REVIEW OF METHODS FOR ESTIMATION OF HIGH WIND AND TORNADO HAZARD FREQUENCIES

Prepared for

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC

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December 2012

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1 INTRODUCTION

1.1 Objective and Scope

The impact of severe weather on operations of commercial nuclear reactors is a common consideration in the probabilistic risk assessment (PRA) models of nuclear power plants. Extreme wind at a site can be generated from high wind (straight wind), tornadoes striking nearby, and hurricanes. Currently, the NRC relies on risk-information (including PRA models) in many regulatory applications, such as performing risk assessments of operational events in nuclear power plants and licensee performance issues. Use of specific PRA information in evaluating performance issues is used in the NRC's Significance Determination Process, which includes a method for assigning a probabilistic public health and safety risk characterization to inspection findings related to reactor safety.

As a part of user need NRR–2010–017, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) will further develop and enhance the External Events risk tools as part of the support provided to the Office of Nuclear Reactor Regulation (NRR). Hazards associated with the extreme winds from hurricanes and tornadoes are expected to be included as potential scenarios of PRA models as needed, where estimates of the annual frequencies of occurrences of extreme wind events at a facility or a site need to the evaluated.

The scope of this report includes

- Performing a literature review to identify, assess, and document methods and data sources that are used to estimate high wind and tornado strike hazard frequencies.

- Identifying recognized experts in tornado and hurricane related hazard assessment.

1.2 Report Organization

This report is organized in five chapters. Chapter 2 discusses the methodology commonly used to assess extreme straight wind events. Chapter 3 discusses the tornado characteristics observed in the United States and the sources of tornado strike information. The methodologies used to estimate the annual tornado strike frequency with wind speeds exceeding specified values are also discussed in Chapter 3. The methodology used to estimate the annual frequency of hurricanes from the Atlantic Ocean and the Gulf of Mexico is discussed in Chapter 4 as is the source of past hurricane-related information. Experts working in the extreme wind-related field are identified in Chapter 5. Appendix A describes the procedure that has been used to estimate the annual tornado hazard frequency at given facility using the methodology described in NUREG/CR–4461 (Ramsdell and Rishel, 2007). The procedure has been described using the tornado strike data set from the National Weather Service (NWS) Storm Prediction Center (SPC). Appendix B described the procedure to estimate the hurricane-generated wind speed at an annual exceedance frequency of 10^{-7} following the methodology given in NUREG/CR–7705 (Vickery, et al., 2011).

2 EXTREME STRAIGHT WIND

Extreme straight wind is generally generated from thunderstorms and its effects are considered routinely in design of a structure. Both American Society of Civil Engineers/Structural Engineering Institute standard ASCE/SEI 7–10 (ASCE/SEI, 2010) and American National Standards Institute/American Nuclear Society standard (ANSI/ANS–2.3–2011 (ANSI/ANS, 2011) provide the minimum extreme wind loads to be considered in designing different types of structures in the United States. Figure 1 of ANSI/ANS–2.3–2011 divides the continental United States in three regions. Table 2 and Figures 2, 3, and 4 specify the design wind speed for these three regions as a function of the mean return period or mean probability of exceedance in a given year. It should be noted that the recommended design wind-speed parameters are intended to assure public health and safety. This standard does not provide the structural design requirements for protection from these winds. Additionally, it does not incorporate the concept of risk-informed insights, performance-based requirements, or a graded quality approach. ASCE/SEI 7–10 (ASCE/SEI, 2010) is a consensus standard that provides the minimum load requirements for the design of different structures. This standard assigns a risk category (I, II, III, or IV) based on general occupancy descriptions and provides a minimum design wind speed for these categories (Figures 26.5-1A through 26.5-1C). In addition to the non-hurricane wind speed, the hurricane wind speed for the coastal regions of the Atlantic Ocean, Gulf of Mexico, Alaska, and Puerto Rico are provided in these figures. However, this standard does not address the wind speeds associated with a tornado. Several Special Wind Regions have been identified in these figures. Winds blowing through river valleys or mountain ranges can develop substantially higher speeds than those indicated in these figures (ASCE/SEI, 2010).

Anomalies in wind speed exist at small-scale due to complex terrain. ASCE/SEI (2010, Section 26.5.3) recommends adjustments of the specified wind speeds using locally recorded data. The standard recommends using the extreme-value statistical analysis procedure to adjust the wind speed values. The Fisher-Tippett Type I extreme value distribution has been recommended to model extreme wind speeds using the wind speed data measured at a site (Mayne, 1979):

$$P(V > v) = \exp\,[-\exp\{-a(v-u)\}] \tag{2-1}$$

where,

$P(V > v)$	=	probability that an observed annual wind V will have a speed larger than v
u	=	location parameter, which is the mode of the measured data
$1/a$	=	scale parameter that characterizes the spread of the measured data

There are several methods to estimate the location parameter u and scale parameter a: graphical techniques, method of moments, linear regression, and maximum likelihood method (Ramsdell, et al., 1986).

The mean μ of the Fisher-Tippett Type I distribution is (Mayne, 1979):

$$\mu = u + \frac{0.5772157}{a} \tag{2-2}$$

where, 0.5772157 is the Euler constant. The variance σ^2 of the wind speed distribution is (Mayne, 1979):

$$\sigma^2 = \frac{\pi^2}{6a^2} = \frac{1.644934}{a^2}$$

or,

$$\sigma = \frac{1.28255}{a} \tag{2-3}$$

Therefore, the scale parameter, $1/a$, is (Ramsdell, et al., 1986):

$$1/a = 0.779697\sigma \tag{2-4}$$

and the mode of the distribution, u, is (Ramsdell, et al., 1986):

$$u = \mu - \frac{0.5772157}{a} \tag{2-5}$$

If the return period associated with the given wind speed, v, is T years, then the annual frequency of exceedance is $^1/_T$ years. Therefore, $P(V > v)$ will be (Mayne, 1979):

$$P(V > v) = 1 - \frac{1}{T} = \exp\left[-\exp\{-a(v-u)\}\right] \tag{2-6}$$

or,

$$v = u - \frac{1}{a}\left[\ln\left\{\ln\left(1 - \frac{1}{T}\right)\right\}\right] \tag{2-7}$$

As PRAs for nuclear power plants are concerned with extreme winds that have return periods significantly larger than 10 years (i.e., T is large), then v can be approximated by (Mayne, 1979):

$$v = u + \frac{1}{a}\ln T \tag{2-8}$$

Equation (2-8) can be used to develop the relationship between wind speed and annual probability of exceedance (or return period) for a site using site measured wind data.

3 TORNADO STRIKE EVENTS

Tornadoes occur in thunderstorms and are often considered an appendage to a thunderstorm (Lewellen, 1990); however, tornadic circulation often extends deep into the parent thunderstorm and is part of the larger thunderstorm circulation. The most intense and long-lived tornadoes occur in a "supercell" thunderstorm (Klemp and Rotunno, 1985). Non-supercell thunderstorms can also produce tornadoes, but these are often weaker and shorter lived than those associated with supercells.

The formation of supercell thunderstorms requires specific and well-understood conditions that include a deep layer of unstable air and strong directional wind shear in the lowest 3-5 km of the atmosphere (Rotunno and Klemp, 1985). Deep layers of unstable air are produced when moist, warm near-surface air is trapped beneath a layer of cold air aloft. This air mass configuration is common in the central plains in the springtime when warm, moist air from the Gulf of Mexico is carried northward while the jet stream at higher levels is still strong. The different air currents also provide the necessary directional wind shear. It is for this reason that tornadoes are most common in "tornado alley," generally the area between the Rocky and Appalachian Mountains, and are most likely to occur in the spring. However, such conditions can occur anywhere at any time, and tornadoes have been reported in every state in the continental United States and in every month of the year.

Non-supercell tornadoes require less specific environmental conditions than supercell tornadoes. These tornadoes can be produced by any thunderstorm, even those that appear relatively weak. Most non-supercell tornadoes result from the interaction of a thunderstorm updraft with a pre-existing near-surface circulation. As the circulation is stretched vertically and thinned by this interaction, conservation of angular momentum requires that the intensity of the circulation increase in the same manner that an ice skater spins faster as they draw their arms inward.

3.1 Source of Tornado Strike Data and Means of Gathering Information

The Storm Prediction Center (SPC) of the National Weather Service (NWS) is part of the National Oceanic and Atmospheric Administration (NOAA). SPC collects information related to tornado strikes in the United States. Information is available from 1950 onward at the website http://www.spc.noaa.gov/wcm/[1]. Tornado strike-related information is given in comma separated values (csv) format, which is readable as a text file or can be imported into Microsoft® Excel® for further processing. The columns of data in the file are as given in Table 3-1.

Table 3-1. Column Information in Storm Prediction Center Tornado Strike Files

Column Number	Information
1	Tornado number, a count of tornadoes during a year
2	Year (1950–2012 present)
3	Month of tornado strike (1–12)
4	Day of tornado strike (1–31)
5	Date of tornado strike (yyyy-mm-dd format)
6	Time of tornado strike (hh:mm:ss format)
7	Time zone

[1] Last accessed on October 19, 2012.

Table 3-1. Column Information in Storm Prediction Center Tornado Strike Files (continued)	
Column Number	**Information**
8	Two letter state abbreviation
9	State Federal Information Processing Standard (FIPS) number
10	Number of tornadoes in this state in this year (Note: discontinued in 2008)
11	Tornado intensity in Fujita (F) scale or Enhanced Fujita (EF) scale after January 2007
12	Injuries
13	Fatalities
14	Estimated property loss information (Prior to 1996, this column used to categorize the damage from tornado into 9 classes varying from less than $50 to $5,000,000,000)
15	Estimated crop loss in millions of dollars (Started in 2007) (Note: an entry of 0 does not mean zero crop loss)
16	Starting latitude of tornado path in decimal degree
17	Starting longitude of tornado path in decimal degree
18	Ending latitude in decimal degree
19	Ending longitude in decimal degree
20	Tornado path length in mile
21	Tornado path width in yard
22	Number of states affected by the tornado (1, 2, or 3)
23	State number: 1 or 0 (1 = entire track in this state)
24	Tornado segment number: 1, 2, or -9 (1 = entire track)
25	1st county FIPS code
26	2nd county FIPS code
27	3rd county FIPS code
28	4th county FIPS code

As shown in Figures 3-1 and 3-2, the number of tornadoes per year increased from approximately 600 in the 1950s to approximately 1,200+ in the 2000s.

The increase in the number of tornadoes per year cannot be attributed to meteorological causes alone (Verbout, et al., 2006). Increasing public awareness, use of Doppler Radar, and the vigilance of the NWS in collecting tornado strike information have contributed to this increase. The contribution of long-term climate change, both natural and anthropogenic, to the upward trend is not known. Recent work suggests that human-induced global climate change may lead to a change in the number and/or intensity of thunderstorms (Burton, 1997).

The Fujita scale (F-scale) relates the wind speed (actually a range of wind speed) with structural damage based on observed events, as given in Table 3-2. An F-scale is assigned to the tornado based on qualitative assessment of the degree and extent of the worst damage produced (Abbey, 1976). Fujita included a description of damage associated with each wind category along with a set of photographs (NWS, 2003). The actual wind speed of a tornado is not routinely measured; rather the wind speed is inferred from the damage caused by the tornado. However, actual implementation of the Fujita scale, as describe in Table 3-2, is complicated by the frequent absence of the “standard” structures. Additionally, the most intense damage usually occurs in a small portion of the entire tornado damage path (NWS, 2003).

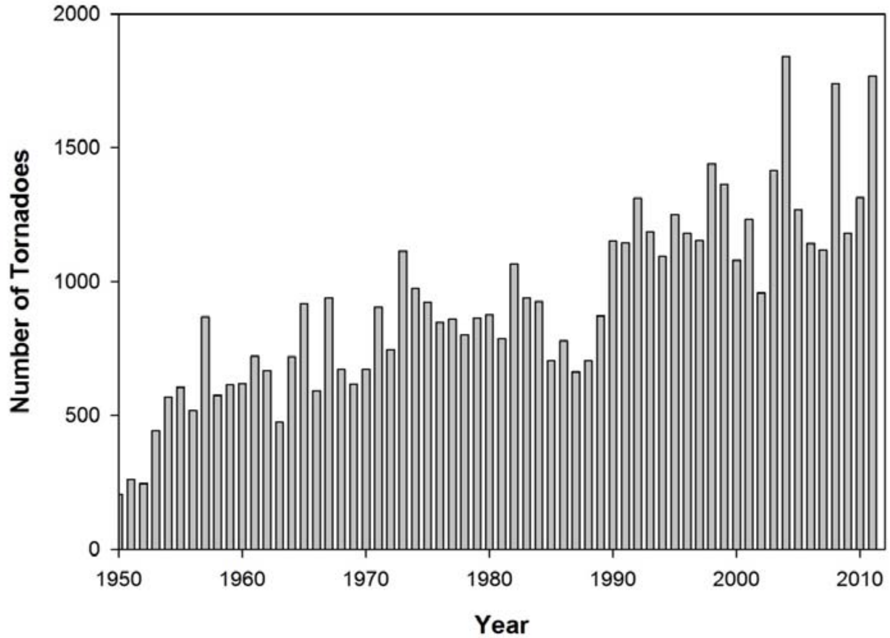

Figure 3-1. Number of Reported Tornado Strikes in the Storm Prediction Center Database

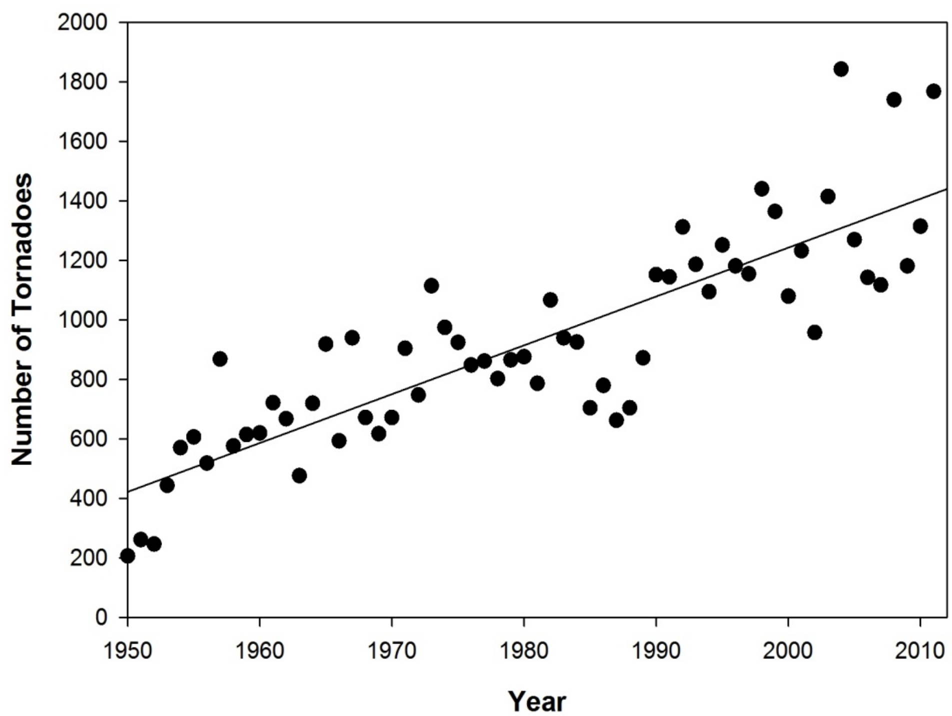

Figure 3-2. Increase in Number of Tornado Strikes in Recent Years in the Storm Prediction Center Database

Table 3-2. Fujita Scale and Related Damage Description (Adopted from NWS, 2003)		
F- Scale	**Wind Speed km/h (mph)**	**Damage Description**
F0	64–116 (40–72)	Some damages to chimney and TV antennae; breaks twigs off trees, pushes over shallow-rooted trees
F1	117–179 (73–111)	Peels surfaces off roofs; windows broken; light trailer houses pushed over or overturned; some trees uprooted or snapped; moving automobiles pushed off roads
F2	180–251 (113–157)	Roofs torn off frame houses leaving strong upright walls; weak buildings in rural areas demolished; trailer houses destroyed; large trees snapped or uprooted; railroad boxcars pushed over; light object missiles generated; cars blown off highway
F3	252–330 (158–206)	Roofs and some walls torn off frame houses; some rural building completely demolished; trains overturned; steel-framed hanger-warehouse type structures torn; cars lifted off the ground; most trees in a forest uprooted, snapped, or leveled
F4	331–416 (207–260)	Whole frame houses leveled, leaving piles of debris; steel structures badly damaged; trees debarked by small flying debris; cars and trains thrown some distance or rolled considerable distances; large missiles generated
F5	417–509 (261–318)	Whole frame houses tossed off foundations; steel-reinforced concrete structures badly damaged; automobile-sized missiles generated; incredible phenomena can occur
National Weather Service (NWS). “A Guide to F-Scale Damage Assessment.” National Oceanic and Atmospheric Administration. Silver Spring, Maryland: U.S. Department of Commerce. April 2003.		

The wind speed varies with height of the tornado. This complex wind field interacts with structures (and vegetation) and can generate additional complexities (e.g., turbulent eddies around obstacles). Moreover, structures in a region are constructed to various standards with significant variations. For example, if the construction quality of certain structure allows the roof to be blown away easily, the walls of the structure would be free-standing and would be much more vulnerable to damage (NWS, 2003).

The NWS conducts aerial surveys as well as ground surveys of the damage caused by a tornado in order to assign the F-scale rating. The ground survey team, which consists of experienced meteorologists and structural engineers (NWS, 2003), map the damage and establish the time sequence of events. Standardized forms and procedures are used in these assessments to ensure consistency. Consistency of ratings is further enhanced through the use of NWS (2003) suggested descriptors.

Shaking induced by the rapidly fluctuating wind velocities in a tornado is assumed to cause weak points in a structure to fail. Duration of the sustained strong wind and impacts from tornado-generated debris can accelerate the destruction of a structure that has already been weakened by violent shaking (NWS, 2003). In addition, multiple vortices may be present in a tornado structure (Rotunno, 1990, 1984), which makes the destruction process more complex (NWS, 2003). The individual vortices within the broader tornadic circulation may be substantially more intense than the parent tornado. These vortices evolve quickly and rotate around each other within the parent tornado circulation. The result can be very complex resulting in dynamic wind fields with complicated damage patterns.

Additional complexities arise in assigning an F3 versus an F4 or an F4 versus an F5 rating to a tornado (NWS, 2003). The original F-scale specifies that no interior walls of a structure remain standing in a F4 tornado. However, judgment may be necessary in cases with heavily damaged free-standing walls as the damage can come from a low F4 or high F5 tornado depending on the structural integrity of the standing walls. Similarly, the F5 category is assigned to a tornado where only the bare foundation of a structure remains after the tornado strike. Determining the F-scale from tornado damage withstood by structures other than frame homes and engineered structures is complicated as the failure thresholds are less well-established and in some cases, may not exist. For example, a tornado passing through open country with few structures in its path may be an F5 tornado, but not be so categorized because there is insufficient evidence of damage (NWS, 2003). Use of damage observed in trees as indicators of the wind speed of a tornado needs further research as wind-related damage to a tree depends on several factors, such as tree type (e.g., conifers typically have shallow roots), season, wetness of soil, and presence of other trees (NWS, 2003).

3.2 Tornado Strike Characteristics

3.2.1 Tornado Intensity

Tornado wind speeds are rarely measured directly, as discussed before, but are estimated from the observed damage. In 1971, Dr. Fujita classified the tornadoes into six damage categories: F0 (Gale: light damage), F1 (Weak: moderate damage), F2 (Strong: considerable damage), F3 (Severe: severe damage), F4 (Devastating: devastating damage), and F5 (Incredible: incredible damage).

Although the original Fujita scale has been used for many years to rate the intensity of tornadoes, actual implementation of this scale to rate a tornado was difficult; primarily due to lack of definitive correlation between damage and wind speed, absence of damage indicators, and not accounting for construction quality and associated variability (Texas State University, 2004). These limitations resulted in inconsistent rating of tornadoes. In some cases, the wind speed of tornadoes was overestimated, especially F4 and F5 tornadoes. To address the limitations of the original Fujita scale, a forum of scientist and engineers, organized by the Texas Tech University Wind Science and Engineering Research Center, proposed an enhancement of the original F-scale (Texas Tech University, 2004). The correspondence between the original F-scale and wind speed, as well as the Enhanced F-scale and the wind speed are given in Table 3-3. As NWS currently measures the 3-s gust wind speed, the Enhanced F-scale is in terms of 3-s gust wind speed. The original F-scale was devised in terms of the fastest quarter-mile wind speed. The equivalent 3-s gust wind speeds for the original F-scale are also given in Table 3-3. Importantly, actual tornadic winds have rarely been measured, so the 3-s wind speed gusts are based on damage models and laboratory data. The wind speed ranges associated with the F-scale have yet to be fully validated in nature.

3.2.2 Tornado Path Length, Width, and Area

As discussed before, although the tornado path can be quite complex (e.g., straight, segmented, left-turn loops, right turn loops, U-turns), a rectangular representation of the damage path is assumed to be adequate for tornado-structure interaction assessment (Twisdale and Dunn, 1983; Garson, et al., 1975a; Ramsdell and Rishel, 2007; Boissonnade, et al., 2000). This rectangular damage path is represented by a path length and path width, which is assumed constant.

Table 3-3. Tornado Intensity F-Scale Versus Wind Speed Relationships (After Ramsdell and Rishel, 2007)					
Original Fujita Scale				Enhanced Fujita Scale	
Intensity	**Description**	**Fujita Scale (Fastest-¼ mile) km/h [mph]**	**Fujita Scale (3-s gust) km/h [mph]**	**Enhanced Fujita Scale (3-s gust) km/h [mph]**	**Intensity**
F0	Light Damage	64–116 [40–72]	72–125 [45–78]	104–136 [65–85]	EF0
F1	Moderate damage	117–179 [73-112]	126–187 [79–117]	137–176 [86–110]	EF1
F2	Considerable Damage	180–251 [113–157]	188–258 [118–161]	177–216 [111–135]	EF2
F3	Severe Damage	252–330 [158–206]	259–334 [162–209]	217–264 [136–165]	EF3
F4	Devastating Damage	331–416 [207–260]	335–418 [210–261]	265–320 [166–200]	EF4
F5	Incredible Damage	417–509 [261–318]	419–507 [262–317]	>320 [>200]	EF5
Note: Wind speed in kilometer per hour (km/h) is approximate					

The SPC database has 54,653 reported tornadoes that have non-zero path length and width information and a specific tornado intensity class. Other reported tornadoes in the database with zero path length and/or path width data or a missing tornado class (i.e., an entry of −9 as the intensity class) are discarded.

The path width and path length of a tornado are non-negative, thus, it is convenient to assume the probability distribution of path dimensions has a zero lower bound. Thom (1963) used the lognormal distribution to represent both the path length and width of a tornado, as have Ramsdell and Rishel (2007). Thom (1963) also used the lognormal distribution to characterize the tornado damage path area. As both path length and width are represented by the lognormal distribution, the path, which is the product of path length and path width, will be lognormal distributed. Thom (1963) also observed a positive correlation with correlation coefficient of 0.39 between the tornado path and width. Meyer, et al. (2002) and Brooks (2004) used the two-parameter Weibull distribution (with shape parameter α and scale parameter β) to describe tornado path length and width data reported in the SPC database and concluded that the Weibull distribution produces a better fit to the data than the lognormal distribution. If $\alpha = 1$, the Weibull distribution reduces to the exponential distribution. The Weibull distribution has also been found to represent non-tornado wind speed distributions, and is widely used, for example, in the wind energy industry to estimate and model potential power production (Seguro and Lambert, 2000).

Meyer, et al. (2002) found that both tornado path length and width increase as the intensity increases based on tornado strike data from 1921 through 1995. The width increase is more noticeable in the period of 1981–1995, which they attribute to the reporting change made by the NWS from average widths to maximum widths of tornado paths.

Brooks (2004) also observed that the mean path length increases as the tornado intensity increases from F0 to F5 using reported tornadoes from 1950–2001. For example, Brooks (2004) calculated the mean path length for F0 tornadoes is 1.4 km [0.9 mi]. The mean path length increases to 54.6 km [33.9 mi] for F5 tornadoes. Similar observations have been made for tornado path width. The mean path width is 28.4 m [31.1 yd] for F0 tornadoes. Brooks (2004) calculated the mean path width increases to 555.5 m [607.5 yd] for F5 tornadoes.

3.3 Annual Strike Frequency Estimation Methodologies

3.3.1 NRC Methodology

The Pacific Northwest National Laboratory developed a probabilistic tornado hazard assessment methodology, which is documented in NUREG/CR–4461 (Ramsdell and Rishel, 2007). NUREG/CR–4461 provides the technical basis for Regulatory Guide 1.76 Design-Basis Tornado and Tornado Missiles for Nuclear Power Plants (NRC, 2007).

The annual frequency of a tornado striking a point structure with wind speed V exceeding a given speed v is the product of the annual frequency that a tornado will strike the point structure and the conditional probability that the tornado will have wind speed V exceeding v assuming a tornado strike *s* has occurred. This annual frequency is (Ramsdell and Rishel, 2007):

$$P_p(V \geq v) = P_p \times P_p(V \geq v|s). \tag{3-1}$$

Annual strike frequency P_p of the point structure is independent of the tornado intensity and is defined as (Ramsdell and Rishel, 2007)

$$P_p = \frac{A_t}{NA_r} \tag{3-2}$$

where, A_t is the total tornado path area in the region of interest, A_r, and N is the number of years of record of tornado strikes. The inherent assumption is that tornado strikes within the area of interest A_r are uniformly distributed. For this analysis, N is 62 years for the recorded data spanning 1950 through 2011. If the region of interest lies within the contiguous United States, the area A_r is approximately 3,020,000 mi^2 (Ramsdell and Rishel, 2007).

The conditional probability of the wind speed V exceeding v given a tornado strike *s* has occurred is (Ramsdell and Rishel, 2007)

$$P_p(V \geq v|s) = \frac{A_{V \geq v}}{A_t} \tag{3-3}$$

where, $A_{V \geq v}$ is the total area impacted by wind speeds greater than v. There are six values of this conditional probability, one for each intensity class of the Enhanced F-scale. Ramsdell and Rishel (2007), represented $P_p(V \geq v|s)$ by the Weibull distribution

$$P_p(V \geq v|s) = exp\left[-\left(\frac{v-65}{a_p}\right)^{b_p}\right] \tag{3-4}$$

where, a_p and b_p are parameters of the Weibull distribution. $(v-65)$ is the wind speed in excess of 65 mph, the minimum speed of a tornado.

The probability of a tornado striking a large structure is greater than for a point structure as the former has a finite length, represented by the characteristic dimension. The additional contribution to the estimated annual frequency is determined by a characteristic dimension of the structure and expected length of tornados. The additional annual strike frequency is given by (Ramsdell and Rishel, 2007):

$$P_l(V \geq v) = P_l \times P_l(V \geq v|s) \tag{3-5}$$

The additional annual strike frequency is defined by

$$P_l = \frac{A_t}{NA_r} = \frac{w_s L_t}{NA_r}. \tag{3-6}$$

The impacted area is the product of a characteristic dimension of the structure w_s and the total length of the tornado paths, L_t. The conditional probability $P_l(V \geq v|s)$ is (Ramsdell and Rishel, 2007):

$$P_l(V \geq v|s) = \frac{L_{V \geq v}}{L_t} \tag{3-7}$$

where, $L_{V \geq v}$ is the total tornado path length with speed equal to or exceeding v. Ramsdell and Rishel (2007) have modeled this conditional probability by the Weibull distribution

$$P_l(V \geq v|s) = \exp\left[-\left(\frac{v-65}{a_l}\right)^{b_l}\right] \tag{3-8}$$

where, a_l and b_l are Weibull distribution parameters. The total annual frequency of a finite structure with a characteristic dimension w_s being struck by a tornado having wind speed V exceeding v is

$$P(V \geq v) = P_p(V \geq v) + P_l(V \geq v) = \frac{A_t}{NA_r} exp\left[-\left(\frac{v-65}{a_p}\right)^{b_p}\right] + \frac{w_s L_t}{NA_r} exp\left[-\left(\frac{v-65}{a_l}\right)^{b_l}\right]. \tag{3-9}$$

The maximum wind speed of a tornado occurs only over a small fraction of the tornado path and only for a short time (maximum 5 to 10 s) at any location. Ramsdell and Rishel (2007) present the estimated fraction of the area associated with each Enhanced F-Scale wind speed class given the intensity of the tornado.

Both tornado impact area and tornado length are necessary to estimate the annual strike frequencies and design speed for finite structures. Ramsdell and Rishel (2007, Table 3-3) provide the estimates of the fraction of wind speeds by length for each intensity. The same table was used to estimate the length of each tornado for each wind speed class.

Ramsdell and Rishel (2007) estimate the annual tornado strike frequency for the contiguous United States. In addition, they divide the 48 states into three regions–West, Central, and East–and estimate the annual tornado strike frequency in each region. Additionally, they estimate the annual strike frequency in 1°, 2°, and 4° latitude-longitude boxes.

As discussed, this method assumes uniform distribution of tornado strikes within the area of interest, A_r. When the area considered in the analysis is significantly smaller than the contiguous United States, such as, 1° or 2° latitude-longitude boxes, the assumption of a uniform distribution will be violated in many boxes. Consequently, they have not reported any results in these boxes. They have suggested that there should be at least 10 strikes, although 20 or more strikes are desirable, in a box to conduct a reasonable analysis (Ramsdell and Rishel, 2007).

3.3.2 Lawrence Livermore National Laboratory (LLNL) Methodology

The Lawrence Livermore National Laboratory (LLNL) developed a probabilistic methodology to assess the tornado strike hazard at nuclear facilities (Boissonnade, et al., 2000). The U.S. Department of Energy (DOE) Standard DOE–STD–1020–2002 (DOE, 2002) specifies this method to be used to assess annual tornado strike frequency at DOE facilities. The tornado wind hazard at a given facility is characterized by the expected annual frequency (may include confidence bounds) that a tornado with wind speed exceeding a specified value will strike the facility. To generate such curves, it is necessary to model the temporal occurrences of tornado touchdowns, touchdown locations, and characteristics, (e.g., intensities, path direction, damage areas, and distribution of wind intensities) within the damage area. The major features of this methodology are (Boissonnade, et al., 2000):

- Estimating the tornado strike-related parameters and associated probability distributions using historical data.
- Modeling the site as an area [in contrast with the point structure and life-line structure in NUREG/CR–4461 (Ramsdell and Rishel, 2007)].
- Defining the hazard to occur if any part of the facility experiences the tornado (contrary to the entire facility experiencing the wind effects).
- Estimating a site-specific intensity distribution.
- Estimating a site-specific occurrence rate of tornadoes in the area surrounding the site.
- Using the historical touchdown location information throughout the contiguous United States.

Although the tornadoes can only be classified as F0 through F5, a level F6 is included in the model to accommodate potentially higher wind speeds >319 mph. It should be noted that this methodology is based on the original F-scale.

Length and width of the tornado path (tornado damage area) are correlated stochastic variables. Empirical distributions derived from the historical record of length and width as a function of F-scale intensity were used in the model. Joint discrete distributions are estimated based on the historical record of tornado path length and width in the SPC database.

This methodology assumes that the temporal occurrence of a tornado can be modeled as a stationary Poisson process. Associated with a site is an area surrounding the site, that is called the Site-Specific Tornado Effect Area (SSTEA). If a tornado strikes within the SSTEA, the site will experience wind speeds of at least intensity F0 (Boissonnade, et al., 2000).

The tornado occurrence rate λ is the expected number of tornado touchdowns in a year within the SSTEA and is a site-specific parameter. If a tornado touchdown occurs within the SSTEA, the probability that the wind speed, V, at the site exceeds v is modeled as a Bernoulli event (Boissonnade, et al., 2000):

$$P = P(V > v \,|\text{a tornado touches down within the SSTEA}) \qquad (3\text{-}10)$$

The occurrence of a tornado in the SSTEA such that the wind speed exceeds v at the site is modeled as a Poisson process with the expected annual frequency given by:

$$\lambda P = \lambda P(V > v|\text{a tornado touches down within the SSTEA}) \tag{3-11}$$

The conditional probability [Eq. (3-11)] that the wind speed at the site exceeds v is a function of the tornado characteristics, which are stochastic variables:

- Intensity of the tornado
- Path direction
- Touchdown locations within the SSTEA
- Size of the tornado damage area (TDA) (i.e., the area in which the wind speeds are at least of intensity F0)
- Variation of the wind speed (i.e., wind field) within the SSTEA

The tornado wind hazard at the site is (Boissonnade, et al., 2000):

$$EF(v) = \lambda \sum_{i=0}^{6} P(V > v|\text{an } Fi \text{ tornado occurs in SSTEA}) \times P_T(Fi) \tag{3-12}$$

where, $P_T(F_i)(i = 0, 1, \ldots, 6)$ is the tornado intensity distribution. In this and later equations, F_i $(i = 0, 1, \ldots, 6)$ corresponds with the tornado intensity scale F0, F1, …, F5, F6 (F6 is an intensity class only used in this model).

The LLNL model (Boissonnade, et al., 2000) uses several relationships between tornado intensity and tornado wind speed given by Twisdale (1978). Within the damage area (tornado path area), the wind intensity varies. This variation has been modeled by constructing areas of increasing 'local intensity' as included rectangles, centered lengthwise at the center of the damage area. Due to combined effects of the radial and tangential wind velocities of a tornado, the wind field profile across the path width is asymmetric about the center of the tornado path. This asymmetry has been modeled by offsetting the center along the width of the included rectangle to the right of the center of the tornado path. Dimensions of the sub-areas of local intensity are proportional to the dimensions of the path $(\delta L, \delta W)$. Several sets of proportional values, based on the literature, have been considered in the LLNL model.

The probability of the wind speed at a site given a F_i tornado touchdown is

$$P(V > v|F_i \text{ in SSTEA}) = \sum_{j \le i} P(V > v|F_j, F_i) \int_{A(S_{ij})} dF(x, y|SSTEA) \tag{3-13}$$

In Eq. (3-13), $P(V > v|F_j, F_i)$ is the probability that the wind speed at the site is larger than v, given winds of intensity F_j within the path of a F_i intensity tornado as the tornado wind speed varies within the path. $dF(x, y|SSTEA)$ is the density function of the distribution of touchdown locations given that a tornado touchdown within the SSTEA has taken place. $A(S_{ij})$ is the F_j intensity subarea within a F_i tornado path(i.e., the touchdown locations such that the wind intensity at the site would be level Fj). $A(S_{ij})$ is a function of the tornado path heading θ, length L and width W of the tornado damage area.

Substituting Eq. (3-13) in Eq. (3-12), the tornado wind hazard is

$$EF(v) = \lambda_s \sum_{i=0}^{6} \left\{ \sum_{j \le 1} P\left(WS > v \middle| F_j, F_i\right) \int_\theta \int_{(L,W)_i} \int_{A(S_{ij})} dF(x,y|\text{SSTEA}) dH(L,W) dG(\theta) \right\} \times P_T(F_i) \tag{3-14}$$

The tornado wind hazard model then depends on the estimates of the expected frequency, the exceedance probability of V, and the distributions of 'true' tornado intensities in the model.

The tornado intensity classification reflects the maximum wind speed within the tornado and depends on observations of the damage produced by the tornadoes. Given the tornado damage, human judgment is required to translate the observed damage to an intensity level, which may introduce classification error. The method treats this classification error as a stochastic error and represents it by a misclassification matrix of conditional probability p_{ij}:

$$p_{ij} = P(\text{true intensity is } F_i | \text{recorded intensity is } F_j) \tag{3-15}$$

The estimate of site-specific tornado occurrence was based on historical tornado touchdown locations in the SPC tornado database. The SPC database was used to estimate the distribution of path heading and tornado path length and width $H(L, W)$. $P(V > v|F_j, F_i)$ was estimated on the basis of the F-scale to wind speed relations and the distribution of wind speeds used to estimate the intensity distribution. An estimate of the expected annual frequency of tornadoes strikes in the contiguous U.S., λ, was developed. Additionally, a two-dimensional kernel was used to estimate the touchdown locations throughout the United States. Given the locations of the historical tornadoes in the contiguous United States in the SPC database, the two-dimensional kernel is (Boissonnade, et al., 2000):

$$dF(x,y) = f(x_1, x_2) = \frac{1}{2\pi h_1 h_2} \sum_{i=1}^{n} exp\left\{ -\frac{1}{2} \sum_{j=1}^{2} \left(\frac{x_j - x_{ij}}{h_j} \right)^2 \right\} \tag{3-16}$$

where, (x_1, x_2) and (x_{i1}, x_{i2}), i = 1, …, n, are the map coordinates (latitude, longitude) of an arbitrary location in the contiguous United States and the map coordinates for touchdown locations of historical tornadoes, respectively, and h_1 and h_2 are the smoothing parameters used to model the expected variability of locations of future tornadoes relative to the locations of the historical tornado strike locations. LLNL used expert judgment to assign the 'best' value of h_1 and h_2. The assigned values of h_1 and h_2 were $\sigma_1 n^{-1/6}$ and $\sigma_2 n^{-1/6}$ respectively, where σ_1 and σ_2 are the standard deviations of the latitude and longitude of the location, and n is the number of historical locations of tornado strikes. LLNL (Boissonnade, et al., 2000) showed that

$$\lambda_s dF(x,y|SSTEA) = \lambda dF(x,y) \tag{3-17}$$

Combining Eqs. (3-14), (3-15), and (3-17), the tornado wind hazard at a site anywhere in the contiguous United States is defined as (Boissonnade, et al., 2000):

$$EF(v) = \lambda \sum_i \left\{ \sum_{j \leq 1} P(WS > v|F_j, F_i) \int_\theta \int_{(L,W)_i} \int_{A(S_{ij})} dF(x,y) dH(L,W) dG(\theta) \right\} \cdot \left[\sum_k p_{ik} P_R(F_k) \right] \quad (3\text{-}18)$$

The TORNADO code (Boissonnade, et al., 2000) uses this model, as given in Eq. (3-18), to estimate the tornado wind hazard at any site within the contiguous United States. It should be noted that the TORNADO code was developed before 2004. As discussed in Section 3.2.1, enhancement of the Fujita scale was proposed in 2004. NWS adopted the Enhanced Fujita scale in February 2007 (Ramsdell and Rishel, 2007). Consequently, the TORNADO code needs to be updated to account for the Enhanced Fujita scale.

3.3.3 Methodology by Twisdale and Dunn

Twisdale and Dunn (1983) developed a tornado wind hazard model considering the probabilistic wind speed and the interaction of a tornado with a structure or a facility. The probability of the maximum wind speed V exceeding a given wind speed v due to a tornado striking a structure or a facility within a time period T, $P_T(V > v)$, is (Wen and Chen, 1973; Twisdale and Dunn, 1983; Banik, et al., 2007):

$$P_T(V > v) = \sum_{N=0}^{\infty} P(V > v|N) \times P_T(N) \quad (3\text{-}19)$$

The number of tornadoes, N, in the time period T can vary from 0 to ∞. $P(V > v|N)$ is the conditional probability that a structure will experience a wind speed larger than v given N tornado strikes within this time period. $P_T(N)$ is the probability of N tornadoes striking the facility (or the structure) during time T and is a stochastic model of tornado occurrence at the site where the structure (or the facility) is located. $P_T(V > v)$ is the probability that the wind speed $V > v$ occurs at least once in a time period T due to tornadoes of intensity F_i.

Assuming that tornado strikes are generated by a Poisson process (i.e., the tornadoes are independent with no memory of past occurrences), the probability of N tornadoes during a time period T is (Wen and Chen, 1973; Twisdale and Dunn, 1983; Banik, et al., 2007)

$$P_T(N) = \frac{(\lambda T)^N}{N!} e^{(-\lambda T)} \quad (3\text{-}20)$$

where, λ is the mean recurrence rate of tornadoes in a region with the area S. The maximum likelihood estimator of λ is N/T assuming that the tornadoes occur randomly within region S. Substituting Eq. (3-20) in Eq. (3-19) and assuming each tornado is independent, Wen and Chen (1973) showed that

$$P(V > v|N) = 1 - [1 - P(V > v)]^N \quad (3\text{-}21)$$

If $\lambda P(V > v)T \leq 0.01$, then $P_T(V > v)$ will be approximately equal to $\lambda P(V > v)T$ with an accuracy of 0.5% (Twisdale and Dunn, 1983).

Wen and Chen (1973) determined that for a Poisson process, $P_T(V > v)$ is:

$$P_T(V > v) = 1 - e^{[-\lambda P(V>v)]T} \tag{3-22}$$

The probability of the peak tornado-generated wind speed V exceeding v during time period T, $P(V > v)$ is (Twisdale and Dunn, 1983; Banik, et al., 2007):

$$P(V > v) = \sum_{i=0}^{5} P(V > v|Fi)P(Fi) \tag{3-23}$$

In Eq. (3-23), F_i (i = 0, 1, 2, 3, 4, 5) represents the tornado intensity in i-th Enhanced F-scale, $P(V > v|F_i)$ is the probability that the wind speed V is greater than v given the occurrence of a tornado of intensity F_i, and $P(F_i)$ is the probability that the tornado has an intensity F_i.

The total tornado risk can be estimated using the mean occurrence rate λ for all intensities and substituting Eq. (3-23) in Eq. (3-22). Twisdale and Dunn (1983) provided an alternative formulation of the total risk $P_T(V > v)$ assuming the occurrence of different intensity tornadoes to be different events. This stochastic models employ λ_i, the annual mean occurrence rate of tornadoes with intensity F_i (i = 0, 1, 2, 3, 4, 5).

The total risk from all tornadoes with intensities F0, F1, F2, F3, F4, and F5 can then be estimated assuming Eq. (3-20) is applicable to tornadoes of intensity F_i (Banik, et al., 2007):

$$P_T(V > v) = \sum_{i=0}^{5} \left[1 - e^{\{-\lambda_i P(V>v|F_i)T\}}\right] \tag{3-24}$$

where, λ_i is the occurrence rate of a tornado with intensity F_i.

The probability of a tornado of intensity F_i striking a facility is (Twisdale and Dunn, 1983):

$$P(V > v|F_i) = \begin{cases} \frac{A_0}{S}, & A_0 \le S \\ 1, & \text{otherwise} \end{cases} \tag{3-25}$$

where, A_0 is the tornado origin area, defined as the locus of all points that would result in a strike on the facility (Twisdale and Dunn, 1983). An inherent assumption of Eq. (3-25) is that the tornado strike locations are distributed uniformly over the area S, which can be the continental United States, three tornado regions (Regions I, II, and III) (NRC, 2007), or within 160 km [100 mi] radius of a nuclear power plant.

Twisdale and Dunn (1983) used two alternative definitions of a tornado strike. A strike by a tornado can be taken if at least one point of the facility/structure is within the tornado path with wind speed $V \geq v$ (union definition). Alternatively, the tornado strike may be defined if the entire facility/structure is within the tornado path (intersection definition). Although the path traversed by a tornado may be complex with several turns, Twisdale and Dunn (1983) judged that a rectangular-shaped tornado path area would be adequate for engineering calculations.

Additionally, the peak wind speed varies significantly across the tornado path width and throughout the life of the tornado (i.e., along the tornado path length direction). Hoecker (1960) was first to observe this in a tornado striking Dallas, Texas, in April 1957. The maximum wind speed to be experienced by a facility or a structure is dependent on the offset distance from the centerline of the tornado path (i.e., path width direction) (Twisdale and Dunn, 1983). This variation is generally explained using the Rankin vortex theory (Garson, et al., 1975a,b).

Variation of wind speed during the life of the tornado is well documented by observed damage characteristics and photographs (Twisdale and Dunn, 1983). Twisdale and Dunn (1983) provided a table of adjustment factors based on 150 tornadoes and using the original F-scale. Information in the table indicates that an F5 tornado has F5 wind speeds over only 14.9 percent of the path length. Therefore, assuming same wind speed over the entire tornado path length would significantly overpredict the probability of exceedance of the wind speed $P(V > v|F_i)$ (Twisdale and Dunn, 1983).

Twisdale and Dunn (1983) developed a Monte Carlo-based simulation code TORRISK to estimate the annual frequency of peak tornado-generated wind speed V being equal or exceeding a specific speed v, $P(V \geq v)$. This program samples tornado intensity, path length, path width, and direction from the historical tornado strike database and then calculates λ [Eq. (2)], tornado intensity distribution $P(F_i)$ [Eq. (3-23)], and the tornado path characteristics with respect to the structure or facility. The wind-field characteristics of the tornado are determined and their compatibility with the tornado path width checked. Tornado-structure interaction using either a union or intersection definition was calculated. Using a Poisson distribution to simulate the tornado occurrences, the wind speed probability $P(V \geq v)$ is estimated.

3.3.4 Summary and Discussion

In this report, three methodologies to estimate the annual tornado strike frequency estimation have been described. All three methodologies assume that tornadoes occur randomly and use the Poisson distribution to model the occurrences in a given time period T, which is usually 1 year. The LLNL (Boissonnade, et al., 2000) methodology uses several weighting factors to account for model variations, based on expert elicitation and experience, which makes direct comparison with other methods difficult. Moreover, both the LLNL and Twisdale and Dunn (1983) methodologies use a Monte Carlo-based simulation program to estimate the annual tornado strike frequency at a site. These simulation codes are not publicly available for comparison with the NRC (Ramsdell and Rishel, 2007) method.

All methods use the historic tornado strike records to estimate the mean tornado occurrence rate within a reference area surrounding a specific site (or a structure or a facility). Only the NRC method (Ramsdell and Rishel, 2007) uses the current standard of using the Enhanced Fujita scale to classify the tornado intensity. Path length and width of the tornado strikes are used to model the distribution of path characteristics. Both NUREG/CR–4461 (Ramsdell and Rishel, 2007) and Twisdale and Dunn (1983) inherently assume statistically homogeneous tornado strike locations within the reference area. LLNL (Boissonnade, et al., 2000) used a two-dimensional kernel to estimate the variance. Smoothing parameters in the kernel model were varied to find the optimum values to represent the path variation.

All methods use a wind field model to account for variation of wind speed (and damage) within a tornado path. The geometric interaction between a structure (or a facility) and the tornado path is accounted for using either the union or intersection definition, although rigor differs. For example, NUREG/CR-4461 (Ramsdell and Rishel, 2007) uses the characteristic dimension of the structure and tornado path length to estimate tornado strike frequency of a finite structure (Eq. 3-6). On the other hand, Twisdale and Dunn (1983) used either the union or the intersection definition to estimate the tornado strike frequency of a finite structure. Both tornado path length and width along with the tornado path heading with respect to the structure, modeled as a polygon, were used to estimate the tornado strike frequency.

Use of the Poisson distribution to model tornado occurrences may introduce some uncertainty in the estimated annual strike frequency. A Poisson process produces independent events. However, tornadoes are more frequent in the summer months than in winter. Additionally, as discussed, several tornadoes can occur (sometimes simultaneously) from a storm system. A good example is the tornado outbreak during April 25–28, 2011, which produced 358 tornadoes in Alabama, Arkansas, Georgia, Mississippi, Tennessee, and Virginia. Maximum number of tornadoes (total 205) developed on April 27, 2011. Formation of clusters of tornadoes will produce significant departure from the Poisson distribution (Thom, 1963). Thom (1963) suggested that the Polya process may be a better model to represent the tornado occurrence with time as it has a time-dependent occurrence rate allowing accounting for correlation among tornadoes in a tornado cluster. Recently, Drton, et al. (2003) proposed a Markov chain model to model the occurrence of tornadoes, as the tornadic activity in a particular day tends to be dependent on the conditions on a previous day, which could be more effectively represented via a Markov process.

All these methods use the tornado reference area. Any tornado that strikes within this area would affect the facility or the structure. Both Twisdale and Dunn (1983) and LLNL (Boissonnade, et al., 2000) models have a component to account for the direction of the tornado path with respect to the structure. It is not clear how this directional effect was modeled in Boissonnade, et al. (2000). NUREG/CR–4461 (Ramsdell and Rishel, 2007) model does not account for the path direction, consequently, a tornado travelling away from the structure would have influence similar to that by a tornado moving toward it. This assumption would add conservatism to the estimated annual strike frequency.

Additionally, the appropriate size of the reference area is not clearly defined. These methods assume that tornado strike locations are uniformly distributed in space so that the strike probability of a point or a finite structure can be estimated as a function of the ratio of tornado path area and the tornado reference area. Figure 3-3 from the Storm Prediction Center shows the tracks of tornadoes from 1950 through 2011. It is evident that tornado strike density (number of tornado strikes in a unit area) varies. Moreover, some areas of the country exhibit highly non-continuous nature of thunderstorm and tornado strike distribution. The most well known is in the Denver area (Crook, et al., 1991), where one side of the mountain has large tornado strike frequency whereas the other side of the mountain (over a distance of 10–20 km) exhibit much lower tornado strikes. NUREG/CR–4461 provides the annual tornado strike frequency estimates using the continental United States and each of the three regions of these 48 states as reference areas. Additionally, NUREG/CR–4461 estimates the annual strike frequency for each 1°, 2°, and 4° latitude-longitude box. A practical difficulty arises when trying to establish the size of the reference area (1°, 2°, or 4°) for a site, especially if the number of recorded strikes is small (e.g., western United States). Figure 3-4 from the U.S. Department of Energy shows their analysis of the annual tornado strike frequency at Yucca Mountain, Nevada (Bechtel SAIC Company, LLC, 2008). With so few recorded strikes surrounding the site, it is difficult to decide what would be the appropriate reference area. Consequently, the estimated annual strike frequency may be very uncertain and the 90 percent confidence interval about the mean, as developed in Ramsdell and Rishel (2007), may be large. The size of the reference area appears to be a function of the tornado strike density, a site-specific parameter. Therefore, determination of the appropriate size of the reference area to estimate the annual tornado strike frequency for a given site (or a facility) needs further investigation.

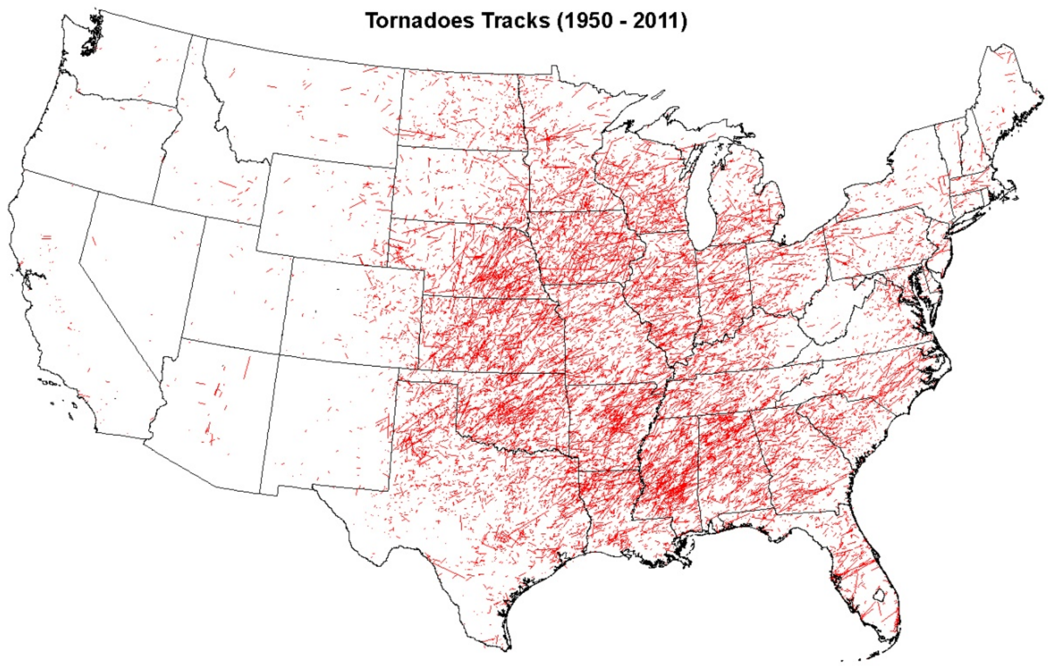

Figure 3-3. Tracks of Tornadoes from 1950 Through 2011 Within the Contiguous United States (From National Weather Service Strom Prediction Center)

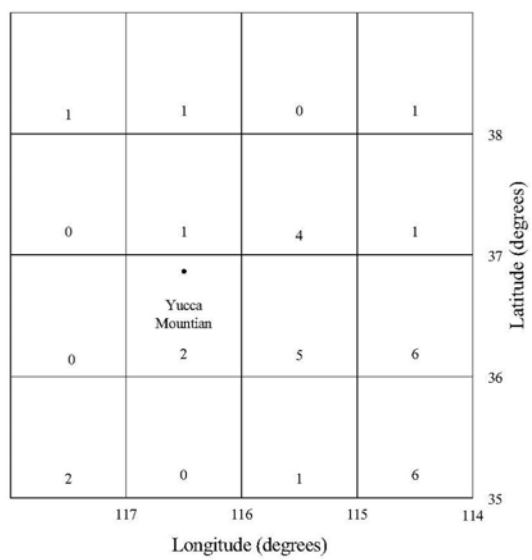

Figure 3-4. Tornado Strike Data Around the Yucca Mountain Site (From Bechtel SAIC Company, LLC, 2008)

4 HURRICANE AND HIGH WIND EVENTS

Most high wind events are generated by severe weather phenomena such as hurricanes, tornadoes, etc. Other phenomena, such as mountain downslope wind can also generate a high wind phenomenon (Liu, 1991). This chapter deals with hurricane-related high wind phenomena following the suggestion of Ramsdell, et al. (1986) as tornadoes affect only a relatively small area compared to a hurricane.

A hurricane is an intense weather system of strong thunderstorms. It forms in the tropics and has a well-defined surface circulation with a maximum sustained winds of 119 km/h [74 mph] or higher. Hurricanes are categorized using the Saffir-Simpson Hurricane wind scale. Saffir-Simpson scale rates hurricanes into five categories based on their wind speed (National Hurricane Center, 2012): Category 1 {119–153 km/h [74–95 mph]}, Category 2 {154–177 km/h [96–110 mph], Category 3 {178–208 km/h [111–129 mph]}, Category 4 {209–251 km/h [130–156 mph]}, and Category 5 {252 km/h [157 mph] or higher}.

4.1 Source of Data

Although the National Hurricane Center maintains a hurricane database, the data need further processing in order to estimate the annual frequency of winds from hurricanes that have speeds exceeding a certain value. This methodology is given in NUREG/CR–7705 (Vickery, et al., 2011) and is described below. A similar methodology has been used to estimate the wind speed data presented in ASCE/SEI 7–10 (ASCE/SEI. 2010).

4.2 Hurricane Strike Frequency Estimation Methodology

The National Hurricane Center uses several models (e.g., GFS, GFDL, HWRF) to forecast tropical hurricanes that may affect the United States. These models forecast the track and intensity of the hurricanes in a real time (e.g., every 6 hours). However, these forecasts, although extremely valuable for emergency preparedness of nuclear power plants, cannot be used to estimate the annual strike frequency of hurricanes at a specific location. Historical records of hurricane-generated winds can provide an estimate of the annual strike frequency of hurricanes at a specific location with wind speed larger than a specified value. Use of historical data is also helpful in obtaining the design-basis wind load at a given location for a structure (ASCE/SEI, 2010). The methodology described in Vickery, et al., (2009a) determines the design-basis wind load on a structure in ASCE/SEI 7–10 (ASCE/SEI, 2010). NUREG/CR–7005 (Vickery, et al., 2011) modified this methodology to estimate the extreme wind distribution (wind with annual frequency of occurrence 10^{-7}) from the Atlantic and Gulf of Mexico hurricanes. This methodology has been adopted in Regulatory Guide 1.221 (NRC, 2011) and is briefly described below.

ASCE/SEI 7–10 (2010) defines the hurricane-prone regions of the Unites States to include the coastal regions of the Gulf of Mexico and the Atlantic Ocean. In these regions, the wind speed from a hurricane is estimated using simulation techniques and extreme value statistical procedures. The model accepted by ASCE/SEI is the Monte Carlo simulation model described by Vickery, et al. (2009a). NUREG/CR–7005 (Vickery, et al., 2011) made minor improvements of this model including sampling key climatic parameters, such as radius to maximum winds, central pressure difference, and translation speed, from probability distributions derived from the historical data. Using this simulation model, the 3-s peak-gust wind, measured at a height of 10 m [30 ft] in flat open terrain, at 3,575 grid points in the eastern and middle portions of the United States is estimated. The contour maps of the wind speed at a probability of exceedance of 10^{-6} and 10^{-7} per year are provided on 0.1 degree grid. The simulation model has three major components: (i) a hurricane track model, (ii) a hurricane intensity model, and (iii) a hurricane wind field model. The model is summarized below. Details of the model are available in NUREG/CR–7005 (Vickery, et al., 2011).

Track Model: The track model describes the variation of the heading and translation speed of a hurricane. The starting location (origin of the hurricane), data, time, heading, and translation speed of a hurricane are sampled from the National Hurricane Center HURDAT database, which contains information of all tropical cyclones of the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea since 1881. The effects of seasonal climatology on storm initiation are preserved by using the historical records. The simulation model estimates the new storm position and speed, based on information in the previous location, in 6-hr increments (Vickery, et al., 2011). The model used for estimating the hurricane track is represented by Eqs. (2-1a) and (2-1b) of Vickery, et al. (2011). Comparison with the historical records indicates that hurricane tracks are reasonably modeled by these two equations.

Intensity Model: The relative intensity of a storm at any location in the simulation is a function of the scaled vertical wind shear at that location and the relative intensity at the previous three steps (or locations at these steps). It is modeled by Eq. (2-2) of Vickery, et al. (2011). The model proposed by Holland (1980) is used to estimate the surface wind speeds of the hurricane, which is a significant improvement over modeling the pressure field using empirical models. The relationship proposed by Darling (1991) is used to determine the relative intensity from the information on central pressure.

The value of the parameter in the model developed by Holland (1980) typically decreases and radius to maximum winds increases after the landfall. Two models are used to estimate the radius to maximum winds parameter using the historical data, one model has been applied to Atlantic hurricanes and another to Gulf of Mexico hurricanes (Vickery, et al., 2011).

Wind Field Model: NUREG/CR–7005 (Vickery, et al., 2011) assumed that the large-scale structure of the wind field of a hurricane changes slowly. Under this assumption, the wind field can be considered constant at any instant so that the Slab model is applicable. The Slab model has been used to estimate the wind speed at a particular location using the central pressure, the Holland model for intensity, and the translation speed. The Slab model uses the finite difference method to solve the steady-state wind field over a set of rectangular grids. Vickery, et al. (2009b) developed an empirical model of variation of mean wind speed of a hurricane with height. This model has been incorporated in the model described in NUREG/CR–7005 (Vickery, et al., 2011).

In the modified model described in NUREG/CR–7005 (Vickery, et al., 2011), a weighted sampling method instead of the full Monte Carlo technique, as used in Vickery, et al. (2009a), is used to simulate hurricane wind speed at an annual exceedance probability of 10^{-6} and 10^{-7}. An assumption has been made that the wind speeds with annual exceedance probabilities of 10^{-6} and 10^{-7} are from landfall hurricanes. Consequently, all simulated hurricanes that would not make landfall can be eliminated from further processing.

The probability that a tropical hurricane with wind speed V exceeding v during time period t is (Vickery, et al., 2011):

$$P_t(V > v) = 1 - \sum_{x=0}^{\infty} P(V > v|x) p_t(x) \quad (4\text{-}1)$$

where, $P(V > v|x)$ is the probability that velocity V is less than v when x number of storms took place and $p_t(x)$ is the probability of x storms occurring during time period t. Vickery, et al., (2011) assumed that $p_t(x)$ has Poisson distribution and time period t is 1 year. Then, the annual probability P_a of exceeding a given speed v is

$$P_a(V > v) = 1 - \exp[-nP(V > v)] \quad (4\text{-}2)$$

where, n is the average number of storms occurring annually in a given location and $P(V > v)$ is the probability that the wind speed of hurricanes is larger than v at that location. $P(V > v)$ is computed from the a simulation that uses the weighted sampling method.

Additionally, to incorporate the effects of small fast-moving hurricanes in estimating the extreme winds, the formulation of the gust factor has been modified assuming that the hurricane wind trace consists of a series of piecewise stationary segments. This is in contrast to the assumption made in Vickery, et al., (2009a) that the strongest wind in a hurricane lasts for approximately an hour.

In addition to the meteorological parameters, ground surface roughness adds additional uncertainty to the estimated wind speed. While friction directly slows the near-surface wind, a rapid change in surface roughness (e.g., when a hurricane moves from water to land) can result in an increase in frictional convergence toward the center of the storm that can potentially induce rapid but short-term intensification.

In reality, the strongest hurricane winds can be short lived and small scale, and are often associated with thunderstorm circulation superimposed on the broader hurricane circulation. Thunderstorms within hurricanes are also known to produce tornadoes, which can exacerbate the damage. NUREG/CR–7005 (Vickery, et al., 2011) has introduced a wind field modeling error term to account for asymmetries in the model pressure fields and to capture small-scale features, such as extreme convective gusts. As a result of inclusion of the error term in the model, the estimated maximum peak gust increased by 1.7 to 1.8 times of the mean wind speed.

NUREG/CR–7005 (Vickery, et al., 2011) presents the estimated wind speed from hurricanes at the annual exceedance probabilities of 10^{-6} and 10^{-7} in grid format as well as contour plots (Vickery, et al., 2011, Figures 3-1 and 3-2). At an annual probability of exceedance of 10^{-7}, the estimated hurricane-generated wind speed exceeds the tornado-generated wind speed along the Atlantic coastline south of the Virginia–North Carolina border (Vickery, et al., 2011, Figure 3-6). The maximum peak gust of 320 km/h [200 mph] with an annual exceedance probability of 10^{-7} occurs in the Florida Keys 100 m [330 ft] inland from the coast.

5 IDENTIFIED EXPERTS

Several researchers can be identified as experts in the field of wind-related hazard assessment. Compiling an all-inclusive listing can become a significant endeavor by itself. Instead, researchers who have contributed to NRC-related activities are identified in this report. Brief information about their contribution in wind-related hazard areas is given below.

J.V. Ramsdell, Jr.

He is a member of the Radiological Science and Engineering Group of the Pacific Northwest National Laboratory. His expertise includes dispersion modeling and applied atmospheric boundary layer description. He is the lead author of NUREG/CR–4461, Tornado Climatology of the Contiguous United States (all versions) and has been on the review teams for DOE, NRC, U.S. Environmental Protection Agency, and National Research Council. He has presented to the National Academy of Sciences Review panels and the Advisory Committee on Reactor Safeguards of NRC.

L. Twisdale

He is a principal engineer and the executive vice president of the Applied Research Associates, Inc. (ARA). He is also the director of technical quality. He has developed a tornado hazard model (Twisdale and Dunn, 1983), described in this report, and also contributed to the LLNL model TORNADO. He is part of the team that developed the ARA catastrophe modeling software HurLoss for the U.S. hurricane risk for the insurance industry. He has also contributed in developing the hurricane wind hazard model used in ASCE 7–10 and NUREG/CR–7005 Technical Basis for Regulatory Guidance on Design-Basis Hurricane Wind Speeds for Nuclear Power Plants.

P.J. Vickery

He is a principal engineer at the Applied Research Associates, Inc. (ARA). He developed the damage functions used in HurLoss, the catastrophe modeling software of U.S. hurricanes that result in reliable damage and loss estimates from a hurricane strike. He is the lead author in developing the hurricane wind hazard model used in ASCE 7–10 and NUREG/CR–7005 Technical Basis for Regulatory Guidance on Design-Basis Hurricane Wind Speeds for Nuclear Power Plants. This document is part of the basis for Regulatory Guide 1.221, Design-Basis Hurricane and Hurricane Missile Speeds for Nuclear Power Plants.

Emil Simiu

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APPENDIX A

ESTIMATION OF TORNADO WIND SPEED USING NUREG/CR–4461, REV. 2, TORNADO CLIMATOLOGY OF THE CONTIGUOUS UNITED STATES

APPENDIX A

ESTIMATION OF TORNADO WIND SPEED USING NUREG/CR–4461, REV. 2, TORNADO CLIMATOLOGY OF THE CONTIGUOUS UNITED STATES

The procedure for estimating the annual frequency of a tornado striking a finite structure following NUREG/CR–4461 (Ramsdell and Rishel, 2007) is described using the Microsoft® Excel® spreadsheet 1950-2011_tornado.xlsx. This spreadsheet is based on the tornado strike data files from the National Weather Service (NWS) website (http://www.spc.noaa.gov/wcm/#data). The comma separated values (csv) format was read using Microsoft® Excel® and saved in Excel xlsx format. The data file gives more columns of information than needed in this analysis. Therefore, only those columns of information needed are kept in the data file. They are:

Column	Information	Column	Information	Column	Information
A	Tornado Number	F	State	K	Ending Longitude
B	Year	G	Magnitude (EF scale)	L	Length (mile)
C	Month	H	Starting Latitude	M	Width (yard)
D	Day	I	Ending Latitude		
E	Time	J	Staring Longitude		

Other columns are derived from these columns. They are:

Column	Information	Column	Information
N	Width (mile)	R	Area (km2)
O	Length (km)	S	ln (length_mi)
P	Width (m)	T	ln (Width_mi)
Q	Area (mi^2)	U	ln (Area_mi^2)

Step 1

Sort the database in terms of tornado intensity F0, F1, F2, F3, F4, and F5. Each may be given a cell highlight color for easy visual identification.

Step 2

Calculate the number of tornadoes under each category (Cells X4, X5, X6, X7, X8, and X9). For example, the number of tornadoes in each intensity class are as follows: F0 = 24,285; F1 = 18,375; F2 = 8,789; F3 = 2,470; F4 = 653; and F5 = 81 using the NWS databases for tornadoes in 1950–2011.

Step 3

Unfortunately, NWS may not have complete information for each tornado. For this analysis, complete information includes tornado (i) intensity in Enhanced Fujita Scale, (ii) path length, and (iii) path width. NWS uses –9 if information is missing for tornado intensity. Additionally, NWS may report path length and/or path width to be zero. It also may be the case that the NWS database has information for some tornadoes on either path length or path width, but not both. Although it may be argued that if at least one parameter has information, it should be considered in the analysis; however, the corresponding parameter to describe the path is missing. In this analysis, only those tornadoes that have data for both path length and path width are considered for further analyses. NUREG/CR–4461 (Ramsdell and Rishel, 2007), however, has adopted the other approach, which will result in a different number of tornadoes for path length, path width, and path area analyses (Step 5 and beyond). Also, note that information is generally missing for tornadoes with lower intensity, such as F0. Tornadoes with higher intensities, such as F3–F5, will generally have all information, as they are infrequent but important events. Additionally, many tornadoes, especially from early years of tornado records, have ending latitude and longitude information missing. This lack of information will only be important if the tornado paths are plotted. They will not affect the analysis described here.

To avoid taking the logarithm of negative values or zero, all tornado records with such records are deleted.

Step 4

Use the 'Descriptive Statistics' function under 'Data' in EXCEL to determine the number of tornadoes in each category along with other information (e.g., Mean, Median, Minimum, Maximum, etc.).

Step 5

Assume tornado path length (mi), path width (ft), and path area (mi^2) are lognormally distributed so that ln (parameter) is normally distributed.

Calculate ln (path length), ln (path width), and ln (path area) in columns S, T, and U.

Step 6

Determine the descriptive statistics for path length, width, and area in logarithmic space for each tornado intensity category:

Average U = AVERAGE (S2:S24286) [for average path length of F0 tornadoes]

Variance V = VAR (S2:S24286) [for variance of path length of F0 tornadoes]

Median = exp (U)

Expected Value = exp (U + V/2)

5^{th} and 95^{th} Percentile = $exp\left[U + \frac{V}{2} \pm Z_{\propto/2}\sqrt{\frac{V}{n} + \frac{V^2}{2(n-1)}}\right]$

where n = number of samples. For standard normal variate when sample size (i.e., number of events larger than 30) is large, $Z_{\alpha/2}$ is 1.645. For small sample size , Z is replaced by $t_{\nu/2}$ distribution with ν = n-1 (use t-distribution statistical table for value of $t_{\nu/2}$).

Tornado Path Area Analysis for a Point Structure

Step 7

As shown in Table A–1, which is reproduced from Table 3-1 of NUREG/CR–4461, the entire tornado path area does not experience wind speeds in the range prescribed for each tornado intensity.

Table A–1. Tornado Path Area Intensity Distribution for Point Structure Design Wind Speed (From Ramsdell and Rishel, 2007)							
		Recorded Tornado F Scale					
	Wind Speed (mph)	**F0**	**F1**	**F2**	**F3**	**F4**	**F5**
EF0	65–85	1	0.772	0.616	0.529	0.543	0.538
EF1	86–110		0.228	0.268	0.271	0.238	0.223
EF2	111–135			0.115	0.133	0.131	0.119
EF3	136–165				0.067	0.056	0.070
EF4	165–200					0.032	0.033
EF5	>200						0.017

Table A–1 shows that 100 percent of the area impacted by F0 tornadoes has wind speeds in the range of 65 to 85 mph. For F1 tornadoes, 22.8 percent of the area has wind speeds in the 86 to 110 mph range, 77.2 percent of the area has wind speeds in the 65–85 mph range. Similarly, 11.5 percent of the area impacted by F2 tornadoes has wind speeds in the 111 to 135 mph wind speed range, 26.8 percent has wind speeds in the 86 to 110 mph range, and the remaining 61.6 percent of the area has wind speeds in the 65 to 85 mph range.

Step 8

Using Expected Value

Tornado Path Area by F-scale (AH71:AH76)

F0 tornado area (AH71) = expected F0 area (AH46) * number of F0 tornadoes (AH3) = 3.173 × 10^{-2} × 24285 = 770.48735 mi^2

F5 tornado area (AH76) = expected F5 area (AM46) * number of F5 tornadoes (AM3) = 3.265 × 10^1 ×81 = 2.644.4946 mi^2

Tornado Area by Wind Speed (AI71:AI76)

F0 tornado area (AI71) = F0 tornado area (AH71) * 1 (AH54) + F1 tornado area (AH72) * 0.772 (AI54) + F2 tornado area (AH73) * 0.616 (AJ54) + F3 tornado area (AH74) * 0.529 (AK54) + F4 tornado area (AH75) * 0.543 (AL54) + F5 tornado area (AH76) * 0.538 (AM54) = 770.487 * 1 + 18538.067 * 0.772 + 30784.854 * 0.616 + 33844.278 * 0.529 + 11506.375 * 0.543 + 2644.496 * 0.538 = 59610.67 mi^2

F1 tornado area (AI72) = F1 tornado area (AH72) * 0.228 (AI55) + F2 tornado area (AH73) * 0.268 (AJ55) + F3 tornado area (AH74) * 0.271 (AK55) + F4 tornado area (AH75) * 0.238 (AL55) + F5 tornado area (AH76) * 0.223 (AM55) = 24997.06 mi^2

F4 tornado area (AI75) = F4 tornado area (AH75) * 0.032 (AL58) + F5 tornado area (AH76) * 0.033 (AM58) = 455.47 mi^2

F5 tornado area (AI76) = F5 tornado area (AH76) * 0.017 (AM59) = 44.95 mi^2

Probability of Wind Speed Exceeding Threshold (AK71:AK76)

F0 tornado (AK71) = $\frac{\text{Total F0 tornado area by wind speed (AJ71)}}{\text{Total tornado area (AI78)}} = \frac{98057.7733}{98057.7733} = 1.00$

F1 tornado (AK72) = $\frac{\text{Total F1 tornado area by wind speed (AJ72)}}{\text{Total tornado area (AI78)}} = \frac{38438.1041}{98057.7733} = 3.92 \times 10^{-1}$

F2 tornado (AK73) = 1.37×10^{-1}

F3 tornado (AK74) = 3.67×10^{-2}

F4 tornado (AK75) = 5.10×10^{-3}

F5 tornado (AK76) =$\frac{44.9564\ \text{(AJ76)}}{98057.7733\ (AI78)} = 4.58 \times 10^{-4}$

<u>Determination of Weibull Distribution Parameters (a_p, b_p) and Annual Strike Frequency P_p</u>

The ‘Regression’ function of Excel was used to estimate the Weibull distribution parameters a_p and b_p by using linear regression between ln [ln(1/P)] versus ln(minimum wind speed–65) or ln (AL 65).

Intercept (AR81) =-3.59035
Slope (x variable 1) (AR82) = 1.135076
R^2 (AR69) = 0.99254

$P_p = \frac{A_t}{N \times A_r} = \frac{98057.77}{62 \times 3020000}$=0.000534 per year (BI68)

Here, A_t = 97057.77 mi^2 (AI78)

N = 62 years (1950 through 2011)

A_r = area of contiguous United States because tornado strike data from all 48 states were used = 3,020,000 mi^2. This value will be different if another reference area, such as tornado regions I, II, or III; or the 1° or 2°, or 4° latitude-longitude boxes; or 160 km [100 mi] radius around a site is used.

$a_p = 23.64358 = e^{(-\frac{AR81}{AR82})} = e^{3.5903/1.135076}$

$b_p = 1.1350$ (AR82)

Similar analysis can be done for the 95 percent and 5 percent confidence interval estimates of tornado path area (AH47:AM47) and (AH45:AM45), respectively.

<u>Tornado Path Length Analysis for a Finite Structure</u>

It has been assumed for this example analysis that the length of the structure is 100 ft. Table 3-3 of NUREG/CR–4461 gives the path length distribution in terms of intensity of a tornado with a given reported intensity and is reproduced in Table A–2.

Table A–2. Tornado Path Length Intensity Distribution for Finite Structure Design Wind Speed (From Ramsdell and Rishel, 2007)							
	Wind Speed Range	**Recorded Tornado F-scale**					
F Scale	**(mph)**	**F0**	**F1**	**F2**	**F3**	**F4**	**F5**
EF0	65–85	1	0.572	0.280	0.116	0.142	0.133
EF1	86–110		0.428	0.352	0.245	0.158	0.102
EF2	111–135			0.368	0.318	0.278	0.189
EF3	136–165				0.321	0.210	0.242
EF4	166–200					0.212	0.185
EF5	>200						0.149

The calculation steps for P_l are same as for P_p. P_l is estimated as

$$P_l = \frac{W_s L_t}{N A_r}$$

where

W_s = Length of the structure, assumed here 100 ft (0.0189 mi)

L_t = Total length of tornado path = 280654.7 mi (AI198)

N = 62 years

A_r = Area of contiguous United States = 3,020,000 mi^2

For Expected Value analysis, $P_l = 2.84042 \times 10^{-5}$ per year

The Weibull distribution parameters, a_l and b_l, are estimated using the 'Regression' function in Excel. When ln [ln(1/P)] is regressed on ln(minimum wind speed – 65) or ln (AL – 65), the following are obtained.

Intercept (AR187) = -5.179789
Slope (x variable 1) (AR188) = 1.40772
R^2 (AR188) = 0.9908

$a_l = e^{-AR187/AR188} = e^{5.179789/1.40772} = 39.6286$ (BI182)
$b_l = 1.40772$ (BI183)

Similar analysis can be done for the 95 percent and 5 percent confidence interval estimates of tornado path length.

Step 10

Total tornado strike frequency P = Tornado strike frequency for point structures + Tornado strike frequency for finite structure

Plot P for various values of wind speed using the Weibull distribution parameters a_p and b_p for point structures and a_l and b_l for finite structures.

References

Ramsdell, J.V., Jr. and J.P. Rishel. NUREG/CR–4461, Rev. 2, "Tornado Climatology of the Contiguous United States." Washington, DC: NRC. 2007.

APPENDIX B

ESTIMATION OF HURRICANE WIND SPEED AT ANNUAL EXCEEDANCE FREQUENCY OF 10^{-7}

APPENDIX B

ESTIMATION OF HURRICANE WIND SPEED AT ANNUAL EXCEEDANCE FREQUENCY OF 10^{-7}

NUREG/CR–7705 (Vickery, et al., 2011) estimated the wind speed for hurricanes at annual exceedance frequencies of 10^{-6} and 10^{-7} on a 0.1-degree grid for the Atlantic and Gulf of Mexico coastal regions. These estimated values are given as contour plots in NUREG/CR–7705 in Figures 3-1 and 3-2. Additionally, the estimated wind speed values are given in tabular form in Appendices A (10^{-6} annual exceedance frequency) and B (10^{-7} annual exceedance frequency). Either the contour plots or the tables can be used to estimate the hurricane generated wind speed. For example, the coordinates of the South Texas Project plant are 28° 47’ 44’’ N and 96° 2’ 56’’ W or 28.7956 and –96.0489[1]. Appendix A (NUREG/CR–7705, page A–8) gives the following estimated wind speeds at two boxes that encompass the South Texas Project site:

- at latitude 28.75 and longitude 95.95: 210 mph or 94 m/s
- at latitude 28.85 and longitude 96.25: 200 mph or 89 m/s

From interpolation, the expected wind speed at an annual exceedance frequency of 10^{-6} is approximately 205 mph or 92 m/s.

Appendix B (NUREG/CR–7705, page B–8) gives the following estimated wind speeds at two boxes that encompass the South Texas Project site:

- at latitude 28.75 and longitude 95.25: 220 mph or 98 m/s
- at latitude 28.85 and longitude 96.25: 210 mph or 94 m/s

From interpolation, the expected wind speed at annual exceedance frequency of 10^{-7} is approximately 215 mph or 96 m/s.

Alternatively, we can use NUREG/CR–7705, Figures 3-1 and 3-2. Figure 3-2 of NUREG/CR–7705 has been reproduced here with the position in Figure B-1 of the South Texas Power plant marked. Using the contour plot, the estimated wind with exceedance probability is approximately 215 mph. Figure 3-1 of NUREG/CR–7705 can be used to estimate the wind speed with annual exceedance frequency of 10^{-6}.

[1] Negative sign for longitude values was omitted in NUREG/CR–7705. All reported coordinates in NUREG/CR–7705 are in the Western hemisphere (West longitude). This aspect should be recognized when plotting these coordinates in a map. To be consistent with NUREG/CR–7705 tables, examples given below also omit the negative sign for longitude.

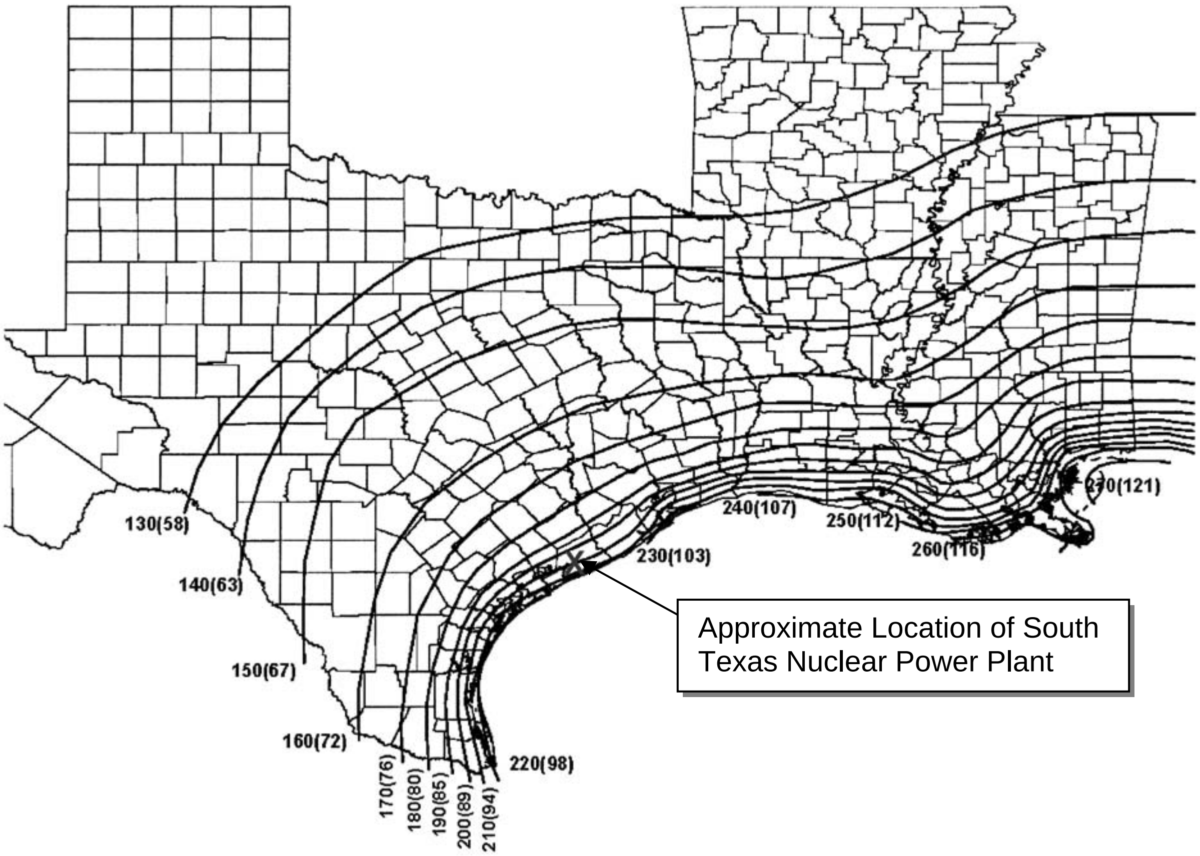

Figure B–1. Contours of Peak-Gust Wind Speeds at 10 m Height in Flat Open Terrain With Annual Exceedance Frequency of 10–7 (Modified from NUREG/CR–7705)

References

Vickery, P.J., D. Wadhera, and L.A. Twisdale. NUREG/CR–7005, "Technical Basis for Regulatory Guidance on Design-Basis Hurricane Wind Speeds for Nuclear Power Plants." Washington, DC: NRC. November 2011.