

Modeling Safety Impact of the Tornado-Borne Missiles for the Slovak NPPs

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Abstract: There are three types of loading caused by the passage of a tornado over a site of the nuclear power plant: 1) wind pressures caused by the direct aerodynamic action of the air flow on the structures, 2) atmospheric pressure change effects and 3) significant impact forces caused by tornado-borne missiles. Impact forces are determined by the missile's velocity, mass, shape and material properties, often reaching speeds that result in severe local damage, such as piercing, scabbing on reinforced concrete walls or other barriers protecting safety systems of the plant. The Tornado Missile Risk Evaluator (TMRE) was used to address questions concerning vulnerability to tornado missiles. The TMRE is a hybrid methodology comprised of two key elements: 1) a deterministic element to establish the likelihood that a specific structure, system, or component (target) will be damaged by tornado-generated missile, and 2) a probabilistic element to assess the impact of the missile damage on the core damage and large early release frequencies. Description and application of the methodology and the results are presented in the paper.

1. INTRODUCTION

A tornado is an extreme form of a storm with the most intense wind speeds. However, the probability of its occurrence in Slovakia is low compared to other extreme weather conditions. The costs of designing and constructing structures resistant to the effects of tornadoes are significantly higher than the expected losses associated with the risk of a tornado, where risk is defined as the product of the loss and the probability of its occurrence. The consequences of structural failure due to tornadoes would be particularly severe in the case of nuclear power plants. Therefore, the tornado resistance must be demonstrated.

The effects of a tornado can be divided into three groups:

1. wind pressure caused by the direct aerodynamic effect of airflow (extreme wind speed) on the structure,
2. effects of changes in atmospheric pressure, and
3. impact forces caused by missiles (projectiles) carried by the tornado.

Extreme wind speeds can cause mechanical damage to buildings and failure of safety systems. Pressure changes (sudden drops and increases in atmospheric pressure) can affect the structural integrity of buildings and lead to damage to building seals. These effects of tornadoes on the J. Bohunice and Mochovce NPP sites are covered by the effects of direct extreme wind in the stability analyses of structures. Therefore, they will not be the subject of analysis according to missiles impacts. The paper is dedicated to the identification and analysis of the impact of missiles caused by tornadoes.

There are no national or European standards available for assessing the resistance of structures to loads caused by tornado missiles in ordinary civil and industrial buildings. The EUROCODES system of design standards does not include loads caused by tornado missiles. Europe is a region with a relatively low occurrence of destructive tornadoes. Although tornadoes of higher intensity on the Fujita scale do occur, they have a very low frequency of occurrence. For nuclear power plants, where the effects of tornadoes must be evaluated, it is necessary to follow foreign guidelines and standards, mostly from the USA [1,3,4,5,7,15,18].

The USA is the country with the highest number of tornadoes in the world. There are three tornado regions in the USA, as defined by the US NRC for nuclear power plants:

1. Region I – highest tornado risk. Includes the most active tornado areas in the USA (central USA). Highest tornado frequency with the potential for very strong tornadoes (EF4-EF5).
2. Region II – moderate tornado risk. Tornadoes occur less frequently but regularly (the Midwest and Southeast of the USA). Fewer tornadoes than in Region I. Tornadoes can occur during most of the year.
3. Region III – lowest risk. These are areas where tornadoes are relatively rare (coastal and mountainous regions of the USA).

The impact of tornadoes on nuclear power plant safety was addressed in the late 1970s in the EPRI reports [2,8,10,13,14]. The knowledge and methods of tornado risk analysis for nuclear power plants accumulated over time are summarized in the NEI report [1]. The report uses imperial units of measurement (inches, feet, etc.). The paper also provides their equivalents in the International System of Units (SI).

Following the introduction, the second part of the paper provides an overview of the method for analyzing the risk of tornado-generated missiles to nuclear power plants. The third part is devoted to conducting site walkdowns of the NPP to identify and collect data on vulnerable structures, systems and components (SSCs), and to identify and classify tornado missiles. The fourth section describes the calculation of tornado occurrence frequency at the site. The fifth section describes the characteristics of targets and missiles. The sixth section is devoted to tornado risk analysis using the PSA method. The seventh section describes application of the methodology for the DG building. The conclusions are presented in section eight.

2. OVERVIEW OF THE TORNADO MISSILES RISK ANALYSIS METHOD

The method enables a conservative assessment of the risk posed by missiles generated by a tornado to NPP operations. The method consists of two key approaches:

- 1) a deterministic approach to determining the probability that SSCs will be struck and damaged by a missile generated by a tornado, and
- 2) a probabilistic approach to assess the impact of SSC damage by a missile on the core damage frequency and the frequency of large early releases of radioactivity into the environment.

The output of the deterministic approach is the Exposed Equipment Failure Probability (EEFP), which is based primarily on the relationship between tornado strength and the amount of materials at the NPP that can be lifted into the air during a tornado. Site-specific EEFP input data include the probability of a tornado striking the site, the resilience, size, and location of the assessed target.

The probabilistic approach utilizes the existing probabilistic safety assessment (PSA) model for the specific power plant, which has been approved by the nuclear safety regulatory authority, to assess the impact of unavailability and loss of SSCs. The risk assessment method is used to determine whether the risks posed by potential tornado debris at the site require the implementation of protective measures.

The analysis method has three main steps:

- 1) Site walkdowns to gather relevant information regarding safety related SSCs that are not protected against tornado-generated missiles and the characteristics of the missiles.
- 2) Calculation of the failure probability of exposed SSCs critical to NPP safety using EEFP. This calculation takes into account the number of missiles that damage SSCs, the exposed area of the SSC, and the Missile Impact Parameter (MIP), which relates to the probability of a missile

hitting a target based on tornado intensity. If a damaging missile strikes an exposed SSC with sufficient force, it is assumed that the SSC will fail.

- 3) Calculation of the increase in the core damage frequency (ΔCDF), the fuel damage frequency in the spent fuel storage pool (ΔFDF), and the large early release frequency ($\Delta LERF$). Assessment of the need to implement protective measures.

3. SITE WALKDOWNS

The walkdowns are conducted to collect data related to sensitive, non-compliant, and safety related SSCs, and to identify any other SSCs that are not protected against tornadoes or missiles. In addition, the inspection is conducted to determine the inventory of missiles used in EEFP calculations.

3.1. Pre-Walkdown Activities

Several activities are recommended prior to the walkdown to ensure it is conducted effectively and completely. Preparations are necessary primarily for the identification and characterization of vulnerable SSCs. Additionally, preparation is required for the portion of the survey concerning the verification of missiles counts.

The walkdown of vulnerable SSCs involves examining all potentially vulnerable locations and non-compliant SSCs to gather the data needed for analysis. The survey of vulnerable SSCs will also assess all SSCs that are not protected against tornadoes, including extreme wind or missiles.

A list of tornado-vulnerable facilities will be prepared for the walkdown team. This is a list of SSCs that need to be checked during the walkdown. The initial list includes a list of identified, potentially vulnerable, and non-compliant SSCs, as well as a list of potentially unprotected SSCs. Additional SSCs may be identified during the walkdown and added to the final list.

The list is based on Level 1 and Level 2 PSA models for nuclear power plant units. It takes into account EPRI guidelines (Walkdown Guidance, EPRI Report 3002008092 for high wind) [2]. The list includes potentially unprotected SSCs and specifies their locations. This is performed prior to the site walkdown based on plant documentation

3.2 Walkdown of Vulnerable SSCs

The walkdown of vulnerable SSCs is therefore conducted to gather information on SSCs exposed to tornado missiles. The survey determines which SSCs are vulnerable to missiles and serves to collect data on the target's location, such as height above ground, surface area, and structural details, as well as the type and location of any local structures that may provide protection.

Data collection is necessary for calculating the EEFP. It can also aid in developing approaches for specific configurations, such as when SSCs are physically correlated (they may be disabled by the same missiles). The EEFP is used to calculate the probabilities of SSC failure.

3.3 Walkdown of Missiles

The second main objective of walkdown is to count the number of missiles. Missiles within a radius of approximately 2,500 feet (762 m) from a common reference point (e.g., the center of the site) that may become airborne during a tornado at the NPP site are identified and counted.

Various types of missiles are identified, each with a different ability to damage exposed SSCs. In addition to loose objects outside structures (e.g., building materials), missiles can also be generated from structures (e.g., warehouses) and their contents if they are unable to withstand the wind pressure

of a tornado and are destroyed during the tornado. The walkdown is usually separate from the walkdown of safety related SSCs.

4. FREQUENCY OF TORNADOES IN THE VICINTY OF THE PLANT

For the analysis of missiles impact risk, the frequency of tornado occurrence in a given location is essential information. A tornado hazard curve for the location should be developed. Tornadoes with wind speeds of approximately 100 mph (44.7 m/s) or higher are of particular importance. For risk analysis purposes, tornadoes are classified using the F' scale (Fujita prime). This scale differs to some extent from the original Fujita scale (F-scale) and the Enhanced Fujita scale (EF-scale); see Table 1 below. The F' scale was chosen for the analyses because the MIP values are based on simulations that used the F' scale to categorize tornadoes.

Table 1 : Relationships between tornado intensity on the Fujita scale and wind speed (mph, km/h, and m/s)

Intensity	Description	Original Fujita	Fujita	Enhanced Fujita (EF)	F'
F0	Light damage	40–72	45–78	65–85	40–73
		64–116	72–126	105–137	64–117
		18–32	20–35	29–38	18–33
F1	Moderate damage	73–112	79–117	86–110	73–103
		117–180	127–188	138–177	117–166
		33–50	35–52	38–49	33–46
F2	Significant damage	113–157	118–161	111–135	103–135
		182–253	190–259	179–217	166–217
		51–70	53–72	50–60	46–60
F3	Severe damage	158–206	162–209	136–165	135–168
		254–332	261–336	219–266	217–270
		71–92	72–93	61–74	60–75
F4	Devastating damage	207–260	210–261	166–200	168–209
		333–418	338–420	267–322	270–336
		93–116	94–117	74–89	75–93
F5	Incredible damage	261–318	262–317	>200	209–277
		420–512	422–510	>322	336–446
		117–142	117–142	>89	93–124
F6	Unimaginable	319–380	-	-	277–300
		513–612	-	-	446–483
		143–170	-	-	124–134

The F' scale probabilities used in the tornado missiles impact risk analysis method are based on location-specific Fujita scale data. These data are used to derive a site-specific hazard curve equation, which is then used to calculate the annual exceedance probabilities for each F' range [1,3]. The frequencies of tornado occurrence for the Slovak NPPs are calculated in [11,12,16].

5. CHARACTERISTICS OF TARGETS AND MISSILES

The probability of failure of exposed SSCs is calculated using the exposed equipment failure probability (EEFP). EEFP is the conditional probability that an exposed SSC will be struck and fail as a result of a tornado of a given size. For each SSC, EEFP values are calculated, one for each tornado category.

EEFP is defined as:

$$EEFP = (MIP) \times (\text{number of missiles}) \times (\text{exposed target area}) \times \text{vulnerability.}$$

The Missile Impact Parameter (MIP) represents the probability of a tornado missile striking the target, the target area, the missile, and the tornado. Generic MIP values are provided as part of the methodology.

Generic MIP values are listed in Table 2. The MIP varies depending on the tornado category and the target's height above ground level. The number of missiles is given for a radius of approximately 2,500 feet (762 m) from the target SSCs.

Some targets that are hard-shelled (e.g., steel pipes and tanks) have different missile requirements than less hard-shelled SSCs (e.g., electrical panels, measuring instruments), because only certain types of missiles can damage hard-shelled and robust targets.

Generic missile supplies are listed in Table 2 for each tornado category, F'2 through F'6. The target area is determined for each specific SSC based on power plant documentation and site inspections.

Vulnerability is the conditional probability that the SSC will fail to perform its function after being struck by a missile; it is assumed to be 1.0 (i.e., the SSC will always fail after being struck by a missile with sufficient force).

The parameters included in the EEFP were developed to provide a conservative estimate of the probability of SSC failure. The values specified for the MIP parameter (number of missiles and vulnerability) were established to be used together and should not be altered. The conservatism in the EEFP depends on the use of the recommended values for all these parameters.

Not every parameter needs to be conservative, but the combination of parameters for different objectives and wind speeds provides an estimate of the change in the CDF associated with non-compliant SSCs. Deviations from the recommended values lead to non-conservative EEFPs and thus to non-conservative results for Δ CDF, Δ FDF, and Δ LERF [1]. The total number of missiles, which may be increased if necessary, based on a site-specific inventory.

A MIP value <30 ft (9.144 m) may be used in cases where it is difficult to determine whether the target is >30 ft above all missile sources. When considering robust targets, a higher percentage may be used.

MIP can be considered as the flow of missiles per unit area, as shown in Figure 1.

The MIP values were developed to be applicable to all nuclear power plants. They were derived based on published data from the TORMIS program in EPRI Report NP-768 [8]. The basis for the MIP values developed for risk analysis is provided in [1].

MIP values vary depending on the tornado's intensity (i.e., the F' scale) and the target's height above the ground. Separate MIP values are listed for each tornado on the F' scale from F'2 to F'6 (data for F'0 and F'1 are not provided due to negligible damage). MIP values increase with increasing tornado intensity, as higher-category tornadoes can lift more missiles and carry them into the air. Separate MIP values are also provided for targets near the ground and at height. Ground-level targets are located at an altitude of less than or equal to 30 feet (9.144 m) above the missile source (typically at ground level), while elevated targets are those at an altitude greater than 30 feet (9.144 m) above the primary missile source. MIP values for near-ground targets are higher than for elevated targets. This is expected because heavier missiles are less likely to reach greater heights due to the tornado's influence, and therefore the number of missiles per unit area is lower for higher elevations.

Figure 1: Missile Impact Parameter per Unit Area

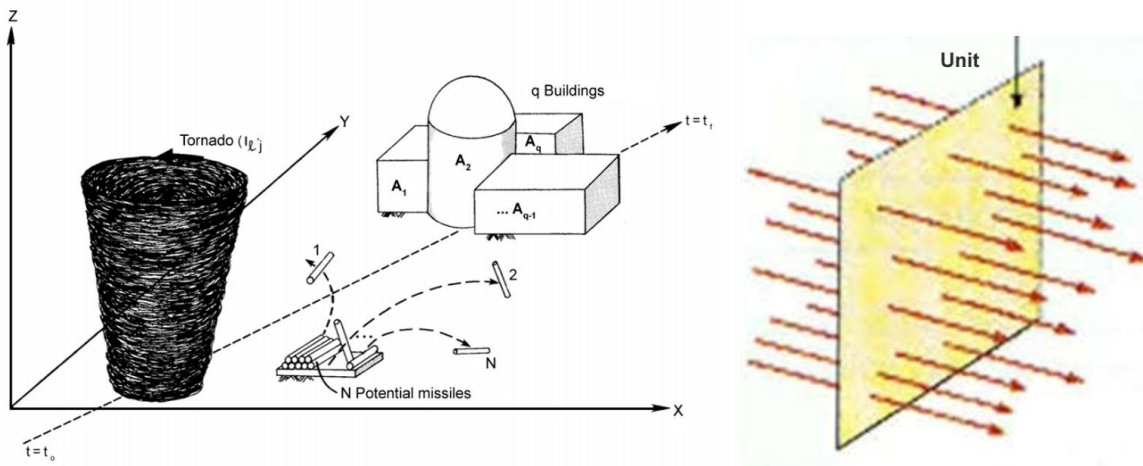


Table 2: MIP Values and Projectile Stocks

Tornado Category	Targets >30' above ground level ^(1,2)	Targets <30' above ground ^(1,2)	Total of missiles ⁽³⁾
F'2	5.8E-11 6.2E-10	1.1E-10 1.2E-09	155,000
F'3	2.0E-10 2.2E-09	3.6E-10 3.9E-09	155,000
F'4	3.4E-10 3.7E-09	6.3E-10 6.8E-09	205,000
F'5	8.7E-10 9.4E-09	1.6E-09 1.7E-09	240,000
F'6	1.3E-09 1.4E-08	2.4E-09 2.6E-08	240,000

- (1) MIP values are expressed as the probability of a hit per unit area (ft², m²) per missile and per tornado.
 (2) Terrain refers to the altitude at which most missiles capable of striking the target are located. This is typically the terrain near the nuclear unit, although this may differ for some targets.
 (3) In this table, the values for the total number of missiles are used; unless the number of missiles is site-specific, it is not limited to 240,000 missiles.

The total number of generic missiles is 240,000. Since many missiles originate from building demolition, which varies depending on tornado intensity, the total number of missiles changes depending on tornado intensity. Table 2 lists the total missiles inventory according to the F' scale.

If a site survey confirms that 240,000 is the site limit, then the missile count parameter in EEFP calculations equals the values listed in Table 2 for targets not defined as robust. The types of robust targets are listed in [1], and the percentage of the total number of missiles for each type of robust target is provided. These percentages have to be applied for the total number of missiles in each F' scale. This is the way to reduce the number of missiles used in EEFP calculations for robust targets. The basis for the total number of missiles and the inventory of robust missiles are provided in [1].

A site may consist of a single unit or multiple units. There is no difference in the total number of missiles based on the number of units at the site.

If the total number of missiles in a site is not limited to 240,000, the number of missiles to be used in EEFP calculations (for non-robust targets) should be the total number of missiles calculated, rounded up to the nearest 5,000 missiles. For tornadoes below F'6, calculations of the origin structure of missiles can be determined using the data provided for various building types. The same percentages of robust targets as listed in [1] are applied to the site-specific number.

6. PSA TORNADO MODEL

The PSA tornado model is used to calculate the risk associated with SSC failures that are not protected from the impact of missiles. The model is developed based on the PSA model of Level 1 and Level 2 for internal events. The key steps in the development of the PSA tornado model are:

- Selection of event trees and failure trees for tornado modeling from the PSA model of internal events (typically LOP failure sequences).
- Replace the LOP event with tornado events.
- Remove recovery and repair logic (or set the failure probability to 1.0) for power supply from the external grid, as recovery and repair are not considered.
- Add SSC failures caused by tornado missiles as needed in the fault tree logic.
- Set the probability of human error to 1.0 for certain interventions outside the main control room and verify the feasibility of the path for other interventions.

One of the assumptions of the analysis method is that a tornado will cause at least a loss of external power supply (LOP) and reactor shutdown. It can be expected that a tornado will also trigger other initiating events. An example is the loss of the essential service water system.

The external power supply therefore remains unavailable. Other aspects that must be considered for a tornado are:

- The required operating times may be adjusted for certain primary events, given that restoration of power from the external grid is not possible.
- Sometime dependencies may be affected by missiles that cause failures of multiple SSCs without the possibility of restoring their functionality.

The tornado-induced initiating events are derived from tornado categories. For sites with multiple units, it is assumed that a tornado will result in a LOP at all units on the site.

The risk change assessment (i.e., Δ CDF, Δ PDF, and Δ LERF) is performed for two cases that need to be modeled and quantified:

1. The case is in compliance with the requirements: all SSCs are protected against missiles.
2. The case is non-compliant with the requirements: tornado-induced failures are considered for all non-compliant SSCs. Failure probabilities are based on EEPF calculations.

Some modifications to the PSA of internal events required to create a tornado PSA model are:

1. PSA event trees and fault trees selected to represent initiating events caused by a tornado,
2. Tornado occurrence frequency,
3. Restoration of external power supply from the grid is not assumed,
4. Unfeasible human interventions are set to 1.0,
5. Consider the impact on primary events,
6. Structures that are not safety-critical are not capable of withstanding the forces associated with a tornado. Their ability to withstand tornado wind pressures must be evaluated.

6.1. Impact on Human Errors

It is highly unlikely that tornadoes at a nuclear power plant would have any impact on safety related structures, given their robust design and structural margin. Therefore, equipment and personnel inside these structures are not expected to be affected.

However, some interventions may be carried out outside these structures or may require personnel to

move outside the structures to reach the location where the intervention is to be performed. For short-term measures (i.e., measures that must be implemented within 1 hour of a tornado's onset), the method assumes that the intervention cannot be performed, and therefore the failure probabilities are set to 1.0.

The reason for this assumption is that during and immediately after a tornado, areas outside the structures may be hazardous due to strong winds, debris, and missiles. Personnel are not expected to endanger themselves in such situations. Furthermore, in the short period following a tornado (the method assumes 1 hour), debris and structural damage may be so significant that they may hinder or prevent personnel from reaching and operating the equipment. Specific plant regulations may require that personnel not leave buildings until a damage assessment has been conducted. It is assumed that this will not take longer than 1 hour after the tornado. This introduces uncertainties into the detailed analysis of human factor reliability during these interventions.

Operator interventions performed inside the control room or other safety related structures are not affected by a tornado if missiles do not reach those areas. However, a detailed analysis is required to reach such a conclusion.

6.2 Impact on Primary Events

The PSA logic models for internal events must be modified to include failures caused by a tornado at exposed SSCs. The failure probability for a given SSC is determined using the EEFP calculation. Note that the EEFP for each exposed SSC is calculated for each tornado category. The models must be modified to ensure that the correct EEFP is applied to the SSC based on the tornado category used for the initiating event.

SSC failures caused by missiles must be taken into account for failure modes that were not previously included in PSA models of internal events (e.g., due to low failure probabilities or low impact on the system failure probability). Examples include:

- Flow diversion or media leakage,
- Tank venting failures (e.g., crushing of the tank vent pipe),
- Valve position change (unintended closure or opening) and
- Ventilation damper failures.

6.3 Non-Safety Related Structures

Structures and buildings that are not safety related are constructed in accordance with industrial or commercial building codes. Such buildings cannot withstand the wind pressure and changes in atmospheric pressure associated with tornado categories. Therefore, the failure of these buildings and damage to the SSC within them is considered with a probability of 1.0.

Although the engine room is not a safety-critical structure, it is usually designed to withstand significant forces. The engine room wall cladding is designed to separate from the frame and prevent structural failure due to wind pressure.

Less robust SSCs that are not safety related (e.g., pumps, air compressors, generators, and other active components), located outside the structures or in the turbine hall, are directly exposed to tornado wind pressures and are therefore considered to have failed.

Robust SSCs (e.g., tanks, pipes, passive valves, conduits) are generally strong enough to withstand tornado wind forces. This is particularly true for steel tanks that are full or nearly full of liquid. Analyses are performed to verify whether SSCs are capable of withstanding tornado wind forces. Structural calculations may be used to determine the wind speed at which such SSCs fail. The probability of failure for such SSCs is 1.0 in cases where they comply with conventional standards, as

well as in cases where they are damaged, for wind speeds (based on tornado category) where their resistance is less than the calculated wind force. For such SSCs, it is necessary to include failures due to tornadoes (i.e., based on EEFP) for tornado categories that do not cause guaranteed failure of the SSC.

6.4 Quantification of CDF and LERF

Risk increases in the form of ΔCDF , ΔFDF , and $\Delta LERF$ are calculated as follows:

$$\begin{aligned} \Delta CDF &= CDF_{\text{Compliance with requirements}} - CDF_{\text{Non-compliance with requirements}} \\ \Delta FDF &= FDF_{\text{Compliance with requirements}} - FDF_{\text{Non-compliance with requirements}} \\ \Delta LERF &= LERF_{\text{Compliance with requirements}} - LERF_{\text{Non-compliance with requirements}} \end{aligned}$$

CDF, FDF, and LERF are quantified in accordance with the relevant quantification requirements (QU) of the PSA standard [9].

7. APPLICATION OF THE METHODOLOGY FOR THE DG BUILDING

7.1 Description of the Building

A tornado threatens the building's walls from all sides, including the roof (see Figure 2), where (a) is the tornado and (b) is the building. Views of the DG building are shown in Figures 3–6. Structural components of the walls are color-coded to distinguish different construction materials. There are 6 DGs in the building, located in separate compartments. The structural components of two parallel walls (east and west views) are repeated six times. The building as a whole is the target for missiles generated by the tornado.

Figure 2: Tornado threat to the DG building

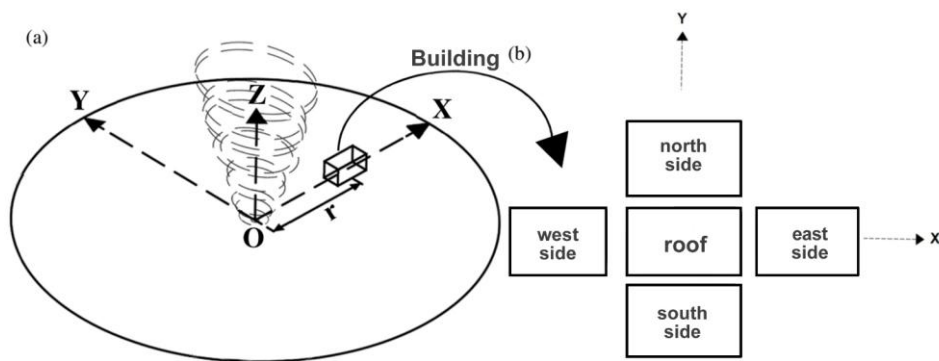
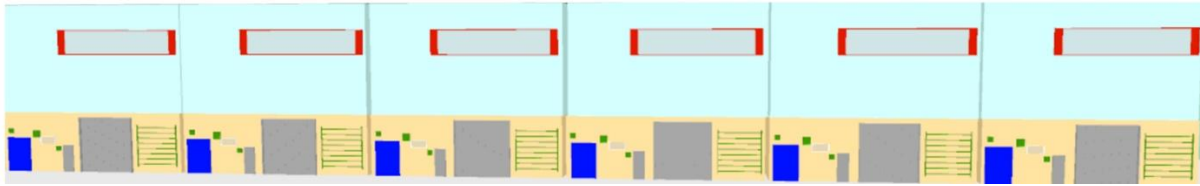


Figure 3: View of the DG building from the east side



Areas of structural wall components on the east side: 1) Yellow area without openings – brick masonry, 2) Turquoise area without openings – aerated concrete interlocking panels, 3) Light gray area – steel window, 4) First gray area, bottom left – steel gates and doors, 5) Red area – Steel hydrant door, 6) Second gray area, bottom left – steel gates and doors, 7) Third gray area, bottom left – steel gate, 7) Fourth gray area, bottom left – steel gates and doors.

Figure 4: View of the DG building from the west side



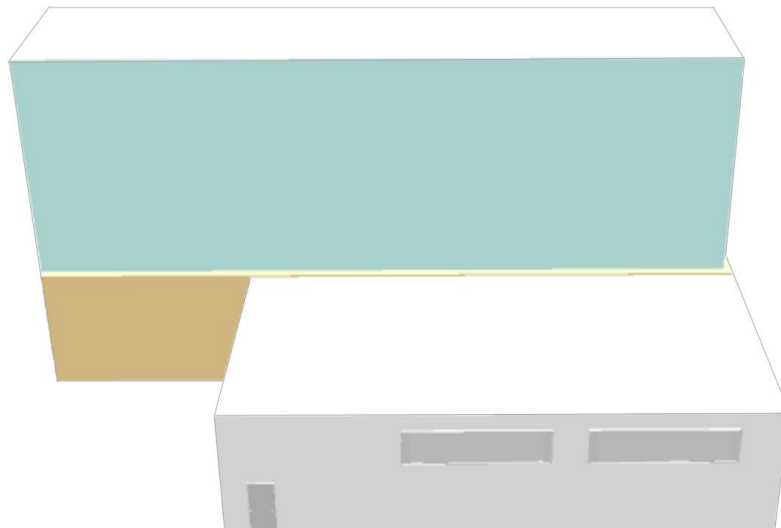
Areas of structural wall components on the west side: 1) Yellow area without openings – brick masonry, 2) Turquoise area without openings – aerated concrete interlocking panels, 3) Red outline – co-pilot window, 4) Dark gray area – steel gates and doors, 5) Green area – ventilation grille, 6) Blue area – steel door, 7) Light gray area with white outline – security grille.

Figure 5: View of the DG building from the south side



Areas of structural wall components on the south side: 1) Yellow area – brick masonry, 2) Turquoise area – aerated concrete interlocking panels.

Figure 6: View of the DG building from the north side



Areas of structural wall components on the north side (the extension is a transformer station, used to supply power to auxiliary operation building, protecting the DG building): 1) Yellow area – brick masonry, 2) Turquoise area – aerated concrete interlocking panels.

7.2 Deterministic modeling

A physical model based on the missile's kinetic energy, the material properties of the wall and the missile, aerodynamic forces, and the material's dynamic strength was used to calculate missile penetration into the wall [17]. The model combines an energy-based and a hydrostatic approach for a

realistic estimate of effective penetration. An example is presented for calculation of penetration of a missile through the wall (a 25 cm thick aerated concrete wall) of the DG building during an EF2 tornado. The missile is a 50 kg wooden block [16].

Input data:

Wind speed [m/s]: 60
Simulation duration [s]: 30
Projectile mass [kg]: 50
Angle of impact [deg]: 0 (perpendicular to the wall)
Wall thickness [m]: 0.25
Wall type: aerated concrete

Projectile dimensions:

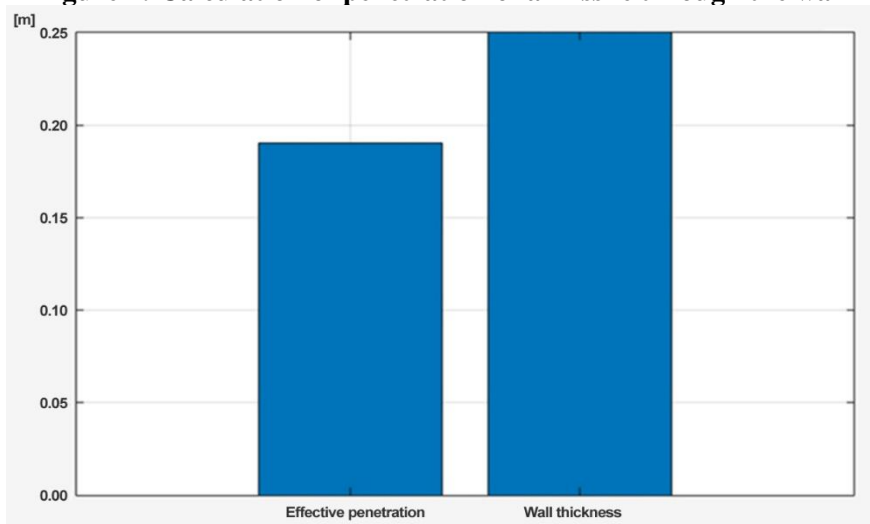
Volume: 0.071 m³,
Diameter: 0.302 m,
Length: 1.00 m
Automatically calculated impact area: 0.071 m²

Results:

Impact velocity: 38.04 m/s
Kinetic energy: 36,181.78 J
Effective penetration: 0.1903 m
Normal force: 190.11 kN
Normal pressure: 2.66 MPa

The wall withstands the missile (see Figure 7).

Figure 7: Calculation of penetration of a missile through the wall



7.3 Calculation of EEFP

The walls of the DG building are able to withstand the impact of missiles. However, the steel doors are penetrated by a wooden missile. The probability of damage to exposed equipment (DG) in the DG building is calculated according to the following equation, presented above for EEFP.

The steel doors are near ground level. $MIP = 1.2E-9$ (see Table 2). The number of missiles is 155,000 (see Table 2). The total area of the steel doors on the DG building is 178.44 m².

$$EEFP1(EF2) = 1.2E-9 \times 155,000 \times 178.44 = 3.3E-2/\text{tornado}.$$

Potentially, all DGs will be lost, despite being separated. The doors to each cell can be breached. DGs are robust targets, but small missiles will enter the building through the openings and damage their support systems.

After incorporating the calculated probability of DG failures into the Level 1 PSA model, there is only a negligible increase in risk because the frequency of EF2 tornadoes is very low.

8. CONCLUSION

The DG building was presented as an illustrative example in the paper. A detailed analysis will be performed following the completed site walkdowns, evaluation of the walkdown findings, and completion of all deterministic and probabilistic calculations. The results will be subject to sensitivity analyses. If necessary, measures will be proposed to increase the tornado resistance for the nuclear units of the Slovak NPPs.

References

- [1] *Tornado Missile Risk Evaluator (TMRE) Industry Guidelines Document*, NEI Technical Report, September 2017
- [2] EPRI 3002008092, *Process for High Winds Walkdown and Vulnerability Assessments at Nuclear Power Plants*
- [3] NUREG/CR-4461, *Tornado Climatology of the Contiguous United States*, Rev. 2, US Nuclear Regulatory Commission, February 2007
- [4] Regulatory Guide 1.200, “*An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-informed Activities*,” Revision 2, March 2009.
- [5] U.S. Nuclear Regulatory Commission, *An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis*, Regulatory Guide 1.174, Revision 2, May 2011
- [6] *Extreme Winds at the Mochovce NPP Site, Tornado-Induced Projectiles*, Technical Report, ÚJV Rež, Mochovce NPP, Units 3 and 4, PNM34635079, 01/2025
- [7] Regulatory Guide 1.176, “*Design-basis Tornado and Tornado Missiles for Nuclear Power Plants*,” Revision 1, March 2007
- [8] EPRI NP-768, *Tornado Missile Risk Analysis*, May 1978
- [9] American Society of Mechanical Engineers/American Nuclear Society, *Standard for Level 1 / Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications*, ASME/ANS RA-Sb-2009, 2013
- [10] EPRI NP-769, *Tornado Missile Risk Analysis*, May 1978
- [11] *SHMÚ Summary Report for the Mochovce Site*, 2021, Rev. 02, February 2025, Bratislava
- [12] *SHMÚ Summary Report for the Jaslovské Bohunice Site*, 2021, March 2022, Bratislava
- [13] EPRI, *Tornado Missile Simulation and Design Methodology*, Volume 1: Simulation Methodology, Design Applications, and TORMIS Computer Code, 1981
- [14] EPRI, *Tornado Missile Simulation and Design Methodology*, Volume 2: Model Verification and Database Update, 1981
- [15] Simiu, E. and Yeo, D.: *Wind Effects on Structures*, 4th Edition, Wiley and Sons, 2019, New York, ISBN 9781119375906
- [16] *Extreme Winds at the Mochovce NPP Site*, Explanation of SHMÚ Wind-Related Values – Technical Report, ÚJV Rež, Mochovce NPP, Units 3 and 4, PNM3463507800-S, 02/2025
- [17] *MathWorks, MATLAB User Guide*, Natick (MA), The MathWorks Inc., 2024
- [18] Gebru, S.: *Calculation of Wind-Borne Debris Impact in Tornado Events*, MIT, June 2017