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DESIGN-BASIS HURRICANE WINDS AND MISSILES FOR NUCLEAR POWER PLANTS

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ABSTRACT

The implementation of the Enhanced Fujita Scale in 2007 by the U.S. National Weather Service resulted in decreasing the design-basis tornado wind speeds suggested by the U.S. Nuclear Regulatory Commission. With the reduction of the design-basis tornado wind speeds, it was no longer clear that the revised design-basis tornado wind and missiles would bound a design-basis hurricane in all areas of the United States. This prompted studies into extreme wind gusts during hurricanes and their relationship to hurricane missile speeds. The study of extreme wind gusts during hurricanes concluded the wind speeds from the design-basis tornado remain bounding, except for locations along the United States Gulf Coast and the southern Atlantic Coast. The study of missile speeds during hurricanes concluded that, because of assumed differences between the tornado and hurricane wind fields, airborne missiles can fly faster in a hurricane wind field having the same 3-second gust wind speed at 10 meters (33 feet) above ground as a tornado wind field. Consequently, U.S. applicants for new nuclear power plants with sites located along the Gulf and Atlantic coasts where the design-basis tornado may not bound the design-basis hurricane are expected to show that their applicable structures can withstand, independently, the total design-basis tornado load and the total design-basis hurricane load as extreme environmental conditions.

INTRODUCTION

Nuclear power plants in the United States must be designed so that they remain in a safe condition under extreme meteorological events, including those that could result in the most extreme wind events (such as tornadoes and hurricanes) that could reasonably be predicted to occur at the site. Nuclear power plants also need to be protected against the effects of missiles generated by such extreme winds.

Initially, the U.S. Atomic Energy Commission (AEC) (predecessor to the U.S. Nuclear Regulatory Commission) (NRC) considered tornadoes to be the bounding extreme wind events and issued Revision 0 to Regulatory Guide (RG) 1.76 (AEC, 1974a) describing a design-basis tornado acceptable to the NRC staff for each of three regions within the contiguous United States. The design-basis tornado wind speeds were chosen so that the probability that a tornado exceeding the design basis would occur was on the order of 10^{-7} per year per nuclear power plant (AEC, 1974b). The development of the design-basis tornado presented in Revision 0 to RG 1.76 relied on the use of the Fujita Scale (F Scale) (Fujita, 1970) as a means of classifying tornado intensity (AEC, 1974b).

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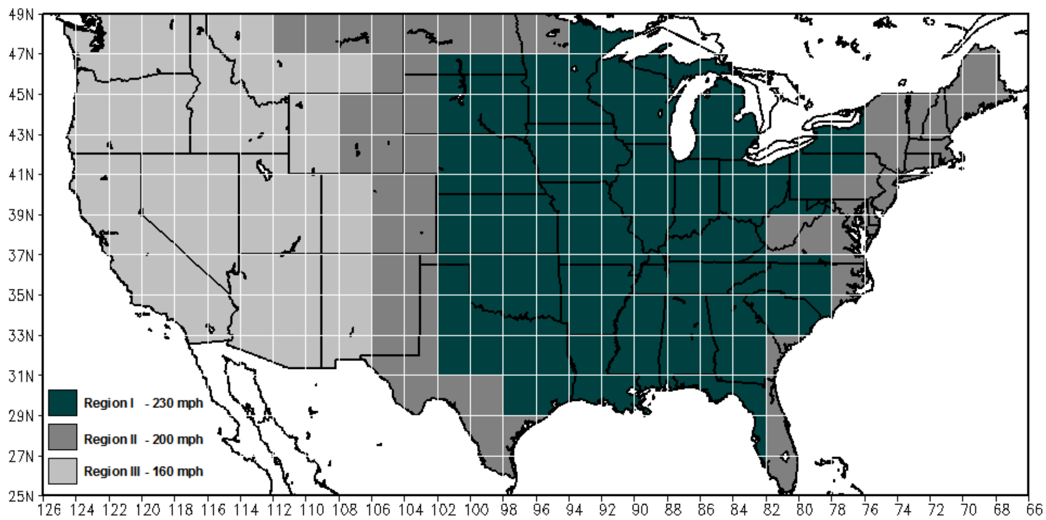
The Enhanced Fujita Scale (EF Scale) (WSEC, 2006) was implemented by the US National Weather Service (NWS) in February 2007 as the official measure of tornado intensity. The EF Scale replaced the original Fujita Scale (F Scale) that had been in use since 1971 and was developed to overcome some limitations of the F Scale. In March 2007, the NRC issued Revision 1 to RG 1.76 (NRC, 2007), which relied on the EF Scale to relate the degree of damage from a tornado to the tornado's maximum wind speed. The design-basis tornado wind speeds in the revised regulatory guide still correspond to the exceedance frequency of 10^{-7} per year (calculated as a best estimate), which is the same as the original regulatory guide. Some of the design-basis tornado characteristics from Revision 1 to RG 1.76 are presented in Figure 1.



TORNADO REGION	MAXIMUM WIND SPEED M/S (MPH)	TRANSLATIONAL SPEED (V_{tr}) M/S (MPH)	MAXIMUM ROTATIONAL SPEED (V_{rot}) M/S (MPH)	RADIUS OF MAX ROTATIONAL SPEED (R_m) M (FT)
I	103 (230)	21 (46)	82 (184)	45.7 (150)
II	89 (200)	18 (40)	72 (160)	45.7 (150)
III	72 (160)	14 (32)	57 (128)	45.7 (150)

Figure 1. Design-basis tornado characteristics from Revision 1 to RG 1.76.

The NRC found that the design-basis maximum tornado wind speeds decreased as a result of the implementation of the EF Scale in Revision 1 to RG 1.76. Table 1 compares the design-basis maximum tornado wind speeds in Revision 0 and Revision 1 of RG 1.76 for three geographic regions.[1] Table 1 shows that the design-basis tornado wind speeds for Region I, where the most intense tornadoes occur, decreased from 161 meters per second (m/s) (360 miles per hour (mph)) to 103 m/s (230 mph).[2]

[1] The geographic regions are similar, but not exactly the same, between the two regulatory guides.

[2] The wind speed frame of reference between Revision 0 and Revision 1 of RG 1.76 is different; the design-basis tornado wind speeds reported in Revision 0 are based on the F Scale fastest ¼- mile winds (defined as the maximum speed of any ¼- mile passage of wind) whereas the wind speeds reported in Revision 1 are based on the EF Scale 3-second gust wind speeds (defined as the highest wind speed averaged over any 3-second period). Nonetheless, the frame of reference between the two sets of wind speeds is similar; for example, the duration of a 300 mph (161 m/s) fastest ¼-mile wind is approximately three seconds.

Table 1: Comparison of maximum tornado wind speeds between Revision 0 and Revision 1 of RG 1.76.

REGION	MAXIMUM WIND SPEED, M/S (MPH)	
	REVISION 0 (1974) (FASTEST ¼-MILE)	REVISION 1 (2007) (3-SEC GUST)
I	161 (360)	103 (230)
II	134 (300)	89 (200)
III	107 (240)	72 (160)

It was therefore no longer clear that the revised design-basis tornado would be the bounding extreme wind in all areas of the United States. For example, Revision 1 to RG 1.76 assigns a design-basis tornado wind speed of 89 m/s (200 mph) to Region II, which includes parts of eastern Florida and Georgia and part of the Gulf coast of Texas. NRC staff observed that at a very low probability of exceedance rate of 10^{-7} per year, hurricane wind speeds in the Atlantic and Gulf regions would approach or exceed design-basis tornado wind speeds. This prompted studies into extreme wind gusts during hurricanes, NUREG/CR-7005 (Vickery et al, 2011), and their relation to design-basis hurricane missile speeds, NUREG/CR-7004 (Simiu and Potra, 2011). These studies resulted in RG 1.221 (NRC, 2011), which provides new guidance that the NRC staff considers acceptable for use in selecting the design-basis hurricane wind speed and hurricane-generated missiles that a nuclear power plant should be designed to withstand to prevent undue risk to public health and safety.

APPROACH

The NRC staff has determined that the design-basis hurricane wind speeds should correspond to the exceedance frequency of 10^{-7} per year per nuclear power plant, calculated as a best estimate. This is the same exceedance frequency used to establish the design-basis tornado parameters in Revision 1 of RG 1.76 and is consistent with the direction provided to the NRC staff by the Commission in defining the design-basis tornado in the staff requirements memorandum (NRC, 2004a) related to Commission paper SECY-04-0200 (NRC, 2004b).

Development of Design-Basis Hurricane Wind Speeds

The analysis used in NUREG/CR-7005 to develop the design-basis hurricane wind speeds is based on the peer-reviewed hurricane simulation model that was used for the development of the basic (50-year) wind speed maps presented in ASCE/SEI 7-05 (ASCE/SEI, 2006). The model generated peak-gust wind speeds at numerous grid points along and inland of the Atlantic and Gulf Coasts of the United States. A stratified sampling approach facilitated a simulation with an effective length of 10 million years that computed wind speeds for each model hurricane at each affected grid point. The range of hurricane parameters in the pre-computed wind fields in the model was extended to cover the smaller and more intense hurricanes that are occasionally simulated in the 10-million-year event set. In addition to the computation of a deterministic peak-gust wind speed for each model hurricane, the analysis incorporated a wind field modeling error term. The error term includes the inability of the wind model to capture some asymmetries in the underlying model pressure fields, as well as the inability of the model to capture small-scale features, such as extreme convective gusts. The inclusion of this error term resulted in an effective maximum peak gust in the range of 1.7 to 1.8 times the mean wind speed.

Figure 2 presents the resulting map for hurricane wind speeds with annual exceedance probabilities of 10^{-7}. These wind speeds are representative of a 3-second peak gust wind speed at a height of 10 meters (33 feet) above ground in flat open terrain, which is consistent with the definition of Exposure C in ASCE/SEI 7-05.

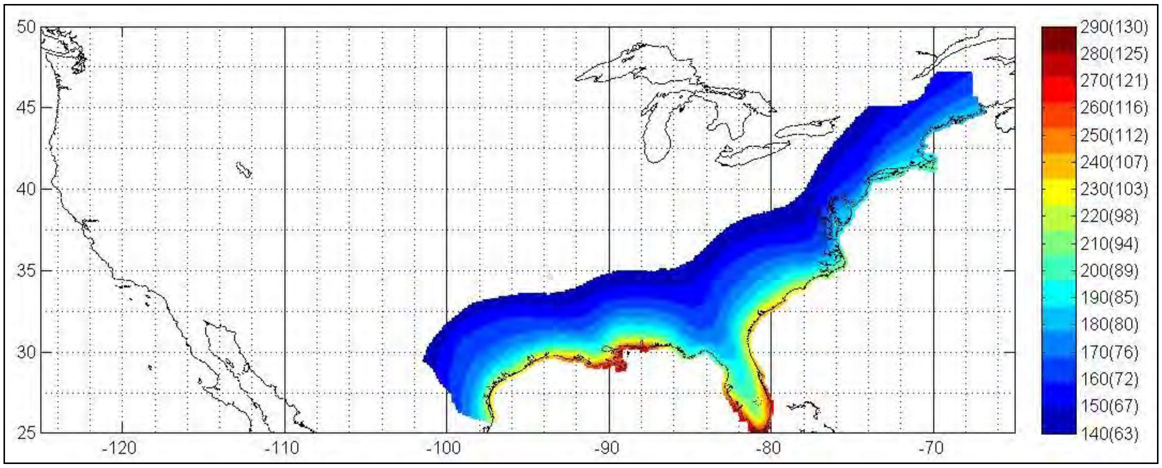


Figure 2. Design-basis hurricane peak-gust wind speeds in mph (m/s) at 10-m height in flat open terrain, annual exceedance probability of 10^{-7} (from Figure 3-4 of NUREG/CR-7005).

Figure 3 shows locations that have design-basis hurricane wind speeds higher than the recommended design-basis tornado wind speeds. Figure 3 shows that along the Gulf and southern Atlantic coastlines, the hurricane-induced wind gusts can be higher than the regionalized gusts produced by tornadoes. This figure confirmed the NRC's staff observation that the design-basis maximum tornado wind speeds do not bound the design-basis hurricane for all areas of the contiguous United States.

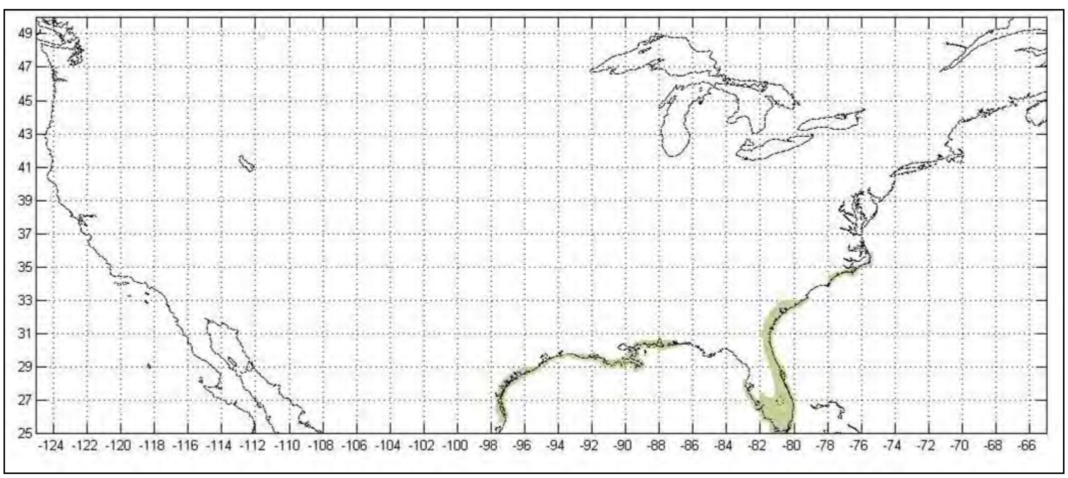


Figure 3. Locations where design-basis hurricane wind speeds exceed those for tornadoes, annual exceedance probability of 10^{-7} (from Figure 3-6 of NUREG/CR-7005).

Development of Design-Basis Hurricane Missiles

To ensure the safety of nuclear power plants in the event of a hurricane strike, NRC regulations require that nuclear power plant designs consider the impact of hurricane-generated missiles, in addition to the direct action of the hurricane wind. Hurricanes are capable of generating missiles from objects lying within the path of the hurricane wind and from the debris of nearby damaged structures. Protection from a spectrum of missiles (ranging from a massive missile that deforms on impact to a rigid penetrating missile) provides assurance that the structures, systems, and components important to safety will be available to mitigate the potential effects of a hurricane on plant safety. Given that the design-basis hurricane wind speed has a very low frequency of occurrence, the representative missiles should be common items around the plant site and should have a reasonable probability of becoming airborne within the hurricane wind field.

When the NRC staff chose the design-basis tornado missile spectrum, a 15.24-centimeter (6-inch) Schedule 40 steel pipe and an automobile were considered to be acceptable as the penetrating and massive missiles, respectively, for use in the design of nuclear power plants. Automobiles are common objects near the plant site, and there is potential for them to be lifted in a tornado wind field. Schedule 40 pipe is also common around plant sites. However, such pipe is intended to represent a rigid component of a larger missile (e.g., building debris or an automobile) that may be lifted in the tornado wind field. Thus, the staff used the maximum speed calculated for the automobile tornado missile for the penetrating tornado missile as well, rather than the speed calculated for a pipe.

Unlike tornado wind fields, forces tending to increase the elevation of the hurricane missile with respect to the ground level (e.g., updrafts) are assumed to be negligible in a hurricane wind field. However, buildings not designed for the hurricane winds can continue to break up during the buildup of hurricane winds. For example, rooftop mechanical (e.g., HVAC) equipment that is kept in place only by gravity connections can be a source of heavy deformable debris when displaced during extreme-wind events. Failures can progress from the exterior building elements inward to the structural members (e.g., trusses, masonry units, beams, and columns). According to Section 7.1.1 of FEMA P-361 (FEMA, 2008), the literature on hurricanes as well as tornadoes contains numerous examples of large structural members that have been transported by winds for significant distances by the wind field when a portion of exterior sheathing remains connected and provides an aerodynamic sail area on which the wind can act. An automobile hurricane missile with an initial elevation of 40 meters (131 feet) above ground could be considered a surrogate for such equipment and structures which can be found throughout a nuclear power plant site.

To evaluate the resistance of barriers to penetration and gross failure, the hurricane missile speeds should also be defined. NUREG/CR-7004 (Simiu and Potra, 2011) describes a method used to calculate the horizontal and total speeds associated with several types of missiles considered for different hurricane wind speeds. The selected design-basis hurricane missile spectrum for nuclear power plants is the same as the design-basis tornado missile spectrum presented in Revision 1 to RG 1.76. This spectrum includes (see Table 2) (1) a massive high-kinetic-energy missile that deforms on impact (an automobile), (2) a rigid missile that tests penetration resistance (a pipe), and (3) a small rigid missile of a size sufficient to pass through any opening in protective barriers (a solid steel sphere).

The hurricane missile analysis presented in NUREG/CR-7004 is based on numerically solving the equations of horizontal and vertical motion of each missile embedded in a hurricane wind field. The missile aerodynamic and initial condition assumptions are similar to those used for the analyses of tornado-borne missile speeds adopted for Revision 1 of RG 1.76. In particular, the missiles were assumed to start their motion with zero initial velocity from an elevation of 40 meters (131 feet) and there was no consideration given to the dependence of missile drag coefficient on missile position or relative missile speed with respect to the wind flow. However, the assumed hurricane wind field differed from the assumed tornado wind field in that the hurricane wind field does not change spatially during the missile's flight time but does vary with height above the ground.

Table 2: Design-basis tornado and hurricane missile spectra.

MISSILE TYPE	DIMENSIONS	MASS
AUTOMOBILE[3]	Hurricane & Tornado Regions I and II 5 m × 2 m × 1.3 m (16.4 ft × 6.6 ft × 4.3 ft)	Hurricane & Tornado Regions I and II 1,810 kg (4,000 lb)
	Tornado Region III 4.5 m × 1.7 m × 1.5 m (14.9 ft × 5.6 ft × 4.9 ft)	Tornado Region III 1,178 kg (2,595 lb)
SCHEDULE 40 PIPE	0.168 m dia × 4.58 m long (6.625 in. dia × 15 ft long)	130 kg (287 lb)
SOLID STEEL SPHERE	25.4 mm (1 in.) diameter	0.0669 kg (0.147 lb)

The resulting automobile and schedule 40 pipe horizontal missile speeds as derived from the analysis presented in NUREG/CR-7004 and as incorporated into RG 1.221 are plotted in Figure 4. The NRC considers the design-basis hurricane missiles listed in Table 2 to be capable of striking in all directions with the horizontal speeds shown in Figure 4 and with a vertical speed of 26 m/s (58 mph). The horizontal hurricane missile speeds shown in Figure 4 were taken from Table 5 of NUREG/CR-7004 and represent maximum horizontal missile speeds in open terrain.

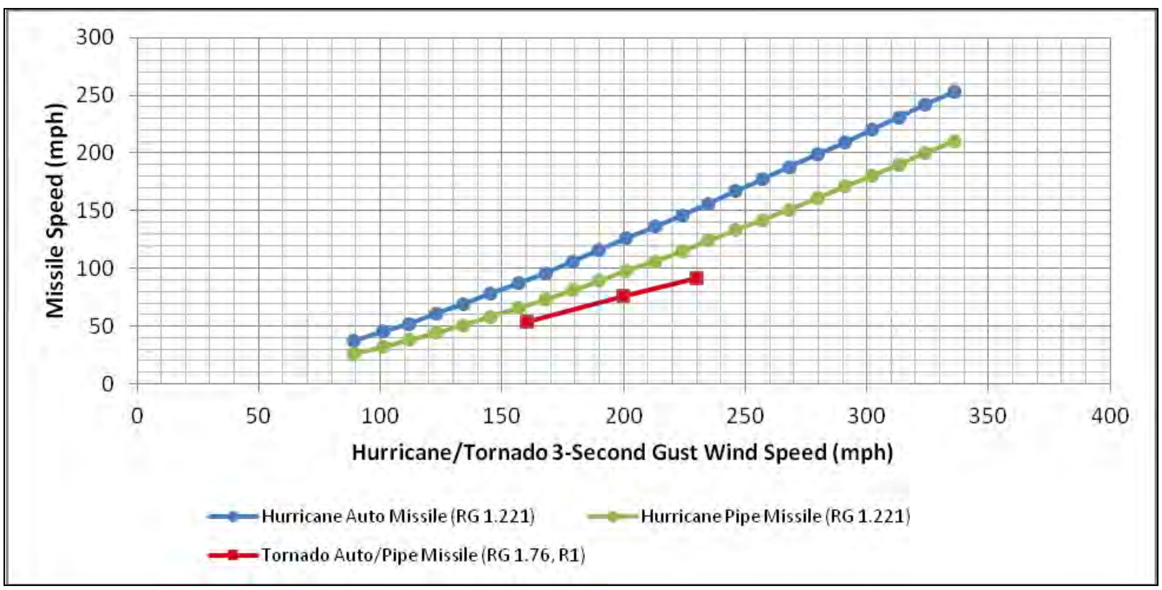


Figure 4. Maximum horizontal speeds for the design-basis hurricane and tornado automobile and schedule 40 pipe missiles.

[3] RG 1.76 uses two different automobile missiles as a function of tornado region (i.e., a larger and heavier automobile for tornado Regions I and II and a smaller and lighter automobile for tornado Region III) because the lighter automobile was found to have a higher kinetic energy in Region III as compared to the heavier automobile. However, in the case of the hurricane wind field, the heavier automobile was found to have a higher kinetic energy for all wind speeds as compared to the lighter automobile; therefore, the design-basis hurricane automobile missile is based only on the heavier design-basis automobile missile presented in RG 1.76.

ANALYSIS

To evaluate the resistance of missile barriers to penetration and gross failure, both Revision 1 to RG 1.76 and RG 1.221 assign missile speeds as a function of tornado and hurricane wind speeds, respectively. As previously discussed, the hurricane missile speeds presented in RG 1.221 are based on missile aerodynamics and initial conditions assumptions that are similar to those used for the analyses of tornado-borne missile speeds adopted for Revision 1 of RG 1.76. However, the assumed hurricane wind field differs from the assumed tornado wind field in that the hurricane wind field does not change spatially during the missile's flight time but does vary with height above the ground. Table 3 compares the assumptions used in calculating the tornado missile speeds for Revision 1 to RG 1.76 with the assumptions used to calculate hurricane missile speeds for RG 1.221.

Table 3: Basic Missile Modeling Assumptions.

TORNADOES (RG 1.76, REV 1)	HURRICANES (RG 1.221)
Horizontal and vertical projections of Newton's second law applied to the missile embedded in the wind flow	Same as tornadoes
Missile spectrum includes an automobile and a pipe	Same as tornadoes
Tornado updrafts are modeled	Hurricane updrafts are negligible
Missile starts motion with zero initial velocity at elevation 40 meters above ground	Same as tornadoes
Tornado wind field is a combination of a vortex moving with a translational speed	Hurricane wind field does not change spatially during the missile's flight time
Wind speeds do not vary with height	Wind speeds vary with height above ground in accordance with power law
Missile drag coefficient is independent of missile position and relative speed	Same as tornadoes

The tornado wind field model, along with the equations of motion used to calculate the maximum tornado missile speeds for Revision 1 to RG 1.76, were derived from Chapter 16 of Simiu and Scanlan (1996). The tornado wind field is modeled as a vortex characterized by (1) a maximum rotational wind speed V_{rot}, (2) a translational speed of the tornado vortex, V_{tr}, and (3) radius of maximum rotational wind speed R_m. The rotational wind speed is defined as the resultant of the tangential velocity component V_t and radial wind velocity component V_r. The tangential wind velocity component is given by the expressions:

$$V_t = (r/R_m) \cdot V_m \qquad (0 \le r \le R_m) \tag{1}$$

$$V_t = (R_m/r) \cdot V_m \qquad (R_m \le r \le \infty) \tag{2}$$

where V_m is the maximum tangential wind speed and R_m is the radius of maximum rotational wind speed. The radial velocity component V_r and the vertical velocity component V_z are given by:

$$V_r = \tfrac{1}{2} V_t \tag{3}$$

$$V_z = \tfrac{2}{3} V_t \tag{4}$$

The radial component is directed towards the center of the vortex and the vertical component is directed upward. The horizontal components of the tornado wind velocity are shown in Figure 5. The winds acting on the missile at any point of time are the resultant of the tangential (V_t), radial (V_r), and translational (V_{tr}) components of the tornado wind field. The wind speeds are assumed to not vary with height above ground.

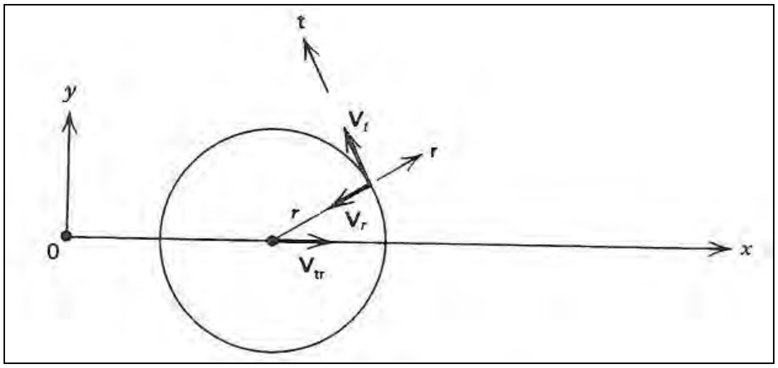


Figure 5. Horizontal Components of tornado wind velocity
(from Figure 16.3.2 of Simiu and Scanlan, 1996).

Figure 6 shows the horizontal location of a 1,810 kilogram (4,000 pound) automobile missile as a function of time when released in a Region II tornado wind field as described by Revision 1 to RG 1.76 (i.e., a tornado with a maximum 3-second gust wind speed of 89 m/s (200 mph), a translational speed of 18 m/s (40 mph), a maximum rotational speed of 72 m/s (160 mph), and a radius of maximum rotational speed of 45.7 meters (150 feet)). The missile is assumed to start its motion at an elevation of 40 meters (131 feet) at a point located on the tornado translational axis, at a distance downwind of the tornado center equal to the radius of the maximum rotational speed as shown in the box labeled “0 sec” in Figure 6. Figure 6 continues to plot the location of the missile in one-second increments during its approximately 6½-second journey before hitting the ground.

Also shown in Figure 6 is the direction and relative strength of the tornado winds acting on the missile as it travels along. Note that, at times, the three components of the tornado wind field (V_t, V_r, and V_{tr}) can act in different (even opposing) directions, meaning that the missile is rarely, if ever, exposed to the maximum wind speeds in the tornado. This is different from a hurricane missile. Because the size of the hurricane wind field is much larger, the hurricane missile is assumed to be subjected to the hurricane’s highest wind speeds throughout its flight.

Figure 7 compares the height and horizontal speed of a 1,810 kilogram (4,000 pound) automobile missile released in a tornado wind field versus hurricane wind field, assuming both wind fields have maximum 3-second gusts of 89 m/s (200 mph). The tornado missile spends approximately twice as much time airborne as the hurricane missile (6½ seconds for the tornado missile versus 3¼ seconds for the hurricane missile), primarily due to the updraft forces that are assumed to exist within the tornado that are not present in a hurricane. However, the highest horizontal missile speed for the hurricane missile is almost twice that for the tornado missile because the hurricane missile is assumed to be subjected to the hurricane’s highest wind speeds throughout its flight.

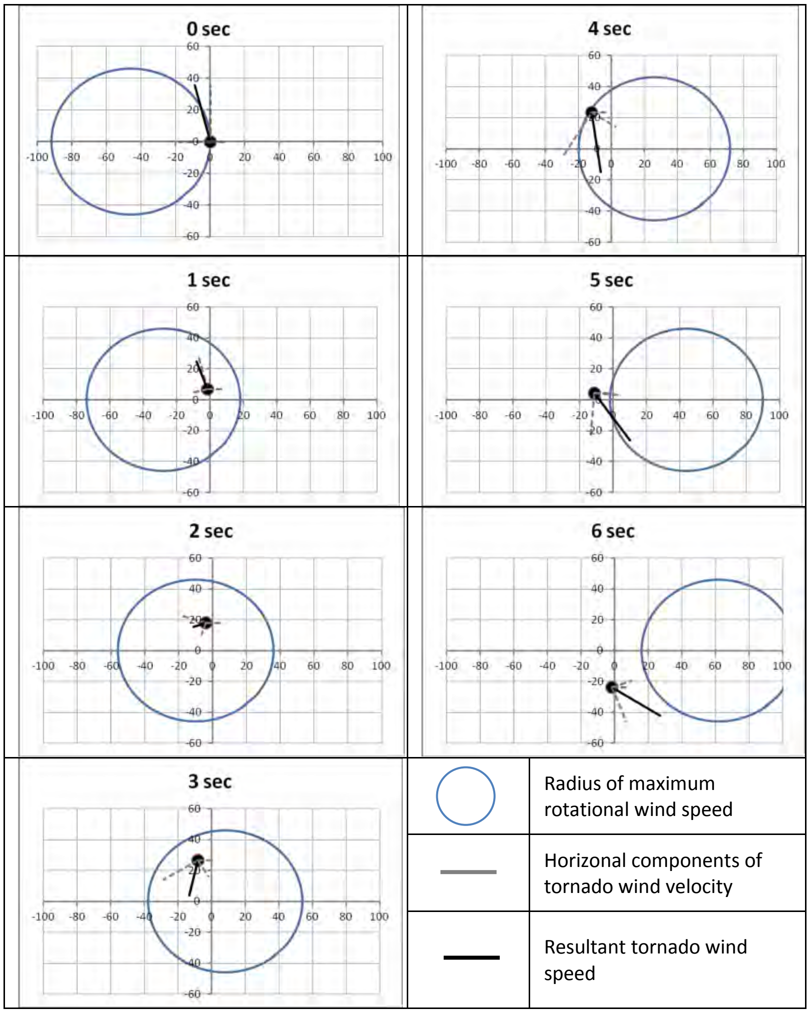


Figure 6. Horizontal location of a 1,810 kilogram (4,000 pound) automobile missile as a function of time when released 40 meters (131 feet) above ground in a Region II tornado wind field.

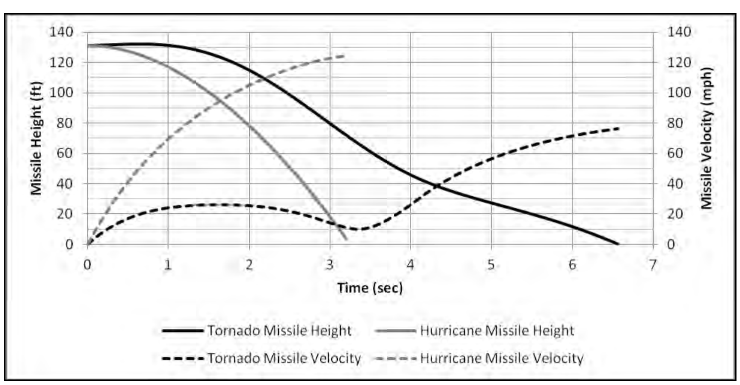


Figure 7. Height and horizontal speed of a 1,810 kilogram (4,000 pound) automobile missile when released 40 meters (131 feet) above ground in a Region II tornado wind field and a 89 m/s (200 mph) hurricane wind field.

CONCLUSIONS

The study of extreme wind gusts during hurricanes concluded the wind speeds from the design-basis tornado remain bounding except for locations along the United States Gulf Coast and the southern Atlantic Coast. The study of missile speeds during hurricanes concluded airborne missiles fly faster in a hurricane wind field having the same 3-second gust wind speed at 10 meters (33 feet) above ground as a tornado wind field. This is due to the assumed hurricane wind field differing from the assumed tornado wind field. Because the size of the hurricane zone with the highest winds is large relative to the size of the missile trajectory, the hurricane wind field is assumed to not change spatially during the missile's flight. In contrast, the tornado wind field is smaller, so the tornado missile is subject to the strongest winds only during limited portions of its flight.

Tornado and hurricane loads on structures include the effects of air flow as well as wind-generated missile impacts. This means that the design-basis tornado may not be bounding at a site where the tornado winds exceed the hurricane winds because the hurricane-generated missiles could be faster. Consequently, applicants for new power plants with sites along the Gulf and Atlantic coasts where the design-basis tornado may not bound the design-basis hurricane are expected to show that their applicable structures can withstand, independently, the total design-basis tornado load and the total design-basis hurricane load as extreme environmental conditions.

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