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Comparison of Consequence Analysis Results from Two Methods of Processing Site Meteorological Data

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Abstract

Consequence analysis to support documented safety analysis requires the use of one or more years of representative meteorological data for atmospheric transport and dispersion calculations. At minimum, the needed meteorological data for most atmospheric transport and dispersion models consist of hourly samples of wind speed and atmospheric stability class. Atmospheric stability is inferred from measured and/or observed meteorological data. Several methods exist to convert measured and observed meteorological data into atmospheric stability class data. In this paper, one year of meteorological data from a western Department of Energy (DOE) site is processed to determine atmospheric stability class using two methods. The method that is prescribed by the U.S. Nuclear Regulatory Commission (NRC) for supporting licensing of nuclear power plants makes use of measurements of vertical temperature difference to determine atmospheric stability. Another method that is preferred by the U.S. Environmental Protection Agency (EPA) relies upon measurements of incoming solar radiation, vertical temperature gradient, and wind speed. Consequences are calculated and compared using the two sets of processed meteorological data from these two methods as input data into the MELCOR Accident Consequence Code System 2 (MACCS2) code.

Introduction

The 95th percentile result from the distribution of consequence results is established by the DOE in Appendix A to DOE-STD-3009-94 as the basis for comparison against the evaluation guideline for nonreactor nuclear facilities [DOE, 2006]. The statistical procedure to determine the 95th result is prescribed to be consistent with that used to determine 95th percentile χ/Q values described in regulatory position 3 of NRC Regulatory Guide 1.145 [NRC, 1983]. The χ/Q parameter represents the amount of dilution that the plume has undergone at given distance during atmospheric transport as predicted by the Gaussian plume transport and dispersion model. This statistical treatment relies upon one or more years of representative meteorological data consisting of hourly averages of wind speed and measure of atmospheric stability at minimum. In regulatory position 3 of NRC Regulatory Guide 1.145, a χ/Q value is calculated for each hourly record of meteorological data and sorted. The χ/Q value that is exceeded by 5% of the calculated χ/Q values establishes the 95th percentile result.

In the Gaussian transport and dispersion model, horizontal and vertical dispersion coefficients (σ_y and σ_z, respectively) are typically determined from established curves showing σ_y and σ_z as a function of atmospheric stability and downwind distance. Atmospheric stability is inferred from measured and/or observed meteorological data. Several methods exist to convert measured and observed meteorological data into atmospheric stability class data. A brief overview of some of these methods is given in this paper, and two of the more commonly used methods are chosen for study. A common method used at DOE sites involves using temperature-difference data from two different elevations as prescribed by long-standing NRC guidance that has been affirmed earlier this year [NRC, 2007]. Recent guidance that was developed by EPA prefers the use of incoming solar radiation, vertical temperature gradient, and wind speed data as a means of determining atmospheric stability [EPA, 2000].

In this paper, one year of meteorological data from a western DOE site is processed for atmospheric stability class using the "NRC method" and the "EPA method". Consequences are calculated and compared using the two sets of processed meteorological data from the two methods as input data into MACCS2 code [Chanin, 1998].

General Discussion

Atmospheric Turbulence and Measure of Stability

Atmospheric boundary layer turbulence is thought of as having two sources. First, mechanical turbulence caused by roughness elements, e.g., irregular surface features, vegetation, trees, buildings, etc. that generate turbulence as wind blows over their rough surfaces and turbulent wakes form. Second, buoyancy (or thermally) generated turbulence is caused by the sun's heating of the earth's surface, or by any mechanism that provides a source of warm, buoyant air near the surface. Warm air near the surface can produce unstable vertical thermal gradients (or uneven horizontal thermal gradients). Mechanical turbulence usually results in smaller eddy sizes than thermally generated turbulence as long as there are not sizeable buildings or terrain changes nearby. The reason for this is that eddies being produced from roughness elements (turbulent wakes from trees, vegetation, etc.) are smaller than the convective structures (thermals, etc.) produced by differential heating of the surface elements. Temperature differences between dark, paved parking lots, bodies of water, or adjoining moist, vegetated surfaces can produce large scale convective eddies in the boundary layer.

Wind speed plays a role in affecting both sources of turbulence. As wind speed increases mechanical turbulence increases due to increased wind shear near the surface. During conditions of very low wind speed and intense sunshine, the production of thermal turbulence through unstable temperature gradients is at a maximum. In the limit of very low wind speeds and strong solar heating the atmosphere is said to be in a state of "free convection".

As the wind speed increases, however, the strong temperature gradients that are present in free convection are weakened by mechanical mixing. This mechanical turbulence becomes the leading contributor to the eddy size distribution spectrum. Eventually, as the wind speed becomes very strong, large thermal eddy structures are destroyed by wind shear and the mechanical production of eddies becomes dominant. Thus, the larger thermal eddies are reduced in size and the smaller eddy sizes tend to dominant the turbulence spectrum under very strong winds. In effect, strong winds push the boundary layer from unstable conditions toward neutral conditions. This affects atmospheric dispersion as well.

The Pasquill-Gifford (P-G) categories for atmospheric dispersion are a simplified way to determine the turbulence intensity level. Turbulence intensity is the underlying factor for determining the amount of spread of a dispersing cloud as it moves downwind. Pasquill first used the standard deviations of the vertical and horizontal wind direction fluctuations to determine turbulence intensity [Pasquill, 1961]. He then expressed the dispersion coefficients, σ_y and σ_z, for the horizontal and vertical spread of a ground level or elevated plume, in terms of these fluctuations. The practical problem with this approach is that the wind direction fluctuations can only be measured with rather specialized instruments (e.g., bidirectional wind vanes). Thus, there was a need to use more commonly measured meteorological variables to determine the dispersion coefficients. Temperature gradients, since they are fairly easily determined, became the most commonly employed method to determine the thermal stability of the boundary layer and thus the method of choice to help predict atmospheric dispersion.

Gifford provided a turbulence typing scheme for relating the temperature gradient to the standard deviations of the wind direction fluctuations [Gifford, 1961]. Six categories designated with the letters A-F were used to relate the amount of spread of the dispersing plume as it moved downwind. These categories were based on the results of dispersion experiments that had been carried out during project Prairie Grass in the U.S. during the 1950s [Haugen, 1959]. Later still, Turner slightly modified Pasquill and Gifford's approach by including time of day, wind speed, cloudiness, and ceiling height in order to more accurately determine the atmospheric stability category [Turner, 1964].

The stability categories A-F were meant to reflect the state of atmospheric stability. The unstable categories A, B, and C reflect daytime solar heating and the stable categories E and F reflect nighttime conditions. At the time Pasquill and Gifford devised the dispersion categories, the neutral category D was presumed to represent the transitional state between early morning sunrise and the onset of solar heating, or the period around sunset when solar heating disappears and the surface begins to cool by radiative processes. As time has progressed, the important role of wind speed in promoting neutral stability conditions became better understood.

Several methods exist to convert measured or observed meteorological data into atmospheric stability class data. Features of methods commonly used are summarized below.

- The P-G stability categories are determined from vertical temperature difference (ΔT_z) with values on each side of the dry adiabatic temperature change (1 degree Celsius per 100 meters) representing unstable (less than the dry adiabatic temperature change) conditions and stable (greater than the dry adiabatic temperature change) conditions [NRC, 2007].

- The P-G stability categories are determined from the Turner method using time of day, wind speed, cloudiness, and ceiling height (requires human observation records of cloudiness and ceiling height) [EPA, 2000].

- The P-G stability categories are determined using the solar radiation delta-T (SRDT) method, which is a modification of the Turner method that involves the substitution of total solar radiation (during the day) data and ΔT_z data (during the night) to replace subjective human observations of cloudiness and ceiling height [EPA, 2000].

- The P-G stability categories are based on wind direction fluctuation measurements (requires sophisticated anemometer instrumentation or bi-directional vanes that may not be available at a given site) [EPA, 2000].

This study focuses on the methods described in the 1st (NRC vertical temperature difference method) and 3rd (SRDT method) bulleted items, which are discussed in fuller detail in the next section.

Overview of ΔT_z and SRDT Methods for Determing Atmospheric Stability

The method that is prescribed by the NRC for supporting licensing of nuclear power plants makes use of measurements of vertical temperature difference to determine atmospheric stability as shown in Table 1 [NRC, 2007]. In this method, ΔT_z is expressed in terms of the vertical temperature difference over 100 meters (ΔT_{100m}). Typically, ΔT_{100m} is determined by doubling the difference in temperature measurements at 60 m and 10 m.

Table 1. Classification of Atmospheric Stability Based on Vertical Temperature Difference.

Stability Classification	P-G Category	Criterion (°C/100 m)
Extremely unstable	A	$\Delta T_{100m} \leq -1.9$
Moderately unstable	B	$-1.9 < \Delta T_{100m} \leq -1.7$
Slightly unstable	C	$-1.7 < \Delta T_{100m} \leq -1.5$
Neutral	D	$-1.5 < \Delta T_{100m} \leq -0.5$
Moderately stable	E	$-0.5 < \Delta T_{100m} \leq 1.5$
Extremely stable	F	$1.5 < \Delta T_{100m} \leq 4.0$

It has been noted by meteorologists that turbulence typing based on boundary layer temperature gradients tend to produce a distribution of P-G categories that is skewed toward the strongly stable (F and G) and strongly unstable (A and B) categories. In contrast, turbulence typing based on bi-directional fluctuations tend to be peaked in the middle of the P-G categories (i.e., the D stability) with minimums at the two ends (A and F). The EPA provides some perspective on the various means of estimating the P-G categories using methods that would be available at different sites, including those with only temperature sensors, those with some method of measuring incoming solar radiation, and those with bi-directional wind vanes [EPA, 2000].

EPA considers the Turner method as the benchmark for determining P-G stability category "by virtue of its historic precedence and widespread use" [EPA, 2000]. It is further noted that the SRDT method and wind-fluctuation methods produce P-G stability category results that correlate reasonably well with the Turner method [EPA, 2000]. In the absence of the requisite human observation data involved with the Turner method, that SRDT method provides an alternative that retains the underlying basis of the Turner method. The SRDT method is outlined in Table 2 [EPA, 2000]. In this method, the wind speed is measured at or near 10 m.

Table 2. Classification of Atmospheric Stability Based on SRDT Method.

DAYTIME				
Wind Speed (m/s)	**Solar Radiation (W/m^2)**			
	≥ 925	925 - 675	675 - 175	< 175
< 2	A	A	B	D
2 - 3	A	B	C	D
3 - 5	B	B	C	D
5 - 6	C	C	D	D
≥ 6	C	D	D	D
NIGHTTIME				
Wind Speed (m/s)	**Vertical Temperature Gradient**			
	< 0		≥ 0	
< 2.0	E		F	
2.0 - 2.5	D		E	
≥ 2.5	D		D	

Consequence Calculations Using MACCS2

MACCS2 models the transport and dispersion of radioactive gases and particulates in the atmosphere, including plume depletion and ground contamination from deposition mechanisms. A particulate release is modeled in this study with an assumed deposition velocity of 1 cm/s specified. Doses and associated health effects are computed for inhalation from the plume, immersion or cloudshine, groundshine, deposition on the skin, and inhalation of resuspended ground contamination. Curve fits for the dispersion coefficients that follow the following simple power-law form may be input into MACCS2 [Chanin, 1998].

$$\sigma_y = ax^p \quad \text{and} \quad \sigma_z = cx^q \tag{1}$$

The Tadmor-Gur curve fits follow this form and are based on P-G curves that were developed from the measurements at Project Prairie Grass. The power-law constants for the Tadmor-Gur curve fits as documented by Dobbins [Dobbins, 1979] are in Table 3.[1] Note that two spatial regimes are covered, namely, 0.5 km to 5 km and 5 km to 50 km.

Table 3 Tadmor and Gur Curve Fits for σ_y and σ_z for P-G Stability Categories.

P-G Stability Category	σ_y		σ_z (0.5 to 5 km)		σ_z (5 to 50 km)	
	a	P	b	q	b	q
A	0.3658	0.9031	2.5E-04	2.1250	NA*	NA*
B	0.2751	0.9031	1.9E-03	1.6021	NA*	NA*
C	0.2089	0.9031	0.2	0.8543	0.5742	0.7160
D	0.1474	0.9031	0.3	0.6532	0.9605	0.5409
E	0.1046	0.9031	0.4	0.6021	2.1250	0.3979
F	0.0722	0.9031	0.2	0.6020	2.1820	0.3310

* NA - Not available, so power-law constants for stability class C are applied, per recommendation of the MACCS2 code developer [DOE, 2004].

Using the stratified random sampling option with MACCS2 with the number of samples per day set for 24 allows the code to sample all 8760 hours of data in the meteorological data file. From the distribution of results generated, MACCS2 provides output at specified distances for the mean and peak values and the 50th, 90th, 95th, 99th, and 99.5th percentile values.

Results

One year (2005) of meteorological data from a western DOE site was processed for atmospheric stability class using both the ΔT_z method and the SRDT method. These meteorological data sets were then run through MACCS2 in order to evaluate the effect on consequence results. Mean and 95th percentile results are compared from these two executions of MACCS2 for the purpose of this paper.

Atmospheric Stabilty Distribution

For the 8760 hourly records, the two methods for determining the P-G stability category yielded the same category only 38% of the time. The resulting distributions for P-G stability category from the two methods are shown in Table 4 and graphically in Figure 1.

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[1] Typographical errors identified by Dobbins are corrected [Dobbins, 1979].

Table 4. P-G Stability Category Distributions.

P-G Stability Category	ΔT_z Method	SRDT Method
A	9%	1%
B	4%	12%
C	4%	12%
D	20%	53%
E	21%	7%
F	41%	15%

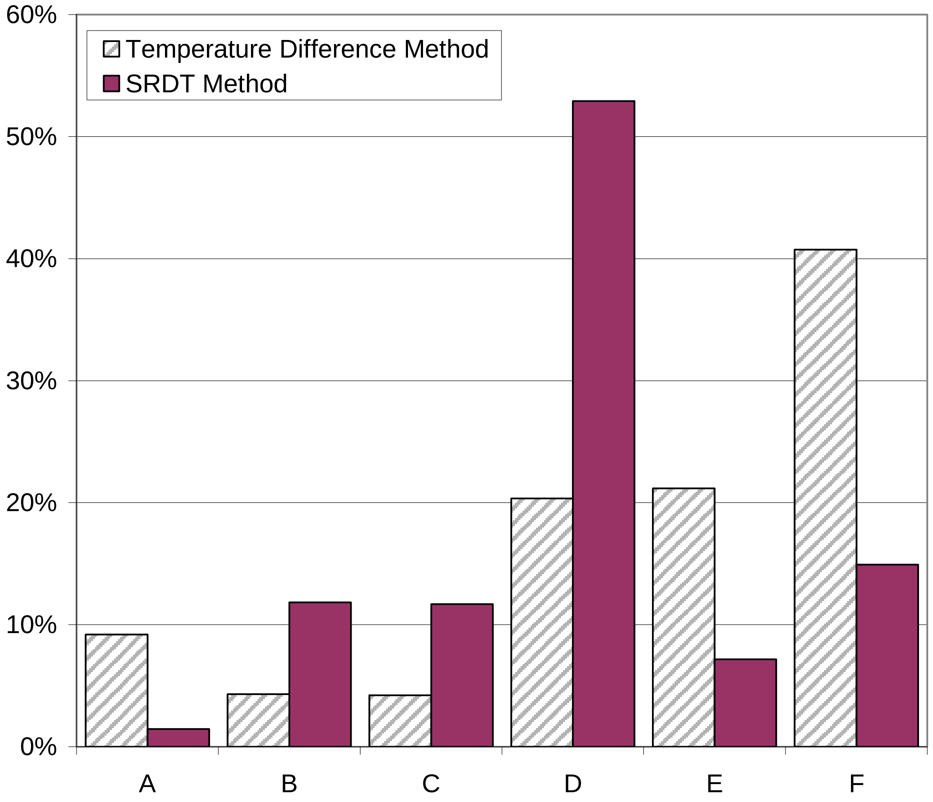

Figure 1. P-G Stability Category Distributions.

The results show that in comparison with the SRDT method, the ΔT_z method tends to over-predict the frequency of extreme meteorological conditions of very unstable (stability category A) and very stable (stability category F) atmospheric conditions and under-predict neutral stability conditions (stability category D).

The Mean and 95th Percentile Consequence Results

Table 4 shows that 62% of the hourly meteorological observations are placed in either the E or F P-G stability category with the ΔT_z method compared with 22% with the SRDT method. Since the highest calculated consequences occur for ground-level, non-buoyant releases with stable atmospheres (e.g., E or F P-G stability category), higher mean and 95th percentile consequences results would be expected using the meteorological data based on the ΔT_z method. The MACCS2 results shown in Table 5 demonstrate this expected effect. Results are shown for the 100-m onsite worker and the maximally-exposed offsite individual (MOI), which for the particular DOE facility modeled is 6 km. Results are presented in terms of the ratio the results from the ΔT_z method to those from the SRDT method. In addition to the 100-m worker and 6-km MOI results, additional results out a distance of 12 km are shown for illustrative purposes.

Table 5. Variation of Consequence Results from MACCS2 Using the Two Meteorological Data Sets (ΔT_z method, SRDT method).

Receptor Distance (km)	**Ratio of MACCS2 Consequence Results (ΔT_z based meteorological data / SRDT based meteorological data)**	
	Mean	95th Percentile
0.1	1.53	1.13
6	1.78	1.16
8	1.85	1.23
9	1.87	1.28
10 - 12	~1.9	~1.4
Note: Ratio values for distances between 0.1 and 6 km range from 1.00 to 1.18.		

Concluding Remarks

The P-G stability category distributions that result from the two tested methods of determining atmospheric stability class data from measured and/or observed meteorological data are noticeably different. The results show that the ΔT_z method produced a distribution with a peak at stability category F. In contrast, the SRDT method produced a distribution with a peak at stability category D.

When the meteorological data sets from these two methods are input into the MACCS2 code for a ground level, non-buoyant release, the calculated mean and 95th percentile doses are higher with the ΔT_z method data set due to the higher percentage of combined E and F P-G stability category records (62% with the ΔT_z method data set in comparison with 22% with the SRDT method data set). The effect on dose calculations is more pronounced with the mean results than with the 95th percentile results. For both the mean and 95th percentile results, the variation between the two set of dose results increases as downwind distance increases.

It is important to bear in mind that the results of this study are limited to one year of meteorological data from one particular western DOE site. While the same general trends are likely to be observed from repeating the analysis for meteorological data from other DOE sites, the degree of variation of consequence results shown in this study may not be indicative of those that would be obtained for other DOE sites.

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