**Probabilistic safety analysis of the first level of small modular reactors using the example of the SHELF-M RF**

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**Abstract**

This report deals with the issues of probabilistic safety analysis of the first level of small modular reactors on the example of a small nuclear power plant (SNPP) with SHELF-M reactor facility (RF).

In this paper, the probability of a severe accident for a small modular reactor used in the SHELF-M RF has been estimated, for which the main engineering solutions used in the SHELF-M RF, the structural composition of the reactor facility were considered. The description of the main and auxiliary systems of the RF is also presented, the methodology for performing probabilistic safety analysis taking into account the design features of the facility for various initiating events, as well as the dominant contributors to the probability of a severe accident when exceeding the maximum design limits for the temperature of fuel cladding and fuel are presented. Based on the developed PSA Level 1 model, preliminary conservative calculations were performed, which made it possible to identify dominant risk contributors, assess sensitivity in relation to the main design solutions and develop recommendations for improving reliability at the system level and the safety of the facility as a whole.

The following initiating events have been shown to dominate risk measures:

* those leading to primary coolant loss,
* those leading to secondary circuit heat removal failure.

At the system and element level, the dominant contributors to the unreliability of the facility are: hydraulic accumulator of the hydraulic distributor system, valves of the makeup system, valves of the emergency core cooling system (ECCS), check valves of the makeup system, valves of the equipment cooling system.

## Introduction

The main objectives of this paper are to perform a probabilistic safety analysis of the SHELF-M RF to determine the frequency of a severe accident (fuel damage in the core above the maximum design limits), determine the dominant risk contributors and ways to improve the safety of the facility.

PSA serves to check the compliance of probabilistic safety indicators of the NPP unit with the safety goal for the nuclear power plant (NPP) by the total probability of a severe accident for each NPP unit for the period of one year equal to 1.00E-05 1/year [1].

## Brief description of the SHELF-M reactor facility developed for small nuclear power plants

The SHELF-M reactor facility (RF) (Figure 1) is designed to operate as part of the SNPP to supply power to facilities for various purposes in remote and hard-to-reach areas with decentralized power supply.

The SHELF-M RF has a thermal capacity of 35.2 MW and an 8-year refueling period. The basis for the development of the RF was the experience in the design, manufacture and operation of nuclear power installations. The RF complies with Russian regulations, standards, modern safety requirements, as well as IAEA recommendations.

As part of the RF, an integral type reactor is used, which ensures the compactness of equipment and media, and also increases the reliability of the facility due to the reduction of communications under the pressure of the primary coolant.

The coolant and moderator of the reactor facility is high-purity water with ammonia additive to generate hydrogen in it to prevent the generation of corrosive oxidative products of radiolysis.

The reactor core has negative temperature, density and power reactivity coefficients in the entire range of RF parameters change, which contributes to self-regulation of these parameters.

Circulation of the primary coolant in the reactor is ensured by two primary circuit electric circulation pumps (PCECP) with sealed electric drives. The features of the primary coolant circulation circuit provide the level of the output power at its natural circulation that is sufficient to continue the facility operation at a power of about 20% of the rated power when the PCECP loses power, as well as to ensure accident-free cooldown of the reactor core.

The RF uses a once-through coil steam generator built into the reactor, which is made of titanium alloys. Structurally, it consists of 32 modules, each of which during repair can be disconnected from the second circuit. On the side of the secondary circuit, the steam generator is divided into four sections, which are promptly disconnected in case of depressurization using shut-off valves.

The design of the RF includes an autonomous emergency cooldown system (ECS) designed to decay heat from the reactor core both during planned outages and in emergency situations.

All equipment of the primary circuit, with the exception of part of the equipment of the system for makeup and emergency insertion of the absorber, is placed in a durable sealed safeguard vessel (SV), which confines the release of radioactive substances from the primary circuit system in case of design basis accidents due to depressurization.

To confine radioactive products in case of beyond design basis accidents, the RF is placed in a reinforced leak-tight containment, which is the main element of the RF vessel. The containment together with the external biological shield protects the RF against severe external impacts: hurricanes, tsunamis, aircraft crash, etc.

All safety systems (except for the makeup and emergency absorber insertion systems) are passive and put into operation without operator intervention and actuation of control and power consumption systems.



Figure 1 - SHELF-M reactor facility (RF) [2,3]

## Level 1 Probabilistic Safety Analysis for the SNPP with the SHELF-M RF

Probabilistic safety analysis (PSA) is performed to determine the probability of accident paths and end states, including the probability of severe accidents, as well as to check the compliance of the integral indicator with the goal specified in the regulatory documentation [4].

### Analysis of the reliability of the SHELF-M RF systems and development of the list of safety functions of the SNPP

The reliability analysis of reactor facility systems is performed to determine probabilistic safety indicators of the plant and, if necessary, to develop a set of measures to change (or refine) the design of the systems in order to ensure the required safety with minimal costs [5, 6].

To generate the list of safety functions (SF), the effect of safety systems on the RF characteristics was analyzed: level, pressure, coolant temperature and reactor reactivity [7]. For the analysis, the systems the trouble-free operation of which ensures the safe operation of the RF were selected.

Fundamental safety functions were used to generate the SF list for the SNPP:

* monitoring and control of reactivity,
* core cooling at all power levels,
* confinement and reliable retention of radioactive elements within the RF.

The results of calculating the reliability indicators of the SHELF-M RF systems are presented in Table 1.

Table 1 Results of calculating the reliability indicators of the SHELF-M RF systems

| Item number | System | Safety function | Reliability indicator |
| --- | --- | --- | --- |
| 1 | Primary circuit system | 1) Reactor scram and keeping it subcritical2) Retention of radioactive elements within the primary circuit by means of isolation valves3) RF protection against overpressure in the reactor vessel | Q = 7.38E − 03 1/reqW = 1.99E − 06 1/h |
| 2 | Secondary circuit system | Reactor emergency cooldown by the secondary circuit | Q = 1.38E − 04 1/reqW = 4.52E − 08 1/h |
| 3 | Reactor unit emergency cooling system | Coolant loss compensation (small, medium and large leaks) | Q = 7.56E − 06 1/req |
| 4 | Reactor emergency cooldown system | Emergency reactor cooldown via ECS | Q = 7.57E − 07 1/req |
| 5 | Equipment cooling system | - | W = 2.84E − 07 1/h |
| 6 | Makeup and Emergency Absorber Insertion System | 1) Reactor emergency outage and maintenance in subcritical state2) Compensation of coolant loss (small, medium and large leaks) | Q = 4.89E − 06 1/req |
| 7 | Steam generator and ECS intermediate heat exchanger overpressure prevention system | RF protection against overpressure in the reactor vessel | Q = 1.47E − 08 1/req |
| 8 | SV and overpressure protection system | Protection of the SV and containment against overpressure | Q = 3.44E − 03 1/req |

Q – Probability of failure system;

W – Failure rate of repairable system.

The reliability analysis of the systems of the power unit with the SHELF-M RF showed that the dominant contributors to the unreliability of the facility are: hydraulic accumulator of the hydraulic distributor system, makeup system valves, ECCS valves, check valves of the makeup system, valves of the equipment cooling system.

### Analysis of initiating events

The following groups were adopted as the main modes for which PSA is performed:

* POS group 1 - PU operation mode at rated power level,
* POS group 2 - PU parking mode.

As part of the IE analysis, events were considered, the potential consequences of which can cause the release of radioactive substances from nuclear fuel located within the location of the ASMM.

Events potentially leading to nuclear fuel damage include internal IEs, IEs arising as a result of on-site impacts (arising as a result of fires, flooding, impacts from flying objects, pipeline run-out), as well as external impacts of natural and man-made nature [8].

Thus, the following groups of events were considered as IE:

1. Internal IE:

1.1 Group of IEs leading to unauthorized reactivity change,

1.2 Group of IEs leading to the loss of heat removal from the core,

1.3 Group of IEs leading to the loss of heat removal by secondary circuit,

1.4 IE group leading to the loss of the primary circuit coolant,

1.5 IE group involving the loss of the system power,

1.6 IE group leading to the loss of nuclear fuel handling;

2. Onsite IEs caused by indoor fires;

3. External IE of natural and cosmic nature (meteorite fall, hurricane wind, extreme weather conditions (including precipitation), sand and snow storms).

### Examples of emergency scenarios

As part of the above analysis, the RF end states were postulated which are involved in the emergency scenarios for the initiating events under consideration and reflect the extent of damage to nuclear materials within the NPP site:

1. State S – successful completion of the emergency scenario,
2. State A – core damage (severe accident).

In sequences 1, 4 (see Figure 2), the reactor power reduction function was performed successfully. The further task of successfully overcoming the accident is to ensure the removal of residual and accumulated heat in the RF components using the ECCS.

Sequences 7, 8 are characterized by the successful reduction of neutron power due to the introduction of a liquid absorber, which makes it impossible to further operate the reactor.

Sequences 2, 5 are characterized by the performance of the reactor power reduction function and the function of the residual heat removal through the makeup system (MS).

Sequences 3, 6, 9, 10 are characterized by the reactor core damage due to the impossibility of the reactor shutdown and heat removal.

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Figure 2 Event tree for the IE "Reactor vessel break"

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Figure 3 Event tree for the IE "PCECP malfunction (disconnection, jamming, speed reduction)"

In sequences 1-3, 7, 8, 12, 13 (see Figure 3), the reactor power reduction function was performed successfully. The further task of successfully overcoming the accident is to ensure the removal of residual and accumulated heat in the RF components using the ECCS.

Sequences 17-20 are characterized by the successful reduction of neutron power due to the introduction of a liquid absorber, which makes it impossible to further operate the reactor.

Sequences 4, 5, 9, 10, 14, 15 are characterized by the performance of the reactor power reduction function and the function of residual heat removal through the MS.

Sequences 6, 11, 16, 21, 22 are characterized by the reactor core damage due to the impossibility of the reactor shutdown and heat removal.

## Results of calculating the severe accident probability, analysis and presentation of results

The severe accident probability (SAP) for internal IEs, onsite impacts caused by fires and flooding, and external impacts excluding seismic impacts, and the overall risk value for
Category A (reactor core damage) were estimated in the process of calculating the PSA model for a power unit with the SHELF-M reactor facility.

Table 2 presents the PSA estimates for all IE types.

Table 2 – PSA estimates for all IE types

| Group of IEs | SAP (Category A) prior to proposed changes, 1/year | SAP (Category A) after proposed changes, 1/year |
| --- | --- | --- |
| 1. Internal IEs |
| 1.1 Group of IEs leading to unauthorized reactivity change | 4.13E-07 | 4.13E-07 |
| 1.2 Group of IEs leading to the loss of heat removal from the core | 2.25E-07 | 2.25E-07 |
| 1.3 Group of IEs leading to the loss of heat removal by secondary circuit | 1.96E-06 | 1.00E-06 |
| 1.4 Group of IEs leading to the loss of the primary circuit coolant | 5.02E-05 | 6.33E-06 |
| 1.5 Group of IEs involving the loss of system power | 3.29E-10 | 3.29E-10 |
| 1.6 Group of IEs leading to the loss of nuclear fuel handling | 1.65E-11 | 1.65E-11 |
| 2. Onsite IEs |
| 2.1 IEs caused by indoor fires | 8.66E-08 | 8.66E-08 |
| 3. External IEs |
| 3.1 IEs of natural origin | 8.27E-10 | 8.27E-10 |
| Total PSA estimate | 5.59E-05 | 8.06E-06 |

The predominant contributors to the SAP in the event of the maximum design limits being exceeded for the fuel cladding and fuel temperature are initiating events:

* leading to the loss of primary coolant,
* leading to the loss of heat removal by the secondary circuit.

The analysis made it possible to identify the predominant risk contributors and the key components of the RF systems that contribute to the unreliability of the facility under consideration, and to develop the following recommendations for improving the reliability at the system level and the safety of the facility as the whole:

1. additional check valves should be installed at the reactor outlet in the direction of the coolant movement through the circuit to reduce the frequencies of initiating events of the “Coolant loss” type associated with the check valve failures,
2. possibility should be provided to ensure redundancy for the hydraulic drives of the shutoff valves,
3. possibility should be considered for redundancy to be provided for the hydraulic accumulator of the distribution valve system.

After implementing the proposed measures to increase the reliability of the design solutions, it was shown that the probabilistic safety indicators of the RF met the safety targets for the NPP.

## Conclusion

This paper presents the results of a level 1 PSA model for a power unit with the SHELF-M reactor facility for internal IEs, onsite impacts caused by fires and flooding, and external impacts.

This analysis of the systems of the power unit with the SHELF-M RF is performed. This analysis showed that the dominant contributors to the unreliability of the facility are: hydraulic accumulator of the hydraulic distributor system, makeup system valves, ECCS valves, check valves of the makeup system, valves of the equipment cooling system.

Based on the developed level 1 PSA model, the overall SAP estimate is calculated
(5.59E-05 1/year). The elimination of the risk dominants identified in the process of analyzing the design solutions has made it possible to reduce the frequency of severe accidents to
8.06Ye-6 1/year, that is, bring it in compliance with regulatory requirements.

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