Digital technologies in nuclear power plant probabilistic safety assessment

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Abstract. The ability of systems, structures and components that provide ultimate heat sink, to perform their functions and to ensure the safety of the nuclear power plant with VVER-1200 reactor in the events of external influences that entail the loss of ultimate heat sink is subject of the study. Necessity of consideration of mentioned events was demonstrated by last events occurred on NPPs worldwide in particular in Fukushima-Daiichi accident. Probabilistic model was developed implementing modern methods for assessment of probabilistic safety values using digital software RiskSpectrumPSA. Calculated probabilistic safety values confirm chosen design solutions and possibility of probabilistic safety assessment application for similar tasks.

1. Introduction
The issue of reliability of nuclear power plants was raised from the very beginning of their development. Nevertheless, in spite of the fact that the first nuclear power plant was launched in Obninsk in 1954, the first large-scale work devoted to probabilistic safety analysis was published in the USA only in 1975 [1]. In Russia, probabilistic methods for calculating the reliability of nuclear power plants have been used since the late 60s of the 20th century. Starting with OPB-88/97 [2], the presence of a probabilistic safety analysis was required as part of the design documentation submitted to obtain a license from the Gosatomnadzor of Russia [3].

Nowadays probabilistic safety assessment is used worldwide except of the main purpose also for design solutions justification, risk-informed safety classification or in-service inspections [4].

Fukushima Daiichi nuclear disaster occurred due to external hazard. Severity of the tsunami consequences can be explained by loss of ultimate heat sink. The ultimate heat sink of a NPP is a complex cooling system to which residual heat removed during a variety of both normal and emergency operating modes. Fukushima Daiichi accident brought innovations to the process of NPP design including probabilistic safety assessment (PSA) [5].

The state of modern science requires a multilateral study of the issues of the operation of a nuclear power plant [6][7][8], and the volumes and necessary timelines for the work are forced to use the latest methods of information processing including digital technologies [9][10].

Consideration of external influences entails special requirements for systems, structures and components of a nuclear power plant [11].

The subject of the study is the ability of systems, structures and components that provide ultimate heat sink, to perform their functions and to ensure the safety of the nuclear power plant in the event of
external influences that entail the loss of ultimate heat sink. The aim of the study is to confirm the justification of design decisions applied at a modern nuclear power plant in relation to external influences associated with the loss of ultimate heat sink, and to evaluate the probabilistic safety indicators associated with this.

To achieve this goal, the following tasks are solved:
• The methods used to evaluate probabilistic safety indicators applying software were described;
• The probabilistic safety indicators for external influences entailing violation of ultimate heat sink were assessed.

2. Materials and methods

The probabilistic safety assessment is an important instrument for determination of potentially weak elements and aspects in NPP units structure and control. One of the specific aspects of PSA application is the assessment process of NPP design for better understanding of its design features, functions of complex systems and personnel actions.

According to international and the Russian regulating and methodical documents [7], [9], [10] the probabilistic safety assessment is subdivided into several levels. Each of them is intended for own purposes and possible use of results.

The basic task of the PSA of Level 1 is to assess frequencies of accident sequences that result in severe damage of nuclear fuel. Reactor and spent fuel pool were taken as sources of radioactivity in current paper. The following tasks shall be performed for the development of the power unit probabilistic model:
• Selection and grouping of plant operational states
• Selection of initiating events;
• Grouping of initiating events;
• Modeling of accident sequences;
• Development of logic models of systems (reliability analysis of systems);
• Determination of safety characteristics for system components and probabilities (frequencies) of initiating events;
• Determination of human error probabilities (personnel reliability analysis);
• Determination and consideration of dependencies (dependency analysis);
• Determination of probabilities of severe accidents resulting from internal IEs.

Depending on the range of recorded initial events, probabilistic safety analysis is classified for internal IE or full-scale. Internal events - all possible failures of NPP equipment or human errors. Full-scale PSA level 1 also takes into account:
• On-site fires;
• In-site flooding;
• Other in-site threats;
• Seismic threats;
• External hazards except seismic threats.

According to the Russian regulatory and technical documents, the target safety parameter of the nuclear power plant in relation to the probability of a severe accident at the interval of one year is $10^{-5}$. Hazards usually associated with loss of ultimate heat sink were taken as initiating events in current study:
• Algae;
• Frazil ice;
• Pack ice;
• Oil spill.

The ultimate heat sink and associated heat transfer systems are designed to remove heat from the reactor in all design operating modes of the plant. The Baltic Sea water is used as a source of technical water supply and a final heat swallower at considered nuclear power plant. Water lines of cooling
water (channels, tunnels) connect the final heat absorber with consumers of sea cooling water of the power unit. All cooling water systems are made according to direct-flow scheme with single circulation of seawater through heat exchange equipment.

The following cooling water systems are accepted for considered NPP:

- Main cooling water system intended for cooling water supply and heat removal to the final absorber from turbine in all normal operation modes;
- Auxiliary cooling water system designed for heat removal to final absorber from equipment not important for safety;
- Cooling water system of essential consumers, which is intended for heat removal to the final absorber from heat exchange equipment of the intermediate circuit system of essential consumers, in all modes of unit operation including extended design modes.

In order to develop PRA model and perform PRA calculations, software Risk Spectrum PSA V1.3 is used. This software is a licensed product of Lloyd’s Register Consulting- Energy AB (Great Britain, www.lr.org/consulting) which is a consulting power division of Lloyd's Register, the world's largest insurance company. Risk Spectrum PSA software has the following advantages:

- It is used for safety analysis for approximately 50% of NPPs in the world.
- Valid license issued by the Russian regulatory authority available.
- High level of service and support, including licensed training courses.
- Associated software for risk monitoring (RISK WATCHER) available.

| Appearance of algae | Plant operation state | Failure of straight water intake | Failure of reverse water intake | No. | Freq. | Conseq. | Code |
|---------------------|----------------------|---------------------------------|---------------------------------|-----|-------|--------|------|
| ALGAE              | 00_POS               | FORWARD                         | REVERSE                         | 1   | OK    |        |      |
| 0                  | 2                   | -HR(2,1,12)                     | FORWARD                         | 2   | -HR(2,1,12) | FORWARD |      |
| 0                  | 3                   | -EO(2,1,12)                     | FORWARD-REVERSE                 | 3   | OK    | 00_POS |      |
| 1                  | 4                   | -HR(3,1,12)                     | 00_POS-REVERSE                  | 4   | OK    | 00_POS |      |
| 2                  | 5                   | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 5   | OK    | 00_POS |      |
| 3                  | 6                   | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 6   | OK    | 00_POS |      |
| 4                  | 7                   | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 7   | OK    | 00_POS |      |
| 5                  | 8                   | -HR(3,1,12)                     | 00_POS-REVERSE                  | 8   | OK    | 00_POS |      |
| 6                  | 9                   | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 9   | OK    | 00_POS |      |
| 7                  | 10                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 10  | OK    | 00_POS |      |
| 8                  | 11                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 11  | OK    | 00_POS |      |
| 9                  | 12                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 12  | OK    | 00_POS |      |
| 10                 | 13                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 13  | OK    | 00_POS |      |
| 11                 | 14                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 14  | OK    | 00_POS |      |
| 12                 | 15                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 15  | OK    | 00_POS |      |
| 13                 | 16                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 16  | OK    | 00_POS |      |
| 14                 | 17                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 17  | OK    | 00_POS |      |
| 15                 | 18                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 18  | OK    | 00_POS |      |
| 16                 | 19                  | -HR(3,1,12)                     | 00_POS-FORWARD-REVERSE          | 19  | OK    | 00_POS |      |
| 17                 | 20                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 20  | OK    | 00_POS |      |
| 18                 | 21                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 21  | OK    | 00_POS |      |
| 19                 | 22                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 22  | OK    | 00_POS |      |
| 20                 | 23                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 23  | OK    | 00_POS |      |
| 21                 | 24                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 24  | OK    | 00_POS |      |
| 22                 | 25                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 25  | OK    | 00_POS |      |
| 23                 | 26                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 26  | OK    | 00_POS |      |
| 24                 | 27                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 27  | OK    | 00_POS |      |
| 25                 | 28                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 28  | OK    | 00_POS |      |
| 26                 | 29                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 29  | OK    | 00_POS |      |
| 27                 | 30                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 30  | OK    | 00_POS |      |
| 28                 | 31                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 31  | OK    | 00_POS |      |
| 29                 | 32                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 32  | OK    | 00_POS |      |
| 30                 | 33                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 33  | OK    | 00_POS |      |
| 31                 | 34                  | -HR(3,1,12)                     | 00_POS-REVERSE                  | 34  | OK    | 00_POS |      |

**Figure 1.** Event tree for initiating event “Algae”.
According to a methodology of the probabilistic safety assessment the main steps for assessment of probabilistic safety values were executed. As PSA of Level 1 shall be performed for the power unit power operation and outage conditions (similar to [8]) plant operational states were elaborated. They were taken reactor plant operating instructions, scheduled maintenance regulations and results obtained by performing this task in PSAs for similar nuclear facilities. Functional event 00_POS takes into account plant operational state duration implementing following equation (1):

$$f_{POS}^{POS} = f_{IE} \cdot f_{POS},$$

where $f_{POS}^{POS}$ – frequency of initiating event occurrence in considered plant operational state; $f_{IE}$ – frequency of considered initiating event; $f_{POS}$ – frequency which model probability of occurrence of plant operational state during the period of one year.

The accident sequences were analyzed based on current design and event trees were elaborated. Figure 1 presents results of development of event tree for initiating event – “Algae”. Due to excessive dimensions of this tree it was reduced using transfer event trees (starting with “>” symbol in Consequences). Table 1 contains notes which simplify how the event tree was built. State of the art methods were used for consideration of external hazards [9]-[10] and human errors [11][12].

| POS | POS description | Accident sequence description |
|-----|-----------------|------------------------------|
| 1   | “Hot” state during shutdown of power unit. | Protective measure against algae were considered (functional event FORWARD), their failure leads to vacuum loss in the condenser and reactor trip. Possibility of change to reverse way of water intake was considered (functional event REVERSE), its failure leads to loss of cooling circuit for essential consumers and reactor trip due to shutdown of reactor coolant pumps. Possibility of cooldown through BRU-A and heat removal through passive heat removal system of steamgenerators. Only reactor is considered as source of radioactivity due to huge amount of time before water in spent fuel pool will boil away (~ 60 hours). |
| 2   | Reactor plant cooldown using the secondary circuit (from 255 °C to 135 °C) | |
| 3   | “Hot” state during startup of power unit | Cooldown of the reactor plant form 135 °C to 60 °C, degasation |
| 4   | “Cold” state during cooldown | Protective measure against algae were considered (functional event FORWARD) and possibility of change to reverse way of water intake (functional event REVERSE) their failure leads to loss of cooling circuit for essential consumers. Only possibility of cooldown through equipment of primary circuit was considered due to unavailability of secondary circuit equipment. Only reactor is considered as source of radioactivity due to huge amount of time before water in spent fuel pool will boil away (~ 60 hours). |
| 5   | Preparing for disassembly, disassembly of the reactor. | |
| 6   | Equipment maintenance Assembly of the reactor. | |
| 7   | Scheduled equipment maintenance | |
| 8   | “Cold” state during power unit startup | |
| 9   | Refueling. Scheduled equipment maintenance | Lack of necessity of safety systems operation is postulated due to huge amount of time before water in spent fuel pool will boil away (~ 60 hours). Protective measure against algae were considered (functional event FORWARD) and possibility of change to reverse way of water intake (functional event REVERSE) their failure leads to loss of cooling circuit for essential consumers. Necessity of heat removal from spent fuel pool was considered. |
| 10  | Inspection of reactor plant. Equipment maintenance | |
| 11  | Heating up to the temperature | Lack of necessity of safety systems operation is postulated due to |
POS | POS description | Accident sequence description
--- | --- | ---
11 | Hydraulic tests of primary and secondary circuits | Minor time of considered plant operational states and heating up processes. Only reactor is considered as source of radioactivity due to huge amount of time before water in spent fuel pool will boil away (~ 60 hours).
12 | Heating to 200 °C | Protective measure against algae were considered (functional event FORWARD), their failure leads to vacuum loss in the condenser and reactor trip (functional event FORWARD). Possibility of change to reverse way of water intake was considered (functional event REVERSE), its failure leads to loss of cooling circuit for essential consumers and reactor trip due to shutdown of reactor coolant pumps. Possibility of cooldown through BRU-A and heat removal through passive heat removal system of steam generators. Only reactor is considered as source of radioactivity due to huge amount of time before water in spent fuel pool will boil away (~ 60 hours).
14 | Power operation | 

Systems analysis was accomplished and fault trees in the software of RiskSpectrumPSA for the selected safety functions were constructed. Fault tree were used as inputs for function events from event trees. Figure 2 presents fault tree modeling protective measures against algae.

![Fault tree for protective measures against algae.](image-url)
3. Results
Table 2 presents results of final quantification. Following abbreviations were used to mark possible types of nuclear fuel damages:
- CD – core damage during power operation;
- CDS – core damage for the events happening during outage modes;
- FDS – damage of fuel in spent fuel pool for the events happening during outage modes.

| IE       | IE frequency, 1/year | Fuel damage type | Value, 1/year | Conditional probability | Contribution to total NFDF % |
|----------|----------------------|------------------|---------------|-------------------------|------------------------------|
| Algae    | 1.05·10^-1           | CD               | 1.87·10-12    | 1.78·10-11              | 0.0001                       |
|          |                      | CDS              | 2.88·10-10    | 2.74·10-9               | 0.0229                       |
|          |                      | FDS              | 1.21·10-12    | 1.15·10-11              | 0.0001                       |
|          |                      | Sum              | 2.91·10-10    | 2.77·10-9               | 0.0231                       |
| Frazil ice| 4.17·10^-2           | CD               | 1.57·10-11    | 3.76·10-10              | 0.0012                       |
|          |                      | CDS              | 1.29·10-9     | 3.09·10-8               | 0.0124                       |
|          |                      | FDS              | 1.56·10-10    | 3.74·10-9               | 0.0124                       |
|          |                      | Sum              | 1.46·10-9     | 3.51·10-8               | 0.1160                       |
| Oil spill | 3.70·10^-5           | CD               | 3.62·10-11    | 9.78·10-7               | 0.0029                       |
|          |                      | CDS              | 2.11·10-9     | 5.70·10-5               | 0.1675                       |
|          |                      | FDS              | 1.03·10-12    | 2.78·10-8               | 0.0001                       |
|          |                      | Sum              | 2.15·10-9     | 5.80·10-5               | 0.1704                       |
| Pack ice | 8.77·10^-3           | CD               | 4.75·10-18    | 5.42·10-16              | 0.0000                       |
|          |                      | CDS              | 5.33·10-19    | 6.08·10-17              | 0.0000                       |
|          |                      | FDS              | 1.79·10-15    | 2.04·10-13              | 0.0000                       |
|          |                      | Sum              | 1.80·10-15    | 2.05·10-13              | 0.0000                       |
| Summary  | –                    | –                | 3.90·10-9     | –                       | 0.3095                       |

4. Discussion
Defense-in-depth, based on the use of a system of physical barriers to the spread of ionizing radiation and radioactive substances into the environment and a system of technical and organizational measures to protect barriers and preserve their effectiveness, ensures the safety of the NPP. In Russian and international practice, systems and elements vary in purpose and impact on safety. The requirements for systems and components in a nuclear power plant depend on the events they must withstand.

Application of digital technologies (special software in current study) reduces time and necessary human resources for performing certain calculations of nuclear power plant safety assessment.

Conditional probability describe the frequency of fuel damage due to some initiating events. Conditional probabilities presented in Table 2 justify sufficiency of implemented design solutions for protection against external hazards leading to loss of ultimate heat sink.

Contribution to total nuclear fuel damage frequency represent which part is taken by the considered initiating event in total nuclear fuel damage frequency. Contributions presented in Table 2 (summary less than 0.3 %) also allow to treat considered initiating events as low contributing.

5. Conclusion
The results show that the applied protective measures against external hazards leading to the loss of ultimate heat sink are sufficient for safety in accordance with international and Russian regulations. It shall be mentioned that used hazard frequencies are estimated in conservative manner. This could lead
to conservatism of presented in current study scenarios estimation and to some extent cover uncertainty related with these loss of ultimate heat sink frequencies values.

The used software facilitates the work, allows to complete it in a shorter time, and simplifies the output of the results for presentation, which helps in discussing the work both at the Russian level and worldwide.

Chosen design solutions allows to reduce time of nuclear power plant construction and in the same time meet all modern safety requirements.

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