

Preliminar Calculation of Tornado Risk in the site of Iperó

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ABSTRACT

General Design Criterion (GDC) 2 to 10 CFR 50 requires that “structures, systems, and components that are important to safety shall be designed to withstand the effects of natural phenomena, such as tornadoes, without loss of capability to perform their safety functions”. According to Regulatory Guide 1.76, the design-basis intensity of a tornado for a nuclear power plant shall not exceed the intensity of the strongest tornado that occurs with the frequency of 10-7/years. Reinforcing the plant to achieve this goal represents a high increase in the costs of the project, and correspondently increase in the time required to have it commissioned. This way, the right definition of tornado risk in a site would represent savings in money for the project and in time for the licensing of a nuclear power plants. This works aims to establish a preliminary calculation of the tornado risk in the site of Iperó, where will work LABGENE from Brazilian Navy, and RMB from CNEN.

1. INTRODUCTION

The designated nuclear site of Iperó, where the Brazilian Navy Project LABGENE is currently under construction, and where it is intended to have the CNEN RMB built, assumed importance when the issue comes to define the probability and risk of tornado occurrence. The U.S., General Design Criterion (GDC) 2 to 10 CFR 50 requires that “structures, systems, and components that are important to safety shall be designed to withstand the effects of natural phenomena, such as tornadoes, without loss of capability to perform their safety functions”. This guideline directly affects the civil engineering project, construction and commissioning of a nuclear facility, since the demanded structural reinforcement represents an increase in the costs of the project, and an increase in the time required to have it licensed by regulatory authority. Therefore, the right definition of probability and risk of tornado in a nuclear site assumes economic importance. Unfortunately, Brazilian statistics of tornados do not have enough consistency to define the associated uncertainty for an evaluated value of risk. National meteorological observations programs do not have official statistics on occurrence of this phenomenon. Therefore, an attempt was made to gather some national characteristics of the phenomenon, as researched in a few scholarly articles available. In the lack of any necessary information, we used the average values available for the occurrence

of phenomena in the U.S., the country where this phenomenon is frequent and abundantly registered.

1.1. Objectives

The main objective of this work is to establish a preliminary calculation of the tornado risk in the site of Iperó, since no reliable data has yet been available. The refinement of this information would allow to correctly defining the structural reinforcement of the plant, and the establishment of project requirements with balance between safety and economic. For this, the methodology described in [1] was followed.

1.2 Acronyms

P_I	Probability of an Event Tornado, according its Intensity
P_S	Probability of Strike
n	Frequency of occurrence
A	Reference Area
a	Tornado Damage Area
R_D	Radius for V_D
V_D	Minimum Speed of Damage
R_{MAX}	Radius for V_{MAX}
V_{MAX}	Maximum Wind Speed of Tornado
Δt	Life time of a Tornado
V_T	Translational Speed of Tornado
σ	Associated Uncertainty

2. CONSIDERATIONS ON TORNADO RESISTANT STRUCTURES

2.1. U.S. Criteria for Tornado Resistance

To fulfil the safety guideline stated in the reference [2], the requirements and criteria for tornadoes resistance are regulated by [3]. Besides the dynamic effect of the mass airflow, the structural resistance must consider the tornado generated missiles which “include at least (1) a massive high-kinetic-energy missile that deforms on impact, (2) a rigid missile that tests penetration resistance, and (3) a small rigid missile of a size sufficient to pass through any opening in protective barriers”. The speed impinged onto these three missiles, its mass, and the dynamic effect of the mass airflow depends on the tornado intensity. The design tornado for a nuclear power plant is the most intense whose frequency exceeds the recurrence of 1E-7 years, considering that the tornado intensity is associated with its maximum wind speed. So, based on meteorological observations, the U.S. NRC staff split the U.S. map according three different regions, considering three different tornado intensities, according table 1:

Table 1: U.S. Tornado intensity region classification, from [3]

U.S. Region	Tornado Intensity Maximum Wind Speed	
Region I – Central Region	230 mph	103 m/s
Region II – East Coast, Northern Border, Western Great Plains	200 mph	89 m/s
Region I Region III – Western Region	160 mph	72 m/s

These wind speeds are used as basis for the numerical model used in the reference [3]. Currently, the true maximum wind speed in a tornado and its field distribution of speed are unknown. The maximum wind speed of a tornado is empirically related to the damage caused through the Fujita scale, or the Enhanced Fujita scale [4], as presented in table 2.

Table 2: Enhanced Fujita Scale, from [3]

EF Number	3 Second Gust (mph)
0	65-85
1	86-110
2	111-135
3	136-165
4	166-200
5	Over 200

2.2. Dynamic Mass Airflow Effects and Missiles Effects

According the classification on table 1, the tornado airflow field and the tornado missiles main physical characteristics are obtained, according to tables 3 and 4, extracted from [3].

Table 3: Tornado airflow field according its region of classification, [3]

	Maximum Wind Speed m/s (mph)	Translational Wind Speed m/s (mph)	Maximum Rotational Speed m (ft)	Radius of Maximum Rotational Speed m/s (mph)	Pressure Drop mbar (psi)
Region I	103 (230)	21 (46)	5.7 (150)	82 (184)	83 (1.2)
Region II	89 (200)	18 (40)	5.7 (150)	72 (160)	63 (0.9)
Region III	71 (160)	14 (32)	5.7 (150)	57 (128)	40 (0.6)

Table 4: Postulated tornado missiles according its region of classification, [3]

Missile Type		Schedule 40 Pipe	Automobile	Solid Steel Sphere
Dimension		0.168 m dia x 4.58m long	Region I and II 5 m x 2 m x 1.3 m	2.54 cm dia
			Region III 4.5 m x 1.7 m x 1.5 m	
Mass		130 Kg	Region I and II 1810 Kg	0.0669 kg
			Region III 1178 Kg	
V _{Max}	Region I	41 m/s	41 m/s	8 m/s
	Region II	34 m/s	34 m/s	7 m/s
	Region III	24 m/s	24 m/s	6 m/s

As long as the frequency of recurrence of the designed tornado is very small ($1E-7$ /year), the choice of missiles seeks to present the most common objects around the facility. The schedule 40 pipe and the solid steel spheres are expected to hit any place of the tornado barrier of the facility, on the other hand, the hit range of the automobile is limited to 9.14 m above all ground levels within 800 m around the tornado barrier.

2.3. Design of Tornado Resistant Structures

The basic criteria in the design of structures in a nuclear facility must be so that it is able to withstand the effects of tornado, without loss of capability to perform its safety function. For nuclear safety functions, we refer to [5] for mechanical components or [6] for concrete structures, from where comes the definition of nuclear safety function as the functions related to “(a)The integrity of the reactor coolant pressure boundary, (b) the capability to shut down the reactor and maintain it in a safe shutdown condition, or (c) the capability to prevent or mitigate the consequences of plant conditions that could result in potential offsite exposures that are comparable to the guideline exposures of the Code of Federal Regulations, Title 10...”.

In a nuclear facility, it is clear that the tornado resistance is only possible to be related to the structures that have an interface with the environment, namely, building walls, ceilings and floors, and penetration barriers, access doors for example. There is no sense in qualifying inner components as tornado resistant, since they are supposed to be protected. To attribute the tornado resistance, each structure must be individually evaluated according of the safety related function, as defined in [5] or [6]. Concrete structures that house systems, equipment or structures related to the safe shutdown of the reactor, and the integrity of the Reactor Coolant Pressure Boundary are not supposed to interfere in the safety function performed by these components, if they collapse. Besides, they are also not supposed to allow the scape of radioactive inventory to the environment, compromising the offsite exposure. So the necessity to safeguard those concrete structures imposing tornado resistance is clear for the reactor building and spent fuel storage pool building among others. Otherwise, the penetrations barriers qualifications may be dispensed, as long as it is proved that they

collapse will not interfere in the safe shutdown reactor requirement, and will not interfere in the integrity of the reactor coolant pressure boundary, and the release of radioactive inventory is not enough to compromise the offsite exposure.

The tornado resistance figures among the most restrictive requirements of a nuclear site. And, as may be proved through numerical evaluations, the most restrictive requirement is the automobile impact. For this reason, an operational restriction in the access if automobiles within 800 m of the tornado resistant structures would represent reasonable economy of resources and time, both related to the design, building and commissioning of the nuclear site.

3. EVALUATION OF TORNADO PROBABILITY AND RISK IN THE SITE OF IPERÓ

3.1. Methodology of Evaluation

In this section, the evaluation procedure to find the probability and risk is presented. According to [1], the design basis tornado must be such that:

$$P_S \cdot P_I < 10^{-7} \quad (1)$$

Where P_S is the probability that a tornado strikes the site, this later considered as a point, and P_I is the probability of an event tornado, according its intensity. P_S is evaluated through the formula:

$$P_S = n \cdot (a/A) \quad (2)$$

Where “n” represents the average frequency tornado of any intensity per year in area “A”, while “a” is the area through which the tornado exerts its influence.

P_I is the product of the statistical observation of tornado events, and its intensity. As an example, figure 1 presents the statically plot of the intensity of a tornado (wind speed) vs. the probability of this intensity, for U.S., extracted from [1].

Considering the associated risk of an event, as a direct relation between probability of occurrence of this event and the grade of its unwanted consequences, the risk of a tornado is implicitly considered in this formulation, as it follows:

- The likelihood of occurrence of the design basis tornado is explicitly evaluated;
- The consequences are considered as the consequences of this design basis tornado. So, to decrease the risk of this design basis tornado, the building of the civil structures of the will have to be reinforced (for example), in order to reduce the unwanted consequences of the design basis tornado, what will supposedly increase the costs and the required time to build. This is the key point of tornado risk analysis, since the correct evaluation of probability in the project phase allows saving in resources during the building phase of the project.

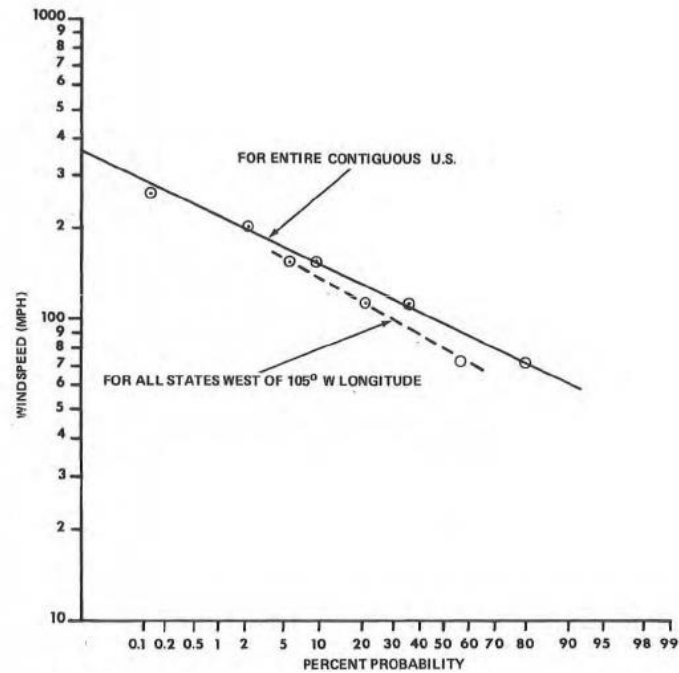


Figure 1: Tornado wind speed vs. occurrence probability, [1]

3.2. Probability of Strike (P_s) in Iperó

3.2.1. Frequency of occurrence (n)

According to [7], between 1991 and 2011, there was 46 occurrence tornadoes registered in the state of Sao Paulo. This range of date was chosen, since from the year of 1991 the influence of the internet helped to spread the information of occurrence of tornadoes. As Brazil do not account on a reliable system to register tornadoes, these registers come mostly from non-technical sources like news in the media, for example. Some uncertainty must be considered, since tornadoes, may occur in remote regions of the state, and for this, they will not be registered. In the other way, occurrences that are not technically tornadoes may be wrongly increase the total number of tornadoes. Looking on these 46 registers in 20 years, the frequency of 2.3 tornadoes per year may would supposed.

In an effort to refine this statistic, in this same work [7], a numerical evaluation was undertaken, producing the figure 2, depicted as following:

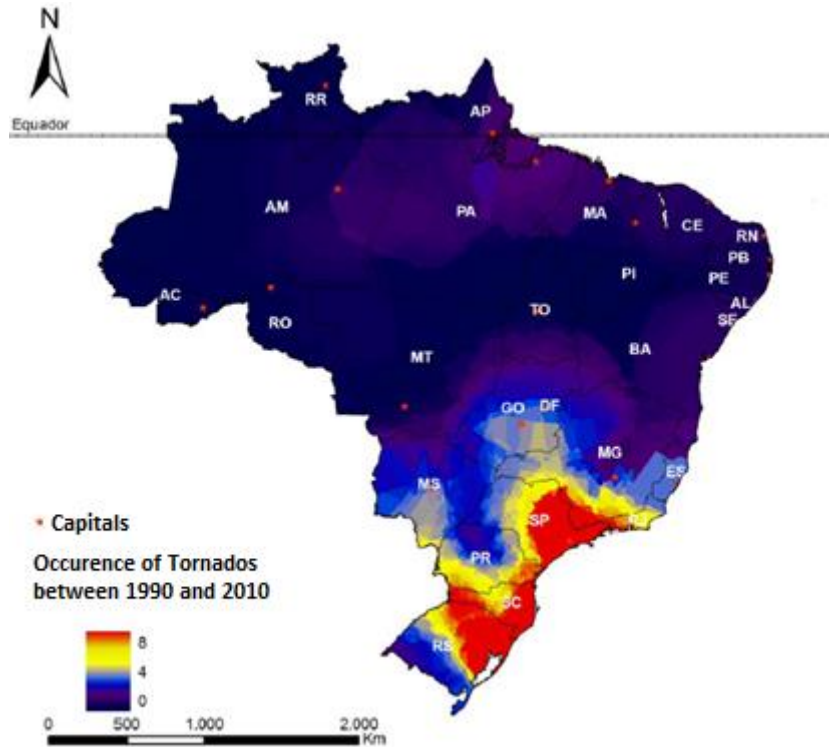


Figure 2: Spatial distribution numerical evaluation of tornado occurrence, translated from [7]

However, the figure 2 may not be used in order to produce a frequency of occurrence (“n”) since the numerical evaluation of the number of occurrence of tornadoes is not presented associated with an area (“A”), as required in [1], and it is hardly understood how, in the same work 46 occurrences of tornadoes for the state of Sao Paulo in 20 years are presented in the annex, while, the occurrence of 46 tornadoes for the same period and same area may not be inferred from the analysis of the figure 2.

For the sake of the safety, this work will consider the frequency of occurrence of tornadoes for the state of Sao Paulo, higher than the value of 2.6 tornadoes per year, in order to compensate a higher probability region of tornado occurrence around Iperó, and to discard eventual misdoings in the register of tornadoes, so:

$$n = 4. (1 \pm 34.1\%) = 4 \pm 1.4 \text{ tornadoes/year} \quad (3)$$

The uncertainty corresponds to one standard deviation (1σ) corresponding to 34.1% of deviation, for a considered Gaussian Curve, on both sides, assumed by the authors.

3.2.2. Area of strike (“a”)

The strike area of one tornado is obtained from its translational speed (V_T), its maximum radius where the wind speed is causes damage (R_D), and its time of duration (Δt). Once these three components are determinate, the damage area is found simply through the application of equation (4):

$$a = 2 \cdot R_D \cdot \Delta t \cdot V_T \quad (4)$$

No definitive data may be found over the above mentioned components, however, assumptions may be made, as it follows.

3.2.3. Maximum radius where the wind speed is causes damage (R_D)

According [4], a F2 tornado (table 2) would be the first to cause considerable damages. So, the reference speed to cause damage (V_D) will be conservatively assumed by the authors for the remaining of this work as 60% of the maximum speed of a F2 Tornado, this means about 70 mph, or 31 m/s. The correspondent radius to this speed is numerically inferred through equation (5):

$$R_D = \frac{V_{MAX} \cdot R_{MAX}}{V_D} \quad (5)$$

Where data to evaluate R_D comes from table 3. Once again, for the sake of safety, let us consider we have a large uncertainty concerning the radius of maximum damage evaluation, of 34.1% on both sides of a supposed Gaussian curve, which give us the data presented in table 5, through the application of eq. (5).

3.2.4. Translational speed (V_T)

Translational speed is numerically assumed one fifth of the maximum rotational wind speed [3]. As described in table 2, the maximum wind speed ranges from a maximum and minimum values, so it is considered the average value, with uncertainty of half of this range. Results are filled in table 5.

3.2.5. Time of duration (Δt)

From [4], “Most tornadoes last less than 10 minutes”. For this information, let us suppose that the duration of a tornado probability has a Gaussian distribution, and that the probability of a tornado have a duration of less than 10 minutes falls behind 10%, or approximately and even more restrictive 1 σ (34.1%) on both sides, so the duration of tornado is like (6):

$$\Delta t = 600. (1 \pm 34.1\%)s = 600 \text{ s} \pm 205 \text{ s} \quad (6)$$

3.2.6. Area of strike (“a”) uncertainty evaluation

Considering the values of V_T , R_D , and Δt , the area of strike may be evaluated through eq. 4. The associated uncertainty σ_a may be evaluated through the application of eq. (7).

$$\sigma_a^2 = \left(\frac{\partial a}{\partial R_D} \cdot \sigma_{R_D} \right)^2 + \left(\frac{\partial a}{\partial V_T} \cdot \sigma_{V_T} \right)^2 + \left(\frac{\partial a}{\partial \Delta t} \cdot \sigma_{\Delta t} \right)^2 \quad (7)$$

3.2.7. Probability of Strike (P_S) – value found and uncertainty

For the evaluation of the probability of tornado strike (P_S) the area of Sao Paulo state is considered 248,808.8 Km² [8], with neglected uncertainty. Therefore, to obtain the average value of the probability of strike, eq. 2 is applied. The uncertainty of P_S is evaluated through eq. (8), and the results are summarized in table 5.

$$\sigma_{PS}^2 = \left(\frac{\partial P_s}{\partial n} \cdot \sigma_n \right)^2 + \left(\frac{\partial P_s}{\partial a} \cdot \sigma_a \right)^2 \quad (8)$$

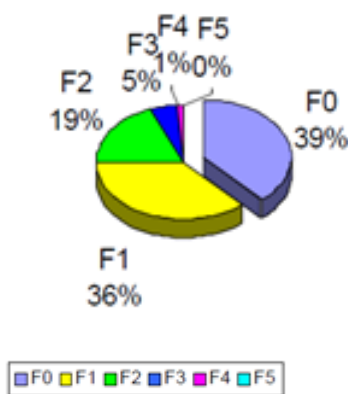
To conclude this section, it is observed that the P_s , as the likelihood of a tornado strike one point in the state of Sao Paulo, is higher for an F3 tornado than for an F2 tornado, since the area affected by an F3 tornado is higher than an F2 tornado. In next section it will be considered the conditional probability of F3 or F2 tornadoes happen.

3.3. Probability of Tornado According its Intensity (P_I) in Iperó

Yet, it is needed to define a conditional probability: once a tornado strikes the point of interest, what is the probability that this tornado is a F3 or a F2 tornado. Others tornadoes of Fujita scale, are not *a priori* considered, since it is supposed their likelihood is much higher or lower than the limit of 10^{-7} . So, *a priori* it is supposed that the design basis tornado is a F2 or F3.

Unfortunately, it was not found in the literature any aid to quantitatively establish this probability to the state of Sao Paulo. Therefore, this value will be inferred from the literature that describes this phenomena in U.S. territory, as may be seen in figures 3 and 4, extracted from [9].

**Tornadoes by F-scale
(1970-2002)**



**Tornadoes By F-Scale
1998-2002**

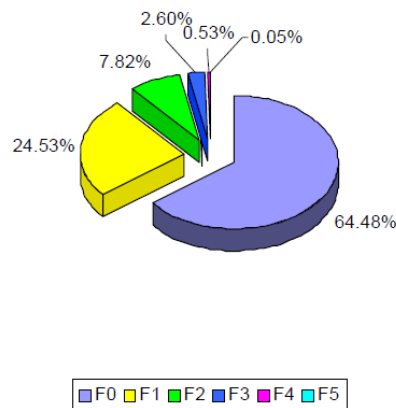


Figure 3: Percentage of Tornadoes, 1970-2002, by F-Scale Damage [9]

Figure 4: Percentage of Tornadoes, 1998-2002, by F-Scale Damage [9]

The same information we seek in figures 3 and 4 is presented in table format within ref. [1]. From this reference, the probability of a tornado be F3 is 7.2 %, and F2 is 26.6%. However, these information comes from 1612 tornados observed in 1971 and 1972, and will be neglected since new information produced under recent technology is available, as in fig. 4. Information on fig. 3 will be neglected face of more recent information of fig. 4. As long as this is information based on a data basis from U.S., we allow 10% of uncertainty margin for both sides, what is summarized in table 5.

3.4. Final Results

The probability of strike of an F2 tornado, and the probability of strike of an F3 tornado are evaluated through eq. (1). The uncertainty is found through eq. (9):

$$\sigma_{P_S.P_I}^2 = \left(\frac{\partial P_I P_S}{\partial P_I} \cdot \sigma_{P_I} \right)^2 + \left(\frac{\partial P_I P_S}{\partial P_S} \cdot \sigma_{P_S} \right)^2 \quad (9)$$

Final results are summarized in table 5, and will be commented in the section 4 of the present work.

Table 5: Area of strike (a) estimative

EF	Δt (s)	R_D (m)	V_T (m/s)	a (Km ²)	P_S	P_I	$P_S \cdot P_I$
F2	600 s \pm 205	90 \pm 45	55 \pm 5	5.84 \pm 2.87	(9.4 \pm 5.6)E-5	7.82 \pm 0.78%	(7.34 \pm 4.45)E-6
F3	600 s \pm 205	110 \pm 55	67 \pm 6.5	8.69 \pm 4.27	(14 \pm 8.3)E-5	2.60 \pm 0.26%	(3.63 \pm 2.20)E-6

4. CONCLUSION

Increase in safety of a project often compromises resources, economy and deadlines of a project, for this reason, safety increasing measures must be preceded by studies that will analyze its motivation, and the possible effects in costs and extension in deadline. Among the strongest impacts on the structural design of a nuclear power plant, figures the effect of tornado, and among the harmful effects of a tornado, figures the automobile demanding the highest structural reinforcement. Therefore, the right evaluation of tornadoes influence in a design phase would avoid unnecessary costs and delays.

The results for $P_S \cdot P_I$ in table 5 indicate the reduction of the risk for the site of Iperó would preliminarily demand the reinforcement of the site considering a F3 tornado, in order to reduce its unwanted consequences, since its probability ((3.63E-6) exceeds the postulated value of 1E-7, according [3].

The methodology of punctual evaluation of tornado risk hereby presented is still a preliminary concept, which could be improved as long as the inputs are refined. The large standard deviation (2.20E-6) would have to be sharpened. Among the most deleterious influences figures:

- the frequency of tornados per year in the state of Sao Paulo, for this number was not obtained through technical methods, rather, by information spread through the media and internet, which inserts intrinsic uncertainty to the value found. Conservatively was adopted in this work $n = 4$ tornados/year;
- The conditional probability that a tornado be F3 or F2, for this information is related to the U.S. climatology. When bringing it to this work, it was conservatively adopted 10% of margin of error.

The uncertainty is still too large in order to offer a sharp final result, which could support the decision to increase or decrease the tornadoes requisites of facility. Regardless the imprecision in the input, the methodology seems to present a nice path to be followed, and still developed. The final result so presented, regardless coarse, may be looked as a highly conservative and would not support a decision to define the design basis tornado of the site as a F2, however, future studies may.

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