Corrosion Detection and Surface Repair with Coatings on Condensate Storage Tanks Internal Surfaces

Matija Guliš, Sanja Smirić, Lenart Pušnik
Nuklearna elektrarna Krško
Vrbina 12, 8270 Krško, Slovenia
matija.gulis@nek.si; sanja.smiric@nek.si, lenart.pusnik@nek.si

ABSTRACT

In the Nuclear power plant Krško, there are two single hull condensate storage tanks with floating diaphragm each containing up to 757 m^3 of demineralized water. The main purpose of these two storage tanks is to provide a capacity of cooling water for cooling the reactor coolant system via steam generators with the use of auxiliary feedwater pumps. This is a very important function from the safety point of view and that is the reason that both storage tanks are listed as safety class 3 components. It is also possible to fill up the condensate system if other means are not available. Condensate storage tanks are subject to periodic testing and periodic inspections to determine the condition of the components. Both tanks are in operation since the start-up of the powerplant, are located outside, and are exposed to different degradation processes. There was a concern that the tanks are leaking because there were often small puddles of water near the tanks. There were no changes in the levels of tanks. The design of tanks is a single hull, so there is no indication if a small leak is present.

In the outage 2018, both tanks were emptied and examined with NDE methods to find any corrosion damage of bottom plates and any untight spots on adjacent welds.

The article is about the NDE methods that were used (Magnetic Flux Leakage, Ultrasonic and Vacuum Box inspection) to determine the condition of the floor plates and adjacent welds as well as the process of internal surface reparation with coatings. Process of coatings qualification for use in safety class components is also explained: dedication process for material up-grade from non-safety related to safety-related because CY tank linings are classified as safety-related according to RG 1.54, rev 2 and corresponding ASTM standards and NEK technical specification SP-A5001. All activities for surface repair with coatings shall comply with safety-related requirements. Also, extensive immersion tests with selected and specially defined parameters were performed in NEK chemical laboratory in order to select the most suitable coating system for surface repair of CY tank floor lining. Further details concerning immersion tests are presented below.

Keywords: *Corrosion, Condensate Tank, NDE, Coating, Aging Management*

1 INTRODUCTION

In the Nuclear power plant Krško, there are two single hull condensate storage tanks with floating diaphragms each containing up to 757 m^3 of demineralized water. They are designated as CY101TNK-001 and CY101TNK-002 respectively (Figure 1). The main purpose of these two storage tanks is to provide a capacity of cooling water for cooling the reactor coolant system via the auxiliary feedwater system. When needed, the water from the condensate storage tanks is pumped with two motor-driven pumps or one steam-driven auxiliary feedwater pump in two steam generators to cool down steam generators. This is a very important function from the safety point of view and that is the reason that both storage tanks are listed as safety class 3 components. The diameter of each tank is 10,6 m with a height of 9,5 m, the nominal thickness of bottom plates is 9 mm and the nominal thickness of shell plates is 15 mm. The material of the plates is carbon steel, which is susceptible to corrosion if it is not treated properly with the coatings. Both tanks are in operation since the start-up of the powerplant, are located outside, and are exposed to influence of the environment. Long-term exposure to environmental conditions can result in a build-up of different degradation mechanisms. Due to the combination of carbon steel and environmental conditions, different forms of corrosion are expected to occur through the lifetime of the components. Condensate storage tanks are subject to periodic testing and periodic inspections to determine the condition of the components. Tanks are monitored through the following plant programs: ADP-1.4.235; Preventive maintenance program for secondary side stabile equipment, TD-2ZZ; aging management program - Above grounds metallic tanks program [1] and TD-A21; aging management program - Internal coatings/linings for in-scope piping, piping components, heat exchangers and tanks [2]. The first program is more operational related, while the other two programs are oriented more toward long-term operation and for managing potential degradation mechanisms.

Figure 1: Condensate storage tanks 1 and 2

Figure 2: Possible signs of leakage on tank 1

There was a concern that the tanks are leaking because there were often small puddles of water nearby the tanks (Figure 2) although there were no measurable changes in the levels of tanks. The tanks are designed as a single hull construction, so there is no indication if a small leak is present. The first concern, that there might be some leaks present on tank no.1 was reported through the Corrective Action Program (CAP) already in 2013 [3]. The following inspection in 2013 was a visual inspection with the addition of ultrasonic (UT) thickness measurement by the 25 cm grid and did not find any deviations from the normal state of the component. Concern for degradation of bottom steel plates was still present, because of the scarcity of the UT thickness measurements. For the following outage in 2016 draining of both tanks was not planned, so only during the outage 2018 complete inspection was possible.

In the outage 2018, both tanks were emptied and examined with Non-Destructive Examination (NDE) methods to find any corrosion damage to bottom plates and to locate any untight spots on adjacent welds [4]. Magnetic Flux Leakage (MFL) was recognized as the most suitable NDT method for the detection of any deviations of the bottom plates thickness due to the corrosion. With this technique, the full coverage was obtained and not only spot measurements as in the 2013 UT inspection. Ultrasonic – UT inspection was still used for interpretation and exact measurement of indications obtained with the MFL technique.

With the UT measurements, on some locations, it's been confirmed that the thickness of bottom plates is less than 50% of the nominal plate thickness ($t_{meas}<t_{nom}$). Nominal thickness is t_{nom}=9mm and measured thickness are t_{meas}=4mm and t_{meas}=2mm).

Corrective actions were taken in a form of welded steel patches on affected areas where $t_{meas}<t_{nom}$. Before coating, steel patches welds were tested with the Vacuum Box technique for tightness.

As for the finish, treatment of repaired surfaces was performed with the use of qualified coatings for such application, because CY tank linings are classified as safety-related according to Regulatory Guide 1.54, rev. 2 [5], corresponding ASTM standards and NEK technical specification SP-A5001 [6]. For potential coatings, extensive immersion tests with selected and specially defined parameters were performed in NEK chemical laboratory to select the most suitable coating system for surface repair of CY tank lining and dedication process for material up-grade from non-safety related to safety-related.

2 PLANT SPECIFIC PROGRAMS: TD-2ZZ AND TD-A21

2.1 TD-2ZZ: Aboveground Metallic Tanks aging management program

This program [1] manages the effects of loss of material on the outer surfaces of above-ground tanks constructed on concrete or soil. This program credits the standard industry practice of coating or painting the external of steel tanks as a preventive measure to mitigate corrosion.

The program relies on periodic inspections of metallic tanks (with or without coatings) to manage the effects of corrosion on the intended function of these tanks. Because lower portions of the tank are on concrete or soil, corrosion may occur at inaccessible locations. Visual inspections cover the entire outer accessible surface of the tank and inaccessible outer surfaces are inspected by UT and MFL from inside when tank is empty.

Accordingly, verification of the effectiveness of the program is performed to ensure that significant degradation in inaccessible locations is not occurring and that the component intended function is maintained during the period of extended operation.

The scope of the TD-2ZZ program are CY101TNK-001 and CY101TNK-002 (condensate system) and DO100TNK-003 (diesel oil system).

This program utilizes periodic plant inspections to monitor the degradation of coatings, sealants, and caulking because it is a condition directly related to the potential loss of materials. Additionally, thickness measurements of the bottoms of the tanks are made periodically for the tanks monitored by this program as an additional measure to ensure that the loss of material is not occurring at locations that are inaccessible for inspection.

Degradation of an exterior metallic surface can occur in the presence of moisture; therefore, an inspection of the coating is performed to ensure that the surface is protected from moisture. Conducting periodic visual inspections at each outage to confirm that the paint, coating, sealant, and caulking are intact is an effective method to manage the effects of corrosion on the external surface of the component except the inaccessible outer surfaces. Potential corrosion of tank bottoms is determined by taking non-destructive examination methods shown in Table 1.

Table 1: Inspection scope for program TD-2ZZ

Tank label	Examination method	Scope	Frequency
CY101TNK-001 and 002	Visual examination	External surface	1 per year
CY101TNK-001 and 002	*UT and *MFL	Bottom thickness	1 per 6 years
DO100TNK-003	Visual examination	External surface	1 per year

*(UT) ultrasonic testing thickness measurements
*(MFL) Magnetic flux leakage

The effects of corrosion of the inaccessible external surface are detectable by UT thickness measurement of the tank bottom and are monitored and trended if significant material loss is detected where multiple measurements are available.

Acceptance Criteria: Any degradation of paints or coatings (corrosion) is reported and requires further evaluation. Corrosion is unacceptable and needs to be evaluated using the corrective action program. UT thickness measurements of the tank bottom are evaluated against the design thickness and corrosion allowance. Any measurements of the tank bottom thickness smaller than 5.0 mm require further evaluation and repair.

Minimal tank bottom thickness criteria is determined in standard EEMUA Publication 159, Above Ground Flat Bottomed Storage Tanks: A Guide to Inspection Maintenance and Repair, Edition 5;

2.1.1 TD-A21: Internal coatings/linings for in-scope piping, piping components, heat exchangers and tanks [2]

This program includes internal coatings/linings that are permanently, temporary or in case of anticipated transient conditions immersed in various media: diverse water (closed-cycle cooling, raw, borated and waste water), fuel or lubricating oils and are safety-related - internal coatings/linings of in-scope piping, piping components, heat exchangers, and tanks exposed to closed-cycle cooling water, raw water, treated water, treated borated water, waste water, fuel oil, and lubricating oil where the loss of coating or lining integrity could prevent the satisfactory accomplishment of any of the SSC’s (structures, systems, components) intended functions.

3 MONITORING, TESTING AND INSPECTION ACTIVITIES

At the request of the Krško Nuclear Power Plant, the outside contracting company performed testing of both condensate storage water tanks CY101TNK-001 and CY101TNK-002. Inspections were performed due to requirements in the CAP [3].

After the tanks were drained and cleaned, the inspection was performed from the inside. The inspection includes:

1. Inspection of the bottom plates with MFL method, scope 100%
2. Inspection of the bottom plates with vacuum box method, scope 100%
3. Inspection of the bottom plate welds with vacuum box method, 100%
4. Inspection of the corner welded joins, with vacuum box method, 100%

3.1 Inspection methods

3.1.1 Magnetic Flux Leakage (MFL) Method

Magnetic flux leakage is an electromagnetic non-destructive testing technique used to detect corrosion and pitting. MFL method uses a powerful magnet to magnetize the conductive material under test. If any discontinuity exists in material like corrosion or material loss, the magnetic field "leaks" from the material.

MFL probes incorporate a magnetic detector placed between the poles of the magnet where it can detect the leakage field. The magnetic field induced in the material (plate) saturates it until it can no longer hold any more magnetic flux (Figure 3). The magnetic flux overflows and leaks out of the plate and strategically placed sensors can accurately measure the three-dimensional vector of the leakage field (Figure 4).

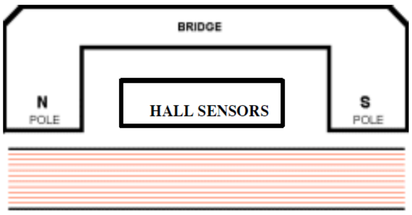

Figure 3: Saturated material (plate)

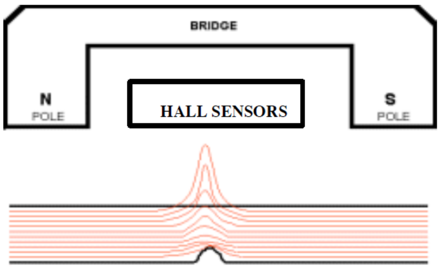

Figure 4: Magnetic flux leaks from material

Figure 5: Inspection of bottom plates using MFL detection scanner.

Inspection of the bottom plates with the MFL method (Figure 5) was performed due to the determination (identification) of pitting corrosion from underneath (bottom side of the plates).

3.1.2 Vacuum box testing method

Vacuum Box testing (Figure 6) is a non-destructive method used to check for any leaks or faults in the welding of the bottom & annular plates of the storage tank. The vacuum pump attached creates a vacuum in the vacuum box, which shows bubbles of the soap water applied to the weld in case of any leaks or faults present. This is one of the most adoptive test methods to detect leaks or defects and is widely used in the inspection of tanks. Inspection of the bottom plates and adjacent welds with the vacuum box method did not reveal any leaking points.

Figure 6: Vacuum box inspection of welded patch

3.2 Inspection results

3.2.1 Visual inspection of the internal surface

Visual inspection confirmed that the internal coating of the tank plates and welds are in very good condition, without chipping, flaking, corrosion, or other damage present. The good condition was confirmed for the bottom surfaces as well as for the shell [4].

3.2.2 MFL Inspection

MFL inspection confirmed damage on the bottom plates from underneath (inaccessible side of the tanks) on both condensate storage tanks. In all locations where damage was detected, additional ultrasonic inspections were performed in order to perform the sizing of the located damage. All locations detected with MFL were confirmed with the ultrasonic inspection.

Two locations with corrosion damages were confirmed on the floor plates on condensate tank CY101TNK-001. Six locations with corrosion damage were confirmed on the lower part of floor plates and two locations with mechanical damage on the upper surface of floor plate on condensate tank CY101TNK-002 [4].

All damaged locations were repaired with welded patches and exanimated with the vacuum box method.

3.2.3 Vacuum box testing inspection

Inspection of the bottom plates with welded patches and adjacent welds with the vacuum box method did not reveal any damage that cause leakage on condensate tanks [4].

4 REQUIREMENTS FOR SURFACE PROTECTION WITH COATING MATERIALS

4.1 Service Level III Coatings

Internal surfaces of condensate storage tanks (internal coatings/linings) are according to Regulatory Guide 1.54, rev 2 "Service Level I, II, and III Protective Coatings Applied to Nuclear Power Plants", US NRC, 2010 [5], corresponding ASTM standards and NEK technical specification (SP-A5001 [6]) classified as Safety Related Service Level III coatings therefore specific requirements for safety-related items and/or services shall be implemented.

Coating Service Level III, as defined by [5], is a term used to describe areas outside Reactor Containment where coating failure could adversely affect the safety function of a Safety Related structure, system, or component (SSC). The selection of coating materials and performance of coating work for this service level should reflect immersion and such other service conditions as might be anticipated throughout the coatings service life expectancy. Specifically, coating work for the following structures and equipment is under Coating Service Level III: fuel pools and canals, if coated, and refueling water storage tanks or such other tanks constituting ECCS water sources.

4.2 Requirements for SL III Coatings

Special activities shall be performed before the application of protective coating systems to steel or any other internal/external surfaces or related coating work such as: Selection and Qualification of coating systems, Manufacturing, Preparation of substrates, Application of the coating system, Testing and Inspection Requirements, Personnel Qualification Requirements, Condition Assessment and Receipt and Storage of safety-related protective coating systems.

The coating/lining Supplier/Manufacturer shall provide products information and characteristics (in accordance with NACE TM0404): Product Data Sheet (PDS), Material Safety Data Sheet (MSDS), QA program, Coating Technology (ambient and material conditions, required surface preparation, application instructions, application and inspection procedures…), Qualification Test Reports, training program, qualification and certification of application personnel and inspectors.

4.3 Immersion Tests

Due to the safety-related nature of internal coatings/linings inside CY tanks and corresponded requirements for material selection and application several tests had to be performed before lining execution. Furthermore, CY tanks contain deionized water (Make-up water) which shall comply with specific chemical criteria listed in NEK procedure ADP 1.6.021 “Kemijske specifikacije in kriteriji za korektivno ukrepanje”, ref.[7].

Table 2: Chemical parameters for DD water in CY101TNK-001/002

Control parameter	Expected Value
Total conductivity at 25°C (μS/cm) Dissolved oxygen (μg/kg) Silicium (μg SiO_2/kg)	≤ 0.1 ≤ 100 ≤ 10
Diagnostic parameter	
Total organic carbon (μg/kg) Hydrazine (μg/kg)	≤ 100 ≥ 3 × [O_2]

NEK performed specific immersion tests following the guidelines to best industrial practice for material selection. Tests were implemented according to NACE TM0174 Laboratory Methods for the Evaluation of Protective Coatings and Lining Materials on Metallic Substrates in Immersion Service, ref.[8] and ASTM D7230 Standard Guide for Evaluating Polymeric Lining Systems for Water Immersion in Coating Service Level III Safety-Related Applications on Metal Substrates[9]. Internal coatings/linings shall meet excellent physical and chemical properties required for the immersion environment and also no leaching of aggressive ions to the working medium shall occur (this may have a negative influence on NEK CPI – Chemistry Performance Indicator for secondary chemistry).

NEK selected several epoxy based coating systems for further immersion tests:

- Belzona 1391T (DFT 500 μm), BELZONA;
- Amercoat 90N (DFT 300 μm), PPG;
- Remoplast RA 122 (DFT 400 μm), REMBRANDTIN;
- Epolor Cargo HB B (DFT 400 μm), HELIOS and
- Hempadur 35560 (DFT 400 μm), HEMPEL.

For the purpose of testing materials all proposed/selected coating materials were applied on test coupons (carbon steel, dimensions 150×75×2.5 mm, 5 test coupons/system) in accordance with ASTM D5139 Standard Specification for Sample Preparation for Qualification Testing of Coatings to be Used in Nuclear Power Plants [10] (see Figure 7 and 8). Before material application, all coupons received surface preparation to grade Sa 2.5 according to ISO 8501-1.

Figure 7: Test coupons Hempel

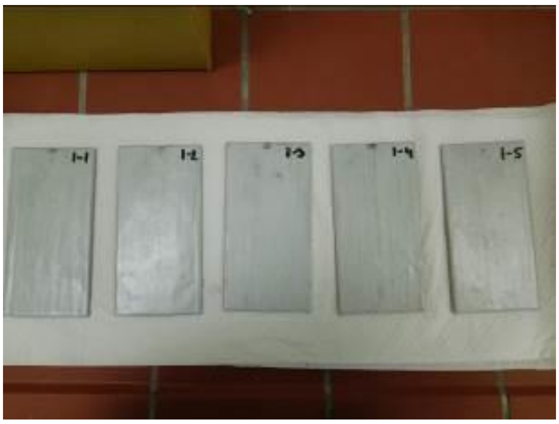

Figure 8: Test coupons Belzona

Before immersion tests a final drying of coating on test coupons was accomplished at room temperature for a period at least of 3 days. Afterwards test coupons were visually examined due to local defects (in accordance with ISO 4628-1 to 5), the dry film thickness was measured, also the adhesion measurement was performed (pre and after immersion tests; in accordance with ASTM D4541 "pull-off test") and finally EIS (Electrochemical Impedance Spectroscopy) was determined (ISO 16773-1 to 4; requirement: no porosity – before/after immersion, Figure 9).

Figure 9: Impedance measurement

Immersion tests (according to NACE TM 0174, procedure B [8]) lasted for 14 days and were performed in NEK chemical laboratory. Three (3) test coupons/coating systems were immersed in pure water (Q water) at a volume of 900 mL (Figure 10).

Figure 10: Test coupons in immersion

Figure 11: Samples of working fluid in NEK laboratory

Samples of working fluid (water medium) were analyzed in the NEK chemical laboratory (Figure 11) to determine the presence of released anions (sulphates, chlorides, fluorides, acetates and formiates – in accordance with procedure CAP-6.552, Določevanje anionov z ionskim kromatografom ICS 3000, [11]) inside specified values defined in ADP-1.6.021, Kemijske specifikacije in kriteriji za korektivno ukrepanje [7]. Samples were analyzed before the beginning of immersion tests, after 7 days and at the end of immersion (14 days period).

$$c_{ekv} = c_{meas} \times \frac{A_{CY} \times V_{test}}{V_{CY} \times A_{coupon}}$$

c_{ekv} … concentration of water medium (in CY tank)

c_{meas} … measured concentration of testing water medium

A_{coupon} … immersed surface of test coupon (200 cm^2)

V_{CY} … volume of water medium in CY tank (700 m^3)

V_{test} … test water medium (900 ml)

Measured concentrations were considered in the equation stated above, so no c_{ekv} (concentration of water medium inside CY tank) was exceeded as stated in ADP-1.6.021[7].

The conclusion of immersion tests confirmed the most suitable coating materials for reparation of floor plates inside condensate storage tanks – Hempadur 35560 and Belzona 1391T. Belzona 1391T was selected because it had been already used in NEK as a Service Level III coating for surface reparation inside Component Cooling Heat Exchangers.

4.4 Dedication process

NEK performed the dedication process as a combination of the technical survey at manufacturer headquarter in the UK and verification of specific critical characteristics of purchased material. After successful completion of the technical survey, laboratory testing for critical characteristics was implemented by NEK in independent and accredited laboratories. NEK Nuclear Coating Specialist selected and defined critical characteristic for material verification such as determination of density and dry solids (in accordance with ISO 2811-1 and ISO 3251), determination of chemical composition by using a method of fingerprinting FTIR (Fourier Transform Infrared Spectroscopy) and also a verification of rheological properties of selected materials (rotational and oscillation tests were performed). All mentioned tests were performed on procured material batches. The extensive dedication process showed positive results in comparison with technical data sheets given by the manufacturer so NEK concluded that the dedication process was successfully completed and material could be used for intended safety related application.

4.5 Application of coating material on internal steel plates

In outage 2018 CY101TNK-002 was emptied so two (2) steel plates inside CY101TNK-002 were coated with coating material Belzona 1391T (working order 126432, Figure 12 and 13). The material application was performed in accordance with product data sheet (PDS) requirements. After drying of coating system several measurements were carried out: dry film thickness, adhesion testing, and solvent resistance rub [12]. It was confirmed that the coating is properly dried and applied before closing and filling the condensate storage tank.

Figure 12: Steel plate inside CY tank

Figure 13: Coated steel plate inside CY tank

During the next outage in 2021 seven (7) steel plates inside CY101TNK-001 were coated (work order 166115, Figure 14 and 15). All required activities were implemented to ensure the adequacy of execution of coating application (DFT and adhesion measurement, solvent rub test).

Figure 14: Steel plates inside CY tank

Figure 15: Coated steel plate inside CY tank

5 CONCLUSION

The inspection of the condensate storage tanks is by the book example of managing the aging mechanisms in the NPP Krško [13]. The purpose of the aging management programs is to monitor components and to detect degradation before that degradation can cause the failure of the component. Periodically, the inspections are performed as per program requirements, but in this case, additional effort was taken due to the possibility of leaking and related CAP report [3].

The inspection did not reveal holes or degraded areas where leaking is possible, only indications of corrosion underneath the bottom plates at some locations. Corrective measures were taken in a form of welded patches, welds tested, and affected areas treated with the qualified coating. Performance of the job as a whole also presents a good practice of cooperation between organization structures within the NPP Krško for solving such a problem during an outage, when time and resources are limited due to a great number of other activities going on in the meantime. With that job done, NPP Krško has set up a benchmark for inspection and repair of single-hull holdup tanks.

6 REFERENCES

6.1 References

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[5] Regulatory Guide 1.54, rev 2 "Service Level I, II, and III Protective Coatings Applied to Nuclear Power Plants", US NRC, 2010

[6] SP-A5001, rev. 0, Service Level III Coatings

[7] ADP-1.6.021, Kemijske specifikacije in kriteriji za korektivno ukrepanje

[8] NACE TM0174 Laboratory Methods for the Evaluation of Protective Coatings and Lining Materials on Metallic Substrates in Immersion Service

[9] ASTM D7230 Standard Guide for Evaluating Polymeric Lining Systems for Water Immersion in Coating Service Level III Safety-Related Applications on Metal Substrates

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[12] ASTM D5161, Standard Guide for Specifying Inspection Requirements for Coating and Lining Work (Metal Substrates)

[13] NUREG 1801 rev.2; Generic Aging Lessons Learned (GALL) Report