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Final Review of Safety Assessment Issues at Savannah River Site, August 2011

Report to Savannah River Nuclear Solutions (SRNS)

BA Napier
JP Rishel
NE Bixler

Reviewed By: JV Ramsdell Jr.

December 2011

Pacific Northwest
NATIONAL LABORATORY

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Acronyms and Abbreviations

CLM	Central Climatology tower
cm/s	centimeter per second
DCF	Dose Conversion Factor
DNFSB	Defense Nuclear Facility Safety Board
DOE	Department of Energy
EPA	Environmental Protection Agency
FGR	Federal Guidance Report
ICRP	International Commission on Radiological Protection
m	meter
MACCS2	MELCOR Accident Consequence Code System
min	minute
NRC	Nuclear Regulatory Commission
NWS	National Weather Service
PHA	preliminary hazard analysis
PG	Pasquill Gifford
PNNL	Pacific Northwest National Laboratory
RG	Regulatory Guide
s	second
SNL	Sandia National Laboratory
SRNS	Savannah River Nuclear Solutions
SRS	Savannah River Site
WSRC	Westinghouse Savannah River

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Introduction

At the request of Savannah River Nuclear Solutions (SRNS) management, a review team composed of experts in atmospheric transport modeling for environmental radiation dose assessment convened at the Savannah River Site (SRS) on August 29 – 30, 2011. Though the meeting was prompted initially by suspected issues related to the treatment of surface roughness inherent in the SRS meteorological dataset and its treatment in the MELCOR Accident Consequence Code System Version 2 (MACCS2), various topical areas were discussed that are relevant to performing safety assessments at SRS; this final report addresses these topical areas.

Invited participants on the review team were Bruce Napier and Jeremy Rishel, Pacific Northwest National Laboratory (PNNL), and Nathan Bixler, Sandia National Laboratory (SNL). Napier is an environmental health physicist and the developer of the GENII software package. Rishel is a meteorologist with experience in radiological safety assessments. Bixler is the principal investigator and custodian for the MACCS2 computer code.

Subsequent to the August meeting, the review team issued a preliminary report (Napier et al. 2011) which summarized discussion on several topical areas, including:

1. SRS Meteorological Data and its Use in MACCS2
2. Deposition Velocities for Particles
3. MACCS2 Dispersion Coefficients
4. Use of Low Surface Roughness in Open Areas
5. Adequacy of Meteorological Tower and Instrumentation
6. Displacement Height
7. Validity of MACCS2 Calculations at Close-in Distances

This final report expands upon some of these topics to address reviewer comments received since the issuance of the preliminary report. In addition, three new topics—“MACCS2 Surface Roughness Scaling Factor (ZSCALE)”, “MACCS2 Time Basis in Plume Meander (TIMBAS)”, and “Advantages of Newer Versions of MACCS2 (WinMACCS)”—are included to address further feedback received on the preliminary report. Where appropriate, the final report provides the review team’s recommendations for addressing issues noted within a given topical area.

1. SRS Meteorological Data and its Use in MACCS2

Meteorological conditions are monitored continuously from a network of nine towers at SRS (WSRC 2002, Hunter 2003). Eight, 61-m towers are located at A, C, D, F, H, K, L, and P Areas; these towers measure horizontal and vertical components of wind direction, wind speed, temperature, and dew point temperature. The eight towers are surrounded uniformly in all directions by a variety of deciduous and evergreen trees and provide meteorological measurements that are representative of the SRS site. The H-Area tower, located near the center of SRS, is the primary tower used for safety assessments. Data from the other seven towers are used for substitution purposes to make a complete dataset. An additional tower, referred to as the Central Climatology (CLM) tower, is located within a clearing in N-Area and measures wind direction and speed, temperature, and dew point temperature at four levels (2, 18, 36, and 61 m, respectively). Observations at all towers are made at 1-s intervals and averaged over a 15-min period to developed estimates of both averages and standard deviations. The meteorological observations serve a diverse set of customers, including as data input for performing safety assessments.

SRS uses the MACCS2 code to estimate dose in safety assessments. As part of its input, MACCS2 requires a specially processed meteorological data file that contains hourly estimates of wind direction, wind speed, stability class, precipitation, and seasonal estimates of mixing height (Chanin and Young 1998). Hunter (2003) describes the development of the five-year (1997-2001) meteorological dataset currently used in MACCS2 safety assessments at SRS.

As noted above, the MACCS2 meteorological data file contains hourly estimates of stability class. MACCS2 utilizes a stability classification scheme, called the Pasquill-Gifford (PG) stability classes, which is used widely in Gaussian-type plume dispersion models to estimate the amount of lateral (σ_y) and vertical (σ_z) plume diffusion as a function of downwind distance (Pasquill 1961, Gifford 1961). Stability classes are defined using discrete letter designations A through F—stability class A represents the most unstable (most diffusive, largest σ_y and σ_z) atmospheric conditions whereas stability class F represents the most stable (least diffusive, smallest σ_y and σ_z) atmospheric conditions. Although not part of the original PG stability class definitions, an additional stability class, "G", is sometimes defined for extremely stable conditions (e.g., see Turner 1994). Parameterization methods for the σ_y and σ_z diffusion coefficients are discussed further in topical area 3, "MACCS2 Dispersion Coefficients."

The SRS site uses a DOE-approved method for estimating PG stability class for MACCS2 based on the draft NRC Regulatory Guide (RG) 1.23 (NRC 1980). This technique is a turbulence-based method that relates the standard deviation of the horizontal wind direction (sigma-theta, σ_A) to corresponding PG stability classes (see Table 3, NRC 1980). The draft RG includes PG stability classes A through F and also recognizes stability class G for extremely stable, low wind speed conditions (NRC 1980). However, MACCS2 only recognizes stability classes A through F; the model automatically converts instances of G to F stability class (Chanin and Young 1998).

The SRS meteorological data for the period 1997-2001 was processed in a manner consistent with the draft NRC RG (WSRC 2002, Hunter 2003). The review team notes, however, that although Section C.1 of the draft RG does mention several methods can be used to determine PG stability class, the draft RG cautions "*…use of and classification by alternative estimators other than temperature difference with height should be justified and may also require modification of the models in Regulatory Guide 1.111 and Regulatory Guide 1.145 with appropriate justification.*" The draft RG does not provide guidance on what justifications or modifications may be necessary if the alternative methods, including σ_A, were to be used to determine PG stability class.

The Environmental Protection Agency (EPA) has published guidance (EPA 2000) on standard methods used for estimating PG stability class from a variety of meteorological observations and measurements, including σ_A (e.g., see EPA 2000, Section 6.4.4). With the exception of not recognizing stability class G, the EPA (see Table 6-9a, EPA 2000) defines an initial estimate of

PG stability class using identical σ_A ranges to the values defined in the NRC draft RG 1.23 (see Table 3, NRC 1980). However, the EPA guidance includes further consideration of (a) adjustments to the σ_A ranges for measurement height, (b) adjustments to the σ_A ranges for surface roughness, and (c) a final adjustment to the PG stability class based on wind speed and time-of-day (i.e., daytime/nighttime). In short, these adjustments are used to normalize estimates of PG stability class by removing the effects of measurement height, mechanical turbulence created by site-specific surface roughness elements, and low-frequency meander under stable atmospheric conditions (Irwin 1980). Estimates of PG stability class using the σ_A method, with these adjustments, generally should yield estimates of PG stability class that are most comparable to other standard methods (e.g., Turner's [1994] method using routine observations from the National Weather Service (NWS), the NRC's [2007] delta-T/delta-Z method, etc.).

As is described in the "Summary of Data and Steps for Processing the SRS 1997-2001 Meteorological Database" (WSRC 2002), the SRS meteorological data for the period 1997-2001 do not include the additional EPA adjustments. As a consequence, measurement height, surface roughness, and meander effects are inherent in the SRS estimates of PG stability class (i.e., they have not been removed). The rationale for not including the adjustments is provided in the WSRC report: "*...the [SRS] bivanes are highly sensitive and are felt to measure quite accurately the σ_A needed in the basic atmospheric diffusion equations*" (WSRC 2002). The WSRC report further notes that the "*Pasquill stability classes derived directly from these measurements should more nearly reflect the true diffusive capability of the atmosphere*" (WSRC 2002).

Although the review team understands this line of reasoning (i.e., σ_A, as an explicit measure of turbulence, is directly proportional to lateral diffusion), Gaussian-type plume models commonly used in safety analysis, such as MACCS2, do not use direct turbulence measurements to estimate diffusion. As already noted, these models use the PG stability classification scheme to estimate lateral and vertical diffusion. These models generally include alternative methods to capture enhanced plume spread acting independently in a single direction, such as vertically for mechanical turbulence caused by surface roughness and horizontally for plume meander. Therefore, to ensure consistency with DOE safety-basis modeling protocols, which encourage application of these alternative methods, we recommend these diffusive effects not be credited in the estimates of the PG stability class.

The review team concludes that the overall impact of surface roughness and meander reflected in the SRS 1997-2001 σ_A data is a shift in the estimates of PG stability class towards more unstable conditions. To support this conclusion, the review team compared a histogram of PG stability class for the year 1999 at SRS to the nearby Vogtle Nuclear Station (Figure 1). Vogtle estimates of PG stability class are made using measurements of temperature difference with height (i.e., delta-T/delta-Z; NRC 2008) from a tower that is located in a predominately cleared, open area. Both datasets use an NRC methodology for estimating stability class (Vogtle - NRC 2007; SRS - NRC 1980), and therefore also include the extremely stable class "G".

The comparison of the methods is illustrative of the presence of surface roughness and meander in the SRS estimate of PG stability classes. As Figure 1 clearly shows, there are many more unstable cases (PG stability classes A, B, C) in the SRS dataset than in the Vogtle dataset; there are comparatively very few extremely stable cases (PG stability classes F and G) in the SRS dataset. With the Vogtle PG stability class data, the 95th percentile result for dose is likely to correspond to either an F or G stability; with the SRS PG stability class data, the 95th percentile result for dose is likely to correspond to E stability. The review team estimates that this corresponds to a one- to two-stability-class shift in the SRS σ_A estimate of PG stability class relative to the Vogtle delta-T/delta-Z estimate.

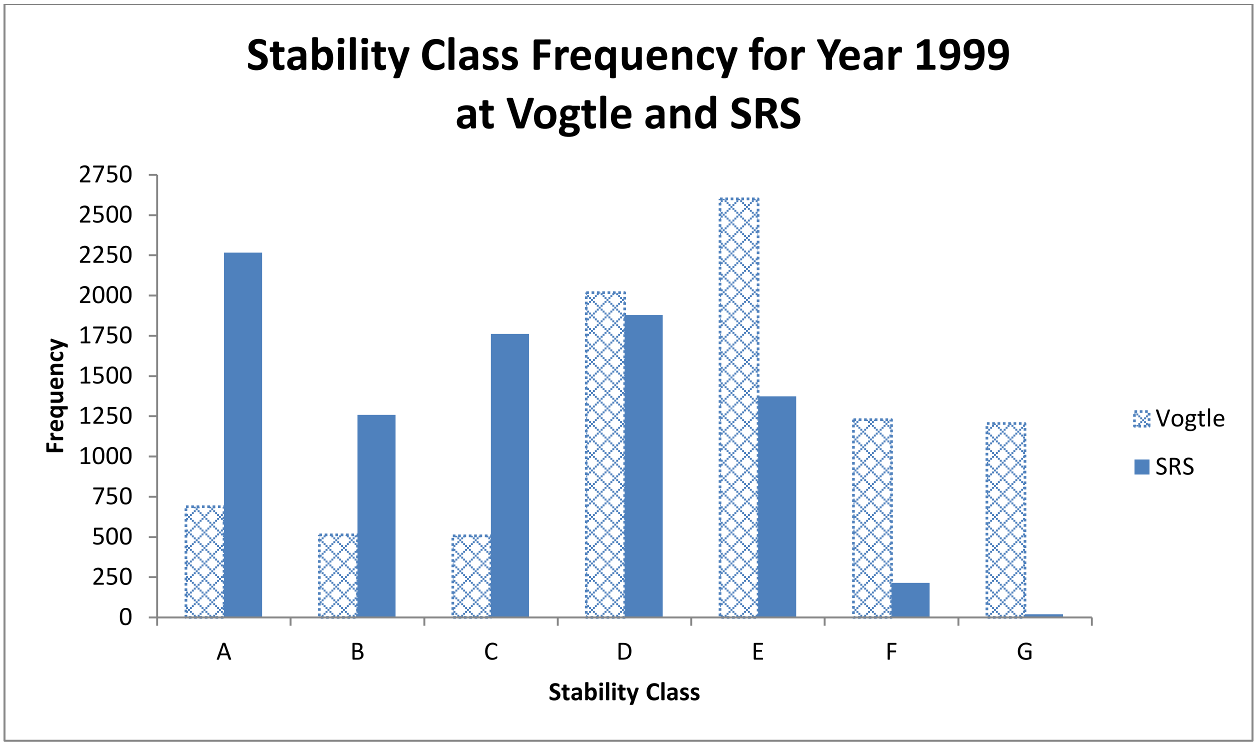


Figure 1: Histogram of Stability Class for Year 1999 at Vogtle (Using the NRC Temperature Difference with Height Method) and SRS (Using the NRC Draft RG 1.23 Sigma-Theta Method).

The review team notes that because of the shift towards more unstable PG stability classes that is inherent in the 1997-2001 SRS dataset, use of this data in MACCS2 will automatically result in larger lateral and vertical plume diffusion. Therefore, the review team's short-term recommendation is to not credit surface roughness or plume meander in MACCS2. The credit for surface roughness can be removed by setting the vertical scaling factor for σ_z (ZSCALE) to 1.0; see topical area 8, "MACCS2 Surface Roughness Scaling Factor (ZSCALE)" for more information on the ZSCALE correction factor. The credit for plume meander can be removed by setting the averaging time basis associated with the σ_y parameterization (TIMBAS) to the plume release duration (PLUDUR); see topical area 9, "MACCS2 Time Basis in Plume Meander (TIMBAS)" for more information on the treatment of plume meander in MACCS2.

As a result of these short-term recommendations, doses will go up by at least a factor of 2.02 at short distances when deposition and meander are negligible. The factor of 2.02 in predicted doses does not generalize to situations where the plume becomes well mixed within the mixing layer or where deposition significantly depletes the plume. The review team's long-term recommendation is for SRS to fully implement the EPA guidance (EPA 2000) by including the adjustments for measurement height, surface roughness, and wind speed/time-of-day if using the σ_A method or to estimate PG stability class using a different method; see topical area 5, "Adequacy of Meteorological Tower and Instrumentation," for more discussion. If these adjustments are implemented, then surface roughness (ZSCALE) and plume meander (controlled through TIMBAS and PLUDUR) should be used in MACCS2 to account for these diffusive effects. The review team notes that the short-term recommendation is only meant to be a temporary "fix" until a new MACCS2 meteorological dataset is available implementing the long-term recommendation.

Finally, the review team notes that SRS wind speeds, which are measured at 61 m, are scaled down to a 10-m level for use in MACCS2 (see topical area 6, "Displacement Height," for more discussion on scaling). The scaling procedure is documented in the meteorological processing report that accompanies the 1997-2001 dataset (Hunter 2003); the wind speed scaling method implements, and is consistent with EPA guidance (EPA 2000). However, because the scaling is functionally dependent on PG stability class, the review team expects that estimates of scaled wind speeds will also change once the long-term recommendation of reprocessing the data is implemented. Review of the wind speed scaling relationship indicates that scaled wind speeds at the 10-m level will go down somewhat, and doses will therefore go up because predicted doses are inversely proportional to wind speed.

2. Deposition Velocities for Particles

Deposition velocities for particles are an input to MACCS2; the values represent the rate at which radioactive particulates are removed from a plume. Dispersion and dose calculations performed with MACCS2 over the past decade have used values of particulate deposition velocity that were recommended in Department of Energy (DOE) guidance (DOE 2004). Different deposition velocities have been specified for two classes of particulates—mitigated/filtered (0.1 cm/s) and unmitigated/unfiltered (1.0 cm/s). Recent Defense Nuclear Facility Safety Board (DNFSB) recommendations reduce both default deposition velocities by a factor of 10, with the option to use well-documented site-specific values (DOE 2011).

As is noted in Attachment 1 to the DOE interim guidance (DOE 2011), GENII is an acceptable code for calculating an unmitigated/unfiltered deposition velocity. However, for particulates that are characteristic of mitigated/filtered releases, GENII calculates a constant deposition velocity that does not match the theoretical minimum deposition velocity for that size range. Therefore, for unmitigated/unfiltered particulate releases, the review team recommends calculating a site-specific deposition velocity using the GENII Version 2.10 computer code (Napier et al. 2010), with surface roughness inputs of 3 cm, 30 cm, and 100 cm. For mitigated/ filtered particulate releases, the review team recommends using the new default deposition velocity of 0.01 cm/s, as specified in DOE's interim guidance (DOE 2011).

3. MACCS2 Dispersion Coefficients

The MACCS2 code allows for the use of different parameterizations of the lateral (σ_y) and vertical (σ_z) dispersion coefficients. Three dispersion parameterization schemes are included in the MACCS2 package, including Tadmor–Gur as presented in Dobbins (1979), as well as the two sets of Briggs curves for urban and open country terrain as presented in Hanna et al. (1982). Additional parameterizations can be added to MACCS through use of lookup tables or power-law functions (Chanin and Young 1998). Current practice at SRS has been to use the power-law parameterization of Tadmor and Gur. Recent inquiries by the DNFSB have suggested that the lookup table parameterization of Briggs open country might be a better choice.

The review team performed a preliminary comparison of the Tadmor-Gur and Briggs open country parameterizations in the distances of interest at the SRS site (100 m to about 11 km). The comparison revealed that the methods are similar, except at distance less than 500 m. Further review of the Tadmor-Gur parameterization reveals that the values are not appropriate for downwind distances less than 500 m. Indeed, as Figure 2 shows, estimates of normalized concentration begin to intersect at distances less than 500 m, which is a result of the Tadmor-Gur parameterization of σ_z for stability classes A and B. Therefore, the review team concludes that both methods are comparable in the range of 500 m to 11 km, and the Tadmor-Gur parameterization should not be used for downwind distances less than 500 m.

The review team also compared the Briggs open country parameterization with other commonly used PG parameterizations in the GENII model (Napier et al. 2010); the comparison is presented in Appendix A. Additional parameterizations available in the GENII code include Eimutis and Konicek (1972), as well as the rural parameterization used in the EPA's Industrial Source Complex (ISC3) model (EPA 1995). The Eimutis and Konicek dispersion parameterizations have been used in past NRC dispersion models, including XOQDOQ (Sagendorf et al. 1982) and PAVAN (Bander 1982). The Appendix A comparison reveals that the various parameterizations, excluding Tadmor-Gur at less than 500 m, are essentially indistinguishable in the distances of interest at the SRS site (100 m to about 11 km). However, the Briggs parameterization does begin to diverge from the other PG parameterizations at distances beyond about 10 km.

As is discussed in Appendix A, Briggs used additional data, along with statistical theory of diffusion, in formulating the parameterizations at longer distances. Briggs also developed separate parameterizations for urban and open country areas. Therefore, in discussions of Briggs, it has been stated that Briggs' parameterizations are 'independent' of surface roughness (Hanna et al. 1982). The review team understands this logic but recognizes the resulting ambiguities in specific applications because the Briggs open country parameterizations are essentially the same as the other PG parameterizations at distances less than 10 km (see Appendix A). The review team notes that the PG parameterizations were developed for grassland sites with a surface roughness of around 3 cm.

As a consequence, there is some question as to whether it is appropriate to credit surface roughness with the vertical scaling factor (ZSCALE) in MACCS2 when using the Briggs open country parameterization (e.g., see DOE 2004, Page A-19). The review team notes that because the Briggs formulations are comparable to other PG parameterizations at distances less than 10 km—and the results are indistinquishable—it is appropriate to apply the ZSCALE factor at distances less than 10 km when using the Briggs open country parameterization. Topical area 8, "MACCS2 Surface Roughness Scaling Factor (ZSCALE)" discusses application of the ZSCALE factor in more detail.

The review team considers the various parameterizations presented in Appendix A to be equally appropriate for use in the distances of interest (100 m to 11 km) at the SRS site. Furthermore, any of the parameterizations would allow for crediting of the site-specific surface roughness in MACCS2 through the ZSCALE scaling factor, once the SRS meteorological data has been reprocessed to include all of the EPA adjustments (see topical area 1, “SRS Meteorological Data and its Use in MACCS2).

Appendix B provides σ_y and σ_z lookup tables for the Eimutis and Konicek (1972) parameterization for use in MACCS2. However, the review team cautions the use of any lookup tables for receptors beyond roughly 2 km, as this can lead to potential errors in the MACCS2 calculations. DOE Safety Advisory 2009-05, which describes the lookup table issue and approaches for avoiding the error, has been found by the review team to be insufficient at addressing the problem (DOE 2009). The review team notes that the use of extremely long distances in the lookup tables is insufficient if, when going from an unstable to a stable condition, the sigma for the unstable condition is larger than the largest sigma for the stable condition. This issue can potentially occur when using any lookup table, including Briggs. Later versions of MACCS2 (version 2.6) have corrected this error and the review team recommends that the DOE toolbox be updated to this version. In the meantime, use of the power-law approach avoids this potential error. Therefore, the review team recommends the use of the Tadmor-Gur power-law for distances greater than 500 m. For distances less than 500 m, use of the PG (e.g., Eimutis and Konicek, Appendix B) or Briggs open country lookup tables is justified. In addition, the DOE Standard 1189, Appendix A, Section A.2 (DOE 2008) value of 3.5E-3 s/m^3 is also appropriate to use at 100 m (see topical area 7, “Validity of MACCS2 Calculations at Close-in Distances”).

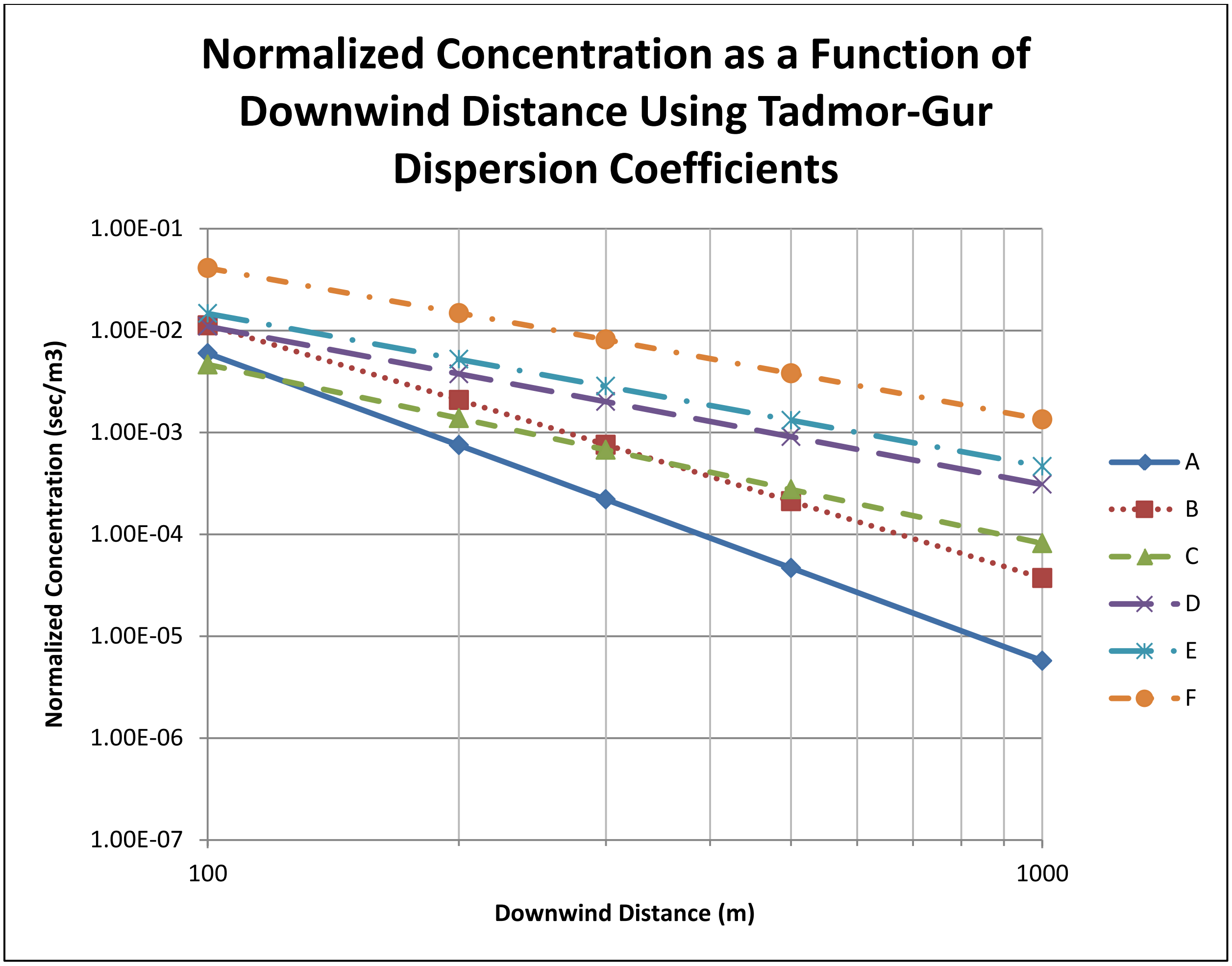


Figure 2: Normalized Concentration as a Function of Downwind Distance Using Tadmor-Gur Dispersion Coefficients for PG Stability Classes A-F.

4. Use of a Low Surface Roughness in Open Areas

DOE guidance directs the use of a standardized methodology when performing dispersion modeling for preliminary hazard analyses (PHA) (DOE 2006). The PHA provides a basis for determining the design pedigree of initially-selected safety systems, structures, and components. One analysis parameter, related to several topical areas discussed in this report, is surface roughness length, which DOE guidance indicates should be set to 3 cm when estimating doses to the public located at the site boundary and co-located workers located at 100 meters; a 3 cm surface roughness length is characteristic of an open, grassland area.

As noted in the DOE guidance, "*as the hazard analysis matures during the design process, these values may be refined based on local site characteristics*" (DOE 2006). The SRS site is predominately forested; the site-specific surface roughness justified for use to assess offsite doses is estimated to be 100 cm (SRNS 2010). SRS currently uses the default value of 3 cm for the co-located worker. The assumption behind this application is that co-located workers will be in open areas around nearby facilities. However, open areas around facilities of interest are generally small compared to surrounding areas of forest. Mechanical turbulence generated by upwind roughness elements (i.e., trees) is likely to persist well downwind into any open areas. Furthermore, most open areas include man-made obstacles and obstructions (e.g., buildings). Therefore, consistent with DOE guidance (2006), the review team recommends that SRS refine the surface roughness estimate applicable to the co-located receptor at 100 meters to reflect site-appropriate values for use in co-located worker dose calculations. Based on SRS site characteristics, it is the review team's expectation that this value is significantly greater than 3 cm.

It should be noted that the importance of surface roughness on predicted doses to co-located workers is significantly reduced when the source is treated as an area source rather than as a point source; this is discussed further in topical area 7, "Validity of MACCS2 Calculations at Close-in Distances".

5. Adequacy of Meteorological Tower and Instrumentation

There are nine meteorological monitoring locations at SRS, consisting of towers in A, C, D, F, H, K, L, N, and P Areas (Hunter 2003). Data recorded at the H-Area tower was used to develop the 1997-2001 MACCS2 meteorological files (WSRC 2002, Hunter 2003). The review team visited the C-Area meteorological tower to examine the site as well as the meteorological instrumentation. The C-Area tower is representative of all of the towers at SRS, except the N-Area tower. The C-Area tower is instrumented at the 61-m level with wind and temperature sensors; it is surrounded uniformly in all directions by a variety of deciduous and evergreen trees. The N-Area tower, called CLM, is a multi-level instrumented climate tower that is located in an open area that is used for generating climate statistics for the site.

Although the review team did not perform a complete review or evaluation of the SRS meteorological monitoring program, the towers appear to be measuring meteorological data that are representative of the SRS site. In addition, the towers are well positioned and routinely maintained for the purposes of reliably measuring meteorological data for use in a safety analysis. The review team believes the standard deviation of the horizontal wind direction (sigma-theta, σ_A), which is currently used at SRS to estimate PG stability class in MACCS2, is an acceptable method if all of the EPA adjustments (see topical area 1, "SRS Meteorological Data and its Use in MACCS2") are applied to the data.

Nevertheless, the review team recommends that SRS explore other methods for estimating PG stability class and compare the results to arrive at a preferred method. The review team notes that there are two additional methods, the standard deviation in the elevation angle (sigma-elevation σ_E, EPA 2000) and the temperature difference with height (delta-T/delta-Z, NRC 2007), that could be implemented using observations already being made at SRS.

The σ_E method (see EPA 2000, Section 6.4.4) is a turbulence-based technique that relates the standard deviation of the vertical wind direction to corresponding PG stability classes. The review team notes that this method is generally preferred to the σ_A method (e.g., see Irwin 1980), as it is not susceptible to horizontal meander which can occur during low wind speed, stable atmospheric conditions. As with σ_A, σ_E is measured at all SRS area towers, which allows for data substitution in the event of instrumentation failure or data loss at the H-Area tower.

The delta-T/delta-Z method (NRC 2007) is straightforward to implement; the method relates temperature difference with height from two measurement levels to corresponding PG stability classes. Since the method is based on temperature measurements typically collected over a cleared, relatively smooth surface, it does not capture the effects of surface roughness. Furthermore, it is not affected by meander. The CLM tower in N-Area is the only tower at SRS that is appropriately instrumented to implement this method. Therefore, direct data substitution is not possible in the event of instrumentation failure or data loss. Instead, data from nearby Vogtle Nuclear Station (which implements this method) or an alternate PG method could be used for data filling purposes.

6. Displacement Height

Straight-line Gaussian dispersion models, such as MACCS2, require a single point-estimate of wind speed at the plume release height for calculating transport and dilution. The wind speed estimate is assumed to apply to the entire model domain. Because wind speed is generally not measured at the plume release height, the value must be interpolated or extrapolated.

Hunter (2003) describes a well-known power-law function for adjusting the SRS measured 61-m wind speed to 10 m for use in MACCS2; this formulation follows EPA guidance for profiling wind speed in “non-complex terrain” (e.g., see EPA 2000, Section 6.2.5). The review team notes that the methodology conservatively uses the ground, rather than the displacement height created by the forest canopy, as the reference point for performing the adjustment. The displacement height is the height above the ground at which zero wind speed is achieved as a result of flow over obstacles, such as trees. In effect, the forest canopy shifts the wind profile upwards by the displacement height distance. Garratt (1992) provides a simple relation for estimating the displacement height:

$$d = 0.75 * h,$$

where “d” is the displacement height and “h” is the mean height above ground level of the vegetated surface. Garratt (1992) notes that the above relationship is particularly representative of crop and forested surfaces. Assuming a 30-m high forest canopy at SRS, the displacement height is estimated to be around 22.5 m.

Consideration of the displacement height in adjusting the wind speed would have the effect of slightly increasing the estimated release height wind speed, because the distance from the measurement point to the assumed 10-m release point will be less. This modification to the meteorological data processing is expected to partially offset the decrease in estimated 10-m wind speed that will result when stability classes are corrected according to the EPA guidance, as described in topical area 1, “SRS Meteorological Data and its Use in MACCS2”.

For consistency, the review team also recommends subtracting the displacement height from the 61-m measurement height when performing the EPA (2000) height adjustments to the ranges of the horizontal (σ_A) or vertical (σ_E) standard deviation of the wind direction when estimating PG stability class; the EPA (2000) height adjustment is also discussed further in topical area 1.

7. Validity of MACCS2 Calculations at Close-in Distances

Several issues were noted by the review team with the current method for evaluating doses to co-located workers at close-in distances of 100 m. First, it is well recognized that Gaussian plume models are not capable of accurately representing doses at such close distances. For example, the MACCS2 User's Guide (Chanin and Young 1998) states on p. 5-4 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.*" However, to compensate for this shortcoming, MACCS2 allows the user to include the effects of a building wake by treating the source as an area source instead of a point source. While the building wake model in MACCS2 is highly approximate, it at least provides estimates at short distances that are more defensible than would be obtained by assuming a point source. However, DOE guidance (DOE 2004) currently prescribes that a point source be used even for doses to co-located workers, resulting in extraordinarily conservative predictions of dose. Using the MACCS2 area-source approximation for a building wake would allow for a more reasonable prediction of dose to a co-located worker. The review team recommends that DOE (2004) guidance be modified to recommend use of area sources rather than point sources, especially for estimation of doses to co-located workers. As a point of reference, the review team notes that DOE-STD-1189 (DOE 2008) co-located worker dose calculation credits a small building (10 m x 25 m).

Related to this issue is the appropriate value of the vertical diffusion scaling factor (ZSCALE) to use for estimating doses at short distances, as discussed above. When the source is treated as a point source, the predicted dose is inversely proportional to this scaling factor, and thus the scaling factor is an important parameter. Current DOE guidance (DOE 2006) is to use a 3-cm surface roughness when performing this calculation. However, if the source were treated as an area source, the value of ZSCALE would have a secondary effect on the predicted dose to a co-located worker. Instead, the predicted dose would be dominated by the height and width of the building because these would control the dimensions of the area source.

Lastly, as an alternative to using MACCS2 at close-in distances, DOE-STD-1189 provides a χ/Q value at 100 m of 3.5E-3 sec/m^3 for the dispersion calculation (DOE 2008); this value is based on inputs described in NUREG 1140 (NRC 1988), including no plume buoyancy, stability class F, 1.0 m/s wind speed, a small building size (10 m x 25 m), and 1 cm/s deposition velocity. Due to close proximity to the source, changes in deposition velocity (see topical area 2, "Deposition Velocities for Particles") should have a negligible effect on χ/Q at the 100 m distance.

8. MACCS2 Surface Roughness Scaling Factor (ZSCALE)

As noted in topical area 1, "SRS Meteorological Data and its Use in MACCS2," a linear scaling factor called ZSCALE can be used in MACCS2 to account for the effects of surface roughness on vertical plume diffusion. DOE guidance (DOE 2004) recommends that the scaling factor be quantified by the formula:

$$\mathrm{ZSCALE} = (z_o/3)^{0.2},$$

where z_o is the site-specific surface roughness in cm. In MACCS2, the vertical diffusion coefficient (σ_z) is multiplied by ZSCALE to account for mechanical turbulence generated by site-specific surface roughness elements.

The review team notes that the ZSCALE formulation above is comparable to the EPA adjustment for surface roughness when using the standard deviation in the horizontal (σ_A) or vertical (σ_E) wind direction to estimate PG stability class (EPA 2000), but a different divisor is used (3 [above] as opposed to 15 [EPA 2000]). The review team reconciles this difference by noting that the PG diffusion coefficients were developed for a site with a 3 cm surface roughness (Pasquill 1976), whereas the EPA adjustments to the σ_A or σ_E ranges were developed for a site with a 15 cm surface roughness (Irwin 1980). The divisors in the formulations should be different and no attempt should be made to make them consistent. Therefore, the basis for adjusting σ_z to account for a site-specific surface roughness, regardless of the method used to estimate PG stability class, is always 3 cm.

From the ZSCALE formulation above, it is clear that the scaling factor is used to increase (or decrease) σ_z in MACCS2 for sites with a surface roughness greater than (less than) 3 cm. A 3 cm surface roughness length is representative of open grassland, which is characteristic of the formulations of the original PG dispersion parameterizations (Pasquill 1976). The SRS site is predominately forested; the site-specific surface roughness is estimated to be around 100 cm (SRNS 2010), resulting in a ZSCALE factor of 2.02 in MACCS2.

The review team notes that use of the ZSCALE factor to increase σ_z to account for site-specific surface roughness is consistent with recommendations made by Pasquill (1976). However, Pasquill notes that this adjustment is dependent on downwind distance (i.e., it is not a constant) and it should only be made out to "a few kilometers", beyond which surface roughness effects are considered "tentative" (Pasquill 1976). Past investigators have developed formulations to account for the surface roughness downwind dependence (e.g., see Nieuwstadt and Engeldal, 1976). The review team prefers the above formulation because, as already noted, it is functionally consistent with the EPA surface roughness adjustments to the σ_A or σ_E methods for estimating PG stability class (EPA 2000). Hanna et al. (1977) and Irwin (1980) suggest that the exponent in the ZSCALE formulation ranges between 0.10 to 0.25, with the larger values being applicable to shorter distances and rougher surfaces. Therefore, we recommend adjusting the exponent in the ZSCALE formulation at select distances at the SRS site, as listed in Table 1, to account for the downwind dependence. Table 1 also provides the resulting distance-dependent ZSCALE factors for three surface roughness lengths: 3 cm, 30 cm, and 100 cm. The ZSCALE values for 100 cm roughness length are appropriate for the SRS site.

Table 1: Recommended ZSCALE Formula Exponents and Resulting ZSCALE Factors for Three Surface Roughness Lengths as a Function of Downwind Distance.

Downwind Distance X (km)	**$0.0 < X \leq 5.0$**	**$X > 5.0$**
ZSCALE Formula Exponent	0.2	0.1
ZSCALE (z_o = 3 cm)	1.00	1.00
ZSCALE (z_o = 30 cm)	1.58	1.26
ZSCALE (z_o = 100 cm)	2.02	1.42

9. MACCS2 Time Basis in Plume Meander (TIMBAS)

As described in the MACCS2 User's Guide (Chanin and Young 1998), MACCS2 includes an expansion factor (called EXPFAC) to account for the effect of plume meander, which widens the plume in the cross-wind direction during downwind transport. Plume meander, which results from the slow, back-and-forth oscillation of the mean horizontal wind direction, can occur during stable, low wind speed conditions. As noted by the NRC (1983), meander has been shown to substantially lower plume concentrations than would otherwise be predicted using traditional Pasquill-Gifford (PG) dispersion parameterizations. Therefore, Gaussian-type dispersion models will often include a method for crediting plume meander. The general formulation used in MACCS2 to account for plume meander is given by:

$$\text{EXPFAC} = [\text{MAX(plume segment release duration, TIMBAS) / TIMBAS}]^{\text{XPFAC}},$$

where TIMBAS is the time basis (i.e., averaging time) associated with the horizontal diffusion coefficient (σ_y) and XPFAC is an exponential factor that controls the size of the expansion (Chanin and Young 1998). The MACCS2 expansion factor acts as a linear factor on σ_y during the calculation of χ/Q, but it does not affect the growth of σ_y. The review team notes that since the MACCS2 expansion factor is applied equally to all PG stability classes, and plume meander occurs generally under stable, low wind speed cases, the MACCS expansion factor more technically corrects for plume averaging time. Topical area 10, "Advantages of Newer Versions of MACCS2 (WinMACCS)", describes a stability-based plume meander model that is more consistent with the NRC plume meander model (NRC 1983).

DOE guidance (2004) specifies a time basis (i.e., TIMBAS) of 180 s to use in the MACCS2 plume meander expansion factor calculation. The MACCS2 User's Guide (Chanin and Young 1998), however, provides an example value of 600 s. Pasquill (1976) notes that the sampling time basis for σ_y was 3 min (180 s). Turner (1994) confirms the sampling time for PG σ_y to be 180 s. Therefore, the review team concurs with DOE guidance (2004)—the correct value to use for TIMBAS when using PG dispersion parameterizations for σ_y is 180 s.

10. Advantages of Newer Versions of MACCS2 (WinMACCS)

Newer versions of MACCS2 (versions 2.4 and 2.5 have been released and version 2.6 is in the offing) are available than the one in the Department of Energy (DOE) Toolbox, which is version 1.13.1. In addition, a graphical user interface (GUI), called WinMACCS, has been developed to aid in the entry of input to the MACCS2 model. The newer versions have a number of advantages over the Toolbox version, including a number of bug fixes and new features. As noted in topical area 3, "MACCS2 Dispersion Coefficients", version 2.6 corrects an error that can occur when using lookup tables for dispersion parameterizations. Furthermore, the newer versions have gone through a software quality assurance process that exceeds the one used to develop version 1.13.1. The newer versions have been released to a large number of nuclear power corporations, to consultants supporting the Nuclear Regulatory Commission (NRC) and DOE, and to most of the DOE laboratories and defense facilities. The newer versions have been used in NRC-related analyses. However, at present, newer versions of MACCS2 are not used for DOE-related analyses because the newer versions are not in the DOE Toolbox.

While a large number of features have been added in newer versions, the ones of potential interest for safety basis applications, where the primary results of interest are site boundary doses, are the following:

1. A new plume meander model based on NRC Regulatory Guide (RG) 1.145 (NRC 1983)
2. An improved plume rise model
3. A new dose conversion factor (DCF) file based on Federal Guidance Report publication 13 (FGR-13), which is consistent with the International Commission on Radiological Protection publication 72 (ICRP-72) for most radionuclides.

These three improvements are discussed briefly in the subsequent paragraphs. Because of the improvements and bug fixes in the newer versions of MACCS2, the review team recommends that the DOE replace the older version of MACCS2 in its Toolbox with version 2.6.

Plume Meander

The original plume meander model in MACCS2 only accounts for the effect of the plume release duration; see topical area 9, "MACCS2 Time Basis in Plume Meander (TIMBAS)" for more discussion of this model. The new plume meander model is based on NRC RG 1.145 (NRC 1983) and recognizes that plume meander is dependent on stability class and wind speed. As shown in Figure 3, this meander model would assign a meander factor as large as 4 to the 95th percentile result, depending on the wind speed. However, the credit for meander diminishes beyond 800 m downwind and approaches unity at longer distances, e.g., 10 km. The meander model is formulated for a one-hour release.

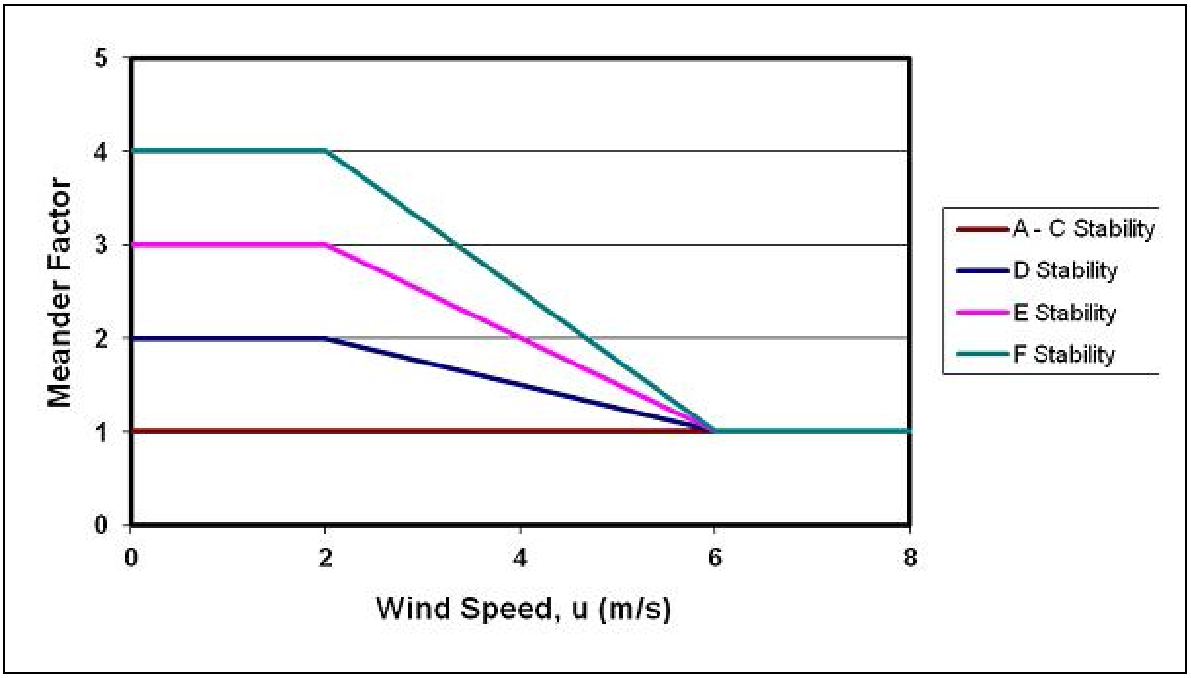


Figure 3: Meander Factors Defined in NRC RG 1.145 (NRC 1983) for Weather Conditions Characterized by Stability Class and Mean Wind Speed.

Plume Rise Model

The improved plume rise model is more accurate and also more conservative than the original model in MACCS2 in the sense that the plume is lofted to a lesser extent under stability classes A through C when the plume is buoyant enough to rise into the atmosphere; this generally would result in higher downwind concentrations and could therefore impact some safety basis calculations that use the plume rise model.

Dose Conversion Factors

The new dose conversion factor file that is available with the newer versions of MACCS2 is incompatible with version 1.13.1 because it has extended features that are not supported by that code version. The newer data in FGR-13 are currently recommended for DOE applications. Adopting a newer version of MACCS2 would alleviate the need for each DOE site to manually modify older DCF files.

Appendix A – Comparison of Various Dispersion Coefficients

The spread of effluents in plumes and puffs is described by dispersion coefficients. In Gaussian models, these coefficients are standard deviations of the concentration distributions. Theoretically, the coefficients are related to atmospheric turbulence and the time since release. In practice many schemes are used to estimate dispersion coefficients. Historically, most of the schemes have been based on Pasquill-Gifford (PG) atmospheric stability classes and distance from the source.

Standard Approximations

Several parameterizations utilize estimates of the PG stability class to approximate atmospheric dispersion. Briggs (1973) developed two sets of dispersion parameters—"urban" and "open country"—to account for inherent differences in dispersion between these two environments. As the name suggests, the Briggs urban parameterization is appropriate for urban environments and includes the influence of increased mechanical turbulence from air flow through building canopies as well as buoyant turbulence during the evening/nighttime hours from the release of stored heat in structures and pavement. The Briggs open country parameterization is appropriate for more rural environments, like SRS, and is based on the combined results of several diffusion experiments (Pasquill [1961], Brookhaven National Laboratory [Smith 1961], and the Tennessee Valley Authority [Carpenter et al. 1971]). The Briggs parameterizations are discussed by several authors, including Gifford (1976) and Hanna et al. (1982). Table A-1 lists the Briggs open country dispersion parameterization as a function of PG stability class.

Table A-1. Briggs Open Country Dispersion Parameters (where x is in meters)

PG Stability Class	**σ_y (m)**	**σ_z (m)**
A	$0.22x(1 + 0.0001x)^{-½}$	$0.20x$
B	$0.16x(1 + 0.0001x)^{-½}$	$0.12x$
C	$0.11x(1 + 0.0001x)^{-½}$	$0.08x(1 + 0.0002x)^{-½}$
D	$0.08x(1 + 0.0001x)^{-½}$	$0.06x(1 + 0.0015x)^{-½}$
E	$0.06x(1 + 0.0001x)^{-½}$	$0.03x(1 + 0.0003x)^{-1}$
F	$0.04x(1 + 0.0001x)^{-½}$	$0.016x(1 + 0.0003x)^{-1}$

The Environmental Protection Agency's (EPA's) Industrial Source Complex (ISC3) model (EPA 1995) rural mode option implements a parameterization that approximately fits the original PG dispersion curves (Turner, 1970). The equation used to calculate the horizontal dispersion coefficient is (with the downwind distance in kilometers):

$$\sigma_y = 465.11628(x)\tan(TH) \tag{A.1}$$

where

$$TH = 0.017453293[c - d\ln(x)] \tag{A.2}$$

The coefficients c and d are dependent upon PG stability class and are given in Table A-2. The vertical dispersion coefficient is calculated using:

$$\sigma_z = a\, x^b \qquad \text{(A.3)}$$

where the coefficients a and b depend upon downwind distance, x (in kilometers), and PG stability class. The coefficients a and b are given in Table A-3.

Table A-2. Coefficients for Pasquill-Gifford (ISC3) Horizontal Dispersion Parameterization

PG Stability Class	Coefficient c	Coefficient d
A	24.1670	2.5334
B	18.3330	1.8096
C	12.5000	1.0857
D	8.3330	0.72382
E	6.2500	0.54287
F	4.1667	0.36191

Table A-3. Coefficients for Pasquill-Gifford (ISC3) Vertical Dispersion Parameterization

PG Stability Class	x (km)	Coefficient a	Coefficient b
A*	< 0.10	122.800	0.94470
	0.10 - 0.15	158.080	1.05420
	0.16 - 0.20	170.220	1.09320
	0.21 - 0.25	179.520	1.12620
	0.26 - 0.30	217.410	1.26440
	0.31 - 0.40	258.890	1.40940
	0.41 - 0.50	346.750	1.72830
	0.50 - 3.11	453.850	2.11660
	>3.11	**	**
B*	<0.20	90.673	0.93198
	0.21 - 0.40	98.483	0.98332
	> 0.40	109.300	1.09710
C*	ALL	61.141	0.91465
D	<0.30	34.459	0.86974
	0.31 - 1.00	32.093	0.81066
	1.01 - 3.00	32.093	0.64403
	3.01 - 10.00	33.504	0.60486
	10.01 - 30.00	36.650	0.56589
	> 30.00	44.053	0.51179
E	< 0.10	24.260	0.83660
	0.10 - 0.30	23.331	0.81956
	0.31 - 1.00	21.628	0.75660

PG Stability Class	**x (km)**	**Coefficient a**	**Coefficient b**
	1.01 - 2.00	21.628	0.63077
	2.01 - 4.00	22.534	0.57154
	4.01 - 10.00	24.703	0.50527
	10.01 - 20.00	26.970	0.46713
	20.01 - 40.00	35.420	0.37615
	> 40.00	47.618	0.29592
F	< 0.20	15.209	0.81558
	0.21 - 0.70	14.457	0.78407
F Continued	0.71 - 1.00	13.953	0.68465
	1.01 - 2.00	13.953	0.63227
	2.01 - 3.00	14.823	0.54503
	3.01 - 7.00	16.187	0.46490
	7.01 - 15.00	17.836	0.41507
	15.01 - 30.00	22.651	0.32681
	30.01 - 60.00	27.074	0.27436
	> 60.00	34.219	0.21716

* If the calculated value of σ_z exceeds 5000 m, then σ_z is set to 5000 m

** σ_z is equal to 5000 m

The dispersion parameterization typically used by the Nuclear Regulatory Commission (NRC) is attributed to Eimutis and Konicek (1972); the parameterization has been used in past NRC dispersion models (MESODIF-II [Powell et al. 1979], XOQDOQ [Sagendorf et al. 1982], PAVAN [Bander 1982], and MESORAD [Ramsdell and Athey. 1981]). The basic equation is

$$\sigma_j = A_j x^{B_j} + C_j \tag{A.4}$$

for j = y, $B_y = 0.9031$ and $C_y = 0$. The other constants are given in Table A-4.

Table A-4. Constants for the PG (NRC) Dispersion Parameterization

		PG Stability Class						
	Distance	**A**	**B**	**C**	**D**	**E**	**F**	**G**
A_y	All	0.3658	0.2751	0.2089	0.1471	0.1046	0.0722	0.0481
A_z	< 100m	0.192	0.156	0.116	0.079	0.063	0.053	0.032
	100 to 1000m	0.00066	0.0382	0.113	0.222	0.211	0.086	0.052
	> 1000m	0.00024	0.055	0.113	1.26	6.73	18.05	10.83
B_z	< 100m	0.936	0.922	0.905	0.881	0.871	0.814	0.814
	100 to 1000m	1.941	1.149	0.911	0.725	0.678	0.74	0.74
	> 1000m	2.094	1.098	0.911	0.516	0.305	0.18	0.18
C_z	< 100m	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	100 to 1000m	9.27	3.3	0.0	-1.7	-1.3	-0.35	-0.21
	> 1000m	-9.6	2.0	0.0	-13.	-34.	-48.6	-29.2

The above parameterizations of the horizontal (σ_y) and vertical (σ_z) dispersion coefficients are plotted in Figures A-1 and A-2, respectively, for the Briggs open country, NRC, and EPA approaches. The three dispersion parameterizations can be compared by calculating the relative concentration (χ/Q, units of sec/m^3) for a ground-level release using the Gaussian centerline plume formulation assuming no vertical plume reflection:

$$\chi/Q = 1/(\pi \sigma_y \sigma_z U) \qquad \text{(A.5)}$$

and an ambient wind speed (U) of 1 m/s. The results are illustrated in Figure A-3.

Discussion of the Briggs Open Country, NRC, and EPA Parameterizations

From Figure A-1, it is apparent that the Briggs open country, NRC, and EPA dispersion parameterizations result in approximately the same values for the horizontal dispersion coefficient, σ_y. The Briggs open country parameterization has slightly larger values for distances less than about 10 km for all stability classes (which would give slightly lower values of concentration), but only by a few percent. Beyond about 10 km, the reverse is true.

As illustrated in Figure A-2, the largest difference between the parameterizations is in the vertical dispersion coefficient, σ_z. Here, the parameterizations for the unstable PG stability classes A and B have quite different representations; those for class A differ significantly. Both the NRC and EPA parameterizations predict significantly more dispersion than the Briggs open country method.

From the simple Gaussian plume formulation given by equation A.5, it is clear that the product of the horizontal and vertical dispersion coefficients is important. As shown in Figure A-3, within the distance range of most interest to SRS (i.e., less than about 12 km), all three parameterizations give essentially the same result, with the exception of the highly unstable PG stability class A. Use of the parameterizations in an actual dispersion model (e.g. MACCS2), however, would result in more comparable results than this simple example indicates, because the model would limit vertical plume dispersion to the depth of the boundary layer, which would tend to increase the concentrations shown for class A at longer distances. Furthermore, the more restrictive dispersion conditions (i.e., PG stability classes D, E, and F) are often of most concern in safety assessments, and the various parameterizations agree to within a few percent out to distances of 10 to 12 km, beyond which the Briggs open country parameterization results in increasingly higher estimates of relative concentration. There is no indication that any of the typing schemes is preferable for SRS for safety assessments; all give essentially the same answer.

A similar discussion to this is provided by Simpkins (1994). It should be noted that Simpkins presents the NRC model of Eimutis and Konicek (1972) exactly as shown here. However, Simpkins presents a composite model, similar to that originally proposed by Pasquill (1976), for what is labeled “Pasquill-Briggs”. The σ_y dispersion coefficient is computed directly from turbulence data (i.e., sigma-theta, σ_A) using the functional relationship between σ_A and σ_y from Pasquill (1976), thereby avoiding the need to use the PG stability class as a method to approximate σ_y. However, Pasquill (1976) recommended that his original parameterization be used for σ_z. Simpkins (1994) employed the Briggs expressions for σ_z, since these expressions were considered more appropriate for stack releases that were common at SRS at the time.

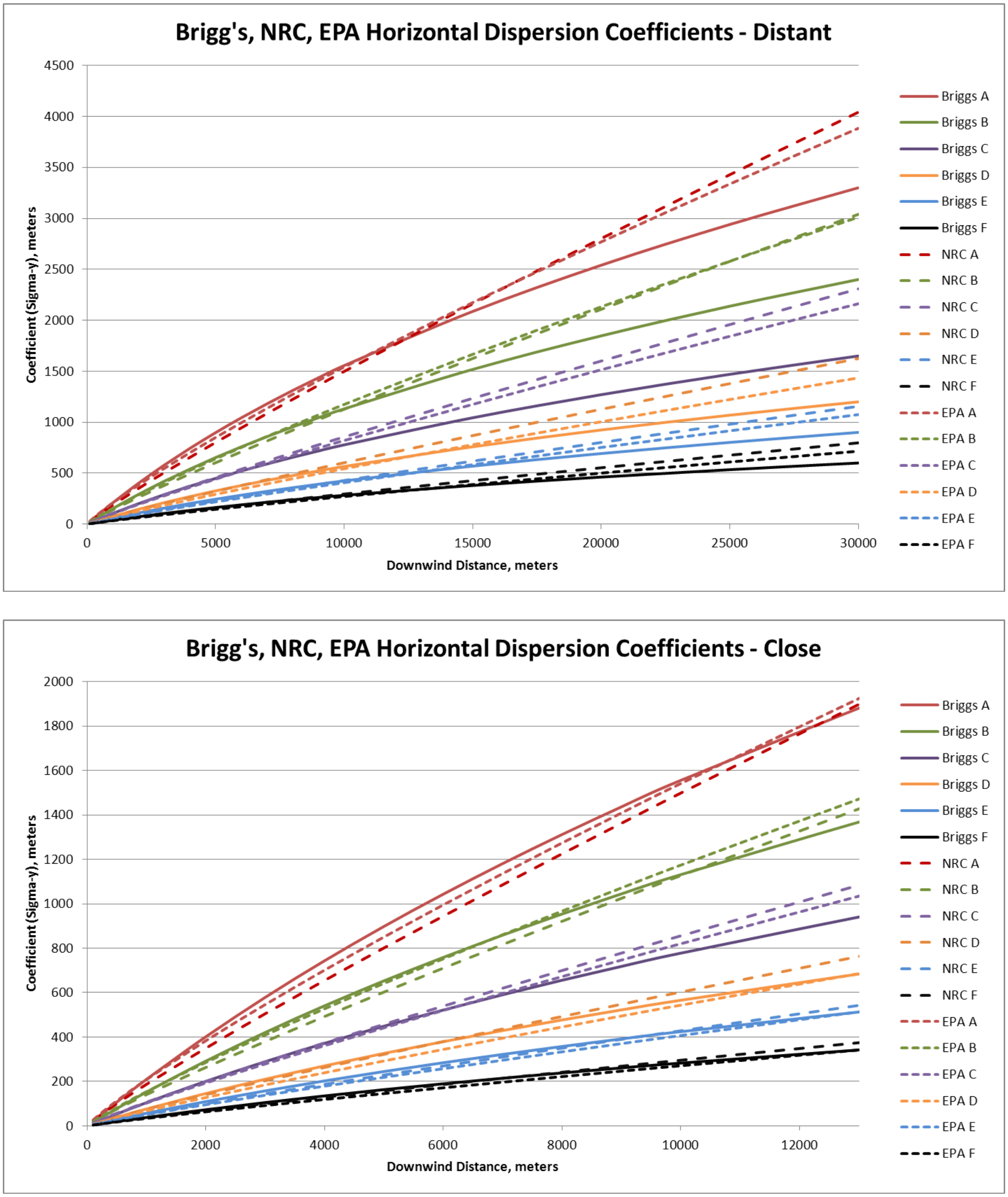
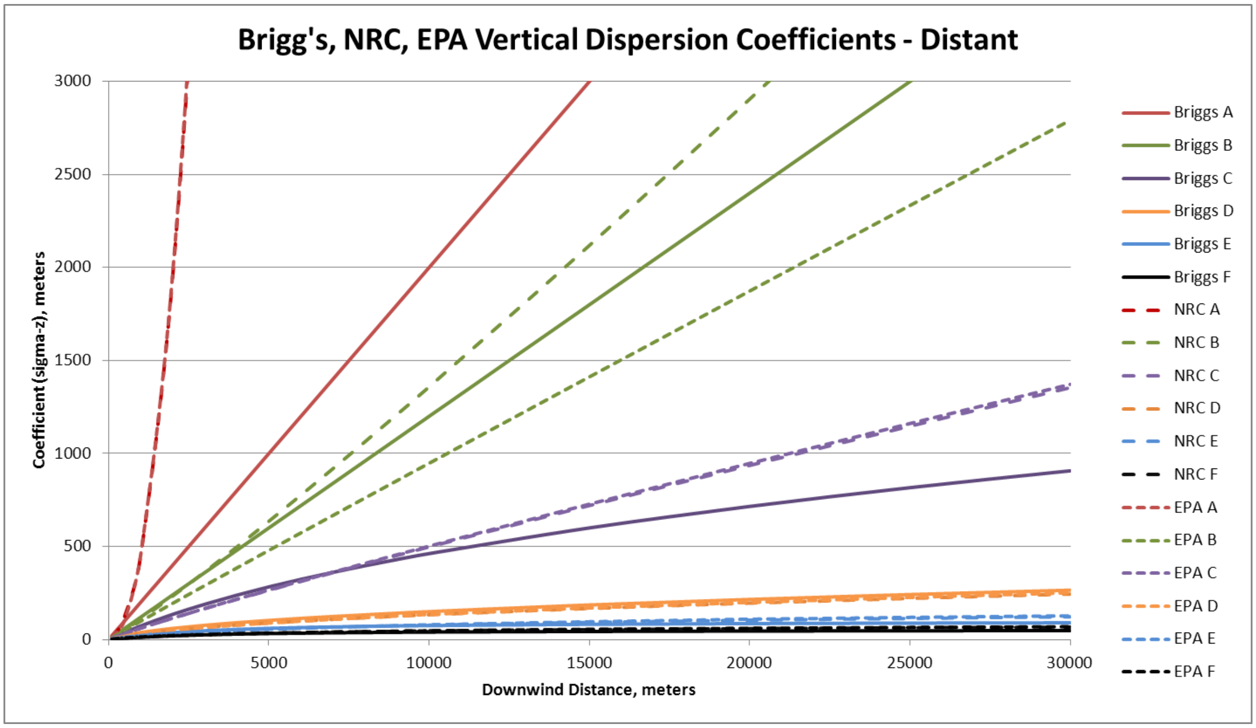


Figure A-1. Horizontal dispersion coefficients (σ_y) estimated using the parameterizations of Briggs open country, NRC, and EPA (a) over a large range in downwind distance (i.e., distant), and (b) within 13 km of the source (i.e., close).



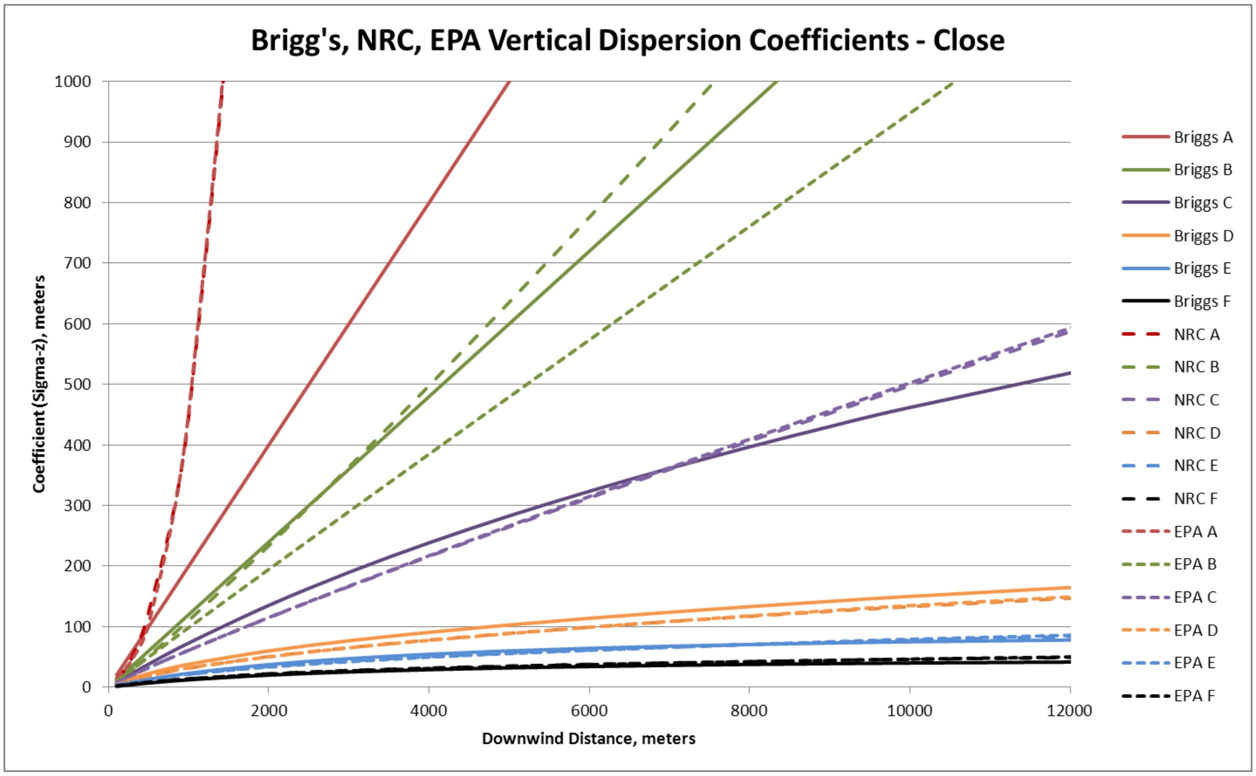


Figure A-2. Vertical dispersion coefficients (σ_z) estimated using the parameterizations of Briggs open country, NRC, and EPA (a) over a large range in downwind distance (i.e., distant), and (b) within 13 km of the source (i.e., close).

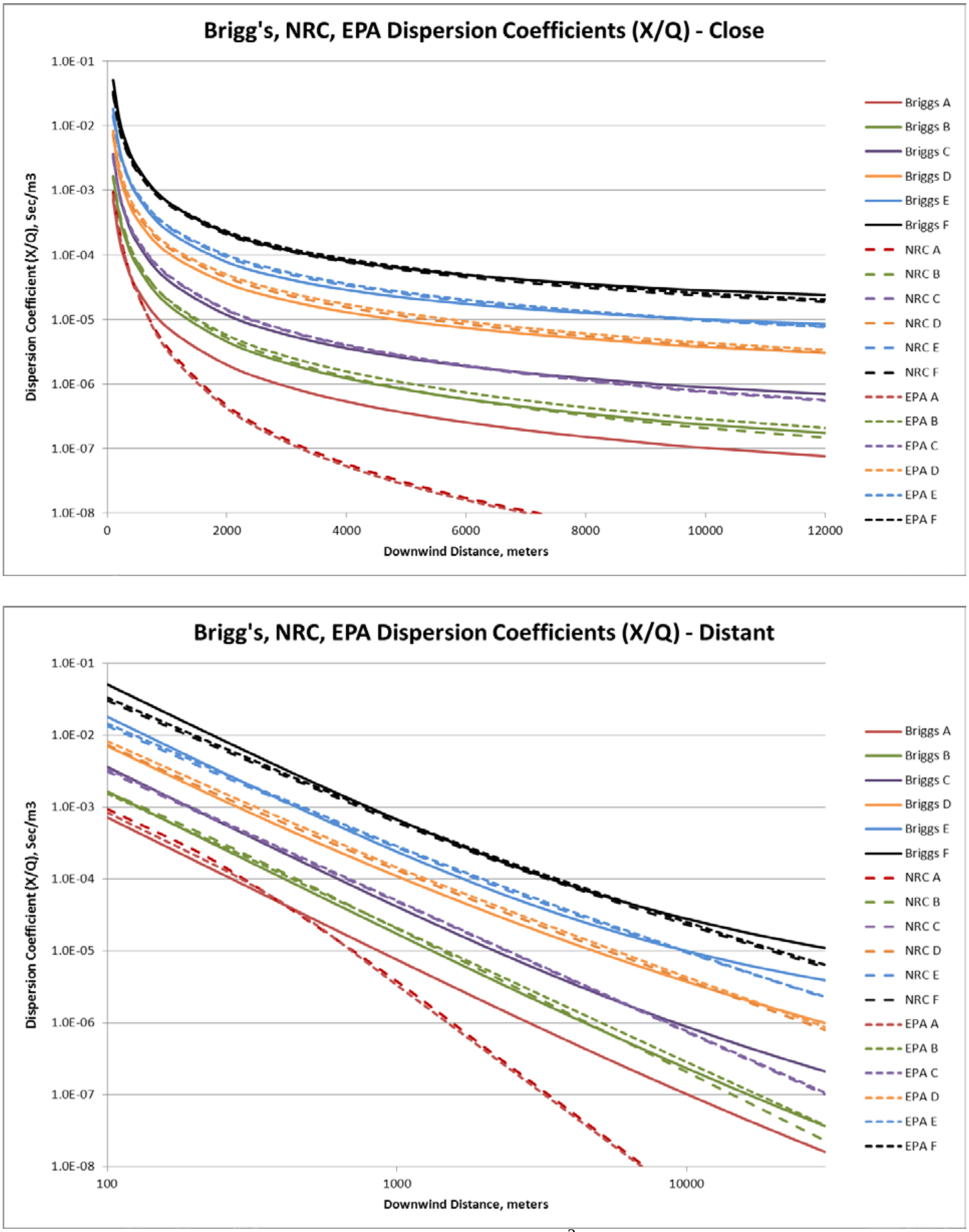


Figure A-3. Relative concentration (χ/Q, units of sec/m^3) for a ground-level release and a 1 m/s ambient wind speed using the dispersion parameterizations of Briggs open country, NRC, and EPA (a) within 13 km of the source (i.e., close), and (b) over a large range in downwind distance (i.e., distant). Note that (b) is presented on a log-log scale.

Appendix B – Discussion of the Tadmor-Gur and Eimutis-Konicek Dispersion Parameterizations

Tadmor and Gur (1969) values for dispersion parameters have commonly been used for documented safety analyses in support of DOE nuclear facilities. The Tadmor and Gur correlation is a power-law fit to the original Pasquill-Gifford (PG) diffusion experiment data. The power law is expressed by the following equation:

$$\boldsymbol{\sigma_j} = A_j x^{Bj} + C_j \tag{B.1}$$

Here,

$\boldsymbol{\sigma_j}$ = dispersion parameter in dimension j (km)
j = represents either y (crosswind distance) or z (vertical distance)
x = downwind distance (km)
y = crosswind distance (km)
z = vertical distance (km)
A, B, C = parameters given in Table B-1

The original work by Tadmor and Gur (1969) had a number of typographical errors in their table for the coefficients for B_z in their equation for $\boldsymbol{\sigma_j}$ over the range $0.5 < x < 5$ km. These errors were corrected by Dobbins (1979). The Tadmor and Gur representation is adequate for estimating dispersion when downwind distances are within either of the specified ranges. The Tadmor and Gur representation should not be used at distances below 0.5 km.

Table B-1: Tadmor and Gur Dispersion Parameters for A_j and B_j. $C_j = 0$.

	Sigma-y (km) 0.5 to 50 km		Sigma-z (km) for 0.5 to 5 km		Sigma-z (km) for 5 to 50 km	
Stability Class	A_y	B_y	A_z	B_z	A_z	B_z
A	0.3658	0.9031	2.5E-04	2.1250	-	-
B	0.2751	0.9031	1.9E-03	1.6021	-	-
C	0.2089	0.9031	0.20	0.8543	0.5742	0.7160
D	0.1474	0.9031	0.30	0.6532	0.9605	0.5409
E	0.1046	0.9031	0.40	0.6021	2.1250	0.3979
F	0.0722	0.9031	0.20	0.6020	2.1820	0.3310

When the downwind distances required for an application exceed 5 km, directly using the Tadmor and Gur formulation is less than ideal. Using the Tadmor and Gur formulation under such circumstances requires that two separate calculations be done with MACCS2 to cover the range below and above 5 km. A better approach is to use a lookup table that combines the two ranges covered by Tadmor and Gur, 0.5 to 5 km and 5 km to 50 km, giving an effective range of 0.5 km to 50 km. However, the Tadmor and Gur formation should not be used when distances below 0.5 km need to be evaluated because this formulation is not valid in that range.

A better representation is the one given by Eimutis and Konicek (1972), which includes the following three ranges of distances: less than 100 m, 100 to 1000 m, and greater than 1000 m.

The parameters for this formulation are provided in Table B-2. This formulation covers all downwind distances of interest for a documented safety analysis. However, like the Tadmor and Gur formulation, direct application of the Eimutis and Konicek formulation would require multiple calculations to be performed when downwind distances of interest exceed either 100 m or 1000 m. To avoid this complication and minimize the computation effort involved in conducting a documented safety analysis, the Eimutis and Konicek formulation is converted into a lookup table that can be used directly in MACCS2. The lookup table values are supplied in Tables B-3 and B-4 below. For completeness, these tables include values for stability classes A through G, although implementation of the EPA (2000) methods for estimating PG stability class only result in stability classes A through F. Stability class G is recognized by NRC (e.g., see NRC 1980, NRC 2007). However, consistent with EPA, MACCS2 only recognizes stability classes A through F and the model automatically converts instances of G to F stability class (Chanin and Young 1998).

Table B-2. Dispersion Parameters for the Eimutis and Konicek (1972) Formulation

	Sigma-y (m) All Distances		Sigma-z (m) For Less than 100 m			Sigma-z (m) For 100 to 1000 m			Sigma-z (m) For Greater than 1000 m		
Stability Class	A_y	B_y	A_z	B_z	C_z	A_z	B_z	C_z	A_z	B_z	C_z
A	0.3658	0.9031	0.192	0.936	0.000	6.6E-04	1.941	9.27	2.4E-04	2.094	-9.6
B	0.2751	0.9031	0.156	0.922	0.000	0.0382	1.149	3.30	0.055	1.098	2.0
C	0.2089	0.9031	0.116	0.905	0.000	0.113	0.911	0.00	0.113	0.911	0.0
D	0.1471	0.9031	0.079	0.881	0.000	0.222	0.725	-1.70	1.26	0.516	-13.0
E	0.1046	0.9031	0.063	0.871	0.000	0.211	0.678	-1.30	6.73	0.305	-34.0
F	0.0722	0.9031	0.053	0.814	0.000	0.086	0.740	-0.35	18.05	0.180	-48.6
G	0.0481	0.9031	0.032	0.814	0.000	0.052	0.740	-0.21	10.83	0.180	-29.2

Table B-3. Horizontal Dispersion, σ_y, Lookup Table for the Eimutis and Konicek Formulation

Sigma-y (m)							
Distance (m)	Stability A	Stability B	Stability C	Stability D	Stability E	Stability F	Stability G*
1.0E+00	3.66E-01	2.75E-01	2.09E-01	1.47E-01	1.05E-01	7.22E-02	4.81E-02
1.4E+00	4.96E-01	3.73E-01	2.83E-01	1.99E-01	1.42E-01	9.78E-02	6.52E-02
2.0E+00	6.84E-01	5.14E-01	3.91E-01	2.75E-01	1.96E-01	1.35E-01	9.00E-02
3.0E+00	9.87E-01	7.42E-01	5.63E-01	3.97E-01	2.82E-01	1.95E-01	1.30E-01
4.0E+00	1.28E+00	9.62E-01	7.31E-01	5.14E-01	3.66E-01	2.52E-01	1.68E-01
6.0E+00	1.84E+00	1.39E+00	1.05E+00	7.42E-01	5.28E-01	3.64E-01	2.43E-01
8.0E+00	2.39E+00	1.80E+00	1.37E+00	9.62E-01	6.84E-01	4.72E-01	3.15E-01
1.0E+01	2.93E+00	2.20E+00	1.67E+00	1.18E+00	8.37E-01	5.78E-01	3.85E-01
1.4E+01	3.97E+00	2.98E+00	2.26E+00	1.59E+00	1.13E+00	7.83E-01	5.21E-01
2.0E+01	5.47E+00	4.12E+00	3.13E+00	2.20E+00	1.56E+00	1.08E+00	7.20E-01
3.0E+01	7.89E+00	5.94E+00	4.51E+00	3.17E+00	2.26E+00	1.56E+00	1.04E+00
4.0E+01	1.02E+01	7.70E+00	5.84E+00	4.12E+00	2.93E+00	2.02E+00	1.35E+00
6.0E+01	1.48E+01	1.11E+01	8.43E+00	5.94E+00	4.22E+00	2.91E+00	1.94E+00
8.0E+01	1.91E+01	1.44E+01	1.09E+01	7.70E+00	5.47E+00	3.78E+00	2.52E+00
1.0E+02	2.34E+01	1.76E+01	1.34E+01	9.41E+00	6.69E+00	4.62E+00	3.08E+00
1.4E+02	3.17E+01	2.39E+01	1.81E+01	1.28E+01	9.07E+00	6.26E+00	4.17E+00
2.0E+02	4.38E+01	3.29E+01	2.50E+01	1.76E+01	1.25E+01	8.64E+00	5.76E+00
3.0E+02	6.31E+01	4.75E+01	3.61E+01	2.54E+01	1.81E+01	1.25E+01	8.30E+00
4.0E+02	8.19E+01	6.16E+01	4.68E+01	3.29E+01	2.34E+01	1.62E+01	1.08E+01
6.0E+02	1.18E+02	8.88E+01	6.74E+01	4.75E+01	3.38E+01	2.33E+01	1.55E+01
8.0E+02	1.53E+02	1.15E+02	8.74E+01	6.16E+01	4.38E+01	3.02E+01	2.01E+01
1.0E+03	1.87E+02	1.41E+02	1.07E+02	7.53E+01	5.36E+01	3.70E+01	2.46E+01
1.4E+03	2.54E+02	1.91E+02	1.45E+02	1.02E+02	7.26E+01	5.01E+01	3.34E+01
2.0E+03	3.50E+02	2.63E+02	2.00E+02	1.41E+02	1.00E+02	6.91E+01	4.61E+01
3.0E+03	5.05E+02	3.80E+02	2.88E+02	2.03E+02	1.44E+02	9.97E+01	6.64E+01
4.0E+03	6.55E+02	4.93E+02	3.74E+02	2.63E+02	1.87E+02	1.29E+02	8.61E+01
6.0E+03	9.45E+02	7.10E+02	5.39E+02	3.80E+02	2.70E+02	1.86E+02	1.24E+02
8.0E+03	1.22E+03	9.21E+02	7.00E+02	4.93E+02	3.50E+02	2.42E+02	1.61E+02
1.0E+04	1.50E+03	1.13E+03	8.56E+02	6.03E+02	4.28E+02	2.96E+02	1.97E+02
1.4E+04	2.03E+03	1.53E+03	1.16E+03	8.17E+02	5.81E+02	4.01E+02	2.67E+02
2.0E+04	2.80E+03	2.11E+03	1.60E+03	1.13E+03	8.01E+02	5.53E+02	3.68E+02
3.0E+04	4.04E+03	3.04E+03	2.31E+03	1.63E+03	1.16E+03	7.98E+02	5.31E+02
4.0E+04	5.24E+03	3.94E+03	2.99E+03	2.11E+03	1.50E+03	1.03E+03	6.89E+02
6.0E+04	7.56E+03	5.68E+03	4.32E+03	3.04E+03	2.16E+03	1.49E+03	9.94E+02
8.0E+04	9.80E+03	7.37E+03	5.60E+03	3.94E+03	2.80E+03	1.93E+03	1.29E+03
1.0E+05	1.20E+04	9.02E+03	6.85E+03	4.82E+03	3.43E+03	2.37E+03	1.58E+03
1.4E+05	1.62E+04	1.22E+04	9.28E+03	6.53E+03	4.65E+03	3.21E+03	2.14E+03
2.0E+05	2.24E+04	1.69E+04	1.28E+04	9.02E+03	6.41E+03	4.42E+03	2.95E+03
3.0E+05	3.23E+04	2.43E+04	1.85E+04	1.30E+04	9.25E+03	6.38E+03	4.25E+03
4.0E+05	4.19E+04	3.15E+04	2.39E+04	1.69E+04	1.20E+04	8.27E+03	5.51E+03
6.0E+05	6.05E+04	4.55E+04	3.45E+04	2.43E+04	1.73E+04	1.19E+04	7.95E+03
8.0E+05	7.84E+04	5.90E+04	4.48E+04	3.15E+04	2.24E+04	1.55E+04	1.03E+04
1.0E+06	9.59E+04	7.21E+04	5.48E+04	3.86E+04	2.74E+04	1.89E+04	1.26E+04

Sigma-y (m)							
Distance (m)	Stability A	Stability B	Stability C	Stability D	Stability E	Stability F	Stability G*
1.4E+06	1.30E+05	9.77E+04	7.42E+04	5.23E+04	3.72E+04	2.57E+04	1.71E+04
2.0E+06	1.79E+05	1.35E+05	1.02E+05	7.21E+04	5.13E+04	3.54E+04	2.36E+04
3.0E+06	2.59E+05	1.95E+05	1.48E+05	1.04E+05	7.40E+04	5.11E+04	3.40E+04
4.0E+06	3.35E+05	2.52E+05	1.92E+05	1.35E+05	9.59E+04	6.62E+04	4.41E+04
6.0E+06	4.84E+05	3.64E+05	2.76E+05	1.95E+05	1.38E+05	9.55E+04	6.36E+04
8.0E+06	6.27E+05	4.72E+05	3.58E+05	2.52E+05	1.79E+05	1.24E+05	8.25E+04
1.0E+07	7.67E+05	5.77E+05	4.38E+05	3.09E+05	2.19E+05	1.51E+05	1.01E+05

*Lookup table values for PG stability class G are provided for completeness. EPA (2000) methods for estimating PG stability class only result in PG classes A through F. NRC (1980, 2007) recognizes stability class G.

Table B-4. Vertical Dispersion, σ_z, Lookup Table for the Eimutis and Konicek Formulation

Sigma-z (m)							
Distance (m)	Stability A	Stability B	Stability C	Stability D	Stability E	Stability F	Stability G*
1.0E+00	1.92E-01	1.56E-01	1.16E-01	7.90E-02	6.30E-02	5.30E-02	3.20E-02
1.4E+00	2.63E-01	2.13E-01	1.57E-01	1.06E-01	8.45E-02	6.97E-02	4.21E-02
2.0E+00	3.67E-01	2.96E-01	2.17E-01	1.45E-01	1.15E-01	9.32E-02	5.63E-02
3.0E+00	5.37E-01	4.30E-01	3.14E-01	2.08E-01	1.64E-01	1.30E-01	7.83E-02
4.0E+00	7.03E-01	5.60E-01	4.07E-01	2.68E-01	2.11E-01	1.64E-01	9.89E-02
6.0E+00	1.03E+00	8.14E-01	5.87E-01	3.83E-01	3.00E-01	2.28E-01	1.38E-01
8.0E+00	1.34E+00	1.06E+00	7.62E-01	4.93E-01	3.85E-01	2.88E-01	1.74E-01
1.0E+01	1.66E+00	1.30E+00	9.32E-01	6.01E-01	4.68E-01	3.45E-01	2.09E-01
1.4E+01	2.27E+00	1.78E+00	1.26E+00	8.08E-01	6.28E-01	4.54E-01	2.74E-01
2.0E+01	3.17E+00	2.47E+00	1.75E+00	1.11E+00	8.56E-01	6.07E-01	3.67E-01
3.0E+01	4.63E+00	3.59E+00	2.52E+00	1.58E+00	1.22E+00	8.45E-01	5.10E-01
4.0E+01	6.06E+00	4.68E+00	3.27E+00	2.04E+00	1.57E+00	1.07E+00	6.45E-01
6.0E+01	8.86E+00	6.80E+00	4.72E+00	2.91E+00	2.23E+00	1.48E+00	8.97E-01
8.0E+01	1.16E+01	8.87E+00	6.12E+00	3.75E+00	2.86E+00	1.88E+00	1.13E+00
1.0E+02	1.43E+01	1.09E+01	7.49E+00	4.57E+00	3.48E+00	2.25E+00	1.36E+00
1.4E+02	1.89E+01	1.45E+01	1.02E+01	6.29E+00	4.72E+00	2.98E+00	1.80E+00
2.0E+02	2.86E+01	2.01E+01	1.41E+01	8.64E+00	6.36E+00	3.99E+00	2.41E+00
3.0E+02	5.17E+01	3.01E+01	2.04E+01	1.22E+01	8.79E+00	5.51E+00	3.33E+00
4.0E+02	8.34E+01	4.06E+01	2.65E+01	1.54E+01	1.10E+01	6.89E+00	4.17E+00
6.0E+02	1.72E+02	6.28E+01	3.84E+01	2.12E+01	1.48E+01	9.43E+00	5.70E+00
8.0E+02	2.94E+02	8.60E+01	4.99E+01	2.66E+01	1.83E+01	1.17E+01	7.11E+00
1.0E+03	4.48E+02	1.10E+02	6.11E+01	3.15E+01	2.15E+01	1.39E+01	8.42E+00
1.4E+03	9.20E+02	1.59E+02	8.30E+01	3.99E+01	2.73E+01	1.79E+01	1.07E+01
2.0E+03	1.95E+03	2.34E+02	1.15E+02	5.06E+01	3.44E+01	2.23E+01	1.33E+01
3.0E+03	4.58E+03	3.64E+02	1.66E+02	6.54E+01	4.34E+01	2.77E+01	1.66E+01
4.0E+03	8.36E+03	4.98E+02	2.16E+02	7.80E+01	5.05E+01	3.17E+01	1.90E+01
6.0E+03	1.96E+04	7.76E+02	3.13E+02	9.92E+01	6.16E+01	3.78E+01	2.26E+01
8.0E+03	3.57E+04	1.06E+03	4.06E+02	1.17E+02	7.03E+01	4.24E+01	2.54E+01
1.0E+04	5.70E+04	1.36E+03	4.98E+02	1.33E+02	7.77E+01	4.61E+01	2.76E+01
1.4E+04	1.15E+05	1.96E+03	6.76E+02	1.61E+02	8.98E+01	5.20E+01	3.12E+01
2.0E+04	2.44E+05	2.91E+03	9.36E+02	1.96E+02	1.04E+02	5.87E+01	3.52E+01
3.0E+04	5.69E+05	4.53E+03	1.35E+03	2.44E+02	1.22E+02	6.68E+01	4.01E+01
4.0E+04	1.04E+06	6.22E+03	1.76E+03	2.86E+02	1.36E+02	7.30E+01	4.37E+01
6.0E+04	2.43E+06	9.70E+03	2.55E+03	3.55E+02	1.59E+02	8.22E+01	4.93E+01
8.0E+04	4.44E+06	1.33E+04	3.31E+03	4.14E+02	1.77E+02	8.91E+01	5.34E+01
1.0E+05	7.08E+06	1.70E+04	4.06E+03	4.66E+02	1.91E+02	9.48E+01	5.68E+01
1.4E+05	1.43E+07	2.46E+04	5.51E+03	5.57E+02	2.16E+02	1.04E+02	6.22E+01
2.0E+05	3.02E+07	3.64E+04	7.63E+03	6.72E+02	2.45E+02	1.14E+02	6.83E+01
3.0E+05	7.07E+07	5.68E+04	1.10E+04	8.31E+02	2.81E+02	1.26E+02	7.56E+01
4.0E+05	1.29E+08	7.79E+04	1.43E+04	9.67E+02	3.10E+02	1.35E+02	8.12E+01
6.0E+05	3.02E+08	1.22E+05	2.07E+04	1.19E+03	3.55E+02	1.49E+02	8.96E+01
8.0E+05	5.51E+08	1.67E+05	2.70E+04	1.39E+03	3.91E+02	1.60E+02	9.59E+01
1.0E+06	8.79E+08	2.13E+05	3.30E+04	1.56E+03	4.21E+02	1.68E+02	1.01E+02

Sigma-z (m)							
Distance (m)	Stability A	Stability B	Stability C	Stability D	Stability E	Stability F	Stability G*
1.4E+06	1.78E+09	3.08E+05	4.49E+04	1.86E+03	4.70E+02	1.82E+02	1.09E+02
2.0E+06	3.75E+09	4.56E+05	6.21E+04	2.23E+03	5.28E+02	1.97E+02	1.18E+02
3.0E+06	8.78E+09	7.12E+05	8.99E+04	2.76E+03	6.02E+02	2.16E+02	1.29E+02
4.0E+06	1.60E+10	9.76E+05	1.17E+05	3.20E+03	6.60E+02	2.30E+02	1.38E+02
6.0E+06	3.75E+10	1.52E+06	1.69E+05	3.95E+03	7.52E+02	2.51E+02	1.51E+02
8.0E+06	6.84E+10	2.09E+06	2.20E+05	4.58E+03	8.24E+02	2.67E+02	1.60E+02
1.0E+07	1.09E+11	2.67E+06	2.69E+05	5.14E+03	8.84E+02	2.80E+02	1.68E+02

*Lookup table values for PG stability class G are provided for completeness. EPA (2000) methods for estimating PG stability class only result in PG classes A through F. NRC (1980, 2007) recognizes stability class G.

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