ASSESSMENT OF TORNADO HAZARD IN THE NUCLEAR FACILITIES SITING AREAS

by

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The potential hazard of destructive tornado effects on nuclear facilities determines the necessity to study the climatic regime of tornado passage and arrange the appropriate protection of these facilities in conformity with the national and international radiation safety standards. One of the most characteristic features of the climate in recent decades is a significant increase in the number of dangerous meteorological events, including tornadoes. The purpose of this study is to assess the level of tornadoes hazard for nuclear facilities and to determine the design characteristics of tornadoes. The data on the tornado passage through the tornado-hazardous subzone A-L on the territory of the former USSR made it possible to estimate the probability of tornadoes passing through a hypothetical nuclear facility site, showing that it does not exceed the probability of the criterion in force in Russia – the threshold probability of 10^{-4} per reactor per year. It is shown that such a threshold probability can be achieved if two or more tornadoes of intensity class F5 on the Fujita scale would pass through subzone A-L. For such a hypothetical scenario, the design characteristics of a probable tornado were determined. The need to improve the regulatory and technical base in the field of nuclear facilities safety is noted to ensure their reliable protection from the effects of tornadoes.

Key words: tornado, radiation safety, nuclear facility, tornado hazard criterion, tornado impact

INTRODUCTION

It is known that nuclear facilities (NF) can be exposed to various external effects of natural and man-made origin [1, 2]. In particular, such items include nuclear reactors, radiation sources, storage of nuclear materials and radioactive substances, storage of radioactive waste, irradiated fuel assemblies of nuclear reactors, nuclear materials, radioactive substances, radioactive waste.

Among the external effects that can lead to accidents at NF with severe radiation consequences, tornadoes are a potential hazard [1, 3, 4].

The destructive effect of tornadoes occurs mainly due to high wind speeds in the vortex, sometimes exceeding 100 ms^{-1}, and pressure drops between the periphery and the center of the tornado, reaching 100 hPa and more [3, 5]. In addition, the destruction of facilities can occur as a result of the impacts of heavy objects captured by the wind flow [5, 6].

Most often, powerful tornadoes are observed in the United States and Canada (about 2/3 of their occurrence in the world), as well as in Bangladesh, much less often and weaker they are observed in Europe and Russia [7-10]. According to statistics from the United States Meteorological Service, in the period from 1950 to 2013 only, more than 50 tornadoes of the highest intensity class (F5 as per the Fujita scale) have been registered in the USA [11]. Tornadoes of this intensity occur quite rarely – in less than 0.1 % of cases [12]. Destructive tornadoes of the F5 class have also appeared in Bangladesh in recent decades [13]. The most intense tornado registered in Russia in 1984 was assigned to the F4 class [14].

The destructive effect of tornadoes is a potential hazard for various types of production facilities. At the same time, tornadoes pose the greatest threat to the population and the environment when tornadoes affect NF, and, in particular, nuclear power plants (NPP) [1, 3, 9]. Such a hazard is explained by the theoretical possibility of beyond-design-basis accidents with a maximum accidental release (discharge) of radionuclides into the environment. However, refusal to run NF is

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impractical, because they generate more than 11 % of all electricity produced in the world, and other types of NF are important for the economy [15].

The need to take into consideration the potential impact of tornadoes on NF and their engineering protection design is based on the probabilistic criterion of tornado hazard [1, 3, 4, 16]. This takes into account the statistical data on the passage of tornadoes of various intensities near the NF sites. The experience accumulated in the construction and operation of NF in various countries over many years, as well as the new knowledge obtained about the climatology of tornadoes, determines the need to analyze the existing regulatory criteria for tornado hazard in the areas where NF are located and the possible strengthening of the NF safety standards. The main arguments in favor of such an analysis are summarized:

There is a steady increase in the number of NF in the world. As of December 2019, there are 450 operating nuclear power units at NPP in 31 countries [17], 38 of which are operating in Russia. Besides, the total number of research and test reactors in the world exceeds 800. Apart from that, a large number of other types of NF are concentrated in the world and Russia. The number of operating NF of various types is increasing from year to year.

Most NF are located in flat areas where tornadoes are most common and where the population density is high. The specific feature of the NF location lies in their concentration on flat areas close to consumed water resources and in those places where there are no dangerous seismic and geological conditions for NF [18]. But it is precisely such areas that are favorable for the emergence of tornadoes as atmospheric vortices move along the trajectories passing along the lowest terrain heights. In connection with this circumstance, the spatial density of the distribution of NF in flat areas can be significant, for example, in the USA, Canada, Europe, and the European part of Russia. Therefore, dangerous cases of the impact or approach of tornadoes to NF were noted [19].

Thus, in June 2010, the F2 class tornado affected the operation of the Enrico Fermi NPP, USA. The US National Meteorological Service reported that a tornado with a path length of 10.5 km and a destruction zone width of 460 m approached the center of the NPP site at about 700 m distance. As a result, the tornado with a maximum wind speed of 49 ms^{-1} tore off the outer casing of the emergency equipment building and damaged it. The tornado also destroyed the transmission power line, causing the NPP to shut down for an entire day [19, 20].

In April 2011, a tornado with an intensity class from F3 to F5 and a destruction zone width from 0.8 to 1.2 km arose near the Browns Ferry NPP, USA [19]. The tornado passed at a distance of approximately 5 km from the center of the NPP site. The tornado wind speed exceeded 60 ms^{-1}. Although the tornado passed at a relative distance from the NPP, all three nuclear reactors were shut down for 15 minutes. Power lines were severely damaged [21]. The tornado lifted several cars into the air and carried them hundreds of meters away. Hundreds of houses were seriously damaged along the tornado's path.

Also, in April of the same year, a tornado with intensity F3 and a wind speed of about 70 ms^{-1} passed through the Surry NPP site, USA. However, it did not inflict any severe damage to the NPP facilities. On the NPP territory, a garage, and a fuel tanker for refueling backup generators were damaged [19, 22].

In June 1998, an F2 category tornado passed near the Davis-Besse NPP, USA, with a maximum wind speed of about 70 ms^{-1}. Although the tornado passed near the cooling tower, it did not damage it. Due to the damage to the electrical distribution system and power lines, an automatic shutdown of the NPP occurred, which was out of operation for two days [23].

In March 1996, a tornado of F3 class passed at a distance of about 4 km from the center of the Quad Cities NPP site, USA. The NPP fence was damaged and the roof of one of the buildings was demolished [19].

In recent years, there have been cases of relatively weak tornadoes of categories F1 and F2 passing near the Russian NPP sites, fig. 1. These tornadoes did not damage the NPP. Regretfully, the photos provided in fig. 1 are of low quality, since rare events, such as the passage of tornadoes, are usually short-lived and their photo or video is taken by household smartphones.

As a result of climate change in recent decades, there has been a clear increase in the frequency and intensity of tornadoes. At present, as a result of climatic changes in the world and Russia, natural disasters have become more frequent, including dangerous meteorological phenomena, such as the passage of tornadoes

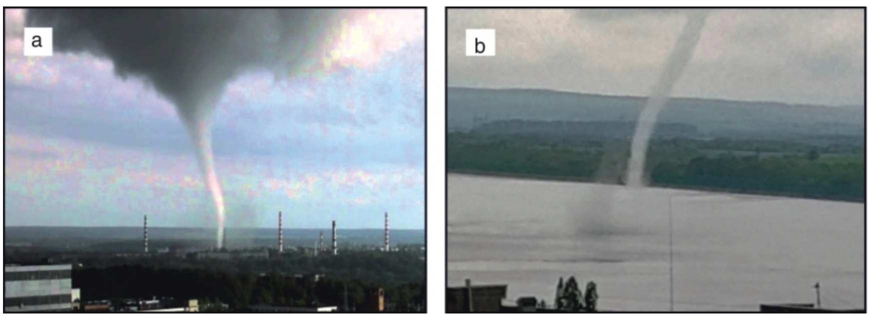

**Figure 1. Tornadoes near the NPP sites:
(a) Obninsk NPP (May 24, 2013) [24];
(b) Novovoronezh NPP (May 20, 2020) [25]**

[26, 27]. This trend has been going on for over 20 years. Therefore, the possibility of the appearance of class F5 tornadoes in Russia is not excluded.

Tornadoes lead to numerous casualties and significant economic damage. According to the data published in [28, 29], the annual damage from tornadoes in the United States amounts to billions of dollars. Also, the number of casualties and injuries is estimated at hundreds.

Different countries have different threshold probabilities of tornado passing, which determine the need to take them into account in the design of engineering protection of NF. In Russia and other countries, the basic safety criterion for the impact of an external factor on NF provides for the condition that the probability of a beyond-design-basis accident with a maximum accidental release (discharge) of radionuclides into the environment $P_G = 10^{-7}$ per reactor per year. However, the consequences of tornado impact on NF may not always inevitably lead to such an accident. This is because tornadoes passing through the NF sites with the P_G probability can be relatively weak [16]. As a criterion for deciding whether to take into account or disregard hazardous external phenomena of natural origin (including tornadoes), the Russian regulatory requirements apply the threshold probability $P_0 = 10^{-4}$ per one reactor per year [1]. Similar criteria are adopted in a number of other countries [30]. At the same time, in the United States and China, national standards in force envisage tornadoes with a lower probability of P_0 [31, 32].

The world-wide trend to tightening requirements for ensuring the safety of nuclear technologies is noted. In recent decades, measures to improve the safety level of nuclear power facilities have been carried out everywhere in the world [33]. This was preceded by severe accidents at NF, the most severe of which occurred at the following sites:

– Kyshtym Chemical Combine, Russia (1957) – the International Nuclear Event Scale (INES) level 6 accident;

– Windscale accident, Great Britain (1957) – the INES level 5 accident;

– Three Mile Island NPP, USA (1979) – the INES level 5 accident;

– Chernobyl NPP, Ukraine (1986) – the INES level 7 accident;

– Fukushima Daiichi, Japan (2011) – the INES level 7 accident.

In many cases, there is significant uncertainty and unreliability in the data on the passage of tornadoes. In many cases, when analyzing the potential impact of tornadoes on NF, there is significant uncertainty in the data on the passage of tornadoes. Information about tornadoes, as a rule, is qualitative, and their description contains approximate quantitative characteristics [9].

The noted circumstances determine the need to analyze the existing probabilistic criteria on tornado hazards in the NF siting areas and the potential tightening of the NF safety standards.

The purpose of this study is to assess the level of tornado hazard on the NF and to determine the design-basis characteristics of tornadoes.

METHODOLOGY

As previously noted, information on the passage of tornadoes is usually qualitative. The main approximate quantitative characteristics are assigned to tornadoes by the Fujita scale [34]. The intensity classes on such a scale are determined based on the descriptions of the consequences of the tornado passage. The characteristic values of the maximum rotation speed of the wall of the tornado funnel, v_k, the length, L_k and width, W_k of the zone of the passage of the tornado of the k-th class on the Fujita scale, as well as the pressure drop between the periphery of the tornado and its center, Δp, are determined using the following expressions [4]

$$v_k = 6.3(k + 2.5)^{1.5}\ \mathrm{ms}^{-1}, \quad L_k = 1.609 \cdot 10^{0.5(k + 0.5)}\ \mathrm{km}, \quad W_k = 16.09 L_k\, m, \quad \Delta p = \rho v_k^2\ \mathrm{hPa} \tag{1}$$

In its turn, the tornado travel speed is determined using the formula known from [35]

$$u_k = 0.25 v_k \tag{2}$$

According to [9], the annual probability, and, strictly speaking, the repeatability of a tornado of the k^{th} class at a fixed point of a tornado-hazardous area, is

$$P = P_S[1 - F(k)] \tag{3}$$

where $F(k)$ is the probability that the tornadoes registered in the given area do not exceed k class. When determining the total area of tornado passage zones, it is considered that the actual number of undetected tornadoes is greater than the observed one. Therefore, to assess the actual number of minor tornadoes with a class not higher than 1 that passed through a given area, a correction coefficient $\alpha(k)$ is introduced, which varies from 2 to 4 for territories with a low population density [9]. For tornado intensity classes higher than 1, $\alpha(k)$ is taken equal to 1. Thus,

$$\alpha(k) = \alpha_0 \text{ when } k \le 1 \text{ and } \alpha(k) = 1 \text{ when } k > 1 \tag{4}$$

For a territory with the area equal to A, within which the tornado passage has been noted for T years, the annual repeatability of tornadoes on its territory P_S is estimated as

$$P_S = \frac{S}{AT} \tag{5}$$

where S is the total area of the destruction zone (trace) of tornado path

$$S = \sum_{k=0}^{l} n_k \alpha(k) L_k W_k \tag{6}$$

where l is the highest class among the registered tornadoes.

Another definition of the probability is given in [3]: instead of P_S 1000 km^2 × P_S is offered, which is interpreted as the probability of a tornado-hazardous event in the NF siting area within the territory of 1000 km^2 surrounding the NF site. However, this interpretation of the tornado probability is incorrect. In particular, it is measured in km^2 per reactor per year.

Due to the discreteness of the tornado intensity classes, the empirical integral probability of their passage is determined ambiguously and for a given class k, it takes n_k values

$$F_i(k) \quad \frac{1}{S} i\alpha_0 L_0 W_0 \text{ when } k \quad 0 (i \quad 1,\ldots n_0)$$

$$F_i(k) \quad \frac{1}{S} \, {}_{j \;\; 0}^{k \;\; 1} n_j \alpha(j) L_j W_j \quad \frac{1}{S} i\alpha(k) L_k W_k$$

$$\text{when } k \quad 0 (i \quad 1,\ldots n_k) \tag{7}$$

Here n_k is the distribution of tornadoes registered in the considered area, according to the intensity class gradations. In many cases, the recorded tornadoes are referred to as intermediate intensity classes divisible by 1/2. When calculating the probabilities $F_i(k)$, such tornadoes are taken into consideration along with tornadoes of integer classes.

According to [9], when graphically plotting the empirical integral probability curve $F(k)$, this curve is satisfactorily straightened using a logarithmic scale. This is explained by the fact that the tornado path area, and consequently the probabilities, grow exponentially as their intensity class increases. Thus,

$$\ln F(k) \quad ak \quad b \tag{8}$$

where

$$a \quad \frac{\langle k\rangle\langle \ln F(k)\rangle \quad \langle k \ln F(k)\rangle}{\langle k^2\rangle \quad \langle k\rangle^2},$$

$$b \quad \frac{\langle k\rangle\langle \ln F(k)\rangle \quad \langle k^2\rangle\langle \ln F(k)\rangle}{\langle k^2\rangle \quad \langle k\rangle^2} \tag{9}$$

The symbol $\langle \;\; \rangle$ here denotes the averaging procedure

$$\langle x\rangle \quad \frac{1}{n} \, {}_{m \;\; 1}^{n} x_m \tag{10}$$

In this expression

$$n \quad {}_{k \;\; 0}^{l} n_k \tag{11}$$

is the total number of tornadoes that have passed through a given area.

For a given probabilistic criterion of tornado hazard P_0, the calculated intensity class k_C of a probable tornado is determined from the condition

$$F(k_C) \quad 1 \quad \frac{P_0}{P_S} \tag{12}$$

from which

$$k_C \quad \frac{1}{a}[\ln(1 \quad P_0 AT/S) \quad b] \tag{13}$$

Despite the above circumstance about the incorrect interpretation of the P_S probability in [3], determination of the calculated intensity class k based on the recommendations of [3] leads to correct results, since both P_0 and P_S are simultaneously increased by 1000 times.

The main design characteristics of a probable tornado are included in the list of parameters in the materials on the NF safety analysis report. These materials, in particular, contain [1]: the probability of tornado passing through the NF site, design-basis intensity class, the maximum rotation speed of the funnel wall, length and width of the tornado affected zone, tornado travel speed, the pressure drop between the periphery of the vortex and its center.

The aforementioned characteristics make it possible to evaluate potential loads and impacts on the NF buildings and structures [1, 5, 6]: loads on the NF buildings and structures, and their combination under the most severe impact, the rate of pressure drop inside the NF's premises that fall into the tornado affected zone, rate of water removal from the NF cooling pond, characteristics of missiles, fragments of buildings and structures captured by a tornado.

DATA

The initial stage of studying the tornado hazard for the territories where NF are located comprises the preliminary collection and analysis of data on the tornado paths and the preparation of a tornado catalogue. When compiling the catalogue, archival data from the meteorological service, data from scientific institutions, as well as literature data and verified information from the mass media, are used.

In this paper, the following initial data presented as catalogues of tornadoes in the former USSR for the period 1844-1988 and in Russia during 1987-2001 were applied: archival data from the Institute of Geography of the Russian Academy of Sciences. the data published in [14], the data for the territory of Russia for the period 1987-2001 [3]. Besides, in the framework of this study, the authors collected additional data on the passage of tornadoes through the territory of Belarus, Latvia, and Lithuania for subzone A-L from 2002 to 2019.

The actual distribution of registered tornadoes in the A-L tornado-hazardous subzone highlighted in [9] is shown in tab. 1. The places where tornadoes were recorded are marked in fig. 2.

Table 1. Statistical distribution of tornadoes recorded in the A-L subzone during 1844-2019, graded by intensity classes

A [1000 km^2]	T (year)	α_0	Statistical distribution of recorded tornadoes by intensity classes, n_k							Number of recorded tornadoes
			0	0.5	1	1.5	2	2.5	3	
229	59	1.5	19	4	23	5	19	1	3	74

Table 2. The results of evaluating design-basis parameters of a potential tornado in the A-L subzone in the event of the hypothetical occurrence of two additional F5 scale tornadoes

P_0 (per reactor per year)	P_S (per reactor per year)	k_P	V_P [ms^{-1}]	U_P [ms^{-1}]	Δp_P [hPa]	L_k [km]	W_k [m]
10^{-4}	1.24 10^{-4}	3.75	98	24	118	68	679

Figure 2. Locations of tornadoes recorded in A-L subzone

RESULTS AND DISCUSSION

As an example, the methodology described above was applied to evaluate the calculated probable tornado parameters for the A-L subzone. The initial data for this evaluation are presented in tab. 2.

The calculation result of the tornado repeatability P_S in the A-L subzone shows that it equals 2.64×10^{-6} per reactor per year. Thus, the repeatability P_S does not reach the regulatory criterion $P_0 = 10^{-4}$ per reactor per year [1], which determines the need to decide on considering tornadoes to ensure NF safety.

As aforementioned, because of the global climate changes, tornadoes are becoming more frequent and more intense [26, 27]. Therefore, the possibility of high-intensity tornadoes (F4 and higher) in Russia is not excluded. In this regard, it is necessary to organize the systematic collection and analysis of new meteorological data, as well as to continue updating the tornado catalogues. Besides, it seems appropriate to expand the categories of hazardous industrial facilities where the destructive impact of tornadoes can cause emergencies with negative technological and environmental consequences.

We would like to consider a hypothetical scenario of high-intensity tornadoes within the A-L tornado-hazardous subzone. The calculations show that the condition for P_S reaching or exceeding the $P_0 = 10^{-4}$ level per reactor per year could be achievable if two or more F5 scale tornadoes pass through the A-L subzone, in addition to the actually recorded tornadoes presented in tab. 1. The calculation results for two additional F5 scale tornadoes are shown in tab. 2. This table also contains the relevant design-basis characteristics of a potential tornado.

The results in tab. 2 demonstrate that the parameters of a potential tornado are characterized by a significant destructive force. Such tornadoes should be taken into consideration in the NF design process when calculating loads and impacts on buildings and structures of NF (such as wind head, the pressure drop between the tornado periphery and its center, impact of objects/fragments carried away by the tornado, *etc*.) [5, 6]. It should be emphasized that the calculations of loads and impacts on the NF buildings and structures are a set of individual complex tasks. In addition, when analyzing the consequences of tornado effects on NF, it is necessary to investigate other consequences, for example, the risks of fires and explosions. Tornado's impact on hazardous industrial facilities can also lead to a release of harmful impurities into the atmosphere and their dispersion in the atmospheric boundary layer, for example, ash from coal-fired thermal power plants (TPP). The mechanism of such transfer is described in sufficient detail in [36, 37]. However, the short duration of the impact of the tornado on TTP and the strong turbulence of the atmosphere in the zone affected by the tornado would hardly result in serious environmental consequences.

Taking into consideration the significant uncertainty in the characteristics of the recorded tornadoes, as well as the minor knowledge of evaluations of the consequences of tornado impact on NF, it seems efficient to use the concept *Best estimate plus uncertainty* [38]. The application of this concept opens up prospects in the organization of an additional safety barrier for NF.

The results obtained indicate the need for further studies of the tornado hazard in the NF siting areas to clarify and update the regulatory and technical base in the field of safety and engineering protection design against the comprehensive impact of tornadoes on NF.

CONCLUSION

Climatic changes occurring in recent decades and leading to growth in the frequency of dangerous meteorological phenomena determine the need to analyze the possibility of the impact of severe tornadoes on NF. This analysis provides for the collection and systematization of new meteorological data to continue to maintain existing catalogues of registered tornadoes. Based on the data on the tornado passage through the tornado-hazardous subzone A-L on the territory of the former USSR, the probability of the tornado passage through a hypothetical NF site was calculated, showing its non-exceeding the criterion in force in Russia, that is the threshold probability of 10^{-4} per reactor per year. It is shown that such a threshold probability can be achieved if two or more additional tornadoes of intensity class F5 pass through the studied subzone. For such a hypothetical scenario, the parameters of a probable tornado were calculated. The need to clarify and supplement the regulatory and technical base in the field of safety of NF and the design of engineering protection against comprehensive tornado impact on NF to ensure their reliable protection is noted. Apart from that, it seems appropriate to analyze the consequences of the tornado impact on other hazardous industrial facilities.

AUTHORS' CONTRIBUTIONS

Processing of data on the tornado passage and calculations, as well as the preparation of the illustrations, were made by G. P. Barulin. The research plan, analysis of the results. and writing of this article were performed by F. F. Bryukhan.

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ПРОЦЕНА ОПАСНОСТИ ОД ТОРНАДА У ОБЛАСТИМА НУКЛЕАРНИХ ОБЈЕКАТА

Потенцијална опасност од разарајућих ефеката торнада на нуклеарне објекте налаже потребу за проучавањем климатског режима проласка торнада и уређивање одговарајуће заштите тих објеката у складу са националним и међународним стандардима сигурности од зрачења. Једна од најкарактеристичнијих особина климе последњих деценија је значајан пораст броја опасних метеоролошких догађаја, укључујући торнада. Сврха ове студије је процена нивоа опасности од торнада за нуклеарне објекте и обликовање карактеристика торнада. Подаци о проласку торнада кроз торнадо опасну подзону А-Л на територији бившег СССР-а омогућили су процену вероватноће проласка торнада кроз хипотетички положај нуклеарног објекта, показујући да то не прелази вероватноћу важећег критеријума у Русији – граничну веровтноћу од 10^{-4} по реактору годишње. Показано је да се таква гранична вероватноћа може достићи ако би два или више торнада, класе интензитета Ф5 на Фуђита скали, прошли кроз подзону А-Л. За такав хипотетички сценарио утврђене су карактеристике облика вероватног торнада. Уочена је потреба за побољшањем регулаторне и техничке основе у области сигурности нуклеарних објеката како би се осигурала њихова поуздана заштита од ефеката торнада.

Кључне речи: торнадо, радијациона сигурност, нуклеарно постројење, критеријум опасности од торнада, удар торнада