41E-02
CASE 10	3.96E-03

## C.5 Conclusions

The results of this study demonstrate that CRAC2 and MACCS2 generate  $\chi/Q$  values than can be considered identical within margins of error. The results given by the models differ substantially only when no building is present to generate additional turbulence.

## C.6 References

1. *Integration of Safety into the Design Process*, [DOE-STD-1189-2008](#), U.S. Department of Energy, Washington, D.C., March 2008.
2. *MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report*, [DOE-EH-4.2.1.4](#), U.S. Department of Energy, Washington, D.C., June 2004.
3. L.T. Ritchie et al. *CRAC2 Model Description*, Sandia National Laboratories, [NUREG/CR-2552](#), SAND82-0342, April 1984.
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7. Sugiyama et al., *Deposition Velocity Methods for DOE Site Safety Analyses*, [LLNL-TR-654366](#), Lawrence Livermore National Laboratory, U.S. Department of Energy, 2014.

## Attachment D: Confirmatory Calculations Using ARCON96 for Radiological Dispersion

### D.1 Purpose and Summary

To provide additional confidence in the use of the default atmospheric dispersion ( $\chi/Q$ ) value in DOE-STD-1189-2008 (Ref. 1), a study was undertaken using the NRC code ARCON96. Developed in 1996, this code incorporates aerodynamic building wake effects on the local atmosphere as well as plume meander. ARCON96 atmospheric dispersion model, documented in NUREG/CR-6331, Revision 1 (Ref. 2), is endorsed by the NRC for application to calculate more realistic  $\chi/Q$  values in the near-field. The code is commonly used by NRC and its licensees for control room habitability evaluations. This short-distance use is justified by the code's empirically-derived horizontal and vertical turbulence magnitudes, which provide a more accurate match for a variety of wind tunnel studies and field tracer experiments. These studies and experiments effectively measured the plume meander and were subsequently used to develop empirical adjustments to the Gaussian model which does not account for it. Due to this scientific enhancement, the ARCON96 code meets NRC's regulatory criteria for receptor distances as near as 10 meters from the release.

Figure D-1, which is reproduced from the RASCAL User Manual, (Ref. 3), provides additional evidence that Gaussian models without any adjustments for plume meander<sup>1</sup> are highly conservative at low wind speeds.

ARCON96 was applied to develop ground-level  $\chi/Q$  values for a co-located worker at 100 meters from a release point. The  $\chi/Q$  values were calculated for three specific cases:

- 1) Release with a 10 m x 25 m building (cross-sectional area of 250 m<sup>2</sup>);
- 2) Release with a 10 m x 36 m building (cross-sectional area of 360 m<sup>2</sup>); and
- 3) Release without a building present.

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<sup>1</sup> Additional detail regarding ARCON96 plume meander can be found in Section 3.2.1 of Reference 2.

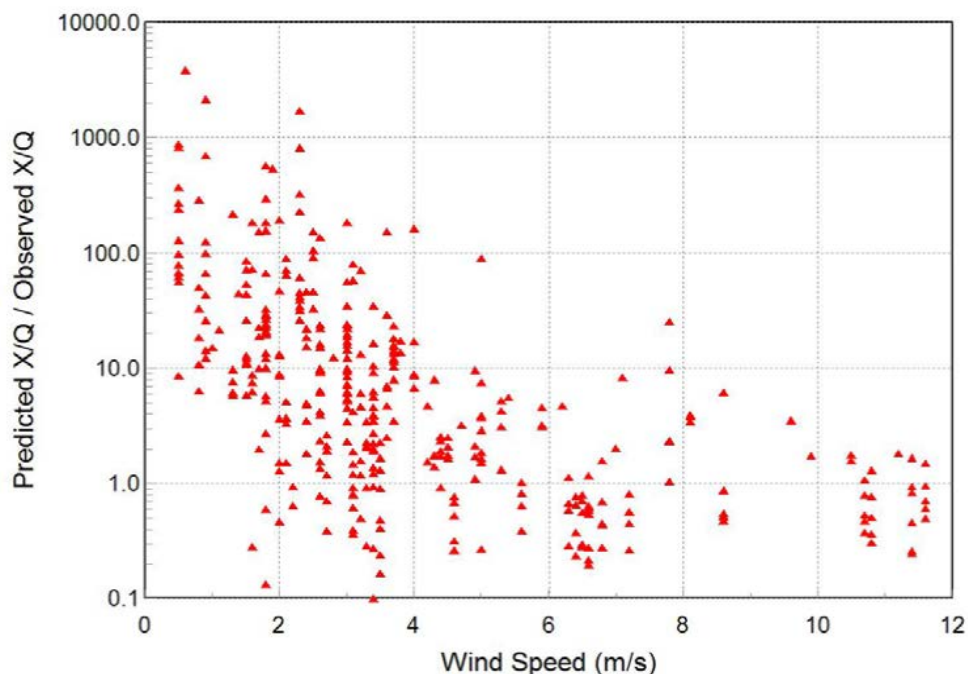


Figure D-1: (from RASCAL User Manual)

## D.2 Calculation of ARCON96 $\chi/Q$ Values for Co-located Worker

The ARCON96 model was run for the three release cases using a range of atmospheric dispersion conditions, assuming a ground-level release, and assuming a ground-level receptor at a downwind distance of 100 meters. The roughness length was set at 0.2 meter. For this purpose, individual meteorological data files were created for each of the stability class<sup>2</sup> and wind speed combinations considered. Wind speeds were assumed to have been measured at the standard 10-meter elevation.

The  $\chi/Q$  values were calculated for a full spectrum of stable atmospheric stability conditions (i.e., E, F, and G Pasquill-Gifford stability classes) and light to moderate wind speed conditions (i.e., 0.5 m/sec to 5 m/sec in 0.5 m/sec increments). These meteorological conditions were chosen in order to obtain the worst case atmospheric dispersion condition.<sup>3</sup>

The results of the ARCON96 runs are summarized in Tables D-1, D-2, and D-3 for the 250 m<sup>2</sup> building, 360 m<sup>2</sup> building, and no building cases, respectively. The  $\chi/Q$  values reported in these tables are centerline values in which the releases are assumed to be transported directly toward

<sup>2</sup> Definitions for the seven stability classes (A thru F) can be found in Appendix A of *MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report*, [DOE-EH-4.2.1.4](#) (Ref. 4).

<sup>3</sup> Stability class G is not an original Pasquill-Gifford stability class. It is a derivative of the F stability class created by the NRC to add conservatism to its dose analyses.



the receptor with no credit for off-centerline concentrations. The  $\chi/Q$  values reported as N/A refer to the fact that stability classes F and G cannot realistically occur with wind speeds greater than 4.0 m/sec.

**Table D-1: 1-Hour  $\chi/Q$  Values for Stability Classes E, F, and G and Wind Speeds from 0.5 m/s to 5.0 m/s (250 m<sup>2</sup> Building)**

Wind Speed (m/s)	$\chi/Q$ Values (s/m <sup>3</sup> ) at 100 m		
	Stability Class E	Stability Class F	Stability Class G
0.5	2.49E-04	2.51E-04	2.52E-04
1.0	3.53E-04	3.60E-04	3.64E-04
1.5	4.55E-04	4.73E-04	4.83E-04
2.0	5.45E-04	5.79E-04	5.96E-04
2.5	6.17E-04	6.70E-04	6.99E-04
3.0	6.68E-04	7.42E-04	7.84E-04
3.5	6.97E-04	7.91E-04	8.46E-04
4.0	7.06E-04	8.14E-04	8.80E-04
4.5	6.96E-04	N/A	N/A
5.0	6.71E-04	N/A	N/A

**Table D-2: 1-Hour  $\chi/Q$  Values for Stability Classes E, F, and G and Wind Speeds from 0.5 m/s to 5.0 m/s (360 m<sup>2</sup> Building)**

Wind Speed (m/s)	$\chi/Q$ Values (s/m <sup>3</sup> ) at 100 m		
	Stability Class E	Stability Class F	Stability Class G
0.5	2.49E-04	2.51E-04	2.52E-04
1.0	3.53E-04	3.60E-04	3.64E-04
1.5	4.55E-04	4.73E-04	4.82E-04
2.0	5.44E-04	5.78E-04	5.96E-04
2.5	6.15E-04	6.69E-04	6.98E-04
3.0	6.65E-04	7.39E-04	7.81E-04
3.5	6.93E-04	7.86E-04	8.40E-04
4.0	7.00E-04	8.06E-04	8.70E-04
4.5	6.88E-04	N/A	N/A
5.0	6.61E-04	N/A	N/A

**Table D-3: 1-Hour  $\chi/Q$  Values for Stability Classes E, F, and G and Wind Speeds from 0.5 m/s to 5.0 m/s (No Building)**

Wind Speed (m/sec)	$\chi/Q$ Values ( $\text{s/m}^3$ ) at 100 m		
	Stability Class E	Stability Class F	Stability Class G
<b>0.5</b>	2.49E-04	2.51E-04	2.52E-04
<b>1.0</b>	3.53E-04	3.61E-04	3.65E-04
<b>1.5</b>	4.57E-04	4.76E-04	4.85E-04
<b>2.0</b>	5.52E-04	5.87E-04	6.06E-04
<b>2.5</b>	6.35E-04	6.93E-04	7.24E-04
<b>3.0</b>	7.05E-04	7.90E-04	8.39E-04
<b>3.5</b>	7.63E-04	8.80E-04	9.51E-04
<b>4.0</b>	8.08E-04	9.60E-04	1.06E-03
<b>4.5</b>	8.44E-04	N/A	N/A
<b>5.0</b>	8.70E-04	N/A	N/A

### D.3 Conclusions

Tables D-1 through D-3 show that the  $\chi/Q$  values for all cases for F stability at 1.0 m/s are virtually the same at  $3.6 \times 10^{-4} \text{ sec/m}^3$ . This value is almost an order of magnitude (factor of 9.7) smaller than the default  $\chi/Q$  value stated in DOE-STD-1189-2008. This substantial difference reflects the enhanced dispersion due to both horizontal and vertical plume meander. At this light wind speed, the building wake effect contribution is minimal, as the wind speed is not strong enough to have an aerodynamic effect on the plume. However, as the wind speed increases, the plume meander magnitude decreases at a greater rate than the increasing wind speed is enhancing the dilution. Thus, the highest ARCON96  $\chi/Q$  values occur at a wind speed of 4.0 m/s. For the no-building case this value is  $1.06 \times 10^{-3} \text{ sec/m}^3$ , or about a third of an order of magnitude (factor of 3.3) smaller than the default value in DOE-STD-1189-2008. At wind speeds of 4.0 m/s and greater, the meander factor decays and the aerodynamic building wake component begins to dominate. However, at higher wind speeds, plume dilution is greater and  $\chi/Q$  decreases from that point on.

In conclusion, this evaluation provides confidence that the default value of  $\chi/Q$  stated in DOE-STD-1189-2008 is conservative when compared to ARCON96  $\chi/Q$  values.

#### D.4 References

1. *Integration of Safety into the Design Process*, [DOE-STD-1189-2008](#), U.S. Department of Energy, Washington, D.C., (March 2008).
2. *Atmospheric Relative Concentrations in Building Wakes*, [NUREG/CR-6331, Revision 1](#), U.S. Nuclear Regulatory Commission, Washington, D.C., May 1997.
3. *RASCAL 4: Description of Models and Methods*, [NUREG-1940](#), U.S. Nuclear Regulatory Commission, Washington, D.C., December 2012.
4. *MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report*, [DOE-EH-4.2.1.4](#), U.S. Department of Energy, Washington, D.C., June 2004.

## **Attachment E: Approach for Determining a $\chi/Q$ Value for Conditions Where the Default Value is Not Appropriate**

### **E.1 Purpose**

As discussed in Attachment B, the use of the default  $\chi/Q$  value in DOE-STD-1189-2008 (Ref. 1) is conservative when the size of a building is equal to or larger than that assumed in the development of the default value. This Attachment focuses on the special condition of when the default  $\chi/Q$  value cannot be used (i.e., the building is not sufficiently sized or a building is not present). This attachment provides examples of an approach for determining a  $\chi/Q$  value under such conditions. The approach outlined hinges on modifying the plume dimensions of the initial release. This attachment is not intended for calculation of  $\chi/Q$  values that are less conservative than the default  $\chi/Q$  value.

### **E.2 Initial Plume Dimensions**

NUREG-1140 (Ref. 2) utilized the CRAC2 model (Ref. 3) for calculation of atmospheric dispersion values. The calculation within CRAC2 effectively disperses the initial plume by increasing the initial standard deviations of concentration ( $\sigma_y$  and  $\sigma_z$ ). The model shares aspects with Equation 1 of NRC Regulatory Guide 1.145, Revision 1 (Ref. 4) and dispersion models such as MACCS2 (Ref. 5). All of these codes and equations attempt to incorporate the impact of initial plume conditions by enhancing the initial horizontal and vertical standard deviations.

The CRAC2 model did not include a plume meander factor, as specified in Regulatory Guide 1.145 (see Equations 2 and 3 of the Guide), but rather included a model based on the release duration and an initial plume dimension determined by the building size. NUREG-1140 states that “*plume meander was not included at 100 m because the plume is considered to be still in the building wake ....*”

This statement is interpreted to mean that (a) the release-duration plume meander model was not applied at 100 m in the supporting NUREG-1140 calculations and (b) the entire plume was immediately entrained in the aerodynamic flow and the cavity region behind the 10 m x 25 m building. In a ground-level release, unlike an elevated release, building downwash and wake factors disperse the downwind concentration by creating an initial plume dimension in proportion to the size of the building.

While Regulatory Guide 1.145 simply adds a factor representing the cross-sectional area of a building, MACCS2 effectively creates an additional virtual distance, upwind of the release point, to account for the initial plume dimension. The building wake from a 10 m x 25 m building in CRAC2 effectively augments the plume dimension at 100 m downwind equivalent to a plume

that has traveled ~300 m downwind from a point source release,<sup>1</sup> Figure E-1. Therefore, at 100 m the assumption of initial plume dimensions, even when associated with a small building, play a larger role in the concentration than the model results from dispersion alone. Results from Gaussian plume models at short distances such as 100 m are highly sensitive to the assumptions regarding the initial plume dimensions.

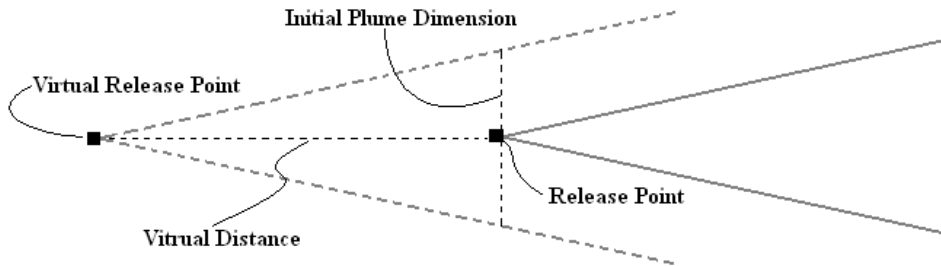


Figure E-1: Virtual release point to establish the initial plume dimension

When the building is shrunk in size or removed entirely, defining the initial plume dimensions based on the release characteristics becomes critical. Releases not associated with a sufficiently large and/or proximate building to induce a comparable initial plume dimension, as used in the default  $\chi/Q$  value, would need to either use a point source for the release or define the initial plume dimensions from the release of the smaller building.

These dimensions can be defined following well-established procedures consistent with Gaussian plume dispersion modeling, such as code guidance for MACCS2. However, this attachment provides a simpler method than a full Gaussian plume model by employing a variation of the Gaussian plume equations in Regulatory Guide 1.145. Rather than accounting for the building impact from a variable building size, constant wake factor, or parameterized wake factor (i.e., Equations 1-3 in Regulatory Guide 1.145, respectively) the method used echoes that performed within Gaussian plume models.

For ground-level releases of volume sources, the initial plume dimensions<sup>2</sup>,  $\sigma_{yi}$  and  $\sigma_{zi}$ , are based on the shortest building width ( $W$ ) and the minimum building height ( $H$ ), divided by a set standard deviation of the concentration of contaminants in a plume.

$$\sigma_{yi} = \frac{W}{4.3} \quad \sigma_{zi} = \frac{H}{2.15} \quad (\text{Equations E.1 and E.2})$$

<sup>1</sup> Note that due to differences in assumptions about building wake, the initial plume dimensions from a 10 m x 25 m building in CRAC2 are equivalent to a 10 m x 36 m building in more modern dispersion codes such as MACCS2.

<sup>2</sup> MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report (Ref. 5).

The assumption of a ground-level release reflects half of the plume in the vertical direction; therefore the standard deviation for  $\sigma_{zi}$  is half that of  $\sigma_{yi}$ . A plume footprint is commonly defined by these standard deviation values. In a Gaussian model,  $\sigma_{yi}$  and  $\sigma_{zi}$  are effectively used for determining the distance from the virtual release point shown in Figure E-1.

Consistent with the methodology in Equation B.1, these initial plume dimensions are added to the downwind dispersion coefficients,  $\sigma_y$  and  $\sigma_z$ , due to 100 m plume travel.

$$\frac{\chi}{Q}(100,0,0,0) = \frac{1}{\pi * U * (\sigma_{yi} + \sigma_y) * (\sigma_{zi} + \sigma_z)} \quad (\text{Equation E.3})$$

Where:

- U      Wind speed diluting the plume (m/s);
- $\sigma_y$     Standard deviation of concentration in the horizontal direction from 100 m plume travel (m);
- $\sigma_z$     Standard deviation of concentration in the vertical direction from 100 m plume travel (m);
- $\sigma_{yi}$     Standard deviation of concentration in the horizontal direction based on the building width (m); and
- $\sigma_{zi}$     Standard deviation of concentration in the vertical direction based on the building height (m).

If one inserts values representing a 10 m x 36 m building, F-stability, a wind speed of 1 m/s, and a 100 m receptor, the  $\chi/Q$  value calculated is of  $3.6 \times 10^{-3} \text{ sec/m}^3$ .

### E.3 Examples

Using Equation C.3, five cases were developed to provide examples of calculated  $\chi/Q$  values. The first case recreates the methodology in NUREG-1140, assuming a release within the wake from a 10 m high by 36 m wide building. Case 2 is an example with no building present, and represents a maximal  $\chi/Q$  value. Case 3 is for a building smaller than initially assumed by the default methodology, and is an example of a  $\chi/Q$  value between the maximal and the default values. Case 4 is for a building that is shorter than the default methodology, but considerably longer. This is to highlight the limitations of the equations' applicability, while also noting that the default value is still used even in the case of larger buildings. Finally, Case 5 is intended to show how a taller, narrower building can result in a  $\chi/Q$  value greater than the default, while still allowing the building to be credited at a longer distance from the release than the default assumption.

**Table E-1: Calculation of  $\chi/Q$  for Special Conditions**

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5
U (m/s)	1	1	1	1	1
$\sigma_y$ (m, at 100 m)	4.62	4.62	4.62	4.62	4.62
$\sigma_z$ (m, at 100 m)	2.25	2.25	2.25	2.25	2.25
Building Width (m)	36	0	25	100	15
Building Height (m)	10	0	5	5	15
$\sigma_{yi}$ (m)	8.37	0	5.81	23.26	3.49
$\sigma_{zi}$ (m)	4.65	0	2.32	2.32	6.98
Calculated $\chi/Q$ (s/m <sup>-3</sup> )	$3.6 \times 10^{-3}$	$3.1 \times 10^{-2}$	$6.7 \times 10^{-3}$	$2.5 \times 10^{-3}$ *	$4.3 \times 10^{-3}$
Max. distance to credit building (m)**	50	N/A	25	25	75

Note:  $\sigma_y$  and  $\sigma_z$  were calculated using the Eimutis-Konicek dispersion parameters.

\* While the calculated  $\chi/Q$  value is less than the default  $\chi/Q$  value, this simplified approach is an insufficient method to establish the use of a value that is less conservative than the default  $\chi/Q$  value.

\*\* For additional details on building proximity, see Section B.2.

#### E.4 References

1. *Integration of Safety into the Design Process*, [DOE-STD-1189-2008](#), U.S. Department of Energy, Washington, D.C., March 2008.
2. S. A. McGuire, *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licenses*, [NUREG-1140](#), U.S. Nuclear Regulatory Commission, Washington, D.C., January 1988.
3. *CRAC2 Model Description*, [NUREG/CR-2552](#), U.S. Nuclear Regulatory Commission, Washington, D.C., March 1984.
4. *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants*, [Regulatory Guide 1.145, Rev. 1](#), U.S. Nuclear Regulatory Commission, Washington, D.C., March 1983.
5. *MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report*, [DOE-EH-4.2.1.4](#), U.S. Department of Energy, Washington, D.C., June 2004.

## **Attachment F: Evaluation of Use of the Default $\chi/Q$ Value for Chemical Releases**

### **F.1 Purpose and Summary**

The purpose of this attachment is to evaluate whether the default  $\chi/Q$  value in DOE-STD-1189-2008 (Ref. 1), is conservative for analyzing the effects of chemical releases on co-located workers. Appendix B of that standard provides guidance on how to calculate chemical exposure at the co-located worker location but does not specify a default  $\chi/Q$  value. This evaluation analyzed and performed calculations of a range of neutrally-buoyant, positively-buoyant, and negatively-buoyant releases under conservative meteorological conditions. The analysis presents information on chemical dispersion to highlight any potential differences with radiological dispersion assumptions. The key differences tested included the impacts from gas buoyancy, the assumptions related to deposition, and release time and dosage calculation. A calculation of the  $\chi/Q$  from a release of various chemicals from an evaporative pool was performed to represent various release types.

### **F.2 Environmental Protection Agency Offsite Consequence Assessment Methodology**

In Section 68.22(b) of 40 CFR Part 68, *Chemical Accident Prevention Provisions* (Ref. 2), the Environmental Protection Agency (EPA) has codified F atmospheric stability class and 1.5 m/s wind speed as the “worst case” meteorological conditions for hazardous substance releases. With respect to radiological releases, NRC’s NUREG-1140 establishes the worst case meteorology at the same stability class but with a wind speed of 1.0 m/s.

### **F.3 Applicable Chemical Consequence Dispersion Models**

DOE’s Central Registry (i.e., “toolbox”) includes several atmospheric dispersion models for determining the consequences of chemical releases:

- Areal Locations of Hazardous Atmospheres (ALOHA) code, Versions 5.2.3 and 5.4.1.2, sponsored by the National Oceanic and Atmospheric Administration (Ref. 4); and
- Emergency Prediction Information code (EPIcode), Version 7.0, owned by Homann Associates, Inc. (Ref. 5).

Other chemical dispersion models have been applied by various federal agencies, their contractors and industry, to analyze chemical releases. These may be applied in a chemical consequence analysis as long as the appropriate software quality assurance procedures are followed and compliance with DOE O 414.1D, *Quality Assurance*, (Ref. 6) and DOE Guide 414.1-4, *Safety Software Guide for Use with 10 CFR 830, Subpart A, Quality Assurance*



and DOE O 414.1C (Ref. 7) can be effectively demonstrated. Three additional chemical dispersion models, also capable of addressing dense gases, are:

- Hazard Prediction and Assessment Capability (HPAC) (Ref. 8);
- Heavy Gas System (HGSYSTEM) (Ref. 9); and
- Dense Gas Dispersion (DEGADIS) (Ref. 10).

#### **F.4 Chemical Consequence Assessment Modeling Inputs and Assumptions**

The following inputs and assumptions are used in chemical consequence modeling:

1. Meteorological conditions of atmospheric stability, wind speed, wind direction, ambient temperature and relative humidity;
2. Dry deposition velocity;
3. Aerodynamic building effects;
4. Averaging time for dispersion;
5. Chemical source term and exposure duration; and
6. Chemical toxicity characteristics.

Each of these is discussed in the subsections below.

##### **F.4.1 Atmospheric Stability, Wind Speed, Wind Direction, Ambient Temperature and Relative Humidity**

EPA's 40 CFR Part 68 and NRC's NUREG-1140 specify that an F atmospheric stability class and 1.5 m/s (EPA) or 1.0 m/s wind speed (NRC) be used for analysis of releases. There may be some variability of the worst case meteorological conditions at different sites (e.g., E stability class or a 1.7 m/s wind speed). In this technical report, both the DOE and EPA conditions were applied, respectively, to evaluate the differences.

Ambient temperature and relative humidity conditions are relevant to chemical releases. For these variables, Section 68.22(c) of 40 CFR Part 68 states:

*“For worst-case release analysis of a regulated toxic substance, the owner or operator shall use the highest daily maximum temperature in the previous three years and average humidity for the site, based on temperature/humidity data gathered at the stationary source or at a local meteorological station; an owner or operator using the RMP<sup>1</sup> Offsite Consequence*

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<sup>1</sup> EPA 550-B-99-0009, *Risk Management Program for Offsite Consequence Analysis* (Ref. 11)

*Analysis Guidance may use 25 °C and 50 percent humidity as values for these variables. For analysis of alternative scenarios, the owner or operator may use typical temperature/humidity data gathered at the stationary source or at a local meteorological station.”*

#### **F.4.2 Dry Deposition Velocity**

The application of a dry deposition velocity is much more complex for releases of individual chemicals than for radionuclide releases, as individual chemicals have the capacity to interact with the environment (i.e., flora, man-made surfaces) in a different manner. In consideration of past discussions in the DOE complex on conservative values of dry deposition velocity applicable to radiological particulates, *Accident Analysis Parameter Update* (Ref. 12) and *Deposition Velocity Methods for DOE Site Safety Analyses* (Ref. 13), and recognizing that chemical deposition is not credited in modeling dispersion under the EPA, this supporting analysis does not include the effects of dry deposition on impacts on airborne concentrations for the base cases. The default radiological value  $\chi/Q$  used in DOE-STD-1189-2008 incorporated a deposition velocity of 1.0 cm/sec, and this analysis examined the relative impact of removing that assumption on chemical dispersion.

#### **F.4.3 Aerodynamic Effects of Buildings**

While no specific building size or dimensions are cited by EPA in 40 CFR 68, the intent of the chemical consequence assessment in this context is to guide the decision on safety significant controls in accordance with Appendix B of DOE-STD-1189-2008. Although not all chemical dispersion models incorporate aerodynamic effects of buildings, maintaining the small building size assumption of 10 m x 25 m in NUREG-1140, is deemed appropriate, when applicable.

#### **F.4.4 Averaging Time for Determining Dispersion**

In NUREG-1140, the radiological  $\chi/Q$  value was stated to be based on a 30-minute release duration. An additional condition is that no credit for plume meander<sup>2</sup> is allowed at 100 m since the plume is considered to be still within the building wake. As specified in EPA's Risk Management Plans, the averaging time reflects the exposure time associated with the toxic chemical exposure guideline of interest, and is generally equal to or less than the release duration. The supporting methods used to establish the appropriateness of the default  $\chi/Q$  value do not vary with changes in the averaging time, given the lack of variation in wind direction, wind speed, or plume meander. For the MACCS2 analysis, the lack of variation is also a result

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<sup>2</sup> Some dispersion codes, such as MACCS2, apply adjustments to horizontal standard deviation of concentration (i.e.,  $\sigma_y$ ) to account for plume meander associated with longer exposure times. This adjustment should not be confused with release duration. The meander is accounted for by multiplying  $\sigma_y$  by a scaling factor, which is a ratio of the larger exposure time to the reference exposure duration (i.e., 600 seconds), raised to the 0.2 power.

of the release duration and exposure time being set to the same value. The dependence on release duration within CRAC2, *CRAC2 Model Description* (Ref. 14), the code used for development of NUREG-1140  $\chi/Q$  values, would only lead to minor increases in predicted impact associated with shorter exposure times. Excluding plume meander from the atmospheric dispersion model is a conservative approach, as the plume meander would further diffuse the plume in cases of longer averaging times. Thus, the chosen default  $\chi/Q$  value is applicable to release durations shorter or longer than 30 minutes. Accordingly, no extra consideration for the length of exposure time is relevant to the application of the default  $\chi/Q$  value.

#### **F.4.5 Chemical Source Term and Exposure Duration**

The chemical exposure duration is generally assumed to be of the same time scale as the release duration for the source term. DOE-STD-1189-2008 recommends that one minute be used as the minimum time scale if the release duration is equal to or less than one minute. Additionally, considerations for the development of an appropriately conservative chemical source term with respect to exposure duration are identified within Appendix B.3 of DOE-STD-1189-2008.

#### **F.4.6 Chemical Toxicity Characteristics**

The toxicity characteristics of the chemical, and the previously-addressed chemical source term and exposure duration, both factor into the time basis for the time-weighted average. The chemical toxicity characteristics are broadly classified into two distinct groups:

- Concentration-dependent chemicals: Those whose toxic effects correlate more closely to a threshold concentration than to the time-integrated exposure (i.e., dose); and
- Dose-dependent chemicals: Those whose toxic effects depend upon the total amount of material taken up by the body.

For concentration-dependent chemicals that correlate more closely to a threshold concentration, an exposure duration that corresponds to the peak emission rate is the typical conservative assumption. This assumption does not directly affect the assumption of the default  $\chi/Q$  value. Additional information about calculation of chemical hazard consequence assessment can be found in Section A.2 of DOE-STD-3009-2014, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis* (Ref. 15).

#### **F.5 Influence of Dry Deposition Velocity and Aerodynamic Building Effects**

To illustrate the influence of deposition velocity and aerodynamic effects of buildings (i.e., wake and cavity effects), the toolbox dispersion model EPIcode—which contains algorithms for modeling both physical effects—was executed for four possible combinations: (1) base case; (2) deposition only; (3) building wake only; and (4) building wake and deposition.

For this comparative analysis, the base case is an evaporative release of a 10-gallon spill of hydrochloric acid occurring assuming F stability class and a wind speed of 1.5 m/s. The base case is further defined as a release in an open field with no building and without considering dry deposition. Case 2 includes a 1.0 cm/s dry deposition velocity effect, while Case 3 includes a 10 m x 25 m building wake effect, and Case 4 considers both dry deposition and building wake effects.

Table F-1 presents the results of this comparative analysis for a receptor at 100 m. Relative to the base case conditions, Case 2 shows about a factor of two reduction in the  $\chi/Q$  value due to dry deposition, while Case 3 leads to roughly a factor of nine reduction due to building wake. Case 4, in which dry deposition and building wake effects are combined, shows nearly a factor of 20 reduction in  $\chi/Q$ .

**Table F-1: EPIcode Comparison Case for Hydrochloric Acid  
(F stability; 1.5 m/s wind speed)**

Case	Building Size	Dry Deposition Velocity (cm/s)	Factor Relative to Base Case	Reduction Factor $(\chi/Q)_{\text{base}}/(\chi/Q)$
1 – Base Case	No building	0	1.00	1.0*
2 – Dry deposition only	No building	1.0	0.47	2.1
3 – Building wake only	10 m x 25 m	0	0.11	9.1
4 – Building wake and dry deposition	10 m x 25 m	1.0	0.05	~19

\* The Base Case  $\chi/Q$  value is  $3.4\text{E-}2 \text{ s/m}^3$ .

Although it may be difficult to defend a dry deposition velocity of 1.0 cm/s for all types of chemical releases, this analysis shows that the relative change in  $\chi/Q$  is much smaller as compared to the more dominant aerodynamic building wake effect. Accordingly, assuming the presence of a small building would be appropriate for most chemical release circumstances without consideration of dry deposition effects.

## F.6 Modeling Dense Gas and Neutrally Buoyant Gas Releases

ALOHA is a unique chemical consequence code in that it contains both dense gas (i.e., negatively buoyant) and Gaussian (i.e., neutrally-buoyant) dispersion models. During an ALOHA run, the code selects the appropriate dispersion model based on the nature of the release, the chemical being analyzed and the receptor distance. For large releases of heavier-than-air chemicals or chemicals at cryogenic temperatures, ALOHA calculates a Bulk Richardson number; which, if greater than 50, selects the dense gas code, a hybrid of the code titled Dense Gas Dispersion (DEGADIS). As the dense gas is transported to the receptor, it mixes with the neutrally-buoyant ambient atmosphere, reducing its density characteristics. ALOHA recalculates the Bulk Richardson number and when it drops below 50, it invokes the neutrally-buoyant Gaussian code for the remainder of the calculation. ALOHA does not permit the user to input a building; only open field (i.e., no building) calculations are allowed.

It should be emphasized that although vertical turbulence is significantly restricted due to the gravitational effects on the dense gas blanket, the horizontal turbulence is much greater than a Gaussian distribution as the blanket spreads out horizontally through its own internal turbulence regime for a worst case meteorological condition. Thus, for the case of dense gas, near-field dispersion under light winds and a stable atmosphere (100 m receptor, F stability class, 1.0 m/s winds), the density of the gas inhibits vertical dispersion while enhancing horizontal dispersion.

In contrast, EPIcode is based solely on a neutrally-buoyant atmospheric transport and dispersion model, but it allows the user to vary the release time and deposition velocity; as well as the implementation of an aerodynamic building wake effect.

Both codes contain algorithms enabling the user to model different horizontal and vertical dispersion coefficients for rural and urban regions of transport and to vary the release time. Since urban regions have larger roughness lengths, the horizontal and vertical dispersion coefficients associated with this type of terrain is more dispersive than the rural terrain dispersion coefficients.

Table F-2 summarizes the results from an earlier study, *Comparison of ALOHA and EPIcode for Safety Analysis Applications* (Ref. 16). This study analyzed ground-level chemical releases and the subsequent impact at the 100 m receptor distance for a meteorological condition of F stability class and a 1.0 m/s wind speed for both rural and urban terrain regions of transport. It reached the following two conclusions:

- The rural region of transport is bounding relative to urban conditions for both ALOHA and EPIcode, since the rural dispersion coefficients are less dispersive than urban; and
- The ALOHA neutrally-buoyant Gaussian model results for a rural region of transport bounds all other dense gas results in both rural and urban regions of transport, as well as all other neutrally-buoyant Gaussian model results.

Conclusions reached in this study would not be materially different if a wind speed of 1.5 m/s had been used.

**Table F-2: Neutrally-Buoyant Gaussian and Dense Gas Model Comparisons for Rural and Urban Regions of Transport**

Case	Chemical	EPIcode Version 7.0 (Gaussian only)		ALOHA Version 5.2.3 (Gaussian and Dense Gas)		
		Evaporation Rate "Q" (g/s)	Plume Concentration "χ" at 100 m (mg/m <sup>3</sup> )	Evaporation Rate "Q" (Maximum Avg) (g/s) **	Plume Concentration "χ" at 100 m (mg/m <sup>3</sup> )	
					Gaussian Model	Dense Gas Model
F Stability Class and 1.0 m/s Wind Speed – Rural Terrain Region of Transport						
1A	Nitric Acid	7.4	320	4.7	<b>230</b>	*88
1B	Chlorine	740	42,000	450	<b>21,000</b>	*3,000
1C	Benzene	13	560	9.6	<b>430</b>	*130
1D	Ammonia	380	22,000	140	<b>*6,900</b>	760
F Stability Class and 1.0 m/s Wind Speed – Urban Terrain Region of Transport						
2A	Nitric Acid	7.4	27	4.7	*48	61
2B	Chlorine	740	3600	450	4,400	*1,500
2C	Benzene	13	48	9.6	90	*91
2D	Ammonia	380	1900	140	*1,400	670
* Dispersion model that ALOHA determined to be applicable.						
** ALOHA uses average sustained evaporation rates over a time period of 1 minute or more.						

The key insight to be gleaned from Table F-2 is that, for a co-located receptor at 100 meters, the neutrally-buoyant Gaussian model can be used to support a bounding reference value for a default  $\chi/Q$  value for chemicals that exhibit neutrally-buoyant and dense gas characteristics. For example, the ALOHA results in Case 1A (i.e., nitric acid) show a  $\chi$  of 230 mg/m<sup>3</sup> for the Gaussian model; in contrast to the 88 mg/m<sup>3</sup> for the dense gas model. The  $\chi$  of 230 mg/m<sup>3</sup> for the Gaussian model is bounding for both the dense gas model results for rural terrain, and also for the concentrations for both the Gaussian and dense gas model results for urban terrain (i.e., Case 2A). The Gaussian model results for rural terrain are bounding for the other three chemicals (i.e., chlorine, benzene, ammonia) in Table F-2. The ALOHA model indicates that the enhanced horizontal dispersion resulting from the dense gas itself on the ambient atmosphere is more than sufficient to overcome the reduced vertical dispersion associated with the dense gas response to gravity; therefore, the neutrally buoyant case is sufficiently bounding.

While the absolute  $\chi/Q$  values from ALOHA (which does not include building wake) exceed the default radiological calculation, they are consistent with other atmospheric dispersion models that also do not include effects from building wakes. If a building wake factor derived from a dispersion model is applied to the ALOHA absolute  $\chi/Q$  results, they become consistent with the default radiological  $\chi/Q$  value.

## F.7 Modeling Pool Evaporation

To provide a basis for determining reference  $\chi/Q$  values, ALOHA calculations for five commonly used chemicals and release types typically analyzed in safety design applications for a pool evaporation release were performed under conditions listed in Table F-3.

**Table F-3: ALOHA Inputs for Ground-level Releases for a Receptor at 100 m**

Inputs or Assumptions	Candidate Inputs
<b>Chemical releases</b>	Nitric acid (70 weight %) Hydrochloric acid (38 weight %) Benzene; ammonia; chlorine
<b>Pool evaporation release conditions</b>	10 gallon unconfined (equivalent to ~4 m <sup>2</sup> at 1 cm unconfined pool depth*) 100 gallon unconfined (equivalent to ~40 m <sup>2</sup> at 1 cm unconfined pool depth*) 1,000 gallon confined (equivalent to ~400 m <sup>2</sup> at 1 cm unconfined pool depth*) 10,000 gallon unconfined (equivalent to ~4000 m <sup>2</sup> at 1 cm unconfined pool depth*)
<b>Meteorological conditions</b>	F atmospheric stability class and wind speed of 1.5 m/s (defined by EPA as the “worst case” 40 CFR Part 68 condition)
<b>Plume model applied</b>	Gaussian neutrally-buoyant for nitric acid, hydrochloric acid, benzene, and ammonia Dense gas negatively-buoyant for chlorine
<b>Aerodynamic building effects</b>	Open field for ALOHA cases (i.e., no building)
<b>Dry deposition effects</b>	No dry deposition effects
<b>Receptor distance</b>	100 m

\* The 1 cm unconfined pool depth assumption is based on 40 CFR Part 68 guidance.

The results for each chemical are reported in Table F-4. In this table,  $\chi$  is the concentration at 100 m and Q is the averaged sustained evaporative release rate averaged over one minute or more.

**Table F-4: ALOHA Analysis for a Range of Evaporative Releases of 70% Nitric Acid, 38% Hydrochloric Acid, Benzene, Ammonia, and Chlorine under Worst Case Meteorological Conditions\***

Chemical	Parameters	10 gal unconfined (1 cm depth)	100 gal unconfined (1 cm depth)	1,000 gal unconfined (1 cm depth)	10,000 gal unconfined (1 cm depth)
Nitric Acid (70%)	$\chi$ (mg/m <sup>3</sup> )	8.9E+0	6.6E+1	2.5E+2	1.2E+3
	Q (mg/s)	2.6E+2	2.3E+3	2.0E+4	1.8E+5
	$\chi/Q$ (s/m <sup>3</sup> )	<b>3.4E-2</b>	<b>2.9E-2</b>	<b>1.3E-2</b>	<b>6.9E-3</b>
Hydrochloric Acid (38%)	$\chi$ (mg/m <sup>3</sup> )	2.8E+2	2.2E+3	8.5E+3	4.3E+4
	Q (mg/s)	9.6E+3	8.6E+4	7.8E+5	7.1E+6
	$\chi/Q$ (s/m <sup>3</sup> )	<b>2.9E-2</b>	<b>2.5E-2</b>	<b>1.1E-2</b>	<b>6.1E-3</b>
Benzene	$\chi$ (mg/m <sup>3</sup> )	2.0E+2	1.6E+3	6.1E+3	3.0E+4
	Q (mg/s)	6.0E+3	5.4E+4	4.9E+5	4.4E+6
	$\chi/Q$ (s/m <sup>3</sup> )	<b>3.4E-2</b>	<b>2.9E-2</b>	<b>1.2E-2</b>	<b>6.9E-3</b>
Ammonia	$\chi$ (mg/m <sup>3</sup> )	2.4E+2	1.7E+3	6.5E+3	3.1E+4
	Q (mg/s)	7.9E+3	6.7E+4	5.8E+5	5.0E+6
	$\chi/Q$ (s/m <sup>3</sup> )	<b>3.0E-2</b>	<b>2.6E-2</b>	<b>1.1E-2</b>	<b>6.2E-3</b>
Chlorine	$\chi$ (mg/m <sup>3</sup> )	1.4E+4	1.2E+5	5.3E+5	2.9E+6
	Q (mg/s)	4.3E+5	4.3E+6	4.3E+7	4.3E+8
	$\chi/Q$ (s/m <sup>3</sup> )	<b>3.4E-2</b>	<b>2.9E-2</b>	<b>1.2E-2</b>	<b>6.8E-3</b>

Based on these analyses, the following conclusions were reached:

- For the 10-gallon unconfined spill cases, the  $\chi/Q$  values at 100 m under an F stability class and 1.5 m/s wind speed meteorological condition are within a narrow range of  $2.9 \times 10^{-2} - 3.4 \times 10^{-2}$  s/m<sup>3</sup>. Note that ALOHA does not model building wake effects, so for very small sources such as a 10- or 100-gallon spill, the results are more appropriately compared to results from other models that do not contain enhanced dispersion associated with the presence of a building; and
- For the 10,000-gallon unconfined spill cases, the  $\chi/Q$  values at 100 m under an F stability class and 1.5 m/s wind speed meteorological condition are within a narrow range of  $6.1 \times 10^{-3} - 6.9 \times 10^{-3}$  s/m<sup>3</sup>. The size of this spill results in an enhanced initial horizontal plume, but not the enhancement in the vertical plume associated with the presence of a small building.

Therefore, the ALOHA calculations for commonly used chemicals and release types typically analyzed in safety design applications for a pool evaporation release maximizes  $\chi/Q$  at  $3.4 \times 10^{-2}$  s/m<sup>3</sup>. This value represents a release unassociated with enhanced dispersion from a building.



Thus, as shown in Table F-1, the enhanced dispersion associated with the wake of a small building is approximately an order of magnitude higher than what would be expected if the aerodynamic effects from a building were included. Therefore, the ALOHA results from unconfined spills are consistent with the  $\chi/Q$  value specified in DOE-STD-1189-2008, given the same assumptions for radiological releases with respect to building wake effects.

## F.8 Conclusions

Using the ALOHA and EPIcode, each within its application domain, the following was demonstrated:

- The ALOHA  $\chi/Q$  values, considering the building wake effects, are consistent with the default radiological  $\chi/Q$  value specified in DOE-STD-1189-2008.
- The aerodynamic effect of buildings on the dispersion is approximately an order of magnitude, and is much larger than the dry deposition effect;
- The dispersion from negatively-buoyant (i.e., dense gas) releases under light wind stable meteorological conditions is greater than neutrally-buoyant releases; and
- The default  $\chi/Q$  value is not sensitive to release durations.

The results of these calculations show that the default  $\chi/Q$  value is applicable to chemical releases. However, the default  $\chi/Q$  value may not be conservative when the building is smaller<sup>3</sup> than 10 m x 36 m.

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<sup>3</sup> Note that due to differences in assumptions about the magnitude of the building wake, initial plume dimensions from a 10 m x 36 m building in more modern atmospheric dispersion codes is equivalent to the 10 m x 25 m building in CRAC2, as used in NUREG-1140.

## F.9 References

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