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The Regulatory Oversight of the Reactor Pressure Vessel Suitability for the Krško NPP Long Term Operation

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ABSTRACT

The reactor pressure vessel (RPV) is one of the most important nuclear power plant passive components. Normally, the RPV's design, material composition and the operating conditions determine its quality and suitability for long term operation (LTO) of the nuclear power plant. Based on the RPV embrittlement, the operating regime is determined. Therefore, during the plant operation particular attention should be paid to the RPV maintenance, testing and in-service inspections (ISI). Appropriate specific programs and related implementation procedures should be in place. Monitoring of operational experience, exchange of information in the context of international initiatives, and international independent reviews further contribute to the effective supervision of the RPV's condition.

The RPV issues related to the Krško NPP extended lifetime operation are discussed in the article with the emphasis on the Slovenian Nuclear Safety Administration (SNSA) regulatory activities.

1 INTRODUCTION

In March 2009, the Krško NPP submitted to the SNSA the application for Ageing Management Program (AMP) which was prepared for the Krško NPP LTO. The AMP is based on the requirements of the US NRC Generic Aging Lessons Learned (GALL) Report (NUREG-1801) and includes safety structure, systems, components (SSCs), non-safety SSCs which failure may prevent the function of the safety SSCs and the SSCs whose operation are assumed in the power plant safety analyses. The ageing management approach of the Krško NPP was confirmed and approved after an in-depth review and assessment process by the SNSA in June 2012. The approved AMP is one of the main prerequisites for the lifetime extension of the Krško NPP from 40 to 60 years of operation. After approval the Krško NPP had to make some changes of the AMP based on the evaluation of changes derived from the new revision of GALL [1].

Consistent implementation of the RPV monitoring activities together with comprehensive ageing management programme and consistent operation within the foreseen operating regime enable reliable determination of the current status as well as prediction of RPV's integrity during the LTO.

The Krško NPP has introduced and continues to implement several measures to mitigate or eliminate the effects of the RPV ageing mechanisms. The main measures are:

Decreasing the brittleness of the RPV material due to irradiation:

- fuel loading scheme with reduced neutron escape. In the Krško NPP the so called "low leakage loading pattern" of reactor core loading is implemented from the 5th nuclear fuel cycle onwards to preventively reduce the neutron flux on the RPV wall,
- regular implementation of the ageing management program,
- a control program with a system of dosimeters ("Ex-vessel Neutron Dosimetry").

Mechanical fatigue of the RPV:

- regular implementation of a program to monitor the growth of damage indications and record transient phenomena in different operating states of the power plant.

Stress corrosion on the primary side (Primary Water Stress Corrosion Cracking, PWSCC) in components containing the Inconel 600/82/182 alloy:

- providing a suitable chemical environment for primary water, including by addition of hydrogen,
- preventive replacement of the RPV head with a new one that does not contain an Inconel 600/82/182 alloy,
- protective coating on welds containing Inconel 600/82/182 alloy.

Additionally, several RPV's safety improvements have been made to extend the operational lifetime of the Krško NPP for additional 20 years. Introduction of the new ex-vessel dosimetry program for the RPV was one of the prerequisites for the AMP approval. Based on different experiences, such as primary water stress corrosion cracking (PWSCC), the Krško NPP addressed and successfully implemented large modifications, i.e., replacement of reactor pressure vessel head based on the experience from the Davis Besse NPP event (Figure 1) and structural weld overlays on the pressurizer. In parallel, some important modifications such as Up Flow Conversion in 2015 was performed to protect reactor core and RPV internals.

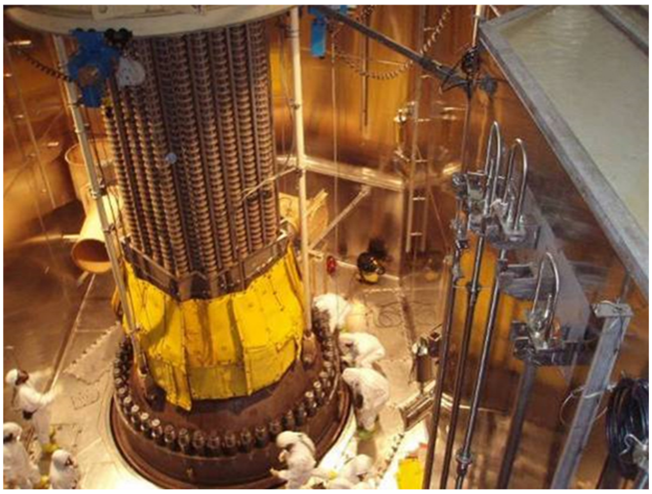


Figure 1: Installation of new RPV's head during outage 2012 at the Krško NPP

2 STATE OF PRACTICE

2.1 Reactor pressure vessel integrity monitoring activities

Basic requirements for ageing management, SSC's maintenance, testing and inspection, including corrective actions and reporting to the SNSA, are included into the Rules JV9 [2]. Methods and criteria for the selection of RPV elements to be monitored are specified in NUREG 1801 [1]. Monitoring activities include non-destructive examinations (ISI), monitoring of mechanical properties of base material and control of fatigue.

The Krško NPP is designed in accordance with ASME B&PV section III [3], Edition 1971, therefore ASME section XI [4] required by US NRC 10CFR50.55a(g) [5] is a basis for the implementation of ISI of RPV's components. The scope of ISI includes pressure boundary, vessel attachments, RPV's head and bottom with penetrations and reactor internals. Figure 2 shows the scope of RPV's pressure boundary welds to be periodically examined, as required by the Krško NPP programme TD-2E/4 [6].

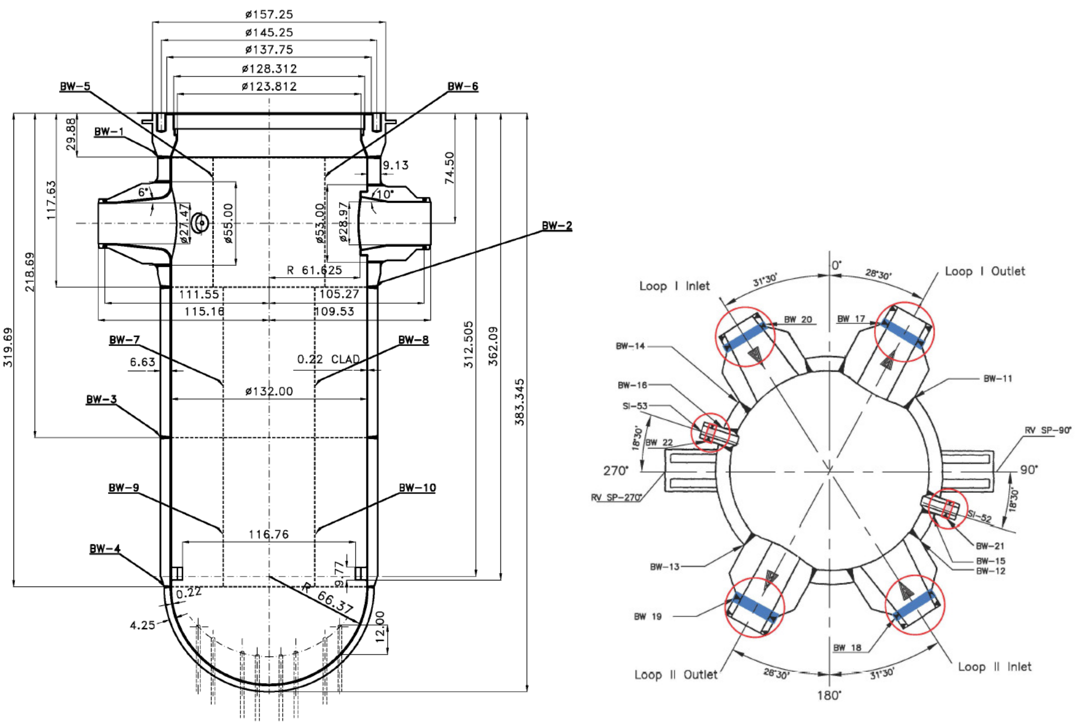


Figure 2: RPV pressure boundary welds

In addition to ISI strict monitoring of base material mechanical properties is required as described in US NRC 10CFR50, app. G and H [7, 8] and the Krško NPP Technical Specifications SR 3.4.9.1.2 [9]. This includes testing of irradiated specimens stored in the inner side of RPV wall as well as monitoring of neutron fluence by the system of ex-vessel neutron dosimeters (EVND) for verification of validity of limit pressure-temperature (p-T) curves until 60 year of operation. The program includes control of properties of six capsules attached to the thermal shield between the reactor core and the vessel. At the end of the Krško NPP cycle 25 in March 2012, the T capsule (penultimate capsule stored in the inner side of RPV wall) was extracted and analysed. Based on these results, safety of extended operation and the specified limit p-T curve, valid for 40 years (34.7 effective years of full power operation - EFPY) and for 60 years (52.2 EFPY) of normal operation, were confirmed and approved by SNSA.

The Krško NPP upgraded the program at the beginning of the operating cycle 25 with the EVND system. The system is designed to further verify the irradiance distribution of the fast neutron flux reactor vessel and allows long-term monitoring of the most restrictive areas. It consists of three sets of chain lets with capsules. After one installation cycle, the system was first extracted and analysed at the end of cycle 25. During the 2021 outage, the system was extracted again, the sample analysis is still ongoing.

2.1.1 Regulatory Oversight

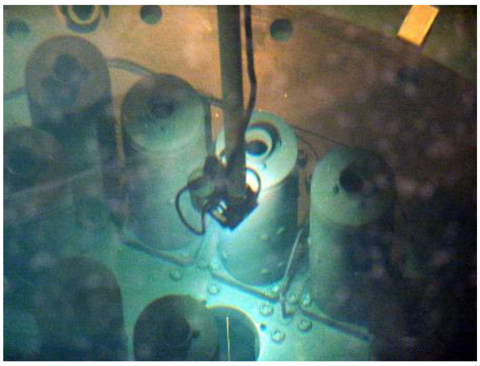
Variety of regulatory activities are in place at the SNSA for verification of integrity of the Krško NPP's RPV, suitability of operator's monitoring activities, implemented corrective actions and improvements. The most important of them are as follows:

- Regulatory inspection reviews,
- Reporting by the operator, required by the JV9 rules [2],
- Licensing process,
- The OPEX system (operational experience feedback),
- The system of SPI (safety performance indicators).

Systematic inspections on ageing management including status of important safety related SSCs are periodically performed. The SNSA inspectors together with experts from the SNSA licensing division review the scope and adequacy of operator's monitoring and preventive activities regarding legislation, standards, industrial practices and best international practice. They also review completeness and results of performed monitoring activities (ISI, fatigue, material properties) together with deviations and performed preventive/corrective actions.

The operator reports to the SNSA on implementation of AMP including performance of ISI activities on annual basis and after each refuelling outage. SNSA's in-detail review of submitted reports is a valuable input to facilitate above-described inspections. Relevant operational experiences and results of the SNSA's SPIs also serve as inputs for inspections.

During the refuelling outages the SNSA carries out continuous inspection supervision with support of other SNSA experts (subject matter experts) and Technical Support Organisations (TSOs). A special TSO is dedicated for supervision of performance of non-destructive examinations within the ISI programme, as required by ASME section XI. The TSO reports on results of their supervision to inspectors who are responsible for potential further actions. Figures 3 – 4 show some of specific non-destructive examinations of RPV components. All these activities are supervised by the SNSA's inspectors and TSOs.



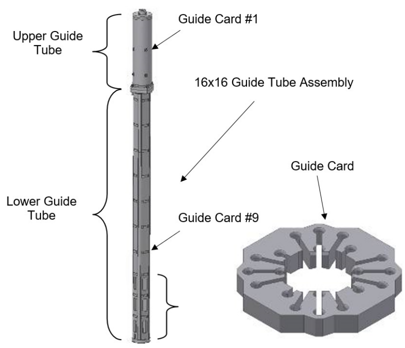


Figure 3: Visual inspection of control rods guide cards in upper reactor internals

Figure 4: Visual inspection of penetrations on the RPV bottom

Within the licensing process SNSA's experts review and approve all safety important design modifications, important changes of ISI programme and each deviation of the scope and methods of performed inspections. The most important implemented design modification regarding RPV was a replacement of the RPV's head during the 2012 outage based on the Davis-Besse experience. In addition to provide the necessary integrity during the extended service life, the modification also significantly reduces the required scope of ISI and thus the radiation exposure of staff. The SNSA also reviewed and approved the implementation of risk-informed ISI where PSA criteria were used to add additional locations into the scope of the ISI programme.

After the expiration of the fourth inspection interval (on 2022/07/22), the fifth ISI inspection interval (2022/07/23 to 2032/07/22) should begin in accordance with ASME Section XI. The Krško NPP will include in the scope of the ISI programme additional locations arising from the implementation of design modifications.

2.2 Control of RPV base material

Special periodic inspections of RPV's base material are not required by ASME or NUREG 1801, nor by any other regulation. Therefore, the Krško NPP operator does not perform this kind of systematic inspections of base material. Nevertheless, it was found that 20 % of the RPV's base material was inspected during the pre-service inspections and 10 % of base material during each periodic in-service inspection. None of the examinations performed identified any defects in the base material.

One of the issues of the base material of RPVs is a potential presence of hydrogen flakes that impair the strength of the RPV. These hydrogen flakes are in form of short and discontinuous internal fissures. Hydrogen flake formation phenomenon, which is driven by the accumulation of hydrogen, may occur after cooling down the steel from high temperature to ambient temperature. Their formation depends on a variety of factors, the most important are the hydrogen concentration and the size of the ingot, which determine the possible accumulation of hydrogen. Important factors are also a material microstructure and stresses in the metal during metallurgical process.

Hydrogen flaking was recently discovered in 2012 on RPVs in two Belgian nuclear power plant units. Western European Nuclear Regulators Association (WENRA) consequently issued new recommendations for integral inspections of RPVs and pertaining documentation in order to harmonize the activities connected with RPVs throughout Europe. In accordance with the WENRA recommendations the Krško NPP responded with the inspection of all the available and relevant documentation on the RPV's manufacturing procedure, notes about heat treatment and the results of the performed pre-service inspection. The Krško NPP concluded that the problem of the appearance of hydrogen flakes in the basic material of its RPV was not expected. However, the SNSA deemed important that the possibility of hydrogen flaking in the base material of RPV was further analysed, particularly in connection with the RPV ageing, before being completely excluded. In this respect, the SNSA required further actions to be carried out by the Krško NPP regarding the RPV base material inspections; these actions were included in the action plan of the first Topical Peer Review (TPR) on ageing management [10]. Apart from that, there were important inspection activities carried out during the 2021 outage and are also planned for the 2022 outage within the frame of the ageing management of the RPV that are directly related to the LTO of the Krško NPP after 2023. These comprise the integral inspection of the RPV, its head and internal parts. Further details are explained below in Section 3.

2.3 Fatigue of reactor pressure vessel material

An important cause of fatigue of the RPV is transients of the system and are generally manifested as temperature and pressure fluctuations. Such fluctuations pose additional loadings and induce variations in component stress levels. Therefore, the Rules JV9 [2] require that after each periodic outage the Krško NPP should submit a report about the design basis transients which occurred in the last fuel cycle. Design basis transients are specified in the Krško NPP Updated Safety Analysis Report (USAR) in accordance with NRC RG-1.70, in Technical Specifications and in specific analyses (i.e. analyses conducted after the change of both steam generators at the Krško NPP in 2000 [11]). Initially, a limited number of design basis transients was determined for design lifetime of 40 years. In order to extend the operation of the Krško NPP for additional 20 years, the Westinghouse performed analyses where binary extrapolation, considering past operation, showed that the stated limit values will not be reached even in the anticipated 60 years of operation.

According to the past operation regime in the Krško NPP, the most limiting transient value is the number of fast shutdowns (reactor trips) from full power. The allowed number of reactor trips with cooldown and no activation of safety injection (SI) is 160 [11]; up to now, the number of such transients is 66 [12]. The time-limited ageing analysis (TLAA) that was prepared for the approval of the ageing management showed that the anticipated number of such transients at the end of the LTO period would not exceed 100. This means that the transient limits will not be exceeded even after additional 20 years of operation, provided that the operational dynamics from recent years is continued. It should be noted that the transients in the Krško NPP were the most numerous in the first five years of reactor operation (1981-1985), but since than the number has gradually decreased. In the last 20 years, there was 1 year without transients, 12 years with one transient, 5 years with two transients and 2 years with three transients; the average number of transients in the last 10 years for the Krško NPP is 1.3/year.

3 OPERATING EXPERIENCES AND INTERNATIONAL ACTIVITIES RELATED TO THE RPV

International activities related to the RPV, i.e., the basic material manufacturing issue, ENSREG international review-Topical Peer Review (TPR) on the Ageing Management, are just some of the activities in the last decade where the Slovenian Nuclear Safety Administration has also played an active role.

In order to investigate any possible connections between potential hydrogen flaking and ageing of the RPV, the SNSA included this topic in the TPR action plan [10] in 2019 as an area for improvement. The Krško NPP actions within the TPR action plan were to follow the relevant operational experiences regarding non-destructive examination (NDE) in the base-material of beltline region in order to detect defects. In addition, the SNSA requested the Krško NPP to follow the current state of the art of the NDE in the base material of the RPV’s beltline region and to implement the improvements of the existing NDE based on feasibility studies of using such techniques. Accomplishment of these actions was checked with an in-depth inspection that was conducted in 2020 by the SNSA. The inspection revealed that the Krško NPP continuously monitors the development of advanced ultrasonic testing techniques through its participation in meetings organized by the Electric Power Research Institute (EPRI). The power plant also monitors new requirements for NDE inspections of the RPV base material by observing the relevant operating experiences. Representatives of the Krško NPP also participated in the PWROG workshop in 2019, where individual NPPs presented their activities and conclusions about possible defects of the RPV basic material. Regarding the latter, the Westinghouse prepared a report [13] that addresses site specific data of the Krško NPP's RPV manufacturing process. Based on the results provided by the Krško NPP and other plants to the Westinghouse study, the report concludes that the integrity of the RPV is not compromised due to potential defects in the base material resulting from the manufacturing process.

During the latest outage at the Krško NPP in 2021 the SNSA monitored extensive ultrasonic- and visual examination of the RPV welds (Figure 5). Such an integral examination of the RPV is vital for the planned LTO and is carried out periodically once per 10 years in accordance with the In-Service Inspection (ISI) programme. The examination included inspection of all circumferential and longitudinal welds, including the welds on all connections and nozzles of the RPV. All the indications/anomalies found in previous ISI inspections were confirmed and one new indication was found during the examination; none of them was evaluated as unacceptable.

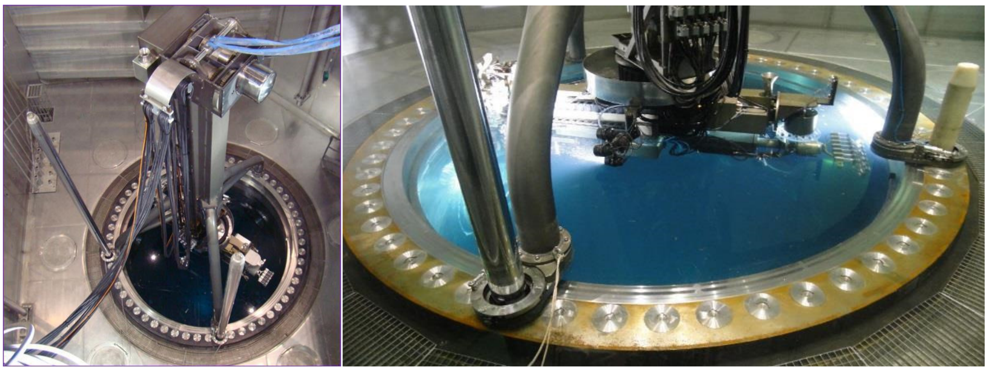


Figure 5: ISI inspection of the RPV at the Krško NPP using NDE methods.

SNSA's inspectors check the adequacy of the operator's response to relevant operating experience as part of regular inspections. It was found that the Krško NPP continuously monitors and analyses operating experience in the field of the RPV integrity and implements needed improvements.

Currently, an important problem is the potential occurrence of the stress corrosion cracking in the environment of the primary coolant (PWSCC) on welds of RPV connections called "Dissimilar Metal Nozzle-to-Safe End Welds" (DMW) from Alloy 600 material. Several methods are known in the industry to mitigate the PWSCC. For DMW the mechanical stress improvement process (MSIP) is one of most appropriate and qualified methods approved by the NRC.

The Krško NPP intends to implement the MSIP during the 2022 outage. A decision is made based on experience from similar foreign NPPs, industrial practices and analysis performed by the Krško NPP. The analysis was discussed as part of the SNSA inspection, and it was found to be an appropriate and conservative decision. The planned modification will be reviewed in detail during the SNSA licensing process and strictly supervised in the implementation phase by SNSA inspectors and TSOs.

4 CONCLUSIONS

The main challenge associated with LTO of NPPs is related to the ageing management of safety-related systems, structures and components, which cannot be replaced. The Krško NPP has prepared and properly implemented ageing programs for monitoring, testing and inspection of the ageing process of the RPV. With appropriate ageing management program implementation and preventive actions, such as modifications connected with the RPV, it is ensured, that the integrity of the RPV, reactor core and RPV's internal parts are not compromised.

The SNSA oversight of the whole AMP process in the Krško NPP is consisted of thematic inspections, outages, periodic safety reviews, modifications, operating experience feedback, review and assessment of AMP documentation and other activities. The SNSA estimates that the RPV ageing management programs are well developed and implemented. The Krško NPP has had no negative experiences until now that would require changes of the methods, acceptance criteria or requirements in that programs. Adequate control of the materials and monitoring of the embrittlement of the RPV has been established. The RPV is in a good condition; no significant deviations have been identified until now.

Based on the inspections performed, reports submitted by the Krško NPP and licensing process of the regulatory authority, the SNSA estimates that the operator carries out all necessary measures to ensure that the integrity of RPV is at the required level even during LTO of the Krško NPP. Additional confirmation of the readiness adequacy of the Krško NPP for LTO will be verified through the ongoing third PSR and IAEA pre-SALTO mission planned for October 2021.

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