RT&A, Special Issue No 5 (75)
Volume 18, November 2023

NPP MAINTENANCE AND REPAIR RISK MANAGEMENT: THE CASE OF RUSSIA

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Abstract

The paper considers the risk management system of the operating organization in the process of maintenance and repair of nuclear power plants in Russia. The following main risks of the process are identified: an energy generation reduction due to extending outages and energy cost increase due to an increase in costs for repair and maintenance needs. The following measures for risk management of the process are considered: inspections of readiness for repair and repair quality, corporate support, development and revision of repair documentation, management of material and technical resources. The process efficiency indicators as indicators of risk tolerance are considered. An effectiveness assessment of the risk management system of the maintenance and repair process is presented. The key shortcomings are identified. The line of further research on shortcomings exclusion is formulated.

Keywords: process, risk matrix, risk criticality, risk significance, risk causes, NPP, M&R

I. Introduction

Risk management is an important tool for ensuring the sustainable operation of nuclear power plants (safe, reliable, economic). The practice of nuclear power plants (NPP) operating indicates the continuing trends in determining priorities – safe operation in order to avoid accidents. The process of NPP maintenance and repair (M&R) as a supporting operation process is not a priority for safety. This circumstance is explained by the fact that poor-quality repairs will not lead to an accident. From the point of view of NPP safety, the most serious consequence of poor-quality repairs is an unplanned shutdown of the power unit. However, neglect of the M&R process leads to the gap of NPP sustainable operation and, as a result, to a diminution of the national energy security. Thus, risk management of NPP M&R process is one of the critical government issue.

The operating organization (Operator) of Russian NPPs – Rosenergoatom Concern JSC – has accumulated wide experience in risk management system development and improvement. This paper discusses Russia's experience in implementation of risk management in a one specific process – NPP M&R.

The paper is structured as follows. The Introduction presents the research relevance. The Methods discusses the risk management methods for Operator’s processes. The Results shows how risk management implements in the M&R process namely M&R key performance indicators as risk tolerance indicators, analysis of identified risks and measures to manage them. The Discussion evaluates the effectiveness of the M&R process risk management system, its shortcomings, and discusses directions for further research.

II. Methods

The risk management system comprises 11 types of risks: production, construction, financial, commercial, organizational, legal, market, environmental, political, reputation, and security risks.

The risk management process includes four stages: risk identification and analysis, development of risk management measures, and monitoring the results of risk management.

The first stage of risk management is identification. The main source of information is statistical data on process key performance indicators, reports on various activities and risks. The second stage is risk analysis, where the risk significance is assessed and a management method is chosen. The third stage involves developing risk management measures with a budget calculation. In the final fourth stage, monitoring of the results of risk management is carried out including the measures performing, their effectiveness evaluation, deviation analysis and the development of new measures. The risk management process is continuous.

In accordance with the Operator's guidelines the following methods of risk identification are recommended: brainstorming and the Delphi method [4], questionnaire [5], SWOT analysis [6], the method of analogies. The last method is mainly applicable in the process of "Construction Management" [7].

The qualitative risk assessment involves assessing risks based on characteristics such as: corresponds/does not correspond, applicable/not applicable, catastrophic/insignificant, etc. The quantitative risk assessment is carried out using the following methods recommended by the Operator's guidelines [4]:

- Hazard and Operability Study (HAZOP)
- Event Tree Analysis (ETA)
- Failure Modes and Effects Analysis (FMEA)
- Failure Modes, Effects, and Criticality Analysis (FMECA)
- Fault Tree Analysis (FTA)
- Human Reliability Analysis (HRA)
- Reliability Block Diagram.

The Operator recommends using the following quantitative risk assessment methods in addition: Tree Decisions [4], Monte Carlo simulation [4], and sensitivity analysis, including the «Butterfly» method [4].

Let us underline that many methods proposed by the risk management system are used in Probabilistic Risk Assessment (PRA) [8] and Probabilistic Safety Analysis (PSA), and in life management. Based on the PRA methodology, PRA combines PSA and life management. In comparison with some foreign countries where PRA is regulated by separate regulatory requirements [9], in Russia PRA is a part of the safety justification concept.

A risk matrix is the tool used for risk assessment, which helps to choose the risk management method and the urgency of performing risk management measures.

To design the risk matrix it is necessary to assess the probability or frequency of risk occurrence, to evaluate the risk consequences, and to determine the risk significance. The risk matrix design methodology is in a proper with [10]. However, some differences are compared to [10]. Firstly, experts assign scores when assessing the probability and consequences. For example, a score "5" is assigned when the probability of risk occurrence is above 0.9, and a score "1" is given for probability below 0.1. Similarly, score "5" is given for consequence which is losses exceeding 100 million rubles and score "1" if losses are less than 5 million rubles. The risk significance matrix is calculated by multiplying the probability of risk occurrence by the consequence score, resulting in a scale of 1 to 25 points. Secondly, the risk matrix named risk critically matrix is visualized using the «Traffic Light» system, where "red" indicates a significant risk ($15 \leq R_i \leq 25$), "yellow" means a manageable risk ($6 \leq R_i \leq 12$), and "green" indicates an acceptable risk ($1 \leq R_i \leq 5$).

For each risk, the degree of its impact on risk tolerance indicators is determined, taking into account limiting factors such as response time, resource availability, etc.

The risk management methods include "acceptance," "mitigation," "sharing," and "avoidance." In our opinion, it is appropriate to describe the risk management process in two strategies: risk decrease strategy and risk increase strategy, which can be implemented using the fore mentioned methods but are not limited to them.

The process owner develops risk management measures. The urgency of developing risk management measures is determined based on the risk significance.

The effectiveness of the measures is assessed using the formula

$$K = \frac{P_1 - P_2}{C_i}, \tag{1}$$

where K is the effectiveness coefficient of measure i, P_1 is the cost of risk consequences before implementing measures in million rubles, P_2 is the cost of risk consequences after implementing measures in million rubles, and C_i represents the cost of measure i in million rubles. The measure with the highest effectiveness coefficient is the most prioritized. P_2 represents the planned value of the measure's effect and serves as the basis for analyzing deviations during the monitoring stage of risk management results.

The Operator's risks are grouped into a consolidated risk register, which is a tool for risk accounting and control. Further, the risks are ranked by significance, and a consolidated risk register is formed in descending order of the initial risk assessment values or costs of risk consequences. Quarterly and annually, the process owner prepares a report on the results of risk monitoring.

III. Results

NPP M&R is a supporting part of the main process «Electricity and Heat Production».

The M&R process document named "M&R process identification summary" (M&R Summary) provides following information: the description of participants and their roles, resources, M&R objects management, key performance indicators.

The M&R process owner is the Department of Production and Operation of Operator. The resources required for M&R process performing include labor, informational, financial, material and technical, and infrastructural resources. The M&R process objects are norms and rules, repair deadlines, readiness for repair, resource needs, services, the organizational structure of M&R management, and equipment.

The M&R process key objective is to ensure the equipment operability while minimizing costs.

The key performance indicators (KPI) were developed and implemented in 2019. In 2022, The M&R process efficiency was assessed using 30 indicators, which are reactive and proactive. The evaluation of the M&R process efficiency is visualized using the «Traffic Light» method. The Operator defines upper, lower, and target values for the boundaries of the zones (red, yellow and green) for each NPP, taking into account the type of reactor and the number of units.

The KPIs are grouped into the following areas:

- Safety indicators
- Operational efficiency indicators.

Russian M&R process KPIs have significant differences from European ones [11].

Quarterly and annually, the Operator monitors the trends of the M&R process KPIs, assesses results' ratings, and carries out corrective actions if necessary. For example, the Operator modifies the target values of indicator boundaries or develops new indicators.

It ought to be noted that the KPIs indicate the level of risk tolerance, and each KPI is linked to a specific risk identified by the Process Owner. Thereby the Operator reviews the list of M&R

process risks and the risk management measures based on the assessment of KPIs' result ratings.

The Operator (Table 1) and separately each NPP evaluate the M&R process KPIs' result rating. The KPIs' trend assessment involves comparing current indicator values with those of the previous year.

Table 1: *M&R process KPIs for Operator in 2022*

KPI Title	Code	Criteria			The value 2022
Unavailability coefficient	M&R-P-1	0≤K≤2	2<K≤4	4<K≤5	1,87
Unavailability coefficient due to M&R shortcomings	M&R-P-2	0≤K≤0,4	0,4<K≤0,8	0,8<K≤2	0,00
Average age of defects in safety-critical systems	M&R-P-3	0≤K≤40	40<K≤72	72<K≤100	9,28
Average age of defects in non-safety-critical systems	M&R-P-4	0 ≤K≤90	90<K≤170	170<K≤300	32,60
Completion of the monthly equipment repair plan	M&R-P-5	98≤K≤100	95≤K<98	0≤K<95	99,00
Adherence to the repair campaign schedule	M&R-P-6	0≤K≤1967	1967<K≤2038	2038,1<K≤2080	1968,00
Exclusion of work scope	M&R-P-7	0≤K≤11	11<K≤22	22<K≤33	2,00
Reduction of injuries' severity during M&R executing	M&R-P-8	K=100	50≤K<100	49≤K<50	0,00
Exceeding the dose budget	M&R-P-9	0≤K≤34	34<K≤70	70<K≤106	0,00
Collective dose	M&R-P-10	0≤K≤64	64<K≤105	105<K≤146	19,72
Shutdowns of power units or turbogenerators within the first month after outage	M&R-P-11	0≤K≤5	5<K≤7	7<K≤9	0,00
Reduction of unplanned shutdowns of power units and turbogenerators	M&R-P-12	9≤K≤10	3≤K<9	0≤K<3	10,00
Number of depressurizations of coolant circuits	M&R-P-13	0≤K≤5	5<K≤10	10<K≤15	0,00
Coefficient of prevention foreign material exclusion from entering equipment	M&R-P-14	98≤K≤100	90≤K<98	0≤K<90	99,70
Number of defects in safety-critical systems	M&R-P-15	0≤K≤111	111<K≤166	166<K≤200	10,00
Number of defects in non-safety-critical systems	M&R-P-16	0≤K≤670	670<K≤1070	1070<K≤1200	57,36
Quality of staff work	M&R-P-17	K=100	99,5≤K<100	0≤K<99,5	100,00
Quality of the contractors' work	M&R-P-18	K=100	99,5≤K<100	0≤K<99,5	100,00
Unplanned restrictions for operation	M&R-P-19	K=0	0<K≤0,5	0,5<K≤1	0,00
Availability of repair documentation	M&R-P-20	K=100	98≤K<100	0≤K<98	99,99
Using procedures	M&R-P-21	K=100	98≤K<100	0≤K<98	100,00
Reducing the number of failures due to repair documentation	M&R-P-22	K=10	0,1≤K<10	0≤K<0,1	93,98
Reducing the number of equipment failures due to repair personnel	M&R-P-23	K=10	0,1≤K<10	0≤K<0,1	80,53

KPI Title	Code	Criteria			The value 2022
The quality of personnel workplaces walkdowns	M&R-P-24	1≤K≤10	0,1≤K<1	0≤K<0,1	3,37
Availability of stocks not to be allowed to run low	M&R-P-25	K=100	70≤K<100	0≤K<70	100,00
Centralized stocking	M&R-P-26	99,9≤K	80≤K<99,9	0≤K<80	98,24
Resource availability ratio	M&R-P-27	K=100	90≤K<100	0≤K<90	100,00
Adherence to repair documentation approval deadlines	M&R-P-28	98≤K≤100	95≤K<98	0≤K<95	100,00
Analysis of repair documentation quality during the repair interval	M&R-P-29	K=100	98≤K<100	0≤K<98	100,00
Analysis of repair documentation quality during the PPM	M&R-P-30	K=100	98≤K<100	0≤K<98	100,00

Due to the volume, the authors do not provide the formulas for calculating each indicator.

Based on the assessment of M&R process KPIs in 2022, the Operator has made the following decisions:

- supplement the KPIs system with four integrated indicators calculated using M&R-P-2-M&R-P-30: repair preparing management (M&R-P-31), repair executing management (M&R-P-32), shutdowns and unloading management for repairs (M&R-P-33), repair quality management (M&R-P-34)
- review the risks' list and the their occurrence causes
- review the risk management measures, taking into account the KPIs in "yellow" and "red" zones at the end of the year.

The major M&R process risks and their causes are provided in Table 2.

Table 2: *The M&R process risks and their causes in 2022-2023*

Risk	Cause
2022	
energy generation reduction	• due to the power unit extending outage • due to the power unit shutdowns caused by equipment malfunctions and failures due to unsatisfactory executed repair
electricity production costs increase	• due to the increase of the M&R costs in repair and operation expense items
2023	
Operator's revenue reduction due to the power unit extending outage resulting from repair works extending	• due to supplementary repair works caused by poor planning or defects identified during the repair process • due to the delayed or failure providing the contractor with up-to-date repair documentation, caused by unreadiness or lack technological documentation • due to the lack of modern technical means and adjustments for repairs caused by poor planning or lack of financial resources
electricity production costs increase due to the increase of the M&R costs in	• due to planning errors in repair works • due to planning errors in material and technical

repair and operation expense items resulting from the execution of unplanned work scope	resources' usage

The risk management measures for the M&R process include inspecting the NPP readiness for PPM, inspecting the performed repair works' quality, corporate support, developing and revising repair documentation, implementing modern equipment and managing material and technical resources.

The statistical data of the notes of the Operator's commissions are presented for following risk management measures: inspecting NPP readiness for PPM in Figure 1, inspecting the performed repair works' quality in Figure 2 and corporate support in Figure 3. The statistical data demonstrates M&R process identified shortcomings.

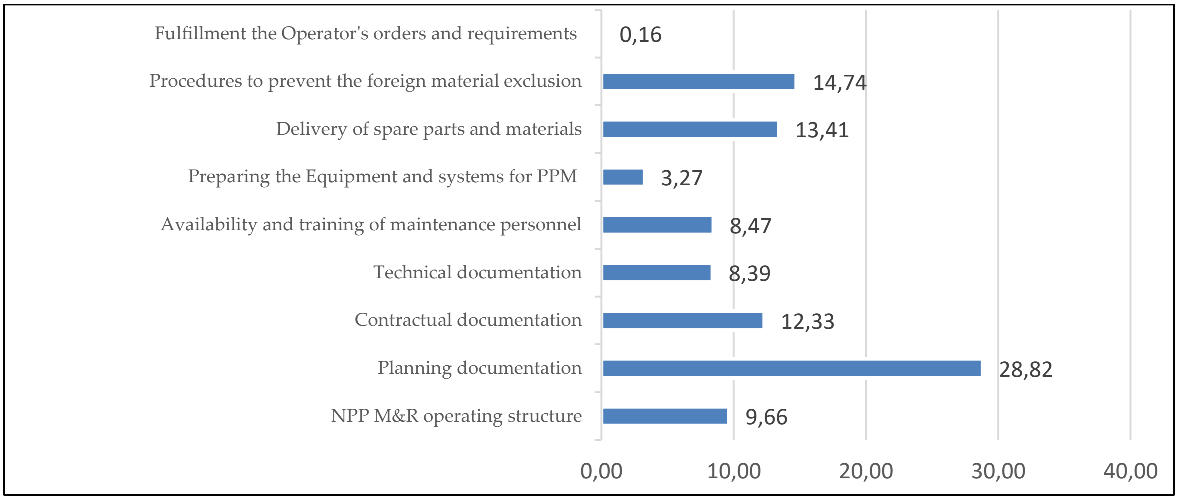

Fig. 1: *The notes of the Operator's visiting commissions for inspecting NPP readiness for PPM on average for 2015-2022, %*

Let us remark that the total number of notes decreased from 70 in 2015 to 22 in 2022, which is more than a threefold reduction. However, the trends continue to show an increase in every line of inspecting, except for "Procedures to prevent the foreign material exclusion from entering equipment."

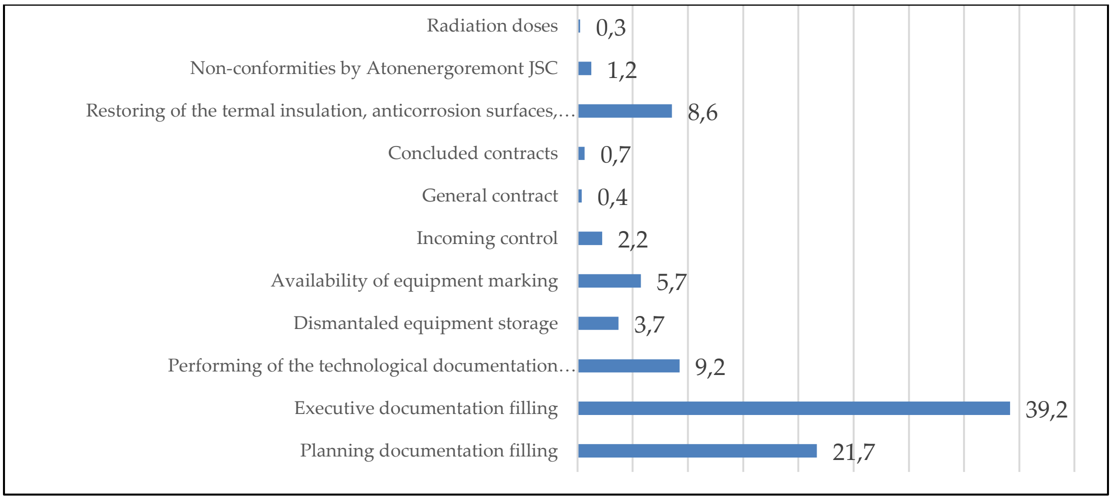

Fig. 2: *The notes of the Operator's visiting commissions for the performed repair works' quality on average for 2015-2022, %*

The changes of the number of notes is unstable. The number of notes fluctuates from year to year between 30-70 notes per year. However, the trends in lines of inspecting remain consistent:

- "Planning documentation filling" and "Dismantled equipment Storage" show an increase trends.
- "Technological documentation" and "Availability of equipment marking" demonstrate stable dynamics.
- The rest lines show a fall in notes.

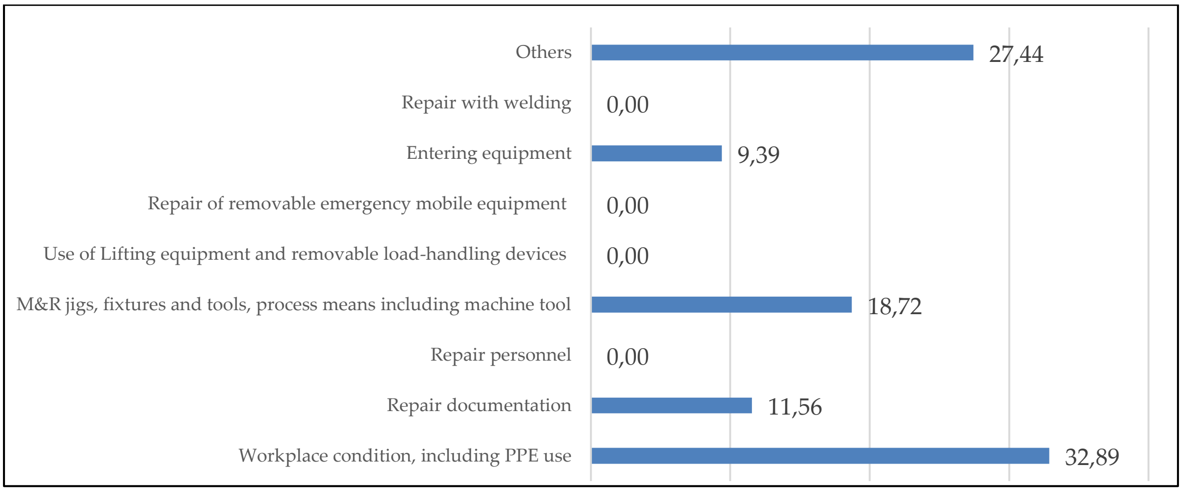

Fig. 3: *The notes of the Operator's corporate support on average for 2019-2022, %*

The number of identified shortcomings shows a downward trend, decreasing from 50 in 2019 to 27 in 2022. However, the trends in reducing the number of notes apply to all lines except for "Other", which includes shortcomings related to the filling of operation and repair documentation, the organization of repair headquarters, the use of specific software for maintenance planning, etc.

Given that the major risks are identified as energy generation reduction due to the power unit extending outage as well as the power unit unplanned shutdowns, it is necessary to analyze this data. The data on the planned outage duration for power units from 2015 to 2022 are provided in Table 3, while the data on unplanned shutdowns are presented in Table 4.

Table 3: *Data on the planned outage duration of power units for 2015-2022, days*

Indicator	2015	2016	2017	2018	2019	2020	2021	2022
Actual duration	1599,5	1873	1826,5	2571	2441,5	2243,5	1982	1848
Planned duration	1832	1980	1953	2621	2502	2374	2089	2000
Duration reduction	202	180,5	243,5	118,5	155	138,5	172,5	198,5
Duration extending	17,5	73,5	117	68,5	94,5	8	65,5	46,5
Duration Changing ("+" reduction,"-" extending)	184,5	107	126,5	50	60,5	130,5	107	152

For every unplanned shutdown, an investigation is conducted to identify the root and immediate causes. On average from 2015 to 2022, in 77% of cases, the root cause of the unplanned shutdown due to unsatisfactory M&R is NPP management shortcomings. Further analysis of this cause shows that 41% is attributable to documentation shortcomings, 40% to M&R procedures, 12% to failure to take actions, and 6% to human errors.

The result of risk monitoring is a report in tabular form, where the risk management system is evaluated on a scoring basis:

4 – risks were not realized, risk management measures were effective

2 – risks were realized, risk management measures were effective

1 – risks were realized, isolated cases of failure to risk management measures executing occurred

0 – risks were realized, lack or failure to risk management measures executing occurred.

Table 4: *Statistics of unplanned shutdowns of power units and turbine generators for 2015-2022*

Year	Duration, days		Quantity, units	
	Total	Caused by Unsatisfactory M&R quality	Total	Caused by Unsatisfactory M&R quality
2015	189,5	58,7	54	18
2016	252,2	49,8	58	10
2017	279,5	25,2	56	9
2018	287,8	85,4	46	14
2019	182,8	23,6	55	10
2020	85,3	12,3	36	9
2021	242,6	30,3	48	10
2022	202,4	14	44	4
Итого	1772,1	299,27	397	84

Let us resume that the Operator's risks were not realized, despite some risks being realized in certain NPPs, and the risk management measures were deemed effective. The effectiveness score of the M&R risk management system is 4.

IV. Discussion

The Operator's risk management system allows assessing risks of processes in accurate approach way.

Furthermore, M&R process risk management includes the use of recommended risk identification methods. However, risk analysis methods are not reflected in the M&R Summary. Nevertheless, it should be noted that all recommended risk analysis methods in the M&R process are used in the safety justification concept. Moreover, Regulator and Operator regulate the risk-centered maintenance. For example, when determining the scope and frequency of metal in-service inspection as well as when planning repair works considering equipment risk significance. For this purpose, domestic software is used:

- BARS for PSA of thermal reactors, the latest version of which was integrated with RiskSpectrum software that provides the following opportunities: data preservation after the RiskSpectrum software developers ceased support and various risk assessment methods enhancing.
- CRISS for PSA of fast reactors. This is a unique Russian software as well that allows assessing risks in M&R process of fast reactors.
- SPA (System of Predictive Analytics) for evaluating the technical condition of equipment based on physical-mathematical and statistical models of equipment and NPP technological processes. SPA is interfaced with the equipment's, defects', and low-level events' databases.
- NPP Experience software for considering operating and repair experience. The M&R Automated Control System as a part of The NPP Experience interfaced with SPA and BARS/CRISS software, is a decision support tool that allows filling of sheet repair works' scope based on forecasting equipment condition changes, requirements of Regulator, Manufacturer and Operator. Time required for repair, the number of personnel by qualification and positions, the spare parts' quantity, the labor intensity, and the cost of the power unit repair in total and by workshops are automatically calculated based on the sheet repair works' scope.

On the other hand the equipment's' and defects' databases are interfaced with the Supplier /Manufacturer database, providing a making informed decision of supplier choosing when equipment and spare parts procurement.

Thus, in our opinion, the shortcoming of the Operator's risk management system is the usage of expert method for assessing the risk probability and consequences. The shortcoming of the risk management system in M&R process is that the analytical relationship between the M&R process KPIs and risk assessment has not been investigated. Consequently, the manageability of risks through M&R process KPIs and risk management measures has not been proven. Therefore the authors' further research is to define the analytical relationship between risk manageability, KPIs and the result rating of risk management measures in order to improve the M&R process.

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