Risk Management Plan at Steam Generator Maintenance of Nuclear Power Plant

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To ensure safety of technical installations, it is necessary to keep all fittings, components, systems and their interfaces in certain conditions. These items maintenance is, therefore, very important. It is a set of activities which keep to ensure that their working conditions are maintained or, in the event of a failure, these conditions are quickly restored. The paper concentrate attention to maintenance of critical component of each nuclear power plant, namely the steam generator. It shows: critical items of steam generator in the Temelin nuclear power plant; risk sources; experience from existing operation; and risk management plan for risk-based maintenance.

Keywords: Maintenance, steam generator, risk, operational safety, monitoring the critical points, proactive maintenance, a maintenance risk management plan.

1. Introduction

Nuclear power plants are critical installations, on one side they are stable and reliable sources of electric energy, and on the other side they have a great potential to threaten themselves and their surroundings. Therefore, their safety is on the first place. From this reason, their organizational processes include: design and construction, construction, operation, and maintenance. These processes are built into three interlinked activities: setting objectives within the economic and social situation of these installations; organization of the installation to meet the set long-term strategic goals; and management of operational activities.

The results of the research summarized in the work (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019) show that the causes of many accidents and failures of technical installations is insufficient maintenance, and therefore, we focus attention to this process in the Temelin nuclear power plant. Generally, maintenance of technical fittings is a set of activities which keep to ensure that their working conditions are maintained or, in the event of a failure, these conditions are quickly restored. In simple terms, the maintenance process can be divided into four areas: supervision; inspection; maintenance; and improvements. Maintenance of technical fittings ensures: extension and optimal use of the service life of the equipment; improving the operational safety; increasing the readiness of the fittings to perform the required function; optimization of operating regulations; reduction in the number of breakdowns; and the ability to plan the cost of operating the equipment. The maintenance of each technical fittings depends on both, the technical design and function of the fittings and on the conditions in which the fittings in question operate. The subject of the article is to draw up a plan for risk management in the maintenance of the WWER 1000 type steam generator.

In order for the maintenance of the steam generator to be safe and economical, the maintenance process needs to be based on risk management in favor of safety. For this reason, we have identified critical points of the steam generator and phenomena (external, internal, human factor and organizational errors) that could disrupt the steam generator function. We have created scenarios of their impacts on the process of steam generator function for normal, abnormal and critical conditions, especially at critical points. Based on our knowledge and practical experience, we formulated specific countermeasures that we discussed with experts to avoid possible conflict situations. The result is a risk management plan that is site-specific.

2. Summary Knowledge on Maintenance

The relationship between maintenance and safety of technical installations can be traced based on the logic that failures, incidents, and accidents of monitored technical installations are the result of disruptions of their safety. The results of the research (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019) based on the evaluation of the above data show that one of the basic internal causes of accidents and failures of technical installations or their technical fittings or components, which occur in all types of technical installations and technical fittings, is maintenance (around 63%); in some cases, it is even a key cause. Specific analyses of accidents and failures of technical installations and technical fittings revealed facts such as: maintenance not carried out; poorly performed maintenance; inadequate maintenance; poor maintenance procedure; poor maintenance schedule; insufficiently qualified maintenance personnel; inadequate preventive maintenance; there is no maintenance and repair mode, i.e. quality maintenance and timely repairs of buildings, machines and other equipment are not carried out with regard to the aging of materials, large wear and tear caused by performance requirements or variable environmental conditions, etc.

Knowledge gathered in the scientific literature and practical experience show that neglected or incorrectly performed maintenance leads to an increase in the vulnerability of the tracked item, and in practice there is a more frequent failure of the item. Each item is decided by human, and therefore, it is necessary to consider the knowledge in question. It is understandable that, given the resources available, maintenance must be optimal from a financial point of view. Therefore, according to (Briš, Soares, Martorell 2009), it is necessary to create a representative set of possible maintenance scenarios, to determine and evaluate the impacts of their risks with regard to the quality of the operation, and then to select a high-quality, i.e. transparent, repeatable and correct method of optimal maintenance scenario from the technical and financial point of view. In doing so, it is important to consider the safety, durability and reliability of the equipment. Since these are not static problems for operations and organizations, but dynamic problems, it is advisable to perform safety management, which includes maintenance issues, using indicators that consider changes over time. Every operation / each organization is unique, so maintenance indicators need to be tailored to it. There is a general logical procedure for their compilation and use, but the use in specific practice must consider local specificities, which is always true in the context of risks (Procházková 2018).

Cost-effective and fecund maintenance of an installation or its business assets is absolutely essential for maximum profitability and long-term survival of the company, business or infrastructure. Documentation and inspections, including the regular audits, especially external audits, are required to assess the level of maintenance. According to American models, the safety of the functions of a business or installation ensures availability (accessibility) and requires the application of the concept of integral safety including the reliability and sustainability. According to the work (Ale, Papazoglou, Zio 2010), in cases where there is little ability of the operator to reduce or mitigate risks, more frequent sophisticated maintenance activities and more frequent sophisticated inspections should be ensured. According to the work (Sobral, Ferreira 2010), the inspection data should be approximated by a suitable mathematical model that best suits, using the following supporting data: linear model; exponential model; power model; logarithmic model; Gompertz model; and the Lloyd-Lipow model. The result is a degradation curve that determines the time it takes to perform maintenance or inspection, so that the probabilities of component and system failures are acceptable.

According to the work (Campbell 2008), reliability measurements in maintenance and measurements of operator performance in the maintenance sector are characterized by the effectiveness of maintenance management, the main criteria are: reliability; availability; maintainability; resource efficiency; and the percentage of unplanned activities. The number of communications devoted to maintenance in the documents (Moubray 1997, Virolainen, Aven 2012) shows that experts are increasingly aware that maintenance has been neglected in recent years for financial reasons and that this has led to an increased incidence of failures and accidents of technical installations / fittings.

In the work (Garg, Deshmukh 2006) authors showed that optimization models for maintenance must cover 4 aspects, namely: a description of the technical system, its function and importance; modelling of system failure over time and possible consequences for the system; a description of the available system information and a description of the activities to support the management of the system; and objective functions and optimization techniques that help to find the best equilibrium conditions. According to the work (Ferreira, Cavalcante, Almeida 2010), this requires: structuring the decision-making problem; creating the table of impacts and consequences of failures; eliminating the dominant alternatives; and evaluating the exchange of inappropriate items.

The aim of the maintenance of equipment, components and systems of technical installation is to ensure the growing demands on the products or products they provide. Maintenance increases the service life of key components and the entire system. Certain procedures must be followed when carrying out maintenance and specific protective measures must be applied in cases where dangers such as the possibility of explosion or fire exist. Therefore, maintenance should be thoroughly planned and prepared according to: the operator's and maintenance instructions from the manufacturer; construction and design materials; the working procedure, the work equipment used, the particulars of the dangerous substances present; operational experience; the experience of operators and maintenance personnel; operating conditions and local conditions; operational alarm plans; the findings of the inspection of the post in question; the deployment of protective equipment (e.g. fire alarm sensors); possible sources of danger in the place and its surroundings, including the surrounding equipment.

Maintenance depends on system operation (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019). We usually divide it into reactive or unplanned and proactive or planned. In the first case, it is a correction of a device, component or system made after their failure. In the latter case, we distinguish preventive and prognostic maintenance. Preventive maintenance includes part replacements or maintenance based on aging. For critical items, prognostic maintenance based on the results of continuous monitoring shall be used.

In the professional literature summarized in the work (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019) it is possible to find information according to which the cost of maintenance of technical installations varies between 15-70% of production costs. Research on these practices has shown that maintenance strategy can be divided into: a corrective (corrective) strategy in which maintenance is carried out only after the failure of the equipment, which leads to large costs; a preventive strategy of carrying out regular maintenance of equipment from a certain age of the equipment, and then replacing the equipment, which can be costly; and a condition-based maintenance strategy in which maintenance is carried out based on the results of equipment condition monitoring, resulting in optimized maintenance costs. In addition, according to the practical experience presented in the literature, the condition-based maintenance (CBM) strategy leads to an increase in production, availability and safety of systems, as the number of equipment failures is reduced.

The results of the research collected in the work (Olde Keizer, Teunter 2015) show that in complex systems, to which technical installations belong, the fact is that CBM strategies are different for different components, and therefore, from the point of view of the whole system it is necessary to carry out some optimization. This means that, according to the criticality of the equipment, preventive and prognostic maintenance should be combined. Throughout the system, preventive component maintenance is carried out on the basis of periodic inspections and prognostic when critical conditions are achieved for a particular component; non-periodic inspections aimed at detecting critical component conditions are understandably more common in older components. Cited authors show that the average minimum cost of various types of maintenance are in interval 35.4 – 206.7 EURs; the greatest one is for maintenance after failure.

Based on the current knowledge summarized in (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019) of the correct maintenance strategy, and especially the maintenance regime, it belongs to the critical processes of the organization from the point of view of the production plan. Since maintenance means interruption of production, for example, the maintenance of equipment that operates only on weekdays is carried out on weekends. Since this is not possible with continuous operation, the so-called selective maintenance problem is solved. Selective maintenance is focused on critical/priority equipment and in such a way that the total cost of maintenance is minimal. When planning it, questions are used: Will the production targets be met in a given time interval?; What result will maintenance bring for operation?; How will maintenance contribute to the overall production process?; How will the production performance trend affect?; and What actions should be taken against phenomena that are key causes of disruption in production performance?

According to the work (Börcsök 2003), periodic maintenance is necessary for all systems that are associated with safety. For example, in rail transport, the directive (IEEE2006) requires that an acceptable level of safety be maintained by changing critical railway processes and maintenance programs at the acceptable operating and maintenance costs of operator. It states that for the process safety management, there are important data on: reliability (distribution of component failures, types of component failures, backups, traffic profile); maintenance (repair and replacement policy, repair time, corrective maintenance, preventive maintenance, inspection); logistic data (replacement parts, delivery times of refunds, time for ensuring delivery); and financial data (cost of replacement parts, penalties in case of non-fulfillment of supplies, corrective maintenance, preventive maintenance, inspections).

Analysis of current knowledge accidents and failures of technical installations / technical equipment and data on maintenance show that routine maintenance mandated by regulations cannot guarantee the safety of the entities being monitored. Maintenance must be carried out according to the criticality of the entities. A number of examples from practice show that when we save and neglect maintenance, we replace components only when they fail (we are talking about the so-called "maintenance". FBM - Failure – Based - Maintenance), we expose ourselves to large costs or accidents with large impacts (Börcsök 2003). An alternative to this method is preventive maintenance, in which after a certain period of time (determined according to the aging strategy of the components) we replace entire component files when a failure occurs in one of the components. While this strategy helps prevent failures by reducing system downtime, it tends to be conservative, i.e. often replaces things that didn't need to be replaced. Therefore, we are currently dividing maintenance into: corrective; preventive; and prognostic (smart, smart).

Condition-based maintenance (CBM) refers to a strategy for forecasting (smart) maintenance. Its maintenance plan is driven by the result of monitoring the condition of the components. Maintenance shall be performed as soon as the monitoring of component condition shows that a certain threshold describing the condition of the component (i.e. a certain criticality) has been exceeded. It is based on non-periodic inspections and is cost-effective (new).

In practice, it is necessary to link the maintenance strategy and the production strategy that feeds the operator of technical installation. Introducing manufacturer's requirements into a maintenance strategy is not always easy, which is why theoretical models of optimized maintenance are not used in practice. Therefore, the maintenance plan and the method of its implementation are among the critical items of the operator of the technical installation. The plan in question must be coherent with the availability of resources with the required reliability and performance (Procházková 2017).

3. Risk and Safety of Technical Installations

Risk is the degree of probable losses and damages to the monitored assets in the event of a harmful phenomenon, which in terms of comparability, is normed per unit of time and unit of space (Procházková 2018). It represents the degree of safety disruption of the monitored element in the event of a possible harmful phenomenon. Since the research of technical installations (Procházková 2017, Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019) showed that incidents, accidents, as well as failures of technical installations occur in about 80% when combining the harmful phenomena, it is necessary to monitor not only partial risks but also the integral risk. Therefore, the integral safety is associated with the management not only of large partial risks posed by beyond design natural disasters, but above all with the management of integral risk.

In above considered concept, safety is understood as a system-level property that is shaped by a human's measures and actions and can only be ensured by high-quality anthropogenic management. Integral safety respects the systemic understanding the monitored element and changes in time and space. It is based on a systemic, proactive and strategically targeted approach. It is understood as an emergent property of an element, on which the existence of an element depends; i.e. it is the most hierarchically determining property of an element. It is a set of measures and activities that, considering the nature of the critical element understood as a system of systems and all possible risks and threats, aim to ensure the functioning the elements, links and flows of critical infrastructure, so that under no circumstances do they fail to endanger themselves or their surroundings. Risk and safety are not complementary quantities, since the safety of each entity can be increased through organizational measures, e.g. by introducing the warning systems and backup solutions, without reducing the risk size; an additional concept to safety is criticality.

4. Data and Methods used at Research

NPP Temelin is a power plant with two WWER-1000 pressure water blocks, model 320 located not far from the Vltava River in the Southern Bohemia (CEZ 1998).

4.1. Data on Temelin Steam Generator

The steam generator (*further* SG*)* is a critical device in a nuclear power plant because its flawless operation ensures the safety of the entire nuclear power plant (ČEZ 1998). It physically separates the primary radioactive circuit from the secondary non-radioactive circuit. It provides the process of cooling water from the primary circuit, which has a high temperature and high pressure - 320 °C, 16 MPa (Cencinger 2008). It is a horizontal heat exchanger with a large heat transfer area, formed by a bundle of "U" pipes, which converts the heat generated in the nuclear reactor into the feed water and steam of the secondary circuit. The temperature and pressure conditions in the SG are set so that intensive steam development occurs on the surface of the pipes, further needed to drive the turbo-generators.

The SG critical components are: hot primary water inlet equipment; equipment for the outlet of cooled primary water back into the primary circuit; pressure vessel of the steam generator; steam separators; equipment for spraying the secondary cooling water on pipes with warm primary water; pipes with primary water; equipment for the removal of saturated steam to the turbine. The scheme of main parts is in Figure 1.

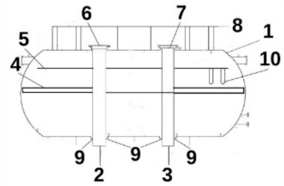

Fig. 1. SG scheme: 1- pressure vessel – SG envelope; 2- refrigerant input from the hot branch of the circulation loop; 3- refrigerant output to the cold branch of the circulation loop; 4- U-pipes a heat transfer surface; 5- feedwater distribution pipes; 6- secondary collector cover; 7- primary collector cover; 8- steam collector – steam output to the turbine; 9- permanent sludge blow-off; 10- outputs from sensors to the block control room.

The nuclear power plant project itself contains the requirements for the maintenance of the steam generator, i.e. the schedule of activities and the methods of their implementation for individual components and their interconnection (Kusín 2008). On the basis of this document, maintenance plans are drawn up, which are implemented since the commissioning into permanent operation. However, during operation, local conditions, such as the aggressiveness of cooling water with chloride levels or changes in the surrounding environment have been impacts, and it has been shown that some critical elements wear out faster than the project anticipated (ČEZ 2015a). Therefore, the entire process of the steam generator function was subjected to a risk analysis, and the critical points of the process that need to be monitored and ensured for timely maintenance, i.e. to set up a risk-based maintenance process, were identified.

4.2. Experiences from Past Operation of Steam Generator

The SG maintenance is carried out according to the maintenance timetable. This timetable contains preventive maintenance activities that are set up according to the manufacturer's recommendations and has the task of preventing the accidental maintenance, and thus ensuring the trouble-free performance of the function of the component throughout the campaign, or throughout the set maintenance period. In the course of its operation to date, this template has been modified several times based on operational experience and inspections, which are included in the evaluation of component aging (ČEZ 2015a,b, Kusín 2008).

Evaluation of component ageing consists in a continuous periodic evaluation of the impact of degradation mechanisms depending on the mode of operation and operating conditions. It is carried out in order to know the physical condition of the installation in terms of ageing and to make sure that safety margins are not drawn during operation, or to know the rate of absorption of safety margins in certain specific operating conditions (ČEZ 2015b).Article (Vidlak, Prochazkova 2021) shows that remedy of some defects is not one-shot action; it has two phases: in the first one, the fast remedy is done; and in the other final remedy is done after integral risk judgement of this solution.

4.3. Methods Used at Risk-Based Maintenance

With aim to perform the SG maintenance safely, fast, with acceptable expenses and with the acceptable limitation of maintenance duration and harms on environment, we manage both types of risks, the big ones connected with maintenance works and the integral one. For decision-making on: partial risks we use limits given in legislation; and integral risks we use decision support system (DSS) in the form of a checklist (Procházková 2018) supplemented by a rule for evaluating questions in terms of (Keeney, Raiffa 1993) and assigning a logical value scale according to(Procházková, Procházka, Lukavský, Beran, Šindlerová 2019). For fast and clear maintenance process we use the process model methodology (Krogstie, Sindre, Jorgensen 2006) and for ensuring the safe process of maintenance we use the risk management plan, which is based on the TQM management method (Zairi 1991). The last mentioned tool ensures the SG integral safety during operation.

5. Sources of Risks and Tools Used for Trade-off with Risks

The maintenance process includes not only the processes associated with the required maintenance operation itself, but also includes other requirements resulting from the maintenance quality requirement. One of the requirements is to provide spare parts in the required quality and in the prescribed level of quality. This requirement applies not only to replaceable parts, but also to additional materials used in welding. We must also not neglect the requirements for the personnel carrying out the maintenance. Such personnel must not only have fulfilled the prescribed qualify-cations, but must also have the prescribed professional experience in the type of maintenance in question. Another important factor for evaluating the condition of a component/system is also the comparison of maintenance results with maintenance results from previous years and in the continuous periodic evaluation of the impact of degradation mechanisms depending on the mode of operation, operating conditions. This evaluation is carried out in order to know the physical condition of the installation in terms of ageing and to make sure that safety margins are not drawn during operation, or to know the rate of absorption of safety margins in certain specific operating conditions (ČEZ 2015 a,b, Kusín 2008).

With regard to results for technical facilities (Procházková, Procházka, Lukavský, Beran, Šindlerová 2019, Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019), data in (ČEZ 2015a,b, Kusín 2008) and experiences from recent operation (Vidlák 2022), we determine the risk sources: errors in maintenance management (sources of organizing accidents); human errors; technical personnel conditions; technical defects of: pressure vessel – SG envelope, refrigerant input from the hot branch of the circulation loop, refrigerant output to the cold branch of the circulation loop, U-pipes a heat transfer surface, feedwater distribution pipes, secondary collector cover, primary collector cover, steam collector – steam output to the turbine, permanent sludge sleeves, and outputs from sensors to block control room; internal or external disasters; insider; and terrorist attack; details in (Vidlák 2022).

The work (Vidlák 2022) contains both, the complete DSS for integral risk of maintenance process determination including the procedure for its use, and the process model for SG maintenance process, which was tested by expert panel (maintenance and operation managers) and has two steps: checking and restoration if necessary.

6. Risk management Plan for Maintenance

The management structure of SG maintenance in Temelin NPP (ČEZ ETE 2022) is: SG maintenance manager; mechanical manager + electrical manager; each of managers in second level has 4 managers: manager for supply of fittings, parts etc.; manager for maintenance inspection; manager for maintenance quality assessment; and manager responsible for real maintenance work personnel; last level is level of critical personnel, the role of which is not followed in detail in this article. This structure is in harmony with ISO

9000 and EU requirements (Delongu 2016). The NPP has for risks mitigation at maintenance process following tools: internal operating rules - IOPs; maintenance and restoration rules - MRRs; emergency operating procedures - EOPs; and organizational rules – OR (ČEZ ETE 2022).

For fast response to expected emerged risks at maintenance process, we use risk management plan constructed according to generic risk management plan in (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019). Complete plan, tested by expert panel (operation managers and nuclear inspection engineers) is in (Vidlák 2022); its example is in Table 1.

Table 1. Risk management plan for SG maintenance process; EOPs - emergency operating procedures; IOPs - internal operating procedures; MRR - maintenance and restoration rules; OR - organizational rules

Risk source	Description of risk	Occurrence probability Size of impacts	Measures for risk mitigation
Coordination problems between mechanical and electrical managers	Disruption of maintenance process safety	Probability: low Impacts: middle	*Measures:* appurtenant OR0+IOPs Execute: SG manager Responsibility: NPP director
……..			
Human errors at real maintenance works	Disruption of maintenance process safety	Probability: low Impacts: great	Measures: appurtenant IOPs + OR Execute: manager responsible for real maintenance work personnel Responsibility: according to authority either mechanical manager or electrical manager
Failure of pressure vessel	Disruption of maintenance process safety	Probability: low Impacts: great	Measures: appurtenant MRR + EOPs Execute: manager responsible for real maintenance work personnel Responsibility: mechanical manager
……			
Failure of sensors OR outputs from sensors to the block control room	Disruption of maintenance process safety	Probability: low Impacts: great	Measures: appurtenant MRR + EOPs Execute: manager responsible for real maintenance work personnel Responsibility: electrical manager
External / Internal disaster	Disruption of maintenance process safety	Probability: low Impacts: great	Measures: NPP EOPs Execute: SG manager Responsibility: NPP director
………			

Based on risk management plan for maintenance based on risk assessment the obligation: to pay more attention at maintenance to all sources of risks that are more than low likely and prognostic maintenance for refrigerant input from the hot branch of the circulation loop and refrigerant output to the cold branch of the circulation loop has been put into practice, In order to avoid the accumulation of several sources of risks, the SG manager is obliged to control the level of integral risk determined according to DSS (Vidlák 2022) after each internal or external unacceptable event that affected SG. Each Manager from the 3rd level process maintenance management continuously monitors the overall condition of the operated equipment and also once a year submits to the SG manager a comprehensive overview of condition and performance of the equipment with regard to the history of operation.

7. Conclusion

Because in the real world every element or component or every interconnection of elements or components ages with time, their vulnerabilities increase over time (Procházková 2018). This means that their conditions gradually approach their design limits either due to their ageing or as a result of the occurrence of a sudden unacceptable external event, which affect their dependability.

Therefore, the introduction of systematic monitoring the both risk sources, the critical partial risks and the integral risk at SG has increased integral safety of cooling process. In practice, they are introduced: a maintenance schedule in which systematic attention is paid to the sources of risks that can disrupt the SG operability; and prognostic maintenance for refrigerant input from the hot branch of the circulation loop and refrigerant output to the cold branch of the circulation loop . Introducing the risk management plan increases the maintenance quality; it removes e.g. conflicts at ensuring the spare parts quality.

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