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WIND-BORNE MISSILES AND DESIGN OF SAFETY-RELATED STRUCTURES

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ABSTRACT

Research conducted to enhance protection against natural phenomena has created a new tornado scale. The tornado wind speeds based on the new Enhanced-Fujida Scale are now lower than the corresponding values based on the earlier scale, and the design-basis tornado wind speeds may no longer bound the design-basis hurricane speeds in certain areas of the US. For re-certification of existing nuclear technologies, the design hurricane wind speed and hurricane-borne missile spectrum must be selected and added to the design-basis list in the Design Control Document (DCD). This paper reviews the USNRC staff's approach to, assumptions made for, and analysis results for inclusion of hurricane-borne missile speeds for the design of Safety-Related Structures. The dynamic behaviour of the wind-borne missiles as a function of properties defining missile, wind fields, initial conditions, and calculation methods are reviewed. It explains how the design-basis hurricane and hurricane-born missile parameters can be selected for the DCD of an existing technology.

INTRODUCTION

Extreme wind conditions considered for design of Safety-Related structures in the US include tornados and hurricanes. Prior to 2007, the tornado wind speeds were based on the Fujida tornado scale and they bounded the hurricane speeds (Fujida, 1978). Subsequently, research conducted to enhance protection against natural phenomena has created a new tornado scale. The tornado wind speeds based on the new Enhanced-Fujida Scale are now lower than the corresponding values based on the earlier scale, and the design-basis tornado wind speeds may no longer bound the design-basis hurricane speeds in certain areas of the US. In response, NRC issued Regulatory Guide (RG) 1.76, Rev. 1 (USNRC, 2007), which opened up a few issues of concern for design of Safety Related structures. To address these new issues, NRC issued RG 1.221, Rev. 0 in 2011 (USNRC, 2011). This new RG requires addition of hurricane wind parameters and hurricane-borne missile spectrum to the design-basis list in the Design Control Document of an existing technology.

To select appropriate hurricane and hurricane-borne missile parameters for an existing nuclear technology, the USNRC staff's approach to, assumptions made for, and analysis results for inclusion of hurricane-borne missile speeds for the design of Safety-Related structures (USNRC NUREG/CR-7004, 2011) are reviewed. This paper explains how the final design parameters for hurricane and hurricane-borne missiles can be selected.

HURRICANE

Tropical storms typically occur from June through November in those parts of the Atlantic Ocean where the surface seawater is warm. The average temperature of the surface seawater in these oceans is about 15.6 degrees C (60 degrees F). These storms are slow-moving, have a long duration and a wide-span. Once the storms reach sufficient strength and wind speeds they are called hurricanes. To start this great weather engine requires surface seawater of 26.7 degrees C (80 degrees F) or more. It also requires moist air and little wind shear—a difference in wind speed at the sea surface and aloft that can tear apart a developing hurricane. Even with all these ingredients in place, they often produce nothing more than a tropical disturbance, which is an unremarkable cluster of thunderstorms. These disturbances look very similar from day to day. Then, for reasons not fully understood, all of a sudden there is a big burst of convection and within hours a storm can grow into a tropical depression and then a hurricane. Similar tropical storm systems are called typhoons in the western Pacific and tropical cyclones in the Indian Ocean.

In a hurricane, the heat of sun-drenched tropical sea sends warm, moist air rushing toward the frigid upper atmosphere like smoke up a chimney. As surrounding air is sucked in at the base of the storm, the rotation of the Earth gives it a twist, creating a whorl of rain bands. These whiptails of thunderstorm activity are strongest near the center of the storm where they converge in a ring of rising and spinning air called the eye-wall. The eye-wall encloses a cloud-free zone. A hurricane can propel itself to an altitude of 15,240 m (50,000 feet) or more, where the rising air finally vents itself in spiralling exhaust jets of cirrus clouds. This cirrus cloud cover can be very wide. The largest ever, the 1979 Pacific typhoon Tip, sent gale-force winds across more than 1,040 km (650 miles).

A hurricane can contain tremendous amount of energy in its winds. Nevertheless, if a storm makes landfall it is a death sentence for the hurricane as once its watery fuel supply has been cut off, the storm inevitably weakens.

SAFFIR-SIMPSON HURRICANE SCALE

Hurricane scales are used to describe the wind speed and the associated flood surge associated with a given magnitude of a hurricane. The most commonly used hurricane scale is the Saffir-Simpson Hurricane Scale, which has a 1 to 5 rating based on the hurricane's intensity (Liou and Gehrig, 2007). This scale is designed to give an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf and the shape of the coastline in the landfall region. All wind speeds referenced in this scale are the 1-minute duration, mean, surface wind speed. The following list gives a brief description of the Saffir-Simpson Hurricane scale:

- Category-I Hurricane: Winds 33.0 to 42.6 m/s (74 to 95 mph). Storm surge generally is 1.2 to 1.5 m (4 to 5 ft) above normal.

- Category-II Hurricane: Winds 42.6 to 49.3 m/s (96 to 110 mph). Storm surge generally is 1.8 to 2.4 m (6 to 8 ft) above normal.

- Category-III Hurricane: Winds 49.3 to 58.2 m/s (111 to 130 mph). Storm surge generally is 2.7 to 3.7 m (9 to 12 ft) above normal.

- Category-IV Hurricane: Winds 58.2 to 69.2 m/s (131 to 155 mph). Storm surge generally is 4.0 to 5.5 m (13 to 18 ft) above normal.

- Category-V Hurricane: Winds greater than 69.2 m/s (greater than 155 mph). Storm surge generally is greater than 5.5 m (18 ft) above normal.

The above scales provide a good reference point for design of common structures related to hurricane. Note that in this paper, these 1-minute hurricane wind speeds are presented primarily in unit of m/s. To better visualize the wind speed, the 10 m/s wind speed near the surface of the ocean roughly corresponds to the wind speed that sea waves begin to break. Similarly, the 1-minute wind speed of Category-I hurricane is approximately 3 to 4 times higher than the sea wave-breaking wind speed; and the 1-minute wind speed of Category-V hurricane is approximately 7 times higher than the sea wave-breaking wind speed or higher.

HURRICANE GUST FACTOR

Hurricane winds have peaks and lulls over a given duration, and the average wind speed tends to be higher when the duration considered is shorter. The time duration considered differs according to the purpose of use. In the above section, we discussed the Saffir-Simpson Hurricane scale, which considers 1-minute duration. The speeds produced by an academic wind-field model are generally representative from 10-minute to 1-hour duration. When their values are compared, the 1-minute average wind speed is, on the average, about 10 to 12% higher than the 10-minute mean value.

Wind gust is a sudden, brief peak in the wind. According to U.S. weather observing practice, gusts are reported when the peak wind speed reaches at least 16 knots (8.3 m/s) and the variation in wind speed between the peaks and lulls is at least 9 knots (4.6 m/s). The duration of a gust is usually less than 20 seconds. For study of wind-borne missiles, 3- to 5-second gusts are of particular significance. Connecting a long-duration wind speed and a short-duration gust wind speed is the gust factor. An example gust factor model is given in Figure 1 (Vickery et. al, 2007). As shown in this figure, gust factor generally increases with the decrease in the time duration considered.

Hurricane gust factor also varies with the height where the wind is observed. Winds, of course, can be obtained for any height above the ground, but those observed at a height of 10 m overland are most commonly used by researchers for comparison purposes. Following this tradition, winds observed at a height of 10 m overland are used in the following discussions.

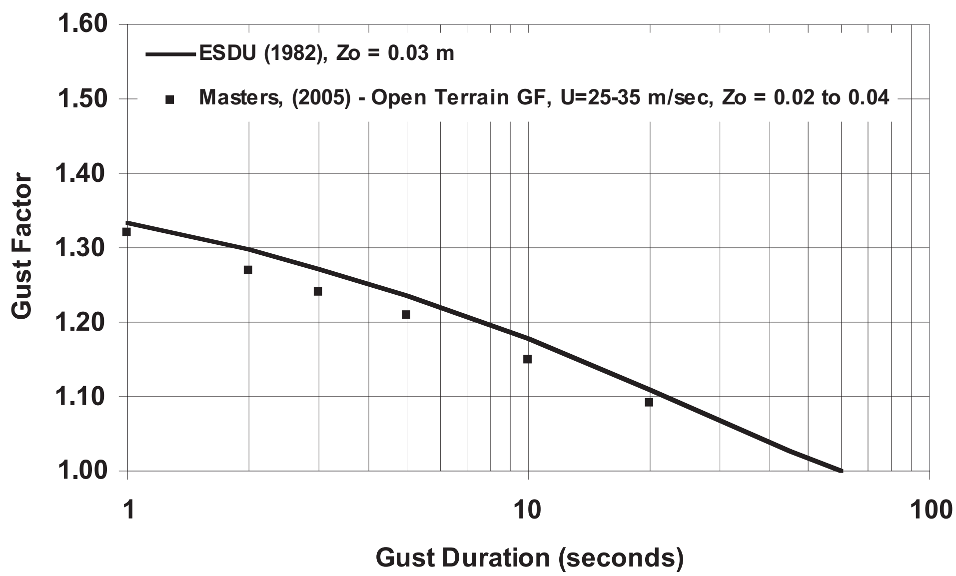

Figure 1. Example Overland Gust Factors in Hurricane

ASCE 7-95 used the gust factor model developed by Krayer and Marshall in the development of the wind speed map (Vickery and Skerlj, 2005). Various data comparisons indicate that although there is considerable variability in the estimated hurricane gust factors, the variability decreases with increasing 1-hour mean wind speed. Furthermore, at high wind speed (near or more than 30 to 35 m/s for 1-hour duration) the mean values approach those predicted by Krayer and Marshall, which is 1.57 at 35 m/s for 1-hour duration wind. For 10-minute mean wind speeds, the observed hurricane gust factors are much lower, and the factor is at 1.31 at 50 m/s.

Based on the published data, the starting, 3- to 5-second gust speed for the Category-V Hurricane can be estimated at 69.2 m/s x (1 – 10 %) x 1.57 = 97.8 m/s, or 100 m/s for all practical purposes.

SELECTION OF DESIGN-BASIS HURRICANE PARAMETERS

The selection of design-basis hurricane parameters must be based on the guidance provided in both RG 1.221 and NUREG/CR-7004. The parameters that characterize a selected hurricane include: maximum horizontal hurricane wind speed, maximum rotational speed, translational velocity, radius of maximum horizontal hurricane wind speed, and maximum pressure drop. These parameters are the same parameters that characterize the design-basis tornado, although the two wind fields are drastically different.

Among the many parameters that define a design-basis hurricane, the maximum horizontal wind speed must be selected first. RG 1.221 includes 3 figures of design-basis wind speeds that the NRC staff considers as acceptable for the design of Safety-Related structures. These wind-speed figures are for U.S. coastlines along the western Gulf of Mexico, the eastern Gulf of Mexico and southeastern Atlantic, and the mid- and northern Atlantic, respectively. Values in these figures are the nominal 3-second gust wind speeds in meters per second at 10 m (33 ft) above ground over open terrain; and they represent an exceedance probability of 10^{-7} per year. The values of the gust factor embedded in these NRC hurricane wind-speed maps are from 1.7 to 1.8, which are much more conservative than values discussed in the previous section. The high gust factors are supposed to make up for a wind model's inability to capture small-scale features, such as extreme convective gusts. Using such conservative hurricane gust factors results in up to a 121 m/s wind speed for some hurricane-prone regions in the contiguous United States.

Faced with high design-basis wind maps provided in RG 1.221, a Standard Design Certification (DC) applicant has to make a tough choice. Based on cost alone, there are two apparent options for the DC applicant. Figure 2 illustrates these options of wind speed selection along the eastern Gulf of Mexico and southeastern Atlantic coastline. An option in-between is possible but this would require cost sharing between the technology provider (the DC applicant) and a technology buyer (a Combined License applicant). Thus, it is unlikely to be selected.

The first option is to select a design-basis hurricane that would produce the same effects on Safety Related Structure as those produced by the already specified design-basis tornado. The associated design-basis hurricane wind speed selected will be a low value relative to 121 m/s. This option, nevertheless, would be the most economical for the DC applicant, as there will be no actual design changes. The costs associated with document changes will also be minimal. However, as a relatively low design-basis hurricane is selected, a Combined License (COL) applicant would be required to use RG 1.221 to determine a site-specific design-basis hurricane and hurricane missile spectra (including missile mass and velocity) for his site. If the site- specific hurricane's wind speed equals or exceeds the selected hurricane wind speed, the COL applicant is required to add those values to its lists of site characteristics in its COL document and Final Safety Analysis Report (FSAR). For example, if the design-basis wind speed is selected at 95 m/s, sites that need to consider site-specific hurricane would include St. Lucie and Turkey Point in Florida and South Texas Project in Texas.

The second option is to select a relatively high design-basis hurricane that would cover all hurricane-prone regions in the contiguous US. Such a hurricane would have a wind speed of 121 m/s. This option would be the most costly for the DC applicant, as there will be maximum design and documentation changes. On the other hand, as a high design-basis hurricane wind speed is specified in the DCD, a COL applicant would not be required to consider site-specific design-basis hurricane winds and missiles.

Table 1 presents the selected values for the design-basis hurricanes for both options. For comparison purposes, the table also lists the corresponding parameters for design-basis tornado presented in the DCD of an existing nuclear technology. These parameters meet the requirements in RG 1.76. The tornado wind speed is high because it was based on the original Fujida scale.

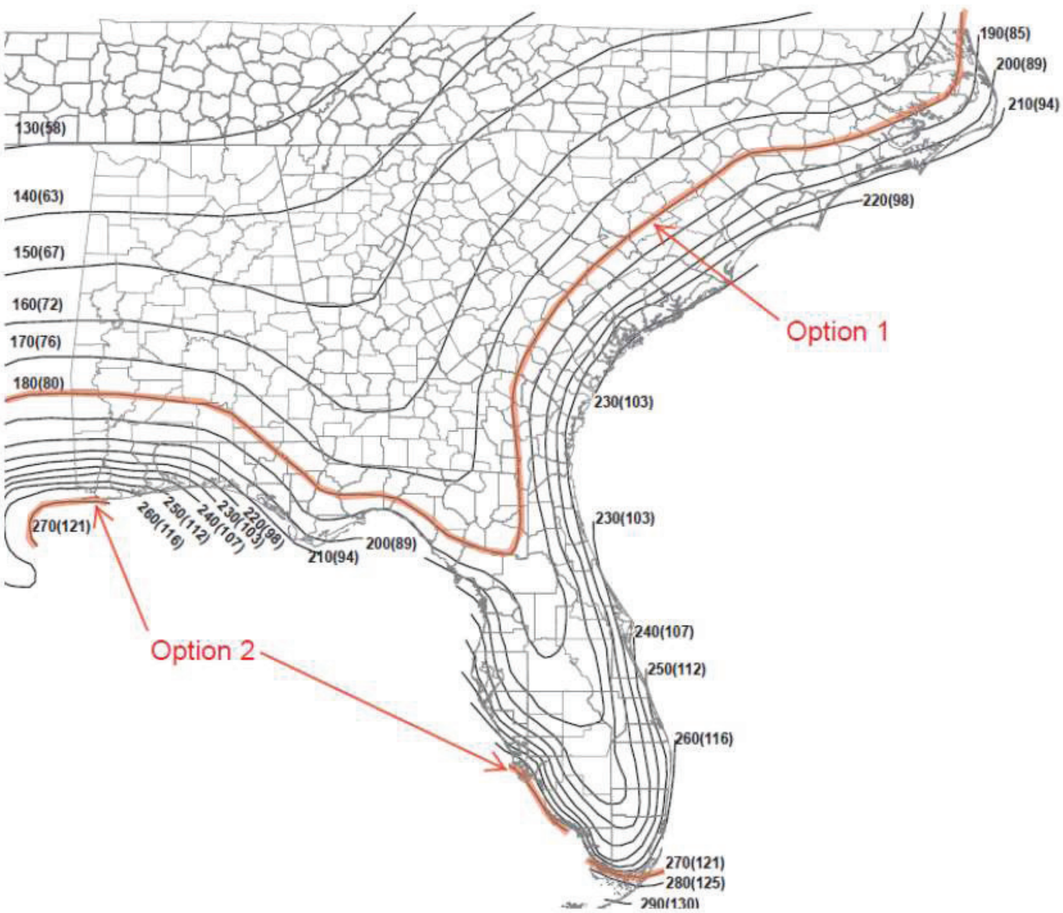

Figure 2. Hurricane Wind Speed Selection Options for Eastern Gulf of Mexico and Southeastern Atlantic Regions

Unlike design-basis tornado, the maximum pressure drop and rate of pressure of the design-basis hurricane in Table 1 are both assumed to be negligible, and a zero value is assigned to both parameters. The radius for the design-basis hurricane (1,500 m) is based on an example given in Basic Assumption section of NUREG/CR-7004. The example is used to illustrate that the differences between hurricane wind fields at the beginning and end of the missile trajectory (i.e., over a time interval of the order of 3 second) are negligible if the translational motion of the hurricane is also taken into account. In comparison with the 1,500-m radius selected for the hurricane, the radius of design-basis tornado is only

45.7 m. Although to a lesser degree, other wind field parameters listed in Table also differ, indicating hurricane and tornado wind fields behave differently.

One important assumption made in RG 1.221 is that the hurricane-borne missiles start their motion with zero initial velocity from an elevation H above the ground (the initial missile elevation). The RG1.221 example just discussed assumes: H = 40m, a hurricane wind speed of 100 m/s, and a missile traveling speed of 100 m/s. There are two issues in this example: the assumed initial missile elevation and the assumed missile traveling speed. Regarding the missile traveling speed, it should be less than the hurricane wind speed over at least part of its trajectory, but the use of a higher value simplifies the calculation and produces a conservative result. This is easier to understand, and it was already explained inside the example itself. For the issue related to initial missile elevation, it will be discussed in a later section of this paper.

Table 1: Comparison of Parameters for the Design-Basis Hurricane and Tornado

	Design-Basis Tornado	Hurricane Option 1	Hurricane Option 2
Maximum Horizontal Wind Speed	134.2 m/s	80 m/s	121 m/s
Maximum Rotational Speed	107.2 m/s	73.1 m/s	114.1 m/s
Translational Speed	26.9 m/s	6.9 m/s	6.9 m/s
Radius	45.7 m	1,500 m	1,500 m
Maximum Pressure Drop	13.827 kPaD	0.0 kPaD	0.0 kPaD
Rate of Pressure Drop	8.277 kPa/s	0.0 kPa/s	0.0 kPa/s

VELOCITY VARIATIONS IN THE DESIGN-BASIS HURRICANES

Aside from those parameters listed in Table 1, the vertical velocities of the wind fields (for both tornado and hurricane) are not listed on purpose. Similar to the difference in the radius (of maximum horizontal velocity), the vertical velocity is another major difference between hurricane and tornado wind fields. For tornado, the vertical velocity is negligible. Therefore, a tornado wind field can be adequately modelled as a single Rankine combined vortex, which possesses only azimuthal velocity.

The wind field of a hurricane, on the other hand, is considerably more complicated than that of a tornado. If the duration of a missile's flight is long, the variations in both vertical and horizontal velocities in the wind field must be considered in the calculation of the wind-borne body. Fortunately, the time interval during which a missile is wind-borne is typically in the order of 3 seconds, which is sufficiently short for the changes in the wind field to be small and the forces that can increase the elevation of the missile's flight with respect to the ground level to be negligible. Thus, the wind field velocities in this short time interval can be assumed to be constant, and the horizontal distance covered by the missile is generally limited to 300 m. However, because the vertical velocity in a hurricane wind field is not negligible, a wind-borne missile would fly differently in a hurricane than in a tornado, even when all other parameters and conditions remain the same.

WIND-BORNE MISSILES AND INITIAL MISSILE ELEVATION

The design of Safety-Related structures against impact of wind-borne missiles generally considers the so-called Spectrum I missiles. Spectrum I missiles consist of 3 types of objects: a massive high kinetic energy missile which deforms on impact; a rigid missile to test penetration resistance of protective barriers; and a small rigid missile of a size sufficiently small to just pass through any openings in protective barriers. These missiles can be a 1,810 kg automobile, a 130 kg, 20 cm diameter armor-piercing artillery shell, and a 2.54 cm diameter solid steel sphere. Typically, the automobile is the governing missile. In the design against tornado-borne missiles, an automobile missile is assumed to impact the target structure at 35% of the maximum horizontal wind speed of the design basis tornado.

In the design against hurricane-borne missiles, the same impact-velocity assumption (35% of the maximum horizontal wind speed) used for tornado-borne missiles cannot be used. The percentage has to be higher due to the larger vertical wind velocity in a hurricane. The relationships between the various hurricane-borne missile parameters are non-linear in nature, and they depend to a large degree upon the horizontal wind speed and the initial elevation assumed for the automobile missile. These relationships can be obtained by numerical simulations and, fortunately, they are given in table forms in RG 1.221. This regulatory guide presents the final impact speeds of missiles for four initial missile elevations: 40 m, 30 m, 20 m and 10m.

Although a hurricane-borne automobile missile is most likely to start its flight from the ground level, an initial elevation of 10 m is assumed in order to obtain the iteration necessary to achieve the final impact speeds of the missile. For Option 1 wind parameters presented in Table 1, a 59% of the maximum horizontal wind speed of the design-basis hurricane is equivalent to the 35% of the maximum horizontal wind speed of the design basis tornado, underlining the importance of the vertical velocity in the hurricane wind fields.

CONCLUSIONS

The design-basis tornados considered prior to 2007 generally bounded the design-basis hurricanes. Subsequent research created a new tornado scale that lowered the tornado wind speeds, and opened up a few design issues related to hurricanes and hurricane-borne missiles. This paper explains how a DCD applicant can address these issues.

Although tornado and hurricane have drastically different wind fields, some parameters that characterize tornado also characterize hurricane. These parameters include: maximum horizontal wind speed, maximum rotational speed, translational velocity, radius of maximum horizontal wind speed, and maximum pressure drop. In addition, gust factor and vertical wind speed are the two important parameters that must be taken into account when dealing with a hurricane wind field. Gust factor connects the average hurricane wind-speeds of different time durations, and those observed at a height of 10 m overland are most commonly used.

The design of Safety-Related structures against impact of wind-borne missiles generally considers Spectrum I missiles. Typically, the automobile is the governing missile. The time interval during which a missile is wind-borne is in the order of 3 seconds, which is sufficiently short for the changes in the wind field to be small and the forces that can increase the elevation of the missile’s flight with respect to the ground level to be neglicted. However, because the vertical velocity in a hurricane wind field is not negligible, a wind-borne missile would fly differently in a hurricane than in a tornado, even when all other parameters and conditions remain the same.

The relationships between missile parameters are non-linear in nature, and they depend to a large degree upon the horizontal wind speed and the initial elevation assumed for the automobile missile. These relationships for four initial missile elevations can be obtained by numerical simulations, and they are given in table forms in NRC Regulatory Guide 1.221. Although a hurricane-borne automobile missile is most likely to start its flight from the ground level, an initial elevation of 10 m is assumed in this study.

REFERENCES

Simiu, E., and Scanlan, R. H., Wind Effects on Structures, 3rd Edition, New York, John Wiley and Sons, Inc., August 1996.

USNRC NUREG/CR-7004, Technical Basis for Regulatory Guidance on Design-Basis Hurricane-Borne Missile Speeds for Nuclear Power Plants, November 2011.

USNRC Regulatory Guide 1.76, Design Basis Tornado Missiles for Nuclear Power Plants, Rev. 1, March 2007.

USNRC Regulatory Guide 1.221, Design-Basis Hurricane and Hurricane Missiles for Nuclear Power Plants, Rev. 1, October 2011

Fujida, T., "Workbook of Tornadoes and High Winds for Engineering Applications," SMRP Research Paper No. 165, September 1978

Liou, D. D., and Gehrig, B., "Building the Framework for Hurricane Chaser, a Conceptual Wind-Energy Harvesting Vessel," Proceedings of the International Conference on Sustainable Engineering and Science, Auckland, New Zealand, February, 2007.

Vickery, P. J., and Skerlj, P. F., "Hurricane Gust Factors Revisited," Journal of Structural Engineering, May, 2005.

Vickery, P. J., Masters, F. J., Powell, M. D., and Wadhera, D., "Hurricane Hazard Modeling: The Past, Present and Future," 12th International Conference on Wind Engineering, Cairns, Australia, 2007.