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UPDATED PROBABILISTIC ANALYSIS OF EXTERNAL EVENTS DATA AND SAFETY OF THE NUCLEAR POWER PLANT IN LITHUANIA

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ABSTRACT

The main purpose of performed work is the probabilistic analysis of extreme external events, which have a potential influence on safety of the present nuclear power plant (NPP) in Lithuania. This analysis can also be related to the future NPP in Lithuania at the same site.

At first, the methodology was established for screening out hazardous events, which impact on the present Ignalina NPP safety is not significant. For risk estimation, the following external events were considered in detail: forest fire, external flood, airplane crash, extreme wind. In order to estimate probabilities of hazards occurrence the statistical data related to various external events were collected, mathematical models were constructed and probabilities of these events occurrence were determined.

Statistical, meteorological and other updated data from the Republic of Lithuania has been used to estimate probability of the most important hazardous events.

Due to many factors affecting the inaccuracy of any result it is not enough to calculate only the estimate of the probability of the event. There is a need also to evaluate errors or variations of result made by such estimation. For such purpose uncertainty and sensitivity analysis was performed for a probability estimate, i.e. frequency of the event. This analysis determines the parameters that have the greatest influence on the probabilistic model results.

The modelling of external events occurrence and its impact on the NPP is significant in order to evaluate the safety of NPP and to prevent failure of the systems important to the safety.

1 INTRODUCTION

This paper describes extreme external events and reflects a part of methodology for the probabilistic safety analysis of extreme events, which may have an influence on safety of the NPP in Lithuania.

In addition, the most recent statistical data analysis of extreme external events is reflected and mathematical models of probability estimation of the external events were developed. Events of aircraft crash, extreme winds, external flooding and forest fire were selected for modelling.

The paper presents the probabilistic modelling and analysis of extreme external events, which may have an influence on safety of the Ignalina NPP. According to the applied technique, the analysis of external event includes two basic parts:

- initiating event descriptions and analysis;
- probability estimation of external event.

The different mathematical models for probability estimation of aircraft crash, extreme winds, strong downpours, flooding and external fire were examined and constructed in detail. Sensitivity and uncertainty analysis is performed in order to estimate an accuracy of results received using the developed mathematical models for aircraft crash and extreme winds [1].

External event in the territory of the NPP represents a very large danger to the plant, including the reactor. They may destroy the roof and walls of buildings, pipelines, electric motors, cases of power supplies, power cables of electricity transmission and other elements and systems that are important for safety.

The modelling of external event occurrence and impact on the NPP is significant in order to evaluate risk and prevent potential failure of the systems important to safety. The probabilities of such event occurrence and impact on the plant are determined using the analyzed statistical data, mathematical models and probabilistic simulations.

2 METHODOLOGY OF EXTREME EXTERNAL EVENTS ANALYSIS

Many different events (natural or caused or modified by human activities) might damage property and structures, change or alter the environment. These include natural disasters (like earthquakes, volcanoes, storms, floods and droughts), but threats are also posed by wars, industrial accidents and structural faults such as aircraft crash.

Extreme external events could be classifying into two groups – natural events and the external events connected to the human being activity.

Many technological external events (apart from sudden industrial accidents) build up slower than natural hazards, but they can create greater cumulative impacts which might affect a much larger area.

The study of extreme external events includes events description, probability analysis and impact on safety of object.

2.1 Methodology for probabilistic analysis of external events

When selecting the methodology for processing of the statistical data and calculation of potential events probabilities, it is necessary to comply with the following principles:

- Approbation. To use methods of the analysis and calculations which are described in the IAEA documents [2] or other well-known probabilistic safety analysis reports.
- Simplicity. Only well-known and mostly used methods should be selected from all mathematical methods, used for processing the statistical data and the estimation of probabilities of external events.

The considered initial events are events, which generates sequences of events in the nuclear power plant potentially resulting in damage of the core (see IAEA documents, e.g. [2]). During the analysis, it is necessary to determine frequency of occurrence of such events. Usually, frequency is measured by the number of events per year.

The analysis of initial events consists of eight tasks:

1. Selection of initiating events;
2. Parameter definition for each initiator;
3. Approximate screening by impact;
4. Detailed screening by frequency;
5. Detailed parameterization of each initiator;
6. Hazard analysis (frequency versus side);
7. Sensitivity analysis;
8. Documentation.

For definition of the initial list of external events, which are potential contributors to the total risk of the Ignalina NPP, it is necessary to review all theoretically possible dangerous events in territory, adjoining to the Ignalina NPP. List of such events is provided in IAEA regulation on safety of nuclear power plants (e.g., 50-SG-S9 [2]), in NRC documents (NUREG/CR-2300 [3]). Frequency and consequence of external events depends on geographic location of the nuclear power plant, geological and meteorological conditions in the given region, concentration of industrial and military objects, intensity of various types of transport, other human being activities. Usually initial list of external events is divided into two groups - natural events and the external events connected to the human being activities.

For revealing those external events which influence on safety is insignificant, the criteria used in procedures of performance PSA [2] may be used. External events are excluded from the further more detailed analysis if they correspond to the following criteria:

- Criterion 1. The event is of equal or lesser damage potential than the events for which the plant has been designed;
- Criterion 2. The event has a significantly lower mean frequency of occurrence than other events with similar uncertainties and it could not result in worse consequences than those events;
- Criterion 3. The event cannot occur close enough to the plant to affect the NPP safety;
- Criterion 4. The event is included in the definition of another event;
- Criterion 5. The event is slow in developing and there is a sufficient time to eliminate the source of the threat or to provide an adequate response.

The use of these criteria excludes the probability to miss significant contributors in total risk and by that allows reducing number of external events for which the detailed analysis of their influence on safety of the NPP is carried out.

In technical project RSA-2 [4] it is determined, that for the NPP in Lithuania it is necessary to consider the following external events:

- aircraft crash;
- extreme winds;
- external fire;
- external flooding and extreme showers.

3 EXTREME EXTERNAL EVENTS

3.1 Aircraft crash

3.1.1 Initiating event description

Within the analysis of an aircraft crash, terrorist actions or other non-ordinary human activities are excluded, because they are impossible to estimate statistically. The analyzed frequency of aircraft crashes depends on the intensity of flights near the target object, the technical condition of the aircrafts, the experience of crew, the meteorological conditions and other factors.

The initial data for the estimation of the aircraft crash probability:

- NPP distance from the civil or military airports;
- arrangement of air transport corridors in the eastern part of Lithuania;

- intensity of flights in the air transport corridors of Lithuanian airspace;
- distribution of aircrafts by their type;
- generalized world statistics of aircraft crashes by their weight and type;
- statistical data on serious aircraft incidents.

Because of high uncertainty of the accident initiating factors, aircraft crash modelling usually is based or leads to the conservative assumptions or the uncertainty analysis of the results [1].

Usually a probabilistic model of aircraft crash frequency depends on the distance between the NPP and the closest airports [5]. If there are no large airports nearby NPP and when flying route distance from the object territory is known, then can also to calculate the aircraft crash probability (event per one year) [6]. If the aircraft flies 2x km route through corridor touching y km radius zone around the NPP with condition of aircraft losing control and start falling, then aircraft crash probability per year on r radius territory is expressed by the formula:

$$P = N_c P_l r^2 g \left(e^{-yg} - e^{-g\sqrt{x^2+y^2}} \right), \qquad (1)$$

where P_l – aircraft crash frequency per flight kilometer, N_c – flight number per year (conservatively calculated at radius of 50 km), g – a constant dependent on type of aircrafts and describe likelihood of close falling [5] (for passenger aircrafts $g = 0.23$, for military $g = 0.63$ and for transport $g = 1$); $s = \sqrt{x^2 + y^2}$ – the distance from aircraft to the analyzed zone centre, where radius of zone is $y = const$ and $2x$ is route through corridor touching y radius zone.

Using this formula it is possible to obtain the aircraft crash probabilities per year on territory with different radius r territory around NPP buildings or reactor.

3.1.2 Probabilistic modelling results

There are no large airports nearby the Ignalina NPP – the largest airport is in Vilnius (Republic of Lithuania), approximately 130 km away from the Ignalina NPP.

Lithuania has defined the prohibited zones for flights; therefore the model should estimate non-flying zones around the Ignalina NPP. Thus, taking into account the decision of the Government of the Lithuanian Republic, a prohibited zone for flights is the height under 5950 meters above 9.265 kilometer radius territory around the Ignalina NPP.

All air corridors pass on a significant distance from the Ignalina NPP. Only three of them are within the 50 kilometer zone around NPP. According to Lithuanian navigating service experts, these corridors are of average congestion. According to the Lithuanian statistics department is no exact statistics on flights at separate air corridors, therefore the calculation of aircraft crash probability per one year uses approximate flight numbers from 40000 (the approximate number of flights in Vilnius airport during 2007 year) to 160000 (the approximate number of flights in Vilnius airspace during 2007 year). Also, it was conservatively assumed that half of those flights were performed by relatively new aircrafts, and the other half – by relatively old aircrafts.

According to non-flying zone it is necessary to adjust the formula (1) slightly. Conservatively, it was assumed that all flights from 50 km radius zone, take place at the periphery of 9.265 km radius zone. As the civil aircrafts compose major number of flights, value of coefficient g was taken 0.23, which at the same time is the most conservative from the above mentioned. This means that probability of the aircraft to deviate 10 kilometers aside its initial trajectory during the accident is 10 times less than to crash on it [7].

If the aircraft flies 100 km route through corridor touching 9.265 km radius zone around the Ignalina NPP (here $x = 50$ and $y = 9.265$ in the formula (1)), then general aircraft crash probability per year on r radius territory around the Ignalina NPP is expressed by the following formula:

$$P = N_c P_l r^2 g \left(e^{-9.265g} - e^{-g\sqrt{50^2+9.265^2}} \right). \qquad (2)$$

In order to estimate probability on the Ignalina reactor building as the part of initial conditions and aircraft crash parameters are not well-known or have different values for different types of planes, the uncertainty analysis was necessary to be performed for the created model. Uncertainty and sensitivity analysis has been performed using SUSA (Software System for Uncertainty and Sensitivity Analyses) [8] software. Values of model parameters for the uncertainty analysis are given in Table 1.

Table 1. Aircraft crash model parameter values.

#	Para-meter	Margins		Reference (mean)	Standard deviation	Distribution
		Min.	Max.			
Initial conditions						
1	P_l	1.2E-09	1.0E-07	5.1E-08	3.29E-08	Normal truncated
2	N_c	40000	160000	60000	40000	Normal truncated
Model parameters						
3	r	0.0	0.4	0.2	0.013	Normal truncated
4	g	0	0.46	0.23	0.15	Normal truncated

The results of the calculated aircraft crash probabilities onto corresponding object are presented in Table 2.

The correlation coefficient between the computer model output and the corresponding output from the multiple regression model is expressed by R^2, which is equal to 0.7 in our case (thus, the analyst can determine which model parameter should be regulated and controlled better in order to decrease unfavourable event occurrence). The sensitivity analysis shows that the most influencing parameter is r, which is the radius of aircraft crash zone around Ignalina NPP.

Table 2. Statistical characteristics of aircraft crash probability per year modelling results.

Results with (0.95,0.95) tolerance interval	P, aircraft crash probability per year
Minimum	3.28E-11
Maximum	3.45E-07
Mean	5.64E-08
Standard deviation	6.45E-08
Distribution	Beta
Quantiles limits in (0.05, 0.95) interval	Lower: 1.33E-09 Upper: 1.86E-07

Influence of correlation values of all parameters are presented in Figure 1 (here 1 parameter is P_1 – aircraft crash frequency per flight kilometre, 2 parameter is N_c – flight number per year, 3 parameter is r – the radius of aircraft crash zone around NPP, 4 parameter is g – a constant dependent on type of aircrafts and describe likelihood of close falling).

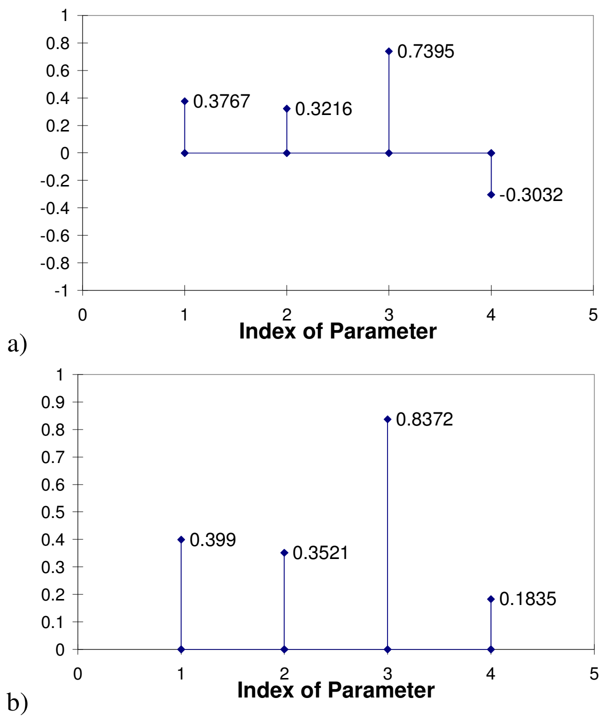


Figure 1. Standard Regression Coefficients (a) and Empiric Correlation Coefficients (b).

3.2 Extreme winds

3.2.1 *Initiating event description*

Extreme winds include hurricanes, tornadoes, cyclone winds etc. Wind can be classified by speed and destruction capacity.

- a weak wind – wind with the speed up to 5.4 m/s;
- an average wind – from 5.5- to 7.9 m/s;
- a strong wind – more than 14 m/s;
- a storm – more than 20-25 m/s;
- hurricane – more than 30-35 m/s.

Squall is a sudden, unexpected, short amplification wind during which the big destruction is possible. Speed of a wind during squall reaches 30 m/s and more.

The tornado – is the strongest whirlwinds of air with a vertical axis (but frequently the axis is bent). Diameter of a tornado may vary from several meters up to several hundreds meters. Inside of tornado the air rises very quickly upwards and is turned round the axis. Speed of the air inside a tornado whirlwind reaches 30-100 m/s and more.

For an estimation of impact of strong winds it is necessary to estimate probability of achievement by a wind of various speeds. In most cases the probability of achievement by the wind of speed x is determined by extreme values distribution. Model parameters are determined statistically, and the particular distribution law is selected according to statistical criteria. For the description of statistical data, the best is the formula for the extreme values function of the Gumbel distribution:

$$F(x) = e^{-e^{(\mu - x)/\sigma}}, \qquad (3)$$

where $\mu = \overline{X} - 0.577\sigma$ and $\sigma = s\frac{\sqrt{6}}{\pi}$ (here $\overline{X}$ denote initial sample average and s denote initial sample standard deviation).

3.2.2 *Probabilistic modelling results*

In the Ignalina NPP territory dominate western and southern winds. The strongest winds are western and south-east directions. The average annual wind speed is 3.5 m/s and maximum speed can reach 28 m/s. No-wind conditions are observed on the average for 6 % of the time and last no more than one day (24 hours) in the summer, and no more than two days in the winter [9].

The predominant wind direction changes depending on the distance above the ground. From the 200 m distance above the ground the predominant wind directions change as follows: in January from south to southwest, in April from south-southeast to southeast, in October from west-northwest to north. Only during July predominant direction is west for the indicated altitudes.

The wind velocity changes depending on the distance from the ground surface. At a distance of 100 m from the ground, the average wind velocity may double in comparison with wind velocities at the height of the wind vane.

Taking into account frequency of extreme wind and a tornado occurrence in the NPP surroundings, the final probabilities for various speeds of the tornado and the strong winds were calculated. The general extreme wind probability per year is expressed by the following formula:

$$F(x) = 1 - e^{-e^{(\mu - x)/\sigma}}. \qquad (4)$$

As the main characteristics of wind (speed, direction) are measured directly, then appear not only errors of measurement (systematic), but also random errors because of the random disturbances of a study.

Random errors can appear because of the geographical arrangement is, i.e., dependent in which environment and in which level it is observed wind speed. Furthermore, very large influence has weather – each time it can change. By measuring the speed of the wind is very strong influence (value) is the time – wind speed can be changed every second, so it is very important to measure not only the average, but the maximum speed.

These reasons influences result, and it will not be always precise. Furthermore, result influences the insufficiency of data, error of calculation, inaccuracy conclusion so forth Therefore for the created model was carried out the analysis of uncertainty.

The values of model parameters for the analysis of uncertainty are given in Table 3.

Table 3. Extreme wind model initial conditions values.

#	Para-meter	Margins Min.	Margins Max.	Reference (mean)	Standard deviation	Distribution
Initial conditions						
1	$\overline{X}$	17.6	24.4	20.63	2.04	Normal
2	s	1.14	7.54	2.87	1.59	Lognormal

The analysis of sensitivity and uncertainty is carried out with the extreme winds, when wind speed it changed from 20 m/s to 90 m/s. It was analyze the individual 6 different wind speeds cases (according to enhanced Fujita scale): 30 m/s, 40 m/s, 50 m/s, 60 m/s, 75 m/s and 90 m/s.

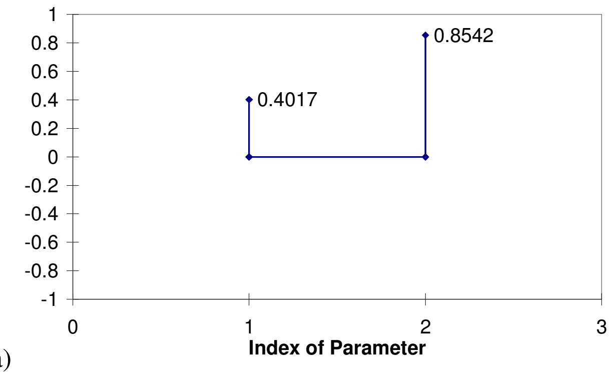
The results of the calculated extreme wind in the NPP surroundings (in Lithuania) are presented in Table 4.

Table 4. Statistical characteristics of different speed extreme wind probability per year modelling results.

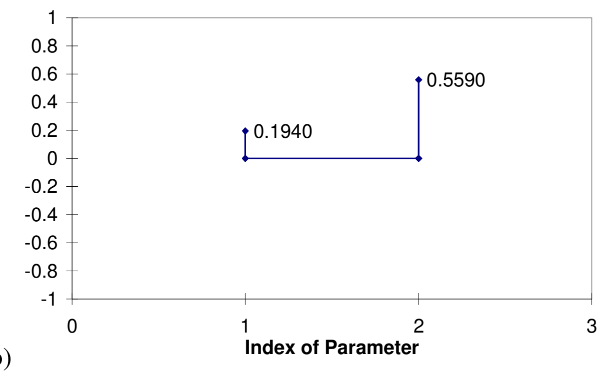
Extreme wind speed, m/s	Min.	Max.	Mean	Std. deviation	Quantiles limits in (0.05, 0.95) interval
30	1.73E-01	2.80E-05	4.46E-02	4.38E-02	Lower: 2.95E-04 Upper: 1.18E-01
40	3.17E-02	2.46E-09	5.16E-03	6.99E-03	Lower: 1.95E-08 Upper: 1.89E-02
50	5.47E-03	2.17E-13	6.69E-04	1.12E-03	Lower: 1.28E-12 Upper: 2.67E-03
60	9.32E-04	0	9.33E-05	1.82-04	Lower: 0 Upper: 4.07E-04
75	6,54E-05	0	5.27E-06	1.21E-05	Lower: 0 Upper: 3.01E-05
90	4,59E-06	0	3.16E-07	8.26E-07	Lower: 0 Upper: 1.87E-06

The average probability 30 m/s of wind speed is sufficiently high and is equal 4.46E-02. Exceeding wind 60 m/s speed the lower limit of interval is very close to zero. Nevertheless, average value of the probability of each, even 90 m/s of speed wind has great significance; therefore it is worthwhile to focus attention especially into the performance of the analysis of safety and risk. By the distribution, which best describes the obtained results, is a beta distribution.

The values of the correlation coefficients of the parameters, are obtained by the analysis of sensitivity with the wind speed of ≥30 m/s and ≥90 m/s, they are represented in Figure 2. It is evident that when speed of the wind of ≥30 m/s standard deviation is more significant after equalling average by value.



a)



b)

Figure 2. Standard Regression Coefficients, are obtained with the wind speed of ≥30 m/s (a) and ≥90 m/s (b).

3.3 External flooding

3.3.1 Initiating event description

Rise of a water level in the lake Druksiai represents the greatest danger to pump station on the lake, since the SWS (Service Water System) is the nearest NPP construction to the lake. Through the supply and discharge water lines water of the lake Druksiai directly streams into the PSL (the pump station on the lake) building and through the trash rack and water cleaning installations by pumps is delivered to a common collector.

The height of walls of the pumps' chamber has a mark of 144.1 m above sea level (i.e. the chamber can keep water up to a level 144.1 m). Floodboard closing pump chambers have the same height. Nominal water level elevation of the lake Druksiai is 141.6 meters above the sea level.

The platform of the other Ignalina NPP construction is located at a level of 148-149 m above the sea level. Rise of a water level in the lake Druksiai up to such mark is impossible and flooding does not represent the direct danger for the NPP in Lithuania.

Other source of external flooding, except lake, may be the intensive downpours.

3.3.2 Probabilistic modelling results

The water level in the lake Druksiai depends on the climatic conditions of the region and regulation of a drain by the hydro unit. From the beginning of the Ignalina NPP operation the drain regulation in the lake is not made, as the shields of the hydro unit with a view of maintenance of a maximum level of water in a reservoir are not lifted, and surplus of water from the lake is drained into the bottom pool of hydro unit by natural way atop of shields.

For probabilistic estimation of external flooding the mathematical model was developed. For probability calculation of fluctuations of maximum water level in the lake Druksiai normal distribution with parameters $\mu = 141.94$ and $\sigma = 0.266$ was applied. Parameter μ denotes mean and parameter σ denote the standard deviation of initial sample [10]. From this model probabilities estimations of various water levels in the lake were calculated (Table 4).

Table 4. Probabilities estimations of various water levels in the lake Druksiai.

Water level, m	Rise from a nominal level of 141.6 m	Probability per year
142.0	0.4	4.1E-01
142.5	0.9	1.8E-02
142.8	1.2	6.2E-04
143.0	1.4	8.6E-05
143.2	1.6	3.2E-06
143.5	1.9	2.1E-08

The probability of water rising higher than 143.5 m mark, i.e. probability of water level rise by 1.9 m from 141.6 m mark is not bigger than 2.1E-08 per year. Water rising above 144.1 m mark, i.e. level rise by 2.5 m above 141.6 m mark, is practically impossible, however flooding of PSL is possible for other reasons as well. For example, destruction of a water intake due to plane falling, occurrence of cracks in a wall, having dug water pipes or the case of the pump.

Using the data the mathematical model of probabilities of extreme precipitation in the Ignalina NPP surroundings was made. The formula for the extreme values function of the Gumbel distribution was chosen:

$$F(x) = 1 - e^{-e^{(\mu - x)/\sigma}}, \tag{5}$$

where $\mu = \overline{X} - 0.577\sigma$ and $\sigma = s\frac{\sqrt{6}}{\pi}$ (here $\overline{X}$ denote initial sample average and s denote initial sample standard deviation).

Using the model the probability estimations of precipitation extreme amount less than in 12 hours were received (Table 5).

The analysis of the statistical data shows, that there is dependence between intensity and duration of a downpour.

Table 5. Amount of precipitation and its probability.

Amount of precipitation, mm	Probability per year
150	4.20E-02
200	9.09E-03
250	1.94E-03
300	4.13E-04
350	8.80E-05
400	1.88E-05
450	3.99E-06
500	8.49E-07

3.4 Forest fire

3.4.1 Initiating event description

General external fire risk is mostly influenced by forest fires. Other fires are not so safety important because they are local and can be extinguish using NPP safety system.

External fire analysis consists of two main steps:

1. At first, the list of inflammable objects, located nearby NPP, is composed. This list should have information about inflammable objects distance from the NPP, their quantities and properties. This list should also include fuel warehouses, buildings in which inflammable objects are stored and forests nearby NPP.
2. Then analysis of the collected statistical data about forest fires frequency should be performed.

Using the collected statistical data on forest fires in territory, the mathematical model for estimation of probabilities of fire surroundings was made. It was chosen lognormal distribution with parameters μ and σ:

$$F_P(x) = 1 - \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}, \tag{6}$$

The selection of lognormal distribution is reasoned that calculation includes not only extreme cases of fires.

In zone around NPP there are 20 km^2 forests. The formula was applied to definition of probability of a forest fire in the 2000 ha area:

$$F(x) = F_P(x) \cdot 2000/S, \tag{7}$$

where $S = 246035$ – the general forests area of east part of Lithuania, *F(x)* – fire frequency (per one year).

3.4.2 Probabilistic modelling results

The NPP in Lithuania is situated in the region, where 30 % of territory is occupied by forests (40 % are grassland and 30 % are occupied by lakes and swamps). The edge of the closest forest is less than one kilometer from territory of the Ignalina NPP. On the territory of the NPP there are only separate trees and grass. On the distance of 150-200 meters from the territory Ignalina NPP there are car parking, where may be parked up to 300 vehicles. There are no other objects representing fire danger near the NPP in Lithuania.

The estimation was based on the statistical data on forest fires in Lithuanian territory for the period 1993-2001.

In 10-kilometer zone around the NPP in Lithuania there are no more than (20 km^2) 2000 ha forests. Estimations of probabilities of fires with the area from 10 up to 100 km^2 in the Ignalina NPP surroundings were given (Table 6).

Table 6. Probability of forest fire in the NPP surroundings.

Fire area, km^2	Probability per year
10	1.35E-03
20	5.54E-04
30	2.97E-04
40	1.82E-04
50	1.21E-04
60	8.51E-05
70	6.24E-05
80	4.72E-05
90	3.66E-05
100	2.90E-05

Table shows that probability of forest fire in the NPP surroundings is rather high.

The fire of environmental forest and grass or fire of cars on parking place do not represent danger to the NPP as the territory of the NPP is surrounded with a fence of 3 m in height. It is improbable that open fire will be thrown on the Lithuanian NPP territory. If such event occurs, in the NPP territory there is no easily inflammable subjects and the fire will be immediately liquidated by the NPP fire-protection service.

4 CONCLUSIONS

In this paper the extreme external events are described and events, which may have impact on safety of the NPP in Lithuania, were selected and analysed. Analysis is performed for aircraft crash, extreme winds, external flooding and forest fire. The sensitivity and uncertainty analysis was performed for the aircraft crash and extreme wind probability estimate. The analysis results of selected extreme events are summarised in the Table 7.

Table 7. The extreme external events probabilities per one year.

External event (remarks)	Probability per year
Aircraft crash on reactor building of the NPP	5.6E-08
External flooding (even for not critical level)	2.1E-08
Extreme winds and hurricanes (F3-F4 class by Fujita scale)	8.3E-07
Forest fire (impact on safety is non-significant)	5.5E-04

As evident from Table 7, the external events have either negligible probabilities or their impact on safety is non-significant. The probabilities of aircraft crash, extreme winds and external flooding are smaller than core damage frequency (6.9E-06), which was estimated considering the risk of internal events in the NPP.

The external event analysis with additional consequence analysis can be incorporated in the probabilistic safety assessment model. As external events data may change in the future it is reasonable to perform recalculations and perform additional importance and sensitivity analysis. It can also determine the highest risk and most important events from the consequence point of view [12].

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