Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

doi: 10.3850/978-981-18-8071-1_P069-cd

Methodology of Compiling A Steam Generator Maintenance Plan

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The steam generator in nuclear power plant is designed in such a way that it physically separates the primary circuit that contains radioactive substances from the secondary circuit, which no longer contains them. The steam generator is a category 1 device, and therefore it is required to minimize breakdowns. Therefore, a device care strategy is chosen that ensures high reliability, i.e. minimizes the occurrence of failures and does not tolerate functional failures between established maintenance cycles. For economic reasons, the preventive maintenance program is controlled by the maintenance of the items that contribute most to the failure of the steam generator. In the paper, we show procedure by which we prepared steam generator maintenance plan for proactive preventive maintenance.

Keywords: Maintenance, steam generator, risk, operational safety; monitoring the critical points, proactive preventive maintenance, maintenance program.

1. Introduction

In order to ensure the safety of a nuclear power plant (*further NPP*), it is necessary to maintain under all conditions the limits that were set in the design for elements, components, systems and their interfaces. In the presented paper, we focus on the critical equipment of the NPP, namely the steam generator (*further SG*). The SG is designed in such a way that it physically separates the primary circuit that contains radioactive substances from the secondary circuit, which no longer contains them. Its task is to ensure that the reactor operates within the permissible range of temperatures and pressures by means of controlled cooling the water of the primary circuit, which has a high temperature and high pressure.

In the WWER 1000 type reactor at the Temelin NPP, the steam generator is a horizontal heat exchanger with a large heat transfer area consisting of a bundle of "U" pipes and is designed for maximum temperature values of 320°C and pressure of 16 MPa. The device conducts heat generated in the nuclear reactor into feedwater and steam in the secondary circuit. Temperature and pressure conditions in the SG are set in such a way that intensive SG occurs on the surface of the pipes, which flows through the steam collector and steam pipes to the turbine, where it serves to drive the turbo-generator.

The basic component of the SG consists of a pressure vessel, which has a number of accessories. In order to maintain optimal performance of the entire system, it is necessary to perform high-quality maintenance of individual system devices and their interconnections according to the size of the risks. The most vulnerable are accessories – fittings, pipes, seals, welds, etc. (ETE 2022). In the NPP design, the designer set maintenance plans for both, the pressure vessel and its accessories. However, the operation at the Temelin NPP has shown that due to local conditions and new knowledge about the operation of heat exchangers in the world, these plans are outdated. Therefore, the maintenance program is gradually modernized in order to minimize the failure of the entire facility in an economical way.

The SG is a category 1 device, and therefore it is required to minimize breakdowns. Therefore, a device care strategy is chosen that ensures high reliability, i.e. minimizes the occurrence of failures and does not tolerate functional failures between established maintenance cycles. The maintenance program is based on the principle of a tiered approach to equipment (ETE 2022). The basic requirement for the implementation of an effective preventive maintenance strategy is knowledge of the condition and performance of the operated equipment. Based on the knowledge of these parameters, the maintenance program is optimized to achieve the required level of safety, performance and reliability.

The proactive preventive maintenance program is based on data on: the design of the SG; the importance of the SG for the NPP safety; the importance of the SG for power generation; and operational experience. The methodology of compiling a new SG maintenance program is based on the concept of proactive preventive maintenance for specific items. The conditions of the items are assessed by a five-step scale: very good condition; good condition; acceptable condition; poor condition; and critical condition. Using a checklist, the sources of risk for each item are assessed and their frequencies are evaluated according to the data in the design and in the operation logs; the size of the impacts; and the average time when a defined condition is reached, which is the latest time maintenance is required. Decision Support System is used to determine the contributions of the failure of individual items to the total risk caused by the failure of the steam generator. For economic reasons, the maintenance program is controlled by the maintenance of the items that contribute most to the failure of the SG.

2. Summary of Knowledge on Maintenance in Nuclear Facilities

As early as 1980s various deficiencies and defects have been discovered to complicate design and operational decisions, owing to the unknown, unclear, or missing design information that become visible during the operation, must of the time latently. The implementation, effectiveness and adequacy of maintaining and retaining facility design information got adversely affected due to this loss or omission of design information. Some of those adverse impacts perpetuated from inadequate processes that are in the control of the owner/operating organizations (e.g. their programs, procedures, culture and resources) while some, such as interruption of external vendor relations, did not (IAEA 2023).

From safety reasons, the role of maintenance steadily increases as shown publications (IAEA 1992, 1997, 2000, 2003, 2005, 2018, 2022, 2023). In nuclear facilities, it is used the maintenance types (IAEA 2022): periodic; preventive; and predictive. Form of preventive maintenance consisting of servicing, parts replacement, surveillance or testing at predetermined intervals of calendar time, operating time or number of cycles. Actions that detect, preclude or mitigate degradation of a functional structure, system or component to sustain or extend its useful life by controlling degradation and failures to an acceptable level.

Preventive maintenance may be periodic maintenance, planned maintenance or predictive maintenance. Form of preventive maintenance performed continuously or at intervals governed by observed condition to monitor, diagnose or trend condition indicators of a structure, system or component; results indicate present and future functional ability or the nature of and schedule for planned maintenance. Maintenance challenges can be divided into four areas, namely: maintenance management; human resources management; plant condition assessment; and business environment. The function of plant maintenance is to preserve and restore the inherent safety, reliability and availability of plant structures, systems and components for reliable and safe operation.

Maintenance in NPPs has specific characteristics that put demands on the way maintenance activities are organized and carried out. These characteristics contribute to the possibility of severe consequences, technical complexity and delayed effects of maintenance. It means that NPP management system also includes the activities of: maintenance; testing; surveillance; and inspection (IAEA 2022). I.e., the management system contains: data on level of detail of procedures for maintenance, testing, surveillance and inspection; types of equipment that need calibration, supervision, and maintenance; criteria and authority to which irregularities are reported; format of records and documentation; devices included in the control of the NPP configuration; checks for backups; analyze of condition monitoring over time; need to perform condition monitoring; and operational feedback. All mentioned activities must be performed by qualified personnel.

Maintenance work planning must respect: permit of work sequences; permit for device isolation; permits for work in radioactive environments; non-radiation safety; exclusion of foreign materials; drainage equipment; ventilation; protection against internal and external threats; equipment for insulation of mechanical and electrical parts; and managing the NPP modifications. It is important coordination of work between individual maintenance teams – mechanical parts; electrical parts; parts of the control system; and civic facilities. It is recommended to use checklist so that nothing is forgotten. It means that maintenance program shall include: definition of roles and responsibilities; understanding the exclusion of foreign objects and chemicals; naming all components and systems; define workflows; coordination of work; and documentation. This program includes all preventive and corrective measures to maintain the design functions of structures, systems and components at an acceptable level. Maintenance activities include adjustment, overhaul, repair and relocation of parts. They may also include testing, calibration and in-service inspections.

Optimal maintenance helps ensure that tasks are being performed with the right equipment at the right time. Maintenance optimization is driven by the imbalance between maintenance requirements and resources used, and it is improved by lessons learned.

Optimization of the maintenance program is vital to asset management (IAEA 2018). Its typical goals are. safety; reliability; cost optimization; availability; and technology enhancement. Optimization tools and methods should be selected and assessed on equipment criticality and maintenance costs. Typical assessments focus on five major areas of the maintenance process: work identification; work control; work execution; work closeout; and overall maintenance program. In harmony with (IAEA 2018) it is in practice (Prochazkova 2015, Prochazkova et al. 2019) used the scale shown in Table 1 for classification of condition of investigated items.

Table 1. Scale of levels and risk rates of item condition.

Item condition /risk rate	Conclusion of the item evaluation
1 very good ⬇ risk rate is low	The item is in perfect physical condition and performs the intended functions. Maintenance costs are in accordance with standards and norms. The item is new or has been recently renewed. Demands on the item operation correspond to the design. None , operational problems of item. All the program is implemented efficiently.
2 good ⬇ risk rate is medium	The item is physically in good condition and performs the intended functions. The cost of maintaining technical equipment is in accordance with standards and norms, but increasing. The item is about halfway through its service life. The demands on the operation of the item correspond to the design, the operational problems of the item equipment are only occasional. All program is fulfilled acceptably.
3 satisfactory ⬇ risk rate is high	The item shows signs of wear and lower performance than intended. Some parts of the item are inadequate. The cost of maintaining the item exceeds the amounts established by the standards and norms and is increasing. The item has been used for a long time or has worked in adverse conditions and is, therefore, in the last phase of its service life. Demands on the operation of item correspond to the design, operational problems of item are frequent. The entire program is mostly fulfilled, but inefficient and inefficient methods of implementation are emerging.
4 bad ⬇ risk rate is very high	The item shows significant signs of wear and performs the intended functions at a low level. Many parts of the item are inadequate. The cost of maintaining the item significantly exceeds the amounts from standards and norms. The item is approaching the end of its service life. The demands on the operation of the item exceed the data in the design, the operational problems of the item are obvious. The entire program is fulfilled only to a very limited extent.
5 critical ⬇ risk rate is extreme	The item is in poor condition and does not work as it should. There is a high probability of its failure. The cost of maintaining the item is highly unacceptable compared to standards and norms, the reconstruction of item is not cost-effective. Replacement is required. The demands on the operation of item are significantly higher than the project ones; the operational problems of the item are serious and permanent. The established program is not fulfilled.

3. Concept of Proactive Preventive Maintenance in NPP

To ensure safety and long-term operation of any technical facility, it is necessary to manage risks of all kinds (Prochazkova et al. 2019). To achieve the goal of safe, economic and reliable operation, plant life management program is essential to identify all requirements for the overall life cycle of a nuclear power plant. Such effective program ensures that NPPs integrate their operations, maintenance, engineering, regulatory, environmental and economic planning activities to manage the material condition of a plant to ensure safe long-term operation.

The organization operating a NPP is responsible for its safety. As well as both internal and external self-assessments, an independent regulatory body provides oversight through inspection activities and enforcement action where necessary. The IAEA's safety standards, developed on the basis of international consensus, address all aspects of safety in the operation of NPPs and regulatory activities. They include requirements for the management of safety and the organizational and technical aspects of safety during the life cycle of NPPs. They include implementing guides for all major types of facilities, namely maintenance (IAEA 1992, 1997, 2000, 2003, 2005, 2018, 2022, 2023).

Maintenance includes preventive and corrective measures that ensure structures, systems and components are able to perform their design functions. Typical activities include overhaul, repair and replacement of system components and may be enhanced by testing, calibration and in-service inspections (Prochazkova et al. 2019, Vidlak, Prochazkova 2022).

Preventative maintenance is regularly performed on equipment to reduce the likelihood of failure. The maintenance is performed while the equipment is functional to prevent breakdowns, repairs, or replacement. Preventative maintenance is a program to establish maintenance on a schedule based on dates or usage usually at the manufacturer's recommendation. Effective preventive maintenance programs allow organizations to demonstrate improvements in overall business costs and business processes. These can include boosted productivity, less waste, better execution, and a decrease in equipment breakdowns. Preventative maintenance is a simple maintenance strategy to implement and execute. It begins by following manufacturer recommendations then create a maintenance schedule for critical equipment. Preventative maintenance will help the business avoid breakdowns and production loss as well as decreasing the actual cost of maintenance. A typical issue with preventive maintenance schedules is incomplete maintenance on assets. Successful preventive maintenance can prevent this by analyzing and optimizing their preventive maintenance program.

Predictive maintenance techniques (EPRI 1998, 2000, 2001) help determine the condition of equipment in order to estimate when maintenance should be scheduled and performed. Regular wear and tear without regular maintenance can cause lower machine efficiency. Preventive maintenance conserves the lifespan of equipment. Planned preventive maintenance can be scheduled to avoid hindrance for production to prevent downtime caused by equipment failure. Predictive maintenance ensures that equipment requiring maintenance is only brought down when maintenance is needed, usually before failure. This creates a reduction in the total time and cost spent maintaining equipment. Condition monitoring equipment needed for predictive maintenance can be costly. Skill level and technical experience needed to accurately interpret condition monitoring data is high. Condition monitoring may have a high upfront cost for organizations. Proper predictive maintenance strategies are cost-effective as maintenance is only performed on machines when it is required.

Mainly from economic reasons planning and scheduling is a critical part of the plant maintenance optimization. According to (EPRI 1998, 2000, 2001) optimization program must consider:

- Advanced Maintenance Strategies: These strategies address what maintenance approaches will be taken to move the maintenance program from reactive to planned. Such approaches include, optimizing the maintenance basis, implementing predictive maintenance program and developing a living proactive maintenance program.
- Work Process: This part of the optimization maintenance program process addresses the how maintenance is accomplished. It examines the work process from work initiation, to planning and scheduling, to work execution, to work completion and finally to continues improvement.
- People: Skills, Work Culture, Management: For maintenance optimization to be successful it requires a well-trained work force, good management and an

organizational structure. A work culture that is respective to new ideas. This aspect of optimization maintenance program approach focuses on who does the work.

- Tools/Technologies: This category of optimization maintenance program focuses on the tools required to support the staff.

Proactive maintenance (EPRI 2001) is a process of learning from past maintenance problems in order to reduce future maintenance work and improve equipment reliability. Root cause analysis is a formal method to determine the most basic reason for a problem and recommend effective corrective actions. Root cause analysis is a natural part of the proactive maintenance process. This guideline was developed in collaboration with several U.S. and European companies (EPRI 2001). Best practices at these companies were compiled together in this guideline.

Proactive maintenance is a daily process that complements the maintenance work process, and the predictive maintenance process. Three major steps in proactive maintenance are: review; analysis; and follow-up.

Proactive maintenance is both a task type, and a plant process (EPRI 2001), and therefore, maintenance tasks are also called project tasks. These are maintenance activities associated with equipment improvement or replacement, not just repair or refurbishment; process is both a daily process and a yearly process. Like other plant processes; it requires people, procedures, and commitment. On a daily basis work is reviewed, analyzed and implemented.

On a yearly basis work is summarized and long term factors are revisited. A proactive process can be more than maintenance, it can also involve operations, engineering, and management. Considering the three proactive steps: events can be defined and reviewed by maintenance or operations personnel; events can be analyzed by engineering, or management personnel; and recommendations can apply to maintenance, operations, engineering, or management personnel.

The facility equipment to be included in the scope of the plant maintenance program must be detailed and prioritized (IAEA 2005, 2007, 2018, EPRI 2000, 2001). This selection must be based on analysis of maintenance records of failures and maintenance requirements as well as other factors. It must consider: items with high maintenance costs; components which are most important to your business; critical and non-critical systems. Due to dynamic development, each maintenance must be a living program.

4. Data on Maintenance of SG in Temelin NPP

The SG in NPP Temelin was described in details in (Vidlak, Prochazkova 2021, 2022). Original maintenance program was done by manufacturer (ETE 1999). A special assessment of component ageing consists of continuous regular assessment of the influence of degradation mechanisms depending on the operating mode and operating conditions. It is carried out in order to determine the physical condition of the equipment in terms of aging and to ensure that safety margins are not drawn during the operation, or to know the degree of absorption of safety margins under certain specific operating conditions (ETE 2015).

On the grounds of experiences and new knowledge, since 2012 a preventive maintenance also uses EPRI guidance and forms; at present forms respecting the form (EPRI 2022).

Based on the above, at the steam generator, it is maintained 135 items (ETE 2023). The current item maintenance program distinguishes, whether item is: critical or otherwise; for normal or difficult conditions; for low or high duty cycles; and classified or other.

According to the classification, schedules are used for items: once per shift; once a day; once a week; once every 2 months; once every 4 months; once a year; once every 3 years; once every 4 years; once every 6 years; and one in 8 years.

Maintenance measures are carried out on the basis of:

- performance monitoring,
- visual checks by operating personnel,
- visual checks performed by systems´ engineer,
- results of non-destructive tests,
- internal inspections and cleaning or replenishment of lubricant or operating fluids,
- conclusions of the leakage tests at operating pressure,
- conclusions of the strength pressure test
- by refurbishment or replacement.

5. Methodology for SG Proactive Preventive Maintenance

To fulfil our aim that is transition from preventive maintenance to proactive preventive maintenance (EPRI 2001), which is more advance, we must more precisely manage with risks. It means to propose procedure for determination of risk rate of each item and measures for improvement of maintenance program, i.e. to perform risk-based maintenance, especially in cases of maintenance schedule, which is connected with exchange of nuclear fuel elements.

For classification of SG items conditions, we use approach given in Table 1. The real risk rate of each item we determine according to results of tests that are stipulated by (ETE 2023). In the first step, the real test risk rates are classified by the following procedure:

- test result does not fulfill the standard requirements - item condition is bad or critical and risk rate is very high or extreme
- and test result has maximum allowable deviation according to the standard requirements - item condition is acceptable and risk rate is high.

In the second step we judge the influence of real result deviation according to operational experiences in operation record (ETE 2022). For decision on risk, it is used the decision support system (Vidlak 2023), which considers:

- frequency of operation problems,
- size of impacts,
- cost of maintenance

and scale 1-3 (Vidlak 2023) with concept "the highest, the worse". If result of judgement is:

- lower than 3, the item condition is very good and risk rate low,
- between 3 and 6, the item condition is good and the risk rate medium,
- higher than 6 and the item condition is unacceptable and risk rate high.

In the last case at critical items in the frame of proactive approach, it is necessary to make corrections or to prepare measures for sharp condition change.

Because cause of item failure is often combination of small errors and each individual nondestructive test has capability to reveal only some partial sources of item risk (Prochazkova et al. 2019), we must also evaluate the risk rate for each item considering the results of all tests. For its determination we use Table 2. The whole scale for classification of conditions of SG items for proactive preventive maintenance for all 135 items is in (CVUT 2023, Vidlak 2023). Its example is in Table 3. If risk level in Table 3 is:

- lower than 25%, the item condition is very good,
- between 25 % and 45 %, the item condition is good,
- between 45 % and 70 %, the item condition is acceptable
- is higher than 70%, the item condition is bad.

Therefore, in case of critical items and in the frame of proactive approach, it is necessary to make corrections or to prepare measures for sharp condition change, especially at maintenance performed during the exchange of nuclear fuel elements.

Table 2. Value scale for determining the risk rate; $r = sr/N$, where sr is the sum of risk rates of individual tests and N is the total number of tests.

Risk rate	**Values** r *in* **%**
Very high	More than 70 %
High	45 - 70 %
Medium	25 – 45 %
Low	Low than 25 %

6. Proactive Preventive Maintenance for Program Steam Generator

The SG proactive preventive maintenance plan (Vidlak 2023) includes:

- list of all SG items and systems,
- procedures for judgement of items conditions according to method described in Table 3,
- definition of workflows,
- way of coordination of works,
- definition of responsibilities
- and documentation.

For SG maintenance plan, namely daily, yearly and at outages is responsible SG manager (Vidlak 2023). The SG manager coordinates works of managers for mechanical, electrical and I &C parts (Vidlak, Prochazkova 2022).

Each partial manager has team of critical persons, who fulfil real works according to schedule (Vidlak 2023). They assess the critical items conditions (CVUT 2023, Vidlak 2023); examples are in Table 3. Each critical person ensures documentation in format determined by the (ETE 2023).

Table 3. Risk rate scale. L – low risk; M – medium risk; H – high risk, V – very high risk.

Item	Used tests	Description of damage	Risk rate scale for item based on all tests	Used standards (ETE 2023, CVUT 2023)
SG shell	* Visual testing * Ultrasonic testing * Magnetic testing * Pressure test * Leak testing	* Linear defects * Fractures * Corrosion * Mechanical Faults * Leaks * Deformation	L < 3.75; M = 3.75- 6.75; H = 6.75- 10.5; V > 10.5	4-JL-000451, ČSN EN 13927, PK 1514-72, ČSN EN ISO 17640, ČSN EN ISO 3059, ČSN EN ISO 9934-1, ČSN EN ISO 9934-2, ČSN 69 0012
Heat exchange tubes	* Visual testing * Eddy current testing * Pressure test * Leak testing	* Fractures * Corrosion * Mechanical faults * Leak * Deformation	L < 3; M = 3 – 5.4; H = 5.4 – 8.4; V > 8.4	4-JL-000451, ČSN EN 13927, ČSN EN ISO 15549, ČSN 69 0012
Welded joints of sleeves to the SG shell	* Visual testing * Capillary test	* Linear defects * Fractures * Corrosion	L < 1.5; M = 1.5 -2.7; H = 2.7 – 4.2; V > 4.2	4-JL-000451, ČSN EN 13927, PK 1514-72, ČSN EN ISO 3059, ČSN EN ISO 3452-1, ČSN EN ISO 3452-2
Heterogeneous weld joints of feed water distribution inside SG	* Visual testing * Capillary test * Ultrasonic testing	* Corrosion * Fractures * Linear defects	L < 2.2; M = 2.25 - 4.05; H = 4.05 - 6.3; V > 6.3	4-JL-000451, ČSN EN 13927, PK 1514-72, ČSN EN ISO 3059, ČSN EN ISO 3452-1, ČSN EN ISO 3452-2, ČSN EN ISO 17640
Feedwater pipeline route	* Visual testing * Capillary test * Ultrasonic testing - Phased Array	* Corrosion * Fractures * Linear defects	L < 2.2; M = 2.25 - 4.05; H = 4.05 - 6.3; V > 6.3	4-JL-000451, ČSN EN 13927, PK 1514-72, ČSN EN ISO 3059, ČSN EN ISO 3452-1, ČSN EN ISO 3452-2, ČSN EN ISO 13588
Sensors, signal, sensor channel	* Visual testing * Input test * Authentication test * Calibration	* False values * Out of operation * Incorrect accuracy	L < 3; M = 3 – 5.4; H = 5.4 – 8.4; V > 8.4	4-JL-000451, TPVŽ 1000/80, MR001
Switchboard cabinets, switchboards	* Visual test * Insulation test	* Physical damage * Out of operation	L < 2.2; M = 2.25 - 4.05; H = 4.05 - 6.3; V > 6.3	4-JL-000451, TPVŽ 1000/80, MR001
……….				

If the critical item condition according to one test is assessed by level higher than 6, the SG manager and partial managers must forthwith apply suitable countermeasures.

If the risk rate of item on the basis of all tests is assessed as high or very high, the SG manager and partial managers increase attention and began to prepare solution, because repair is not simple in many cases. The article (Vidlak, Prochazkova 2021) shows that the correction of some defects is not a one-time action; it has usually two stages: in the first, a quick correction is carried out; and in the second, the final corrective solution is implemented after an integral risk assessment of this solution.

7. Conclusion

Based on the present knowledge summarized in (Prochazkova et al. 2019), we need resilient and economic performance of SG and the whole NPP. The proactive preventive maintenance we consider as very effective.

At present, NPP Temelin uses the preventive maintenance for SG. In the paper, it is shown procedure by which we prepared the SG maintenance plan for proactive preventive maintenance. Ground of method used is to judge risks of critical items by assessment of their conditions at main maintenance during the regular reactor outages by the way designated in Table 3; and to apply countermeasures so risk rates of critical parts of SG was acceptable.

The presentation of our strategy to nuclear power plant experts and to experts of Nuclear Regulatory Body obtained support. During the next reactor outage, we obtain possibility to compare finances demands of original and new maintenance strategy.

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