

Modernization of the Film Forming Amine Injection Skid and Performance Evaluation of the 2025 Film Forming Amine Application at Krško Nuclear Power Plant

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ABSTRACT

Nuklearna Elektrarna Krško (NEK) operates a Pressurized Water Reactor (PWR) in which the integrity and long-term reliability of the secondary water–steam cycle represents a critical factor for safe and efficient plant operation. During extended refuelling outages, secondary-side components are exposed to atmospheric conditions, significantly increasing the risk of corrosion and deposit formation. To mitigate these effects, NEK implemented Film Forming Amine (FFA) technology for the first time in 2021. While the initial application demonstrated positive chemistry-related effects, operational challenges were observed, primarily associated with dosing skid limitations and feedwater flow measurement disturbances.

Based on lessons learned from the first campaign, a comprehensive modernization of the FFA dosing skid was performed prior to the second application in 2025. The upgrade focused on improving system reliability, operational controllability, and chemical dosing accuracy. Key modifications included redesign of the suction and flushing lines to enable effective rinsing after chemical injection, improvements to the mixing tank drainage concept, optimization of heating control through relocation and modification of temperature sensors in the dosing water lines, installation of alternative level measurement and visual inspection ports to overcome condensation-related radar sensor failures, and implementation of enhanced cleaning and service procedures following dosing completion. Factory Acceptance Tests (FAT) and Site Acceptance Tests (SAT) were conducted to verify functional performance and instrumentation response prior to site deployment.

The refreshed FFA application was executed between September 2 and September 18, 2025, comprising 13 dosing days with controlled pauses. A total of 750 Liters of 5 wt.% ODA[®]CON[®]F emulsion was injected into the secondary cycle while maintaining free FFA concentrations below the defined operational limit of 300 ppb. Real-time adjustment of dilution ratios and pump stroke settings enabled stable concentration profiles and prevented anomalies in feedwater flow measurements, which had been a major concern during the first application.

Operational and chemistry data confirmed that no adverse effects on plant performance occurred during the injection period. Increased steam generator blowdown flow supported removal of mobilized corrosion products, while pH, conductivity, ammonia, and hydrazine parameters remained within specification limits. Visual inspections performed during the subsequent refuelling

outage revealed a pronounced water-beading effect on several secondary-side components, indicating successful formation of a protective hydrophobic film.

The results demonstrate that targeted skid modernization combined with an optimized dosing strategy significantly improved the robustness and operational compatibility of FFA application at NEK. The experience gained provides a validated technical framework for future FFA campaigns and supports broader implementation of film forming technologies in PWR secondary systems.

Keywords: *Film Forming Amine (FFA), FFA injection, Secondary Side Chemistry, PWR Water–Steam Cycle, Corrosion Mitigation, FFA Dosing Skid, Feedwater System, Condensate System, Outage Chemistry, ODAICON®, Nuclear Power Plant Krško*

1 INTRODUCTION

After the steam generators (SG) replacement and subsequent power uprate, secondary side of the powerplant has been facing an increased release of iron and iron oxides from carbon steels (piping, high and low pressure turbine housings, etc...). Due to poor quality of the demineralized (DD) water and the unavoidable iron ingress to the SGs the formation of hard sludge deposits on the SG tube sheet was formed, paving the way for the first indications of denting, which were detected during the 2018 outage (RE2018).

The action plan for ensuring long-term SG operation, prepared by the SG Working Group inside the powerplant included the option of applying Film Forming Amines (FFA) to mitigate the iron transport to the SG during on-line (OL) operation and more importantly during the startup of the powerplant coming out of an outage. In addition, based on recommendations from WANO and OSART FACT, the decision was made during a thematic discussion in September 2020 to perform FFA injection into the plant's secondary circuit prior to outage RE21.

At the end of operating cycle OL31, Nuclear Power Plant Krško (NEK) carried out the injection of ODAICON®F chemical with the aim of protecting the components of the secondary circuit. The chemical formed a temperature-resistant hydrophobic protective film, preventing the access of oxygen and water to the internal surfaces of secondary side components, thereby inhibiting corrosion processes, especially during outages when components are open. An additional objective of this action was to reduce iron ingress into the SGs and to lower the hard sludge deposit buildup inside the SGs during OL operation.

In the initial phase of FFA chemical injection, impurities accumulated on the internal surfaces of the secondary system pipelines are mobilized, which can affect measurement instrumentation and was particularly noticeable in the measurement of the main feedwater flow.

From a chemical standpoint, it can be stated that FFA had a positive contribution to plant operation, as evidenced by record-low trends of measured iron in the condensate (CY) and feedwater (FW) system during plant operation. After the first FFA application the trends indicated a degradation of the FFA layer; therefore, it was necessary to repeat the FFA application before the end of cycle OL34 in order to maintain low levels of Fe transport in the secondary circuit.

Due to the reasons stated above NEK decided to repeat the FFA injection in 2025 prior to outage but with some changes to the injection protocol, plant operational setup, procedural changes and implement a skid modernization to be able to control the dosing rate.

2 FFA SKID DESIGN, OPERATIONAL ISSUES, AND MODERNIZATION IMPROVEMENTS

2.1 FFA Skid design overview

The first iteration of a FFA skid consisted of a main mixing tank for chemical preparation, equipped with a mixer, breather valve, level indicator switch, temperature indicator and piping connected to two injection pumps with a double head design. Dosing of chemicals was secured via a dosing pump that was connected to a FFA chemical tank. DD water to the mixing tank was connected through a flow meter, and a set of electrical heaters connected in series, with a temperature switch for heat control and a temperature indicator for an independent temperature measurement control with a solenoid valve for automatic water dosing at the end. On the pressure side of the injection pump, the skid has a relief valve to prevent over pressurization, an expansion vessel, pressure indicator and a check valve. The mixing tank and chemical feed tank were equipped with a heating blanket since the best solubility is achieved when the temperature is above +60 °C. Skid was equipped with a programable controller (PLC), power cabinet, piping, valves and strainers. Everything was encased in a retaining vessel to prevent spillage of hot chemicals during a leak except for the FFA chemical container which were of a double layer design.

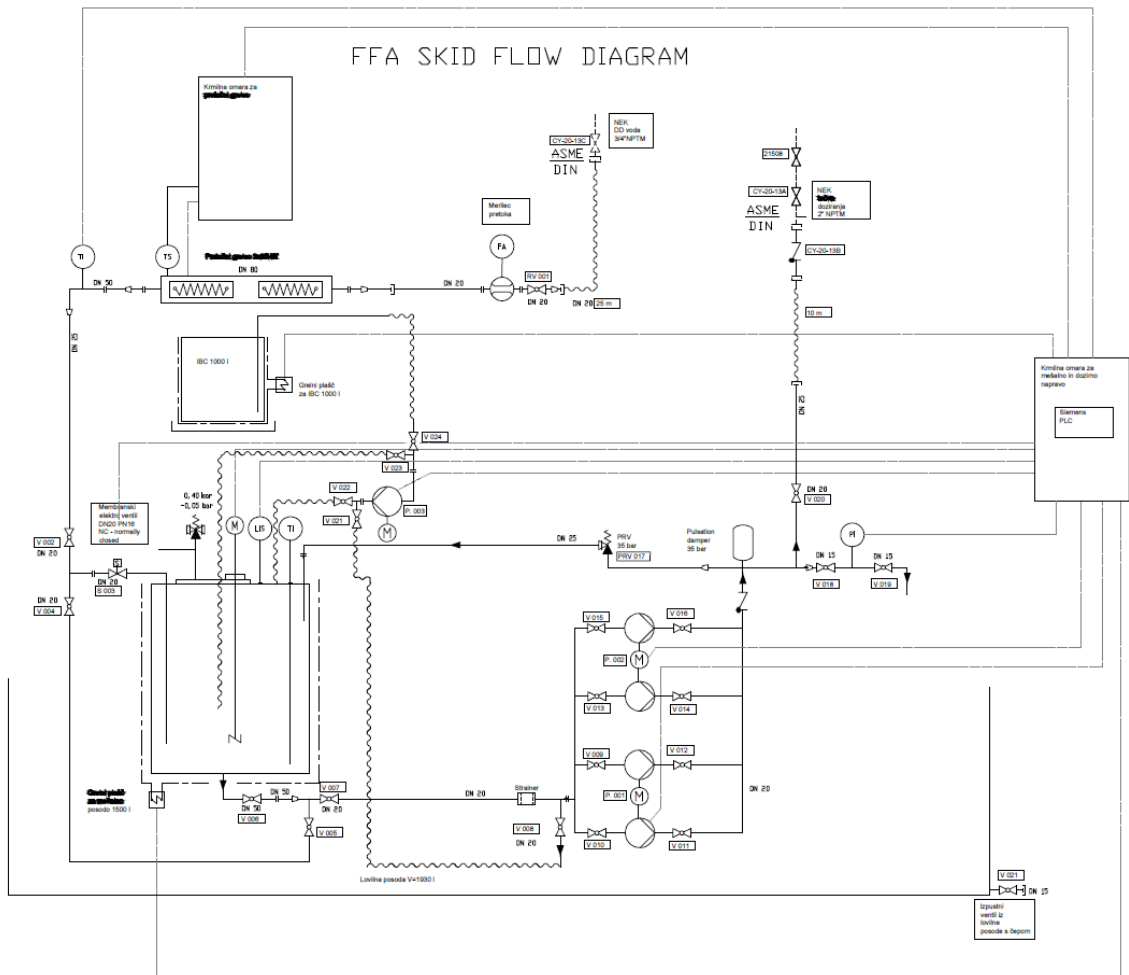


Figure 1: 2021 FFA skid design

2.2 Identified Issues During First FFA Application

During execution, several deviations of the FFA skid were observed, which was also documented in the final report prepared by NEKs contractor for FFA injection. The main issues concerning the FFA skid design were:

- Since the ODAICON solution was delivered in a double-layer container, the chemical had to be pumped out from the top of the tank. This method did not allow flushing of the dosing line which could lead to clogging. Therefore, an additional drum with demineralized water was used to flush the line but the water was unaccounted in the PLC as a water addition, rather as a chemical addition and therefore, the automatic counter was ineffective.
- Level measurement inside the mixing tank proved to be extremely difficult. Factors affecting accuracy are related to FFA solubility. To properly dissolve the chemical liquid the temperature must be above 60 °C and the mixer must be turned on. At this temperature and with mixing, water vapor and some foaming occurred, which interfered with the radar sensor accuracy. Since the PLC was programmed to automatically close the solenoid valve for water supply the inaccuracy of the level measurement control meant that the valve closed early or too late, thus causing a wrong FFA mixture inside the mixing tank.
- Originally prior to FFA injection the mixing tank came equipped with an inspection opening to monitor the dosing inside the mixing tank. But because of inaccurate level measurement due to fluid mixing and vapor interference this opening was utilised for an additional level sensor that was more resistant to turbulent conditions.
- During draining, it was not possible to completely empty the tank or the dosing line, therefore the draining method was improvised.
- The temperature sensor on the electrical heaters was too short and therefore responded too slowly to changes in heating of the demineralized water. That resulted in overheating the demineralised water inside the mixing tank which accelerated vapour forming inside the mixing tank and therefore propagating the level measurement inaccuracy. Hysteresis and temperature variation inside the mixing tank were too large, meaning the cooling phase lasted too long, resulting in an inadequate FFA concentration in the mixing tank.
- FFA skid was also inadequately designed for leaning after the injection.
- PLC programming was performed in a way that the programme did not account for problems that could occur with level instrumentation, water temperature monitoring, chemical dose pump rinsing issues, inability of skid draining, etc... and was therefore, in part responsible for an inconsistent chemical dosing rate to the secondary water steam cycle (WSC).

Additionally, since NEK had an issue to provide adequate quality of demineralised water when feeding the secondary WSC with a high flow line of the demineralised system, the decision was made to keep the WSC closed and to divert the SG blowdown (BD) flow to main condenser and not to the Sava River. Consequently, that meant that all mobilised impurities stayed within the WSC and accelerated their effect on some of the process control instrumentation [1].

2.3 Implemented FFA Skid Modernization Measures and Procedural Changes

Prior to 2025 FFA injection the skid underwent a modernization which included [2]:

- Chemical dose pump suction line redesign and flushing integration. The chemical feed pump suction hose was reconstructed in a way that the suction line could be rinsed after the chemicals have been fed to the mixing tank. This was achieved with the installation of additional isolation valves and quick connectors.

- Improved level measurement was achieved with an installation of a stilling well/shielding tube inside the mixing tank to battle the vapour formation and turbulent flow caused by the mixer. Additional sight glass tube was added for a visual representation of the fluid inside the mixing tank. An option to rinse the sight glass tube with warm water was also implemented, to prevent FFA emulsion buildup on the level indicator tube.
- Visual access was restored with the installation of a new opening in the mixing tank side.
- Additional valves, relief valves and pipes were installed on the mixing tank to allow for a better rinsing, pressure control and drainage of the mixture to the WSC. The bottom of the mixing tank was changed to accommodate the new slope incline towards the new bigger outlet connection.
- Heater temperature control was improved with the reposition of the temperature sensor and reduced hysteresis. This resulted in improved and stable temperature accuracy and prevented temperature overshooting's, thus minimizing the vapour production inside the mixing tank. Also, ODAFON®F solubility was controlled, so no clogging of any lines was observed.
- Additionally for the skid modernization NEK also included a more detailed servicing and cleaning plan for all major components, testing of skid prior FFA injection with the original equipment manufacturer, PLC programmer, FFA chemical injection contractor and NEK personnel.
- Human Machine Interface (HMI) which is operated through PLC had been completely redesigned and rewritten to be able to operate independently when an issue of any input signal would occur.

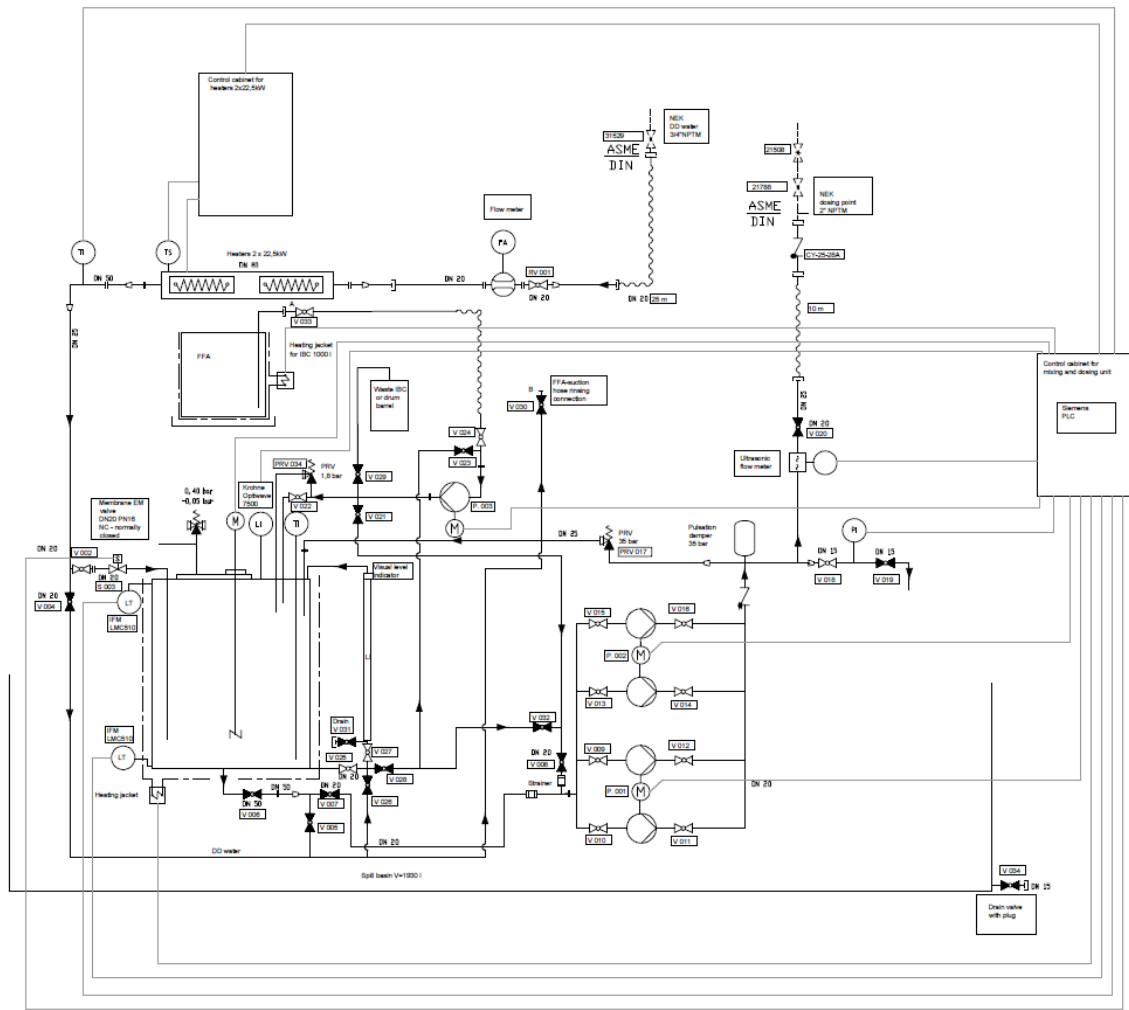


Figure 2: FFA skid schematics after the modernization in 2025

Major procedural changes for a second FFA injection included [3]:

- In 2025 BD flow was maintained between $2 \times 10 \text{ m}^3/\text{h}$ maximum and $2 \times 8 \text{ m}^3/\text{h}$ minimum and diverted to the Sava River. The flow was diverted to the Sava before the planned dosing.
- Due to diversion of BD flow a sufficient make-up flow of DD water was assured, which contributed to about $414 \text{ m}^3/\text{day}$ at min BD flow or at least $510 \text{ m}^3/\text{day}$ at max BD flow.
- Chemical compound of ODACON®F was reduced from previous 5 % to 2.5 % solution to mitigate the possibility of a higher than planned chemical dose rate during the injection.
- NEK also implemented an additional FW flow independent measurement in case there would be a repeat on the flow instrumentation as seen during the first injection. No adverse influence on FW flow measurement or any vital plant instrumentation was observed during the 2025 campaign.
- Dosing of chemicals was performed with a slower rate, longer injection times and larger soak times.

3 COMPARISON OF 2021 VS 2025 CAMPAIGNS

3.1 Introduction of FFA technology implemented at NEK

Film Forming Amines (FFA) is a patented technology with an aim to protect the water-steam cycle of a power plant against corrosion. The technology has been already implemented at several nuclear power plants worldwide [4].

One of the actions to minimize the denting process is to apply Film Forming Amines (FFA) to mitigate the iron transport to the SG during on-line (OL) operation and more importantly during the startup of the powerplant coming out of an outage. This was performed in 2021 and re-applied in 2025. Denting is a long-term concern therefore the continuous reduction of corrosion product transport into the SGs is very important.

FFA substances have positive impact on preventing further degradation processes caused by chemistry impacts (i.e. corrosion mechanisms: pitting, flow accelerated corrosion or denting). FFA is applied in order to minimize secondary system corrosion mechanisms during outages (all subsequent operational phases, i.e. startup, power operation and shutdowns) and subsequent minimization of corrosion products transport into the steam generators.

A commercial product, chemical ODACON®F, was used as FFA, a stable aqueous emulsion with a content of 5 wt-% of the filming amine (hydrogenated and distilled tallow amine) contains mainly ODA and HDA (Hexadecylamine). The emulsion is stable without the need for the addition of emulsifiers and easily mixable with demineralized water [5].

3.2 FFA campaign in 2021

In the 2021 Campaign secondary system was closed circled throughout the entire FFA dosing since the DD water did not meet NEK chemistry criteria (c_{Na} was around 1 ppb). SG blowdown (BD) flow was diverted from both steam generators (SGs) to Main Condensate (CY). This configuration led to higher concentration of ODACON®F solution in the secondary system. There was also a limitation of lower injecting FFA into the secondary system.

3.3 FFA campaign in 2025

Between both campaigns in 2021 and 2025 Water Treatment (WT) modification was applied, which had a positive impact on DD water conditions. Due to that SG blowdown (BD) flow from both steam generators (SGs) was diverted to the Sava River with optimized flow rate (8 m³/h - 10 m³/h per SG). FFA injection was implemented without deviations or power fluctuation and the behaviour of the dosing skid was also in accordance with NEK expectations. As a result, the entire amount of ODACON®F chemical has been injected into the secondary system.

3.4 Results after FFA application

Figure 3 shows trends of cumulative Fe₃O₄ deposition to SGs before applying first FFA application in 2021, between 2021 and 2025 FFA campaigns and after second FFA application in 2025 (OL29-OL35 cycle). After the first FFA application in 2021, the expected effect after the addition of the ODACON®F solution was the formation of a mono-molecular hydrophobic film, which was adsorbed on metal surfaces and consequently lower release of iron and iron oxides in OL32. Particulate iron measurements, which were performed before the Rx shutdown on OL31 and after the first FFA application showed less release of iron prior FFA injection. Cumulative Fe₃O₄ deposition to SGs was much lower than before. Visual inspection and tests on the surfaces of the condenser, moisture separator (MSR) and heat exchanger (HEX) in RE 2021, confirmed the desired behaviour of water droplets and the formation of hydrophobic film, as a result of the application. During OL32-OL34 period figure 3 shows gradual increase of iron and iron oxides release. After re-

application of FFA at the end of OL34, the release of iron and iron oxides in OL35 is almost at the same level as in OL32.

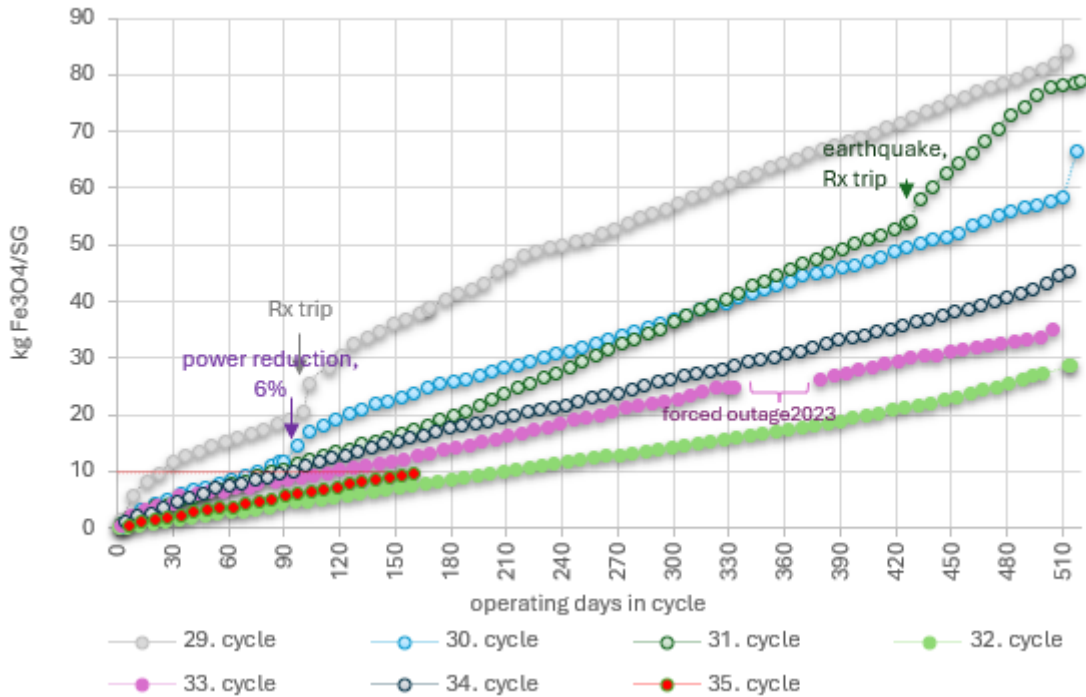


Figure 3: Cumulative Fe_3O_4 deposition to SGs during OL 29-OL35 cycle

During the following outage right after the FFA re-application, a few components were visually examined such as: MSR, Heater 6A, Condenser and Condensate Transfer Tank. Figure 4 shows the photographs taken during visual inspection in Outage 2025 for some components. It can be seen that hydrophobic layer of FFA was successfully formatted on internal surfaces.

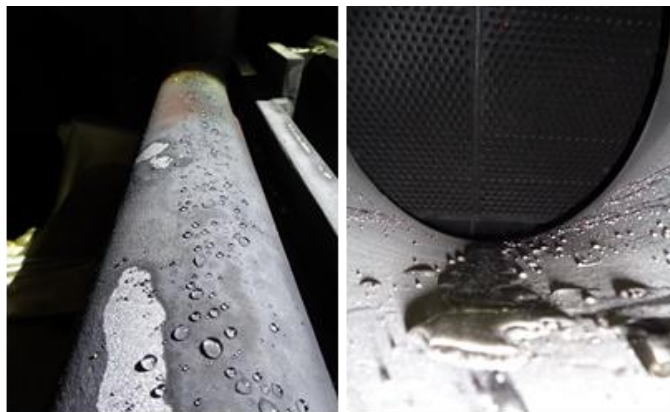


Figure 4: Visual inspection of condenser and MSR (during outage 2025)

4 CONCLUSION

The modernization of the FFA skid significantly contributed to improved control of ODAICON® F solution injection, as design deficiencies were addressed and the PLC/HMI system was upgraded to ensure more stable and reliable operation. Enhancements in level measurement,

temperature regulation, and system flushing and draining enabled more accurate preparation and control of the required chemical concentration in the mixing tank. Furthermore, the implemented process and instrumentation improvements eliminated negative impacts regarding NEK feedwater (FW) flow measurement instrumentation, resulting in a better overall system performance.

FFA applications were successful from the chemical standpoint. FFA had a positive contribution to plant operation, as evidenced by record-low trends of measured iron in the condensate (CY) and feedwater (FW) system during plant operation. It is recommended to perform the FFA application every third cycle or optional every second cycle (based on the cumulative amount of Iron in the secondary side).

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