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TORNADO VS HURRICANE – WHICH IS MORE DETRIMENTAL TO THE SAFETY OF US NUCLEAR POWER PLANTS

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ABSTRACT

Regulatory Guide 1.221, issued in 2011, describes new requirements for design basis hurricane winds in coastal regions of the United States. The motivation for the new guidance was a reduction in the regionalized design basis tornado wind speeds in Revision 1 of Regulatory Guide 1.76, issued in 2007. The reduction in the tornado wind speeds makes it more likely that hurricane winds may govern the design of nuclear power plant structures in some locations. Differences in the assumed characteristics of the wind fields associated with tornadoes and hurricanes make a straightforward comparison of maximum wind speeds inconclusive. Structure dimensions can play a significant role in determining which wind case will govern, so wind pressure profiles must be examined on a structure by structure basis. Hurricane missile velocities also differ from tornado missile velocities. The new requirements have potential significance when considered relative to the parameters previously used for both existing plants and new certified designs. This paper discusses the latest Regulatory Guide requirements, the characteristics of hurricane and tornado wind fields, and the different velocities considered for wind-borne missiles. The impact of the requirements is also discussed relative to the design basis for existing nuclear power plants and for recent new plant designs.

REQUIREMENTS FOR DESIGN BASIS TORNADO AND DESIGN BASIS HURRICANE WIND

Regulatory Guide (RG) 1.76 [6] specifies design basis tornado characteristics for regions of the United States. When it was originally issued in 1974, the basis was WASH-1300 [2]. WASH-1300 chose design basis windspeeds so that the probability that a tornado exceeding the design basis would occur was 10^{-7} per year per nuclear power plant. However, WASH-1300 considered only two years of observed tornado intensity data to derive the probability of the maximum windspeed exceeding a specified value. Revision 1 of RG 1.76 [7] was issued in March 2007. The Enhanced Fujita Scale and additional tornado data discussed in detail in NUREG/CR-4461, Rev. 2 [3] supported a decrease in design basis tornado wind speed criteria. Figure 1 provides maps of the three regions defined in Revision 0 and Revision 1 of RG 1.76, and Table 1 provides a comparison of the speeds associated with each region. Revision 0 of RG 1.76 did not specify a tornado missile spectrum. Table 2 provides the tornado missile spectrum required by Revision 1. Previously, it was considered that design basis tornado winds would govern over design basis hurricane winds. With the decrease in design basis tornado wind speeds in Revision 1 of RG 1.76, that will no longer always be true. This led to the development of RG 1.221 [9] for separate guidance on design basis hurricane winds and missiles.

Regulatory Guide 1.221 [9] was issued in October of 2011 and provides guidance on design basis hurricane wind and missiles for nuclear power plants corresponding to an exceedance frequency of 10^{-7} per year; the same frequency used to establish the design basis tornado parameters in RG 1.76. Table 3 provides the hurricane missile spectrum required to be considered by RG 1.221. The missile types are the same as those required for tornado per RG 1.76.

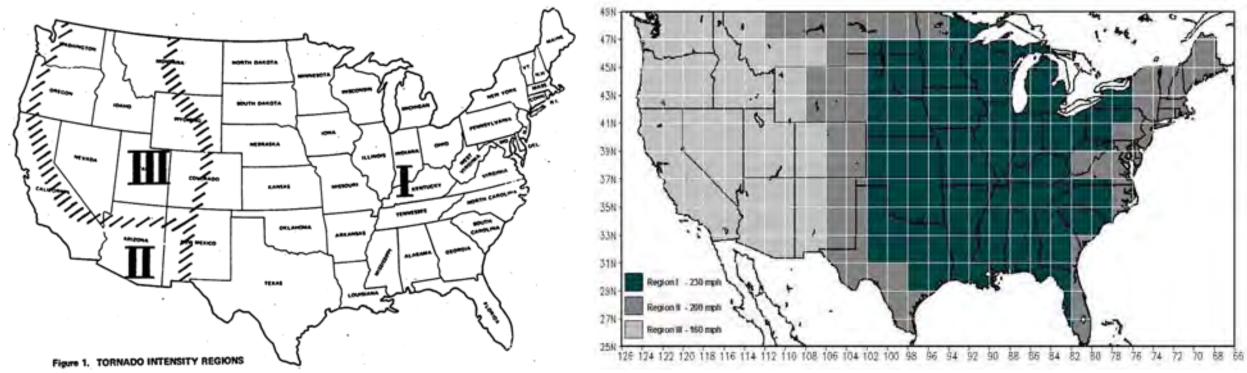


Figure 1. Maps of regionalization of tornado wind speeds from Regulatory Guide 1.76 Revision 0 (left) and Revision 1 (right).

Table 1. Comparison of regionalized tornado wind speeds (mph) per RG 1.76 Revision 0 and Revision 1.

	Revision 0	Revision 1
Region I	360	230
Region II	300	200
Region III	240	160

Table 2. Tornado missile spectrum for RG 1.76, Revision 1.

Missile Type		Schedule 40 Pipe	Automobile	Solid Steel Sphere
Dimensions		0.168 m dia × 4.58 m long (6.625 in. dia × 15 ft long)	Region I and II: 5 m × 2 m × 1.3 m (16.4 ft x 6.6 ft x 4.3 ft)	2.54 cm dia (1 in. dia)
			Region III: 4.5 m x 1.7 m x 1.5 m (14.9 ft x 5.6 ft x 4.9 ft)	
Mass		130 kg (287 lb)	Region I and II: 1810 kg (4000 lb)	0.0669 kg (0.147 lb)
			Region III: 1178 kg (2595 lb)	
C_DA/m		0.0043 m^2/kg (0.0212 ft^2/lb)	Region I and II: 0.0070 m^2/kg (0.0343 ft^2/lb)	0.0034 m^2/kg (0.0166 ft^2/lb)
			Region III: 0.0095 m^2/kg (0.0464 ft^2/lb)	
V_{Mh}^{max}	Region I	41 m/s (135 ft/s)	41 m/s (135 ft/s)	8 m/s (26 ft/s)
	Region II	34 m/s (112 ft/s)	34 m/s (112 ft/s)	7 m/s (23 ft/s)
	Region III	24 m/s (79 ft/s)	24 m/s (79 ft/s)	6 m/s (20 ft/s)

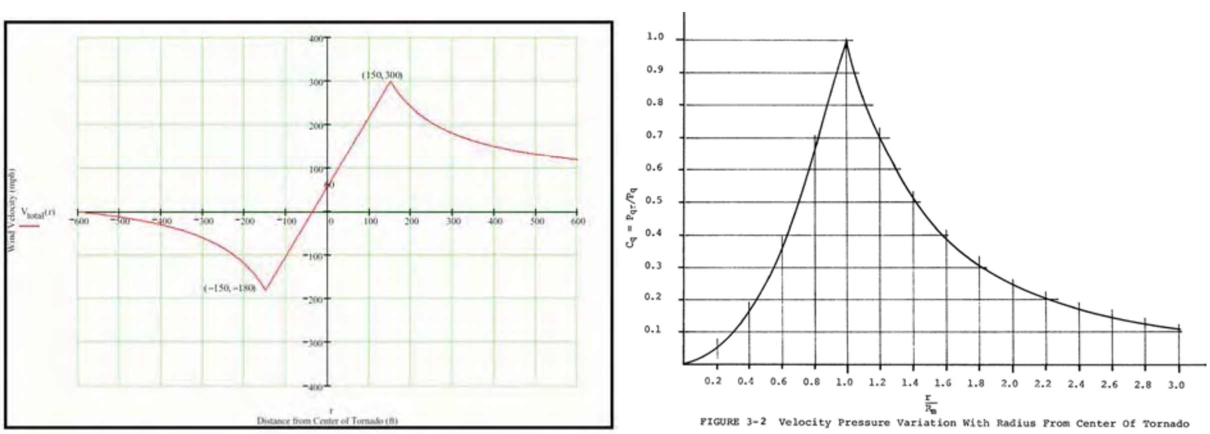
Table 3. Hurricane missile spectrum for RG 1.221.

Missile Type	Dimensions	Mass
Automobile	5 m × 2 m × 1.3 m (16.4 ft x 6.6 ft x 4.3 ft)	1,810 kg (4,000 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)

CHARACTERISTICS OF TORNADOES AND HURRICANES

Wind Field Characteristics

The assumed characteristics of hurricane wind differ in several significant ways from tornado winds. The wind pressure profile of a hurricane increases with height above ground (similar to a normal wind field), while the wind pressure due to a tornado is taken to be constant with height. A hurricane can be hundreds of miles wide, whereas a tornado is typically hundreds of feet wide. The wind velocity can be considered constant across the width of a hurricane, while the wind velocity of a tornado varies with the distance from the center. Figure 2 shows the tornado velocity variation with distance from the tornado center and the velocity pressure variation with the radius from the tornado center. These differences, along with the geographical location of a plant, dictate which wind load will be more critical for a given plant structure.



(a) (b)

Figure 2: Variation of tornado velocity (a) and velocity pressure (b) [4] with distance from tornado center.

Wind-borne Missile Characteristics

Wind-borne missiles due to tornados and hurricanes are considered differently based on the characteristics of each storm type. The same spectrum of missiles is required to be considered by RG 1.76 and RG 1.221, but the velocities differ. A hurricane missile is considered to be subjected to the highest wind speeds throughout its trajectory because the hurricane wind field is so large relative to the missile size. A tornado wind field is much smaller, so the missiles are assumed to only be subject to the highest winds at the beginning of their flight. This means that a missile in a hurricane wind field will have a higher maximum horizontal velocity than the same missile in a tornado wind field with the same maximum wind speed. For example, a Region 1 tornado has a horizontal automobile missile velocity of 91.9 mph (41.1 m/s). A hurricane with a similar wind speed (235 mph vs. 230 mph for a Region 1 tornado) has a horizontal automobile missile velocity of 156.4 mph (69.9 m/s). The hurricane missile velocity is 70% higher than the tornado missile velocity. Figure 3 shows the variation of horizontal missile velocity with wind speed for both hurricanes and tornadoes. The speed of a Region 1 tornado automobile missile is comparable to an automobile missile due to a hurricane wind speed of only 161.1 mph (72 m/s). In a place like Florida, which falls into Region II for tornado wind per RG 1.76 but has high hurricane winds per RG 1.221, a hurricane automobile missile may have nearly double the velocity and 4 times the energy of the same tornado missile. As stated in RG 1.221, "Hurricane missiles are among the most extreme effects of credible natural phenomena that can occur at nuclear power plant sites subject to hurricanes."

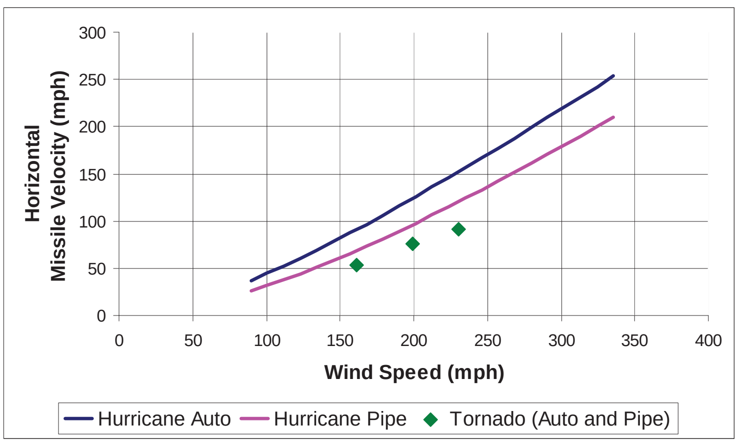


Figure 3. Variation of horizontal missile speed with wind speed for tornadoes and hurricanes per RG 1.76 and RG 1.221.

The vertical velocity of a tornado missile is taken as 67% of the maximum horizontal velocity. The vertical velocity of a hurricane missile is always taken as 58 mph (26 m/s). This results in the vertical missile speed for a hurricane being approximately equal to the vertical missile speed for a Region 1 tornado (58 mph vs. 61.5 mph).

REGIONS WHERE BOTH TORNADOES AND HURRICANES OCCUR

The highest tornado wind speeds per RG 1.76 occur in Region 1, which covers the central United States. Region 1 extends to the Gulf Coast (Texas, Louisiana, Alabama, Mississippi, Florida) and a small portion of the East Coast (North and South Carolina). Region 1 considers a tornado wind speed of 230 mph. Figure 4 shows tornado-prone regions of the United States, and Figure 5 shows hurricane-prone regions. Figure 6 is a map showing the locations of nuclear power plants that are licensed to operate in the United States. A comparison of Figure 4, Figure 5 and Figure 6 shows that many of the plants fall into the critical region of the country for both tornado and hurricane winds.

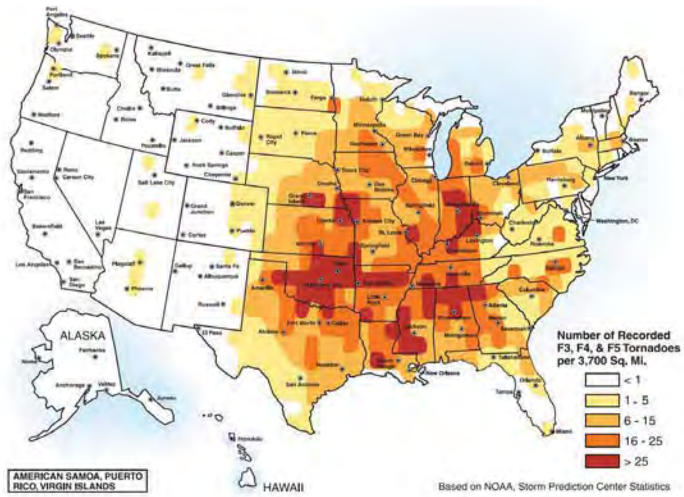


Figure 4. Tornado-prone regions of the United States specified by FEMA [1].

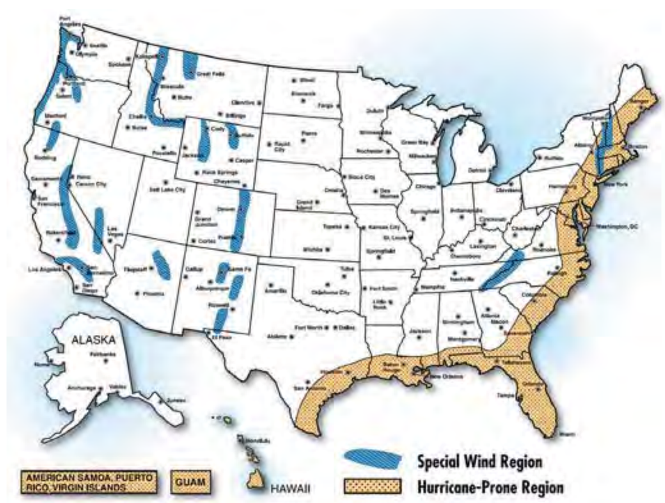


Figure 5. Hurricane-prone regions of the United States specified by FEMA [1].

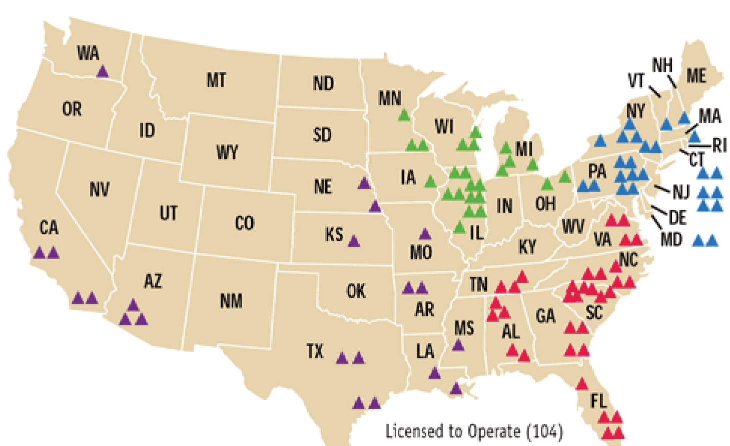


Figure 6. Locations of licensed nuclear power plants in the United States [NRC].

EFFECTS OF STRUCTURE SIZE ON WIND PRESSURE PROFILES

Due to the characteristics of tornado wind and hurricane wind discussed above, the determination of which wind case will be most critical for design of a structure is not always straight forward. Comparison of the maximum wind speeds specified by each Regulatory Guide at the geographic location of the plant is not sufficient. The size of each plant structure (its width and height) may determine which wind case is more critical for design. The same wind case may not govern for every structure at a plant.

Hurricane pressure increases with height, while tornado pressure is uniform. This means that even if the tornado wind speed is somewhat higher, at a certain height, hurricane pressure will exceed tornado pressure. The velocity pressure coefficient, K_{zt}, for tornado wind is specified as 0.87 per Standard Review Plan 3.3.2 [8]. K_{zt} for hurricane wind follows Table 6-1 of ASCE 7-05 [5] with the additional stipulation of being greater than or equal to 0.87. Figure 8 shows the global wind pressure profile (windward wall plus leeward wall) due to tornado and hurricane on a structure (a) 50 feet tall and a structure (b) 200 feet tall. A size factor is not included for this comparison. The hurricane pressure only exceeds the tornado pressure on the 50 foot structure above 30 feet, and only by a small amount (approximately 10 psf). For the 200 foot structure, the hurricane pressure exceeds the tornado pressure for the full height, and the magnitude of the exceedance is much greater (more than 50 psf at the top).

Tornado pressure decreases with width (due to size effect), while hurricane pressure is uniform. The velocity of tornado wind varies with the radius from the center of the storm. By taking the size of the structure relative to the size of the tornado into consideration, credit can be taken for the non-uniformity of the resulting pressure. Figure 7 plots the coefficient that can be used to reduce the maximum pressure (P_{max}) to the pressure for design (the average pressure across the structure, P_{ave}). As the ratio of the structure size to the radius of maximum rotational speed, R_m, increases, the size coefficient decreases. The larger the structure is, the larger the reduction in pressure will be. For example, for a structure width that is twice the radius of maximum rotational speed (i.e. $L/R_m = 2$), the pressure across the structure is reduced to 45% of the maximum pressure. This means that even if the tornado wind speed at a site is somewhat higher than the hurricane wind speed, at a certain structure width, hurricane pressure will become more critical. Figure 9 shows the global wind pressure profile due to tornado and hurricane on a structure (a) 50 foot wide and (b) 300 foot wide. Due to the size factor, the tornado pressure drops off significantly for the 300 foot structure as compared to the 50 foot structure.

Due to both of the effects described above, hurricane wind pressure is more of a concern for large structures (tall and/or wide).

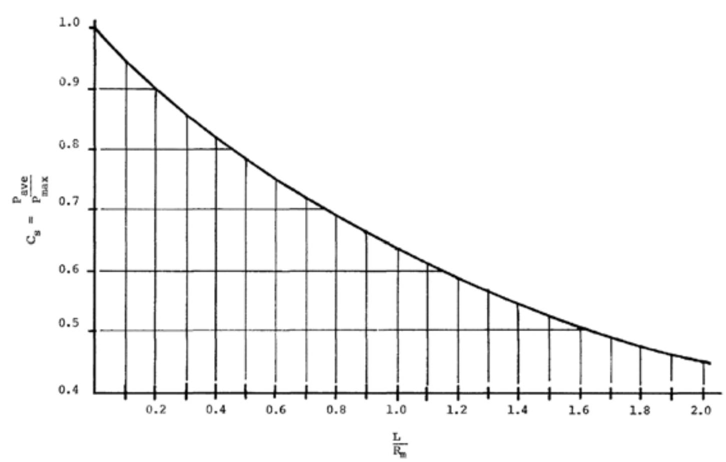
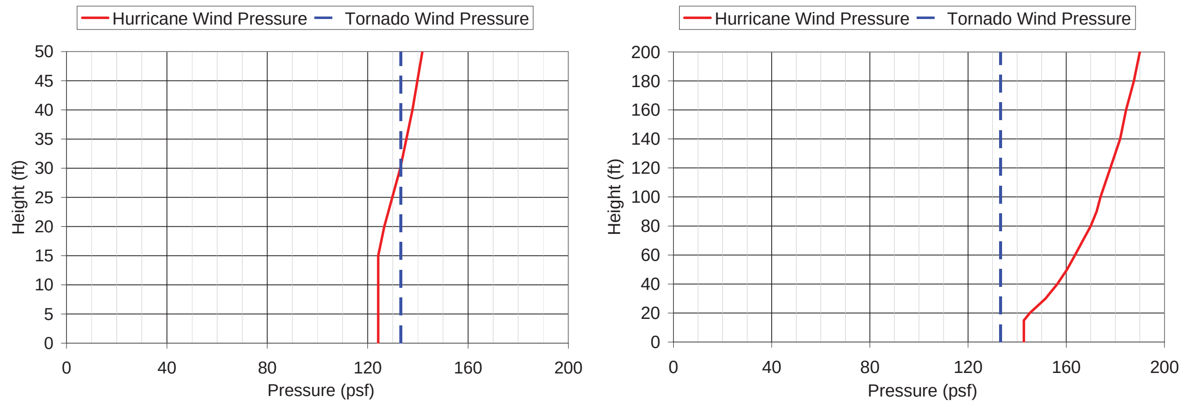
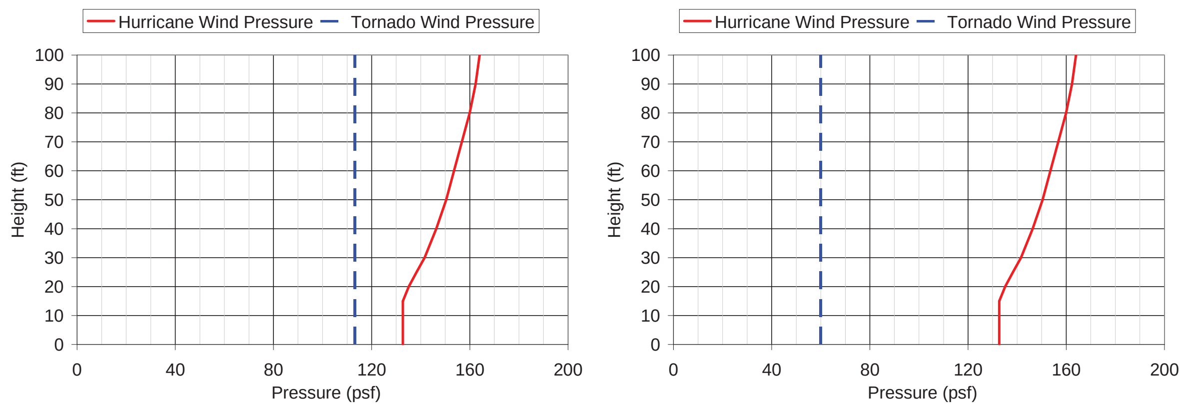


Figure 7. Tornado size effect factor [4].



(a) (b)

Figure 8. Hurricane wind pressure profile and tornado wind pressure profile for a structure (a) 50 ft tall (b) 200 ft tall (considering 200 mph for both hurricane and tornado windspeeds).



(a) (b)

Figure 9. Hurricane wind pressure profile and tornado wind pressure profile for a structure (a) 50 ft wide (b) 300 ft wide and 100 ft tall (considering 200 mph for both hurricane and tornado windspeeds).

DESIGN CONSIDERATIONS FOR SAFETY-RELATED AND NON-SAFETY-RELATED STRUCTURES

Designing safety-related nuclear power plant structures for tornado and hurricane winds requires four different assessments: (1) local assessment for minimum concrete thickness, which checks for penetration, perforation, and back-face scabbing due to rigid missile impact, (2) local assessment of panel capacity, which checks the plastic capacity of reinforced panels against the combined effect of impact force due to both rigid and crushable missiles and wind pressure, (3) global assessment of structural capacity, which checks the capacity of the lateral load resisting system for the global effects of missile impact force and wind pressure, and (4) global assessment of stability, which checks the factor of safety for the structure against sliding and overturning due to combined missile impact force and wind pressure. The design of large safety-related structures is typically governed by seismic demand. Smaller safety-related structures may be governed by tornado or hurricane.

Designing non-safety-related structures for tornado and hurricane winds requires only two different assessments: (1) global assessment of structural capacity, which checks the capacity of the lateral load resisting system for the global effects of missile impact force and wind pressure, and (2) global assessment of stability, which checks the factor of safety for the structure against sliding and overturning due to combined missile impact force and wind pressure.

EXISTING AND NEW NUCLEAR PLANTS

The new hurricane wind requirements have potential significance when considered relative to the parameters used for existing nuclear plants as well as new designs.

The design basis tornado wind speed for existing nuclear power plants is typically based on RG 1.76, Rev. 0 with maximum tornado wind speeds of 360 mph and 300 mph for Regions I and II, respectively. Also, for safety-related structures, typically the overall design of the lateral load resisting system and the stability of structure against sliding and overturning are governed by seismic loads and the reduction in tornado pressure due to size effect does not result in any design change. However, design of lateral load resisting systems of Seismic Category II structures such as turbine buildings may have taken credit for significant reduction in tornado pressure due to size effect. Thus, for Seismic Category II structures, hurricane winds may be more critical than tornado winds.

Design basis tornado wind speeds for safety-related structures included as part of standard plant structures in the new certified designs such as ABWR, ESBWR, and AP1000 are 300 mph or higher. In addition, since these structures are designed for a maximum ground acceleration of 0.3g, the overall and local design of these structures are not expected to be governed by hurricane. On the other hand, the site-specific safety-related structures and Seismic Category II structures are typically licensed based on RG 1.76, Rev. 1 and site-specific Safe Shutdown Earthquake (SSE). For these structures, hurricane winds may be more critical than tornado winds for both local and global effects. Figure 10 shows the locations of projected new nuclear power plants in the United States based on applications received by the NRC. As with the existing plant locations shown in Figure 6, many of these are in regions affected to some degree by hurricanes.

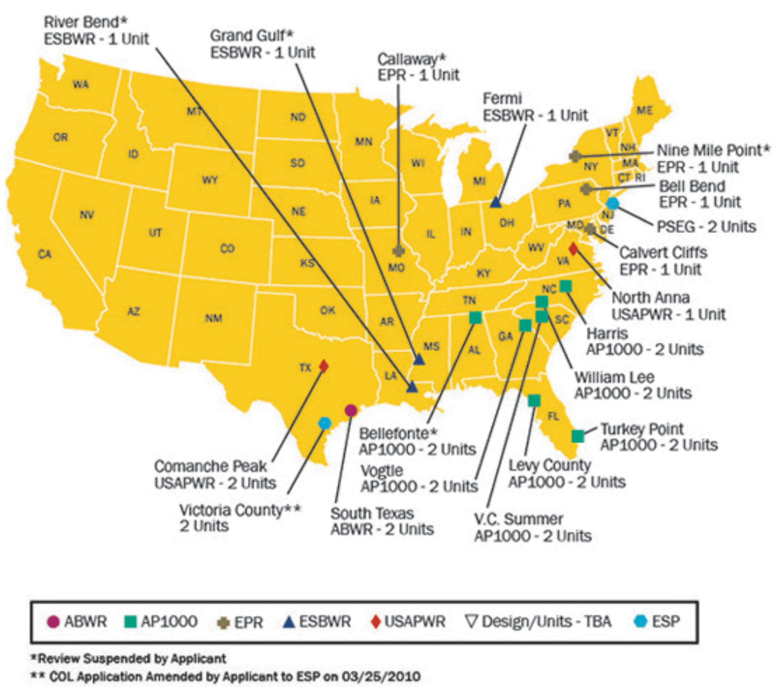


Figure 10: Locations of projected new nuclear power reactors (NRC).

CONCLUSION

The issuance of new Regulatory Guide 1.221 raises the question of what possible effects design basis hurricane wind and missiles may have on existing nuclear power plant structures and new plant designs. For existing plants, the most likely impact is on Seismic Category II structures. Though most existing designs were based on the higher tornado wind speeds of RG 1.76, Rev. 0, if a size effect was considered in determining the tornado wind pressure, hurricane wind pressure may be more critical. For structures in new certified designs, the potential impact of RG 1.221 is on site-specific safety-related structures as well as Seismic Category II structures. These designs are typically licensed based on RG 1.76, Rev. 1 and site-specific Safe Shutdown Earthquake (SSE), so hurricane winds and missiles may be critical for both local and global design. Much of the most critical region for hurricane winds in the United States overlaps with the most critical region for tornado winds along the Gulf Coast and East Coast. In these areas of the country which are subject to the most extreme of both wind types, structure geometry may be the determining factor for which wind load governs. Different structures of the same plant may be governed by different wind cases. In the categories of structures potentially affected (Category II structures of existing and new plants and site-specific safety-related structures of new plants), the larger structures, such as turbine buildings, may see the greatest increase in loads due to hurricane wind.

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