Journal of Energy

VOLUME 71 Number 2 | 2022

journal homepage: http://journalofenergy.com/

Mechanical and 1st Chemical Cleaning of NEK Steam Generators

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***Summary* — Sludge removal is performed on two steam generators (SG's) at the Krško Nuclear Power Plant (NEK) during every outage. SG's are a meeting point of five major plant systems: Reactor Coolant System (RC) on the primary side and four systems on the secondary side – Auxiliary Feedwater System (AF), Blowdown System (BD), Main Feedwater System (FW), and Main Steam System (MS). Sludge removal activities take place on the secondary side of the SG's on the top of the tube sheet. It always consists of classical Sludge Lancing (SL) which is done by spraying water at different angles (30°, 90°, 150°) between the tube gaps in the steam generator tube bundle with a pressure of around 220 bars. Another method is Inner Bundle Lancing (IBL) which means spraying water directly inside the tube bundle with a traveling lance tape with a spraying nozzle at the end. Water is sprayed at an angle or directly on the top of the tube sheet with a robot-guided manipulator which is placed inside a steam generator. The manipulator and therefore the spraying action is controlled by an operator and at times it is fully autonomous to provide the highest protection measures possible. Another method of sludge removal which was for the first time utilized in 2019 at the Krško site was Chemical Cleaning (CC) of both SG's. During this process, a chemical was injected into the SG's through the BD system and periodically pumped between the two SG's to create a dynamic flow and maximize the cleaning effect. To achieve the best results, a constant temperature of the chemicals had to be maintained at all times. Upon completion of chemical cleaning, a rinsing phase was followed to remove any post-treatment chemicals. After all sludge removal activities, a televisual inspection (TVI) of the top of the tube sheet was performed to access the hard sludge area and to search for potential foreign objects in the SG's. If for instance an object of importance during TV inspection is found, an attempt to retrieve it would usually take place. Other methods of sludge removal such as upper bundle flushing or ultrasonic cleaning have not been implemented in NEK thus far. Since the power plant uprate in May 2000, NEK conducted SL on both SG's every outage also starting with IBL in 2013 and 2015, and the same method was used in the 2018 outage. During the outage in 2019, all three methods (SL, IBL, and CC) have been utilized with the main purpose to extend the full load operation of the plant, preventing and/or stopping denting processes in the SG's from occurring, reducing and stopping the build-up of hard sludge area to increase/sustain efficiency and remove foreign objects found in the SG's.SG's U-tubes are a barrier between the primary side coolant and the secondary side of NEK and the environment. Therefore, it is crucial to keep the highest level of integrity of the U-tubes because any leak could potentially mean a release of radioactive material into the atmosphere. This paper describes the purpose and workflow of sludge removal activities in the outage of 2019 in NEK.**

***Keywords* — Steam Generators (SG's), Sludge Lancing (SL), Inner Bundle Lancing (IBL), Chemical Cleaning (CC), televisual inspection (TVI), Foreign Object Search and Retrieval (FOSAR), Krško Nuclear Power Plant (NEK)**

I. Introduction

NEK's steam generators are safety related components that are required to operate during normal, abnormal, and emergency conditions. During normal power operation, steam from steam generators is supplied to the turbine. During shutdown conditions, they are vital components in the decay heat removal process. Additionally, steam generators act as a third barrier for preventing radioactive releases into the environment. Due to this the cleanliness and operability of steam generators are vital for safe operation.

The driving factor to perform the Chemical Cleaning process at NEK was the discovery of the denting indications in 2018, which have also been confirmed later by re-evaluation of old Eddy Current Testing (ECT) data from 2006 and 2012. Denting is tube deformation due to material ingress into the space between the tube and tube sheet (for details see Chapter 2).

For SG #1 there was a significant increase in the hard sludge area between 2010 and 2016 which has been observed in the hot leg and is being constant until the last visual inspection in 2018- before CC. From the past data re-evaluation, there were 33 denting indications discovered in the hot leg, which were detected in 2006 and 2012. They are all located not only in the hard sludge area but also in its periphery. Since 2012 no new denting indications have been detected in the hot leg. The hard sludge area in the cold leg detected in 2012 and 2018 but were not detected in 2016, which is classified as an inconsistency. The 5 denting indications first time detected in the cold leg in 2018 are located in the hard sludge area and the low-flow zone. The low-flow zone was determined by Computational Fluid Dynamics (CFD) calculations.

For SG #2 there was a significant increase of hard sludge area between 2010 and 2016 in the hot leg, which has been constant until the last visual inspection in 2018 before Chemical Cleaning (CC) (similar to SG #1). In 2012 detected denting indications are located mainly outside of the hard sludge area seen in 2010. The newest detected indications in 2018 are located mainly in the periphery of

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the hard sludge deposits. On the cold leg side of SG #2, no denting indications occurred.

In total at the end of the outage in 2018, NEK had confirmed 121 denting indications on both SG's collectively.

Mechanical sludge removal activities take place on the secondary side of the SG's on the top of the tube sheet. It consists of regular Sludge Lancing (SL) which is done by spraying water at different angles (30°, 90°, 150°) between the tube gaps in the steam generator tube bundle with a pressure of around 220 bars. Another method is Inner Bundle Lancing (IBL) which means spraying water directly inside the tube bundle directly on the top of the tube sheet with a robot-guided lance which is placed inside a steam generator. The robot is controlled by an operator and at times fully autonomous to provide the highest protection measures possible. After these activities, a televisual inspection (TVI) of the top of the tube sheet is performed to access the hard sludge area and to search for potential foreign objects in the SG's. If an object is found, an attempt to retrieve it would usually take place.

This paper describes the chemical cleaning process that took place during the outage in 2019 and the mechanical sludge removal process in NEK in the same period. Descriptions from setting up the equipment, differences between Sludge Lancing and Inner Bundle Lancing, additionally the purpose of TV inspection and FOSAR attempts will be included. The paper will offer an insight into the results of this year's outage as well.

II. Degradation Mechanism Denting

Denting is the mechanical deformation of the Steam generator tubes due to the external pressure forces acting on the outer diameter. When rapid growth of the material trapped in the crevices of tube-to-tube sheet occurs it causes a reduction in the tube diameter. Historically this degradation mechanism was mostly reported in crevices between tube-to-tube support plates, but recently the mechanism is seen as in NEK case in the tube-to-tube sheet locations despite the better tube material (690) than historically more susceptible alloy 600 and alloy 800.

There are two contributing factors for denting mechanism to occur. The first precondition is the existence of metallic iron in the crevice which can be present due to carbon steel tube sheet or due to the ingress of ferritic particles originating in the secondary water-steam cycle of the NPP.

A second contributing factor is the presence of oxygen in the area of said ferritic material. That leads to a rapid expansion of the volume of the impurities and thus affecting the outer/inner tube diameter. If the crevice is exposed to additional corrosive impurities the reaction is only accelerated by interacting with basic tube sheet material – often carbon steel. Since Top of Tube Sheet (TTS) hard sludge area is present in Krško SG's it blocks the free expansion of interacted materials thus causing them to deform SG's tubes.

The formation of the initial crevice in a tube-to-tube sheet is a consequence of the manufacturing process. Since it was not advisable to expand the tubes till the very top of the tube sheet due to the possibility of overexpansion and causing an initial crack, the hydraulic expansion was suspended 1~2 mm below TTS and therefore creating a small crevice in the described area.

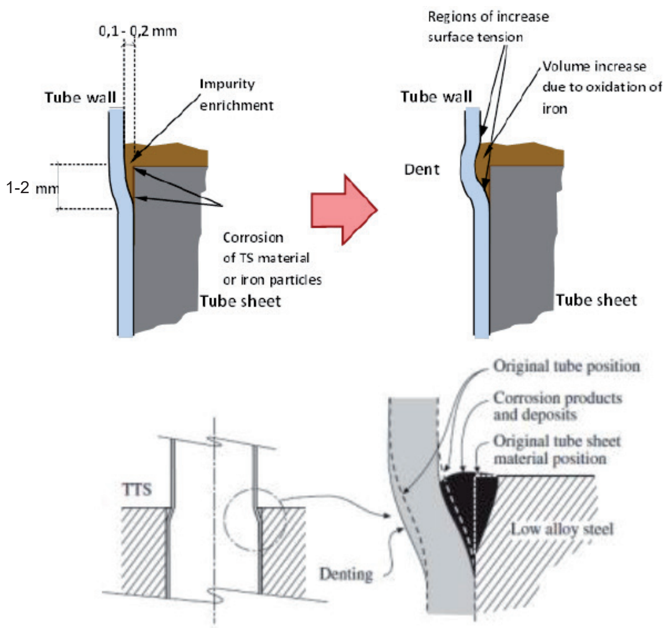

Fig. 1: Origination of dents on TTS

Regulation dictates that all tubes of SG must be checked with ECT every 5 years. ECT probes must fulfill something known as Fill Factor, which dictates that the probe diameter must be at least 80 % of the SG tube inner diameter. If the tube is inaccessible or its diameter is reduced due to excessive denting which causes that the fill factor criteria can't be met, the tube must be plugged preventatively. In the worst-case scenario denting can cause Outer Diameter Stress Corrosion Cracking (ODSCC).

2.1 Mitigation of denting

Denting can be mitigated with two main preventive actions and one corrective.

Firstly, the goal should be to limit particulate releases in the secondary water-steam cycle. This can be achieved by adhering to strict pH control or use of erosive/corrosive resistant materials, operating in steady state conditions, or injection of Film Forming Amines.

Secondly, the goal should be to limit oxygen levels in the secondary water-steam cycle. This can be achieved with strict control of Feed Water (FW) during On-Line (OL) operation, strict control of Auxiliary Feedwater (AF) during startup and shutdown, conservation of the secondary side of SGs with hydrazine, wet layup, and Film Forming Amines (FFA) during an outage.

Thirdly, the curative action is to remove the particulates accumulated on TTS. This can be achieved with the use of Blow Down (BD) system, Sludge Lancing (SL), Inner Bundle Lancing (IBL), chemical cleaning, Upper Bundle Flushing techniques, or installation of CY magnets. Newer options for sludge removal are the use of Poly Acrylic Acid (PAA) dispersants.

III. Chemical Cleaning – Flow of Events from the Decision to Execution

After the denting discovery in outage 2018, the technical debate was convened in NEK, where a mitigating strategy was presented and the decision for chemical cleaning in outage 2019 was formalized. Since NEK had no previous experience a benchmark of two NPPs that have performed where utilities used two different CC vendors. The first NPP was ASCO in Spain and the second was Belleville, France. This led to the realization of important factors the chemical cleaning process had to assure. The scale of equipment used for chemical cleaning had to be small enough to fit in the planned NEK area. Additionally, the process had to be efficient to clean the desired hard sludge area on TTS. Also, the process had to "fit" into the planned time schedule of the 2019 outage plan.

The bidding process was finished in March of 2019 and the selected vendor was Framatome GmbH for CC and mechanical cleaning operation. NEK had performed the QA audit the following month and received the "NEK Replacement Steam Generator Assessment Study" the month after. The study analysed a wide range of secondary chemistry data, the result of which was a selected process for chemical cleaning called DART LT - Deposit Accumulation Reduction Treatment at Low Temperatures with EDTA (95–100 °C). In June Adaptation study document followed which in detail defined the chemical cleaning procedure. Several performance tests were running simultaneously as well as presentations to the Slovenian regulatory body, Krško Safety Comitee (KSC), and internal organization. Additional walkdowns were performed and an equipment laydown area was prepared to facilitate the planned equipment.

IV. Setup of equipment

The arrival of equipment and its security check took place on 26/9/2019. The equipment was set up in the following days, which included the two separate units for SL and IBL processes both equipped with separate filtration systems and a Chemical injection container, two equipment containers, 2 additional quick shop containers, one large Waste sump trailer, and one insulated trailer for DD water, 4 TRAMETHYN – EDTA IBC double wall storage tanks, Severe Accident Mitigation Equipment (SAME) air compressor, and some additional spare equipment container.

The equipment was placed on the west side of the TB next to CY storage tanks.

Fig. 2: Equipment setup outside Reactor Building

Cable and hose routing was set up through Intermediate Building 100 (IB 100) elevation and consequently to Reactor Building (RB)100 and RB107 upon emergency hatch opening. Additionally, the heaters used for chemical cleaning and the distribution control were set up in IB100 as well to be as close as possible to SG's and to maximize the efficiency of the process.

After the arrival of personnel, a detailed pre-job briefing and basic general employee training were conducted. For of chemical/ mechanical cleaning containment integrity is not required, so as soon that's the case, the equipment inside the RB and outside of it is connected and water was recirculated through both systems to ensure a leak-tight connection. During the first recirculation, a water sample is taken to prove the cleanliness of the cleaning equipment before the introduction of that water inside the NEK's SG's.

V. Operation

5.1 Chemical cleaning

The proposed sequence of sludge removal process was:

- SL1 on SG #2, Drying, TVI1 on SG #2 + FOSAR;
- CC on SG #1 and SG #2;
- Rinsing of SG #1 and SG #2 after CC;
- SL1 on SG #1, Drying, TVI1 on SG #1 + FOSAR, IBL on SG #1, SL2 on SG #1, Drying, TVI2 on SG #1 and FOSAR2;
- IBL on SG #2, SL2 on SG #2, Drying, TVI2 on SG #2 and FOSAR2.

The reason for the difference in the cleaning sequence was that SG #2 had reported foreign object (FO) in the non-desirable area during the 2018 outage and it was desirable to retrieve it first. Another reason was to maximize the efficiency of the chemical cleaning process, the RCS had to be drained as to prevent the heat reduction of the chemicals if it were to "escape" to the primary system through filled SG tubes.

5.2 Sludge Lancing (SL)

An SL robot is positioned and operated in the NO-Tube lane to remove the loosened sludge accumulated inside the hot leg (HL) and cold leg (CL) out of the tube bundle. The water is directed to the SG through high-pressure (HP) pumps (200 bar and 250 bar). Then the mixture of water plus sludge is removed from the SG by diaphragm pumps and trapped by high-performance filtering elements. The water is then conducted to a storage tank, to be re-injected into the steam generator by high pressure and peripheral jets pumps (see Figure 1). A bypass loop cools the water from the storage tank and purifies it so the SL cleaning process uses as neutral water as possible inside the SG's.

Because of the triangular pitch of the Krško SG's, the SL robot can be used in a 90° direction and 30°/150° from the NO-Tube lane. With the orientation of the jet stream in the direction of 30°, 90°, and 150°, it is possible to reach both a higher number of passes of the HP jets and various areas of the tube bundle compared to cleaning only at 90°. In this manner, the "shadow areas" which are behind the U-tubes from the perpendicular direction of the NO-Tube lane are also reached and cleaned.

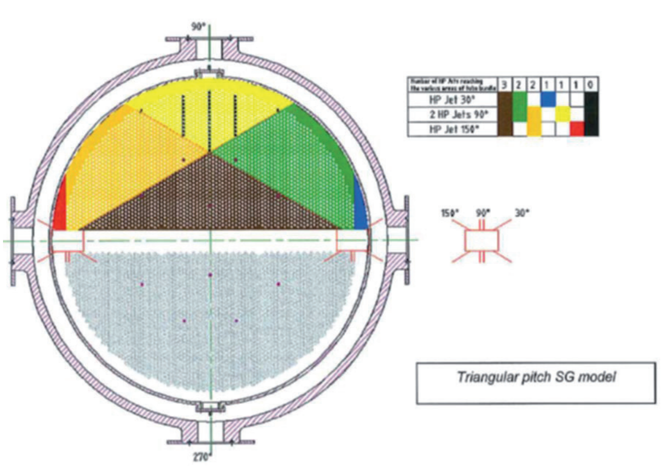

Fig. 3: Direction of High Pressure (HP) jets inside SG during the sludge lancing phase

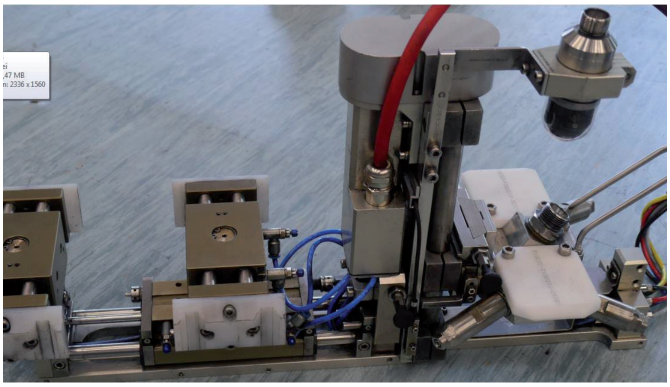

Fig. 4: SL manipulator

5.3 Inner Bundle Lancing (IBL)

A manipulator installed in the NO-Tube lane is equipped with an HP lance which can enter between tubes. Its goal is to break hard sludge deposits inside the tube bundle in the very low-velocity water area. The lance can be guided at a 90° angle and can reach the farthest area of SG tube rows. IBL lance travels between the tube bundle at different heights depending on the hard sludge situation. The spray head is spraying at a 60 ° angle which is constantly adjusted by the software program.

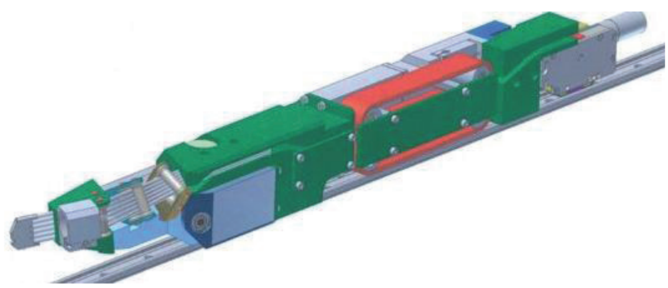

Figure 5: IBL manipulator

5.4 Drying

After SL, the SG must be prepared for TV inspection. Due to high humidity inside the SG after SL/IBL phase, the camera lens could get foggy and the image becomes blurry, therefore the drying equipment is introduced. The drying equipment consists of two intake units with HEPA filters, a double fan unit with a heater, and connection hoses. The discharge hoses are connected to the SG's inspection holes in the direction perpendicular to the NO-Tube lane. At least one secondary manway must be opened to effectively dry the SG before TV inspection. This process lasts about 10 hours.

5.5 TV inspection and FOSAR

Remote visual inspection is performed to inspect the inner tubes on the tube sheet, after the Sludge Lancing, to check the cleanliness, locate eventual foreign objects and check the result of the Sludge Lancing. A manipulator works the same as the IBL one, but instead of a high-pressure tape, the system uses a camera tape for inspection. Additionally, as a backup the vendor uses a crawler moving in the NO-Tube lane. The lance goes into each inter column at 90°, from the NO-Tube lane to the peripheral lane. The gap between each U-tube is approximately 3.6 mm when the tubes are new and no sludge has been accumulated. A small layer of sludge on the tube can block a camera path regardless of the fact, that the lens is only 2.7 mm thick. Another obstacle inside the SG is the space between a Tie-Rod and a U-tube.

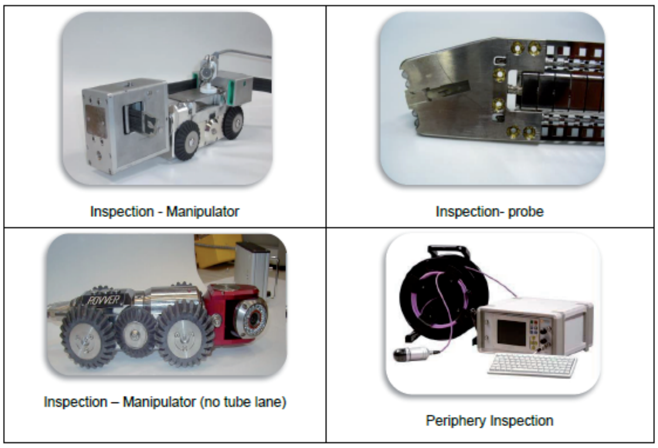

Fig. 6: TVI inspection tools

If a foreign object is found inside the SG, its location is carefully noted, the object is categorized, its length, weight and material is approximated. The categorization is carried out using the EPRI Technical Report 1020989 Steam Generator Management Program: Foreign Object Prioritization Strategy for Triangular Pitch Steam Generators. Based on the shape, size, and position of the object, its general location inside the SG, and some other factors, a decision will be made if a retrieval attempt is performed. TV crawler in that case acts as a guide for the operator who manually inserts the tool and tries to grab the object stuck inside the SG. The success rate of these attempts varies and depends mostly on the skill of the operator of the FOSAR tool and experience. If an object is retrieved, a detailed analysis is conducted to determine its origin and structure. If the attempt fails, the location is reported and ECT inspection of the contact and surrounding tubes is performed at the shortest possible interval. Some objects are monitored during the entire time of operations in the SG's.

VI. Results

6.1 Introduction

The results of mechanical and chemical cleaning of the Krško NPP steam generators in the outage of 2019 are satisfactory, particularly in terms of the amount of removed sediment: 223 kg out of an estimated 290 kg. The estimation included total sludge inventory in the tube sheet area up to a height of approximately 1m. However, we can be less satisfied with the fact that we have not been able to clean both top-of-tube sheets (TTS). After the finished activity and "Lessons learned" we can now summarize the influencing factors, good and bad experiences, and give an evaluation of performance.

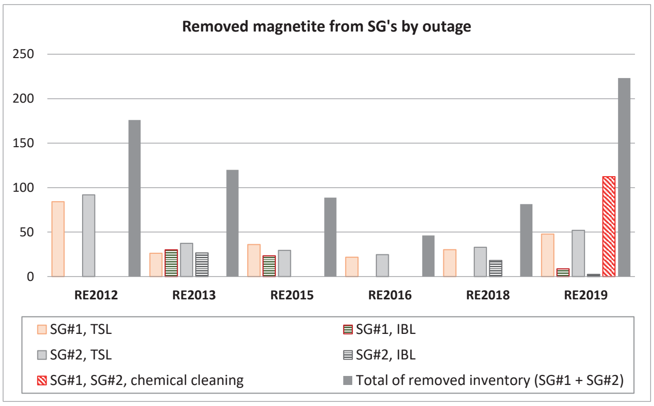

Fig. 7: Balance sheet of removed magnetite from SG's since 2012

6.2 The short duration of the chemical phase (minus grade)

In October 2018, the length of the chemical cleaning activity was set based on the maximum length of the planned outage which was 28 days. At that time, the planned duration of the chemical phase was 80 hours, although the contractor's recommendation was from 100 to 110 hours. In addition, the "Performance Test" was performed at a time of t ≈ 100 hours. Due to other interconnected activities such as SL, IBL, VT, and FOSAR, no additional time was available in the overall Outage Plan.

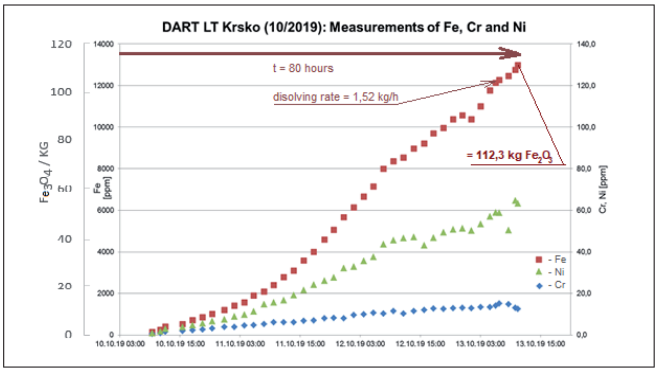

Fig. 8: Concentration rate of Fe, Cr, and Ni in EDTA solution during NEK application

At the moment when the dissolving rate of Fe was 1.52 kg/h, we discussed the possibility of process extension. The contractor proposed to extend it to 94 hours, which would provide 6 hours of "Safety margin" based on the 100-hour "Performance Test" qualification. We organized a meeting to extend the activity on the critical path, but during the meeting trend slowed down and the additional extension time was not agreed upon. Assuming that the chemical cleaning phase was prolonged, likely another 25 kg of Fe or more would be dissolved (1.36 x 25 = 34 kg Fe_3O_4). This would further improve the overall balance and reduce the hard deposits area. It should also be noted here that the amount of dissolved Ni and Cr was much lower in the chemical treatment than in the Qualification Performance Test, which means that there was no significant impact on the materials or systems.

Table I

Removed sludge balance sheet

Removed sludge balance sheet (SG #1 & #2 in R´19 /out of 290 kg estimated)		
	SG #1 [kg]	**SG #2 [kg]**
1. SL		32,65 (before C.C.) *
Chemical cleaning ∑ (SG#1 + SG#2)	112,3	
1. SL	18,18 (after C.C.)	
IBL	8,598	2,536
2. SL	29,663	19,342
∑ (SL+IBL)	56,445	54,528
Mechanical cleaning ∑ (SG#1 + SG#2)	111,0	
∑ (CC + MC)	**223,3**	

* Since SL was performed on SG #2 before CC, it is believed that was the reason for an overall cleaner TTS on SG#2

6.3 Chemical composition of soft and hard sludge and influence on the chem. dissolution rate (minus grade)

2019 outage dissolutions of Fe or. Fe_3O_4 in EDTA solution was significantly slower and smaller in the site-implementation process than in the Performance Qualification Test under laboratory conditions at contractors' facilities, where previously removed (soft) sediment from the Krško NPP was used.

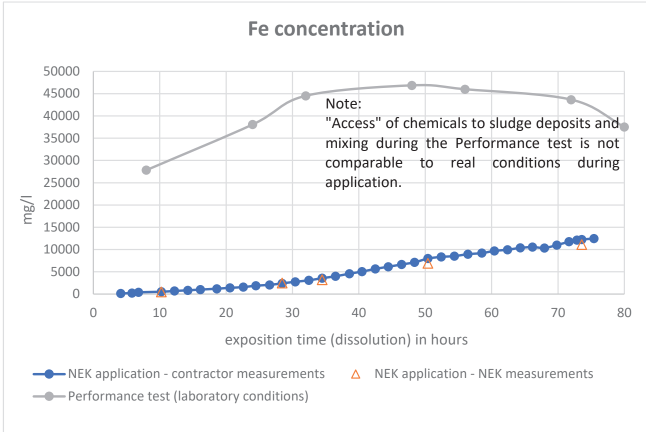

Fig. 9: The dynamics of real-life dissolution in the Krško NPP compared to the Performance Qualification test.

Some influential factors that have reduced solubility and slowed down the process can be identified:

- The hard sediment in the steam generator is compact, a kind of "concreted magnetite" that has been formed layer after layer since the replacement of SG's in 2000. Magnetite used in the "Performance test" was in the form of soft sludge like wet powder compared to hard sediment in the steam generator that had to be dissolved layer after layer again. The process was therefore slower and less efficient than in the laboratory.
- Mixing the medium in a laboratory autoclave was much more efficient than with the actual process in steam generators, where the tube bundle represents a large hydrodynamic flow resistance. Kinetics of a chem. reaction in the steam generators was, therefore, smaller and the process slower.
- The chemical composition of soft sludge is not the same as that of hard sediment. The presence of silicon (Si) and aluminium (Al) is known to have a negative effect on the dissolving of magnetite because it promotes the formation of highly resistible deposits. The last exact chemical composition of sediments is from the outage of 2012. The Si content increased from 2004 (the first analysis of sludge morphology) to 2012. Al in sediments (2004, 2006, 2009, and 2012) has not been reported.
- The laboratory can efficiently control the temperature during the whole process whereas the real-life application experiences some variations during this time.

6.4 Comparison of SG #1 and SG #2 cleaning sequence (plus SG#2 assessment)

Due to the outage plan and the fact that SG #2 was available earlier, the cleaning sequence started before SG #1. The proposal to start with SL (Sludge Lancing) was accepted, so the sequence of activities on both was a little different, which in the end contributed to a more efficient sludge removal on SG #2. The sequence of activities was:

Table II

Comparison of SL1 between SG #1 and SG#2 before and after CC

Comparison of SL1 between SG#1 and SG#2 before and after CC		
	SG #1 (kg)	**SG #2 (kg)**
1. SL (Sludge Lancing)	18,184 (after C.C.)	32,650 (before C.C.)

From the large amount of soft sediment removed on SG #2, it was be concluded that on SG #1 a chemical dissolution of soft sludge took place which could have been removed by SL if the sequence of sludge removal was the same as on SG #2. Based on chemical principles and kinetics, the chemical reaction of dissolving the soft granulate* is faster, rather than the hard layers of magnetite, which at that time were mostly covered with soft sludge. Access to hard sludge to EDTA was severely restricted and this is the reason that the chemical dissolution of hard sediment at SG #1 was not as effective as at SG #2. Basically, at SG #1, we believe we used a chemical process to remove a lot of soft sludge that would be easier to remove with SL. Therefore, the final mass of sludge was smaller. (Soft granulate*: a mixture of dust and small moving particles of soft sludge of different sizes on the TTS).

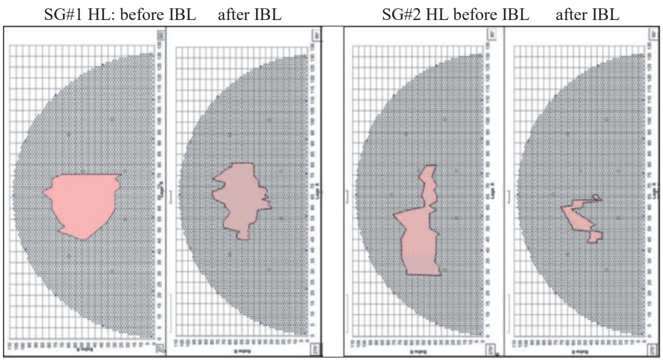

Fig. 10: Hard sludge deposits on Hot Legs of SG#1 and SG#2 before and after IBL

The surface area of hard sludge at the top of the tube sheet (TTS), which is a basic precondition for the formation and progression of the denting mechanism, decreased largely on SG #2 than it did on SG #1 after all removal activities. We expected similar sludge removal efficiency on both SG's but the distinction in the sequence of the mechanical and chemical cleaning process is probably the reason for the resulting differences.

6.5 Scraping / peeling off of brittle scales on SG tubes (plus grade)

Before the final VT (visual inspection) of the tube sheet, where foreign bodies were registered and the size of the area with hard sludge was determined, the plan was to dry the tube bundle with hot air as in previous outages. As a result of drying, peeling of a thin layer of hard scales on the tubes occurred. This is probably due to a combination of chemical cleaning and later hot air drying, which led to an uneven expansion of the scaling material and tubes of the steam generator (Figure 5). The result was a large amount of magnetite "scales" that were washed into the BD system and not taken into account in the final mass balance of removed sludge.

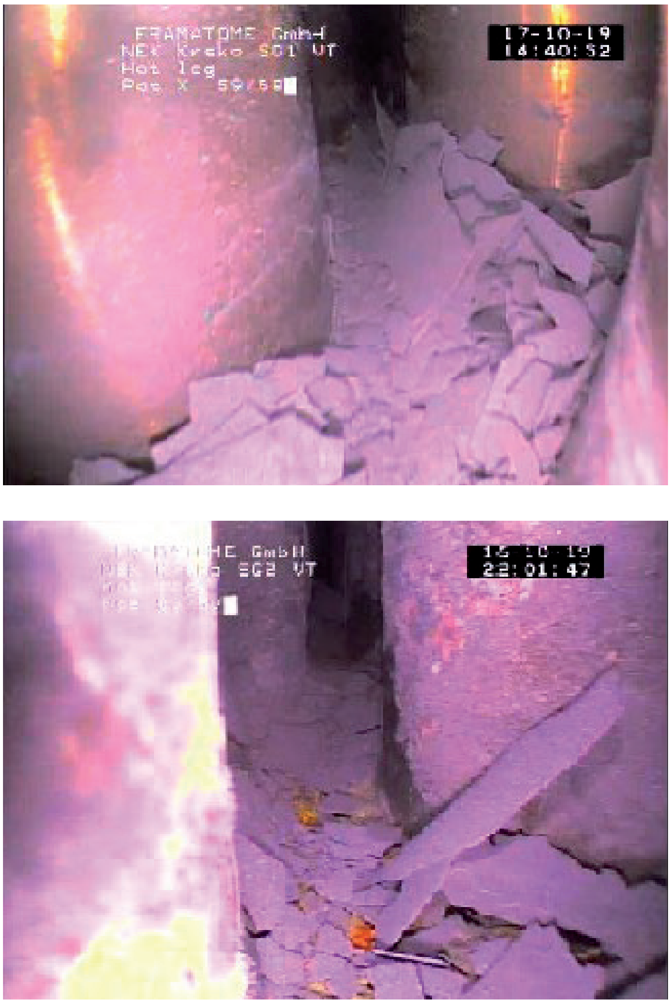

Fig. 11: Fallen scales of magnetite after SG drying phase

6.6 Appearance of a large number of foreign objects and their classification (plus grade)

Chemical cleaning was used to dissolve the hard sludge at the top of the tube sheet, which also revealed some foreign objects that were in deeper layers and had never been discovered before. The number of foreign objects is high, but most of them are thin wires that probably belonged to a wire brush.

Due to their weight and size the discovered foreign object are non-dangerous (classification: Type 1 / Category 3; Foreign Object Classification), but they leave a bad impression and they will have to be monitored in the future. If the process of accumulation of hard sludge continues, it will "disappear" over time. Their removal is not necessary and would often be technically impossible or at least very complicated and time-consuming.

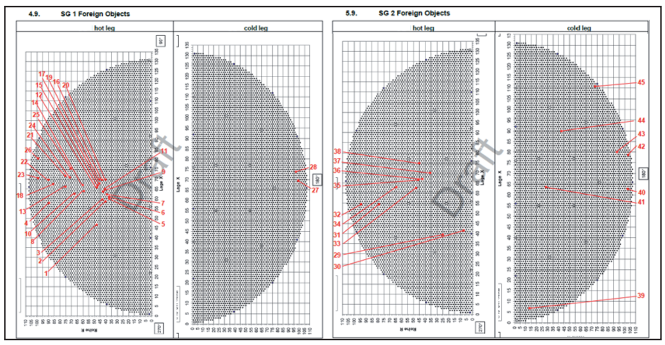

Fig. 12: Foreign object placement after outage 2019

Limiting Object Categories[1,6]

Classification Type Number	Object Type Classification	Category 2 (Medium) Acceptable Object Dimensions (inch)[2]	Category 3 (Low) Acceptable Object Dimensions (inch)[2]
1	Wire[3]	2.5 long x 1/16 dia	1.75 long x 1/16 dia
2	Rod[4]	2.0 long x 1/8 dia	1.5 long x 1/8 dia
3	Rectangular Metal Objects	1/2 x 1/8 x 1/8	1/4 x 1/8 x 1/8
4	Machine Turning	1/2 x 1/8 x 1/8	1/4 x 1/8 x 1/8
5	Gasket[5]	1.75 long x 1/4 x 1/8	1.25 long x 1/4 x 1/8
6	Machine Remnant	1/2 x 1/8 x 1/8	1/4 x 1/8 x 1/8
7	Sludge Rock	1 x 1/4 x 1/4	3/4 x 1/4 x ¼ Or any size if soft or crumbles
8	Balls	1/2 Dia	3/8 Dia
9	Scale	-	Any size if soft or crumbles
10	Wire Bristle	3.0 inch Long 1/32 dia. - If small number found (no clumping found)	2.0 inch Long 1/32 dia. - If small number found (no clumping found)

(1)These object sizes are representative object dimensions based on two operational cycles or three years of plant operation. Actual part geometry, location, orientation and configuration may result in a more aggressive object and, therefore, would require a corresponding change to a higher priority.

(2)These sizes are based on finding the object in the annulus or on the tubesheet behind a tube. If the object is wedged between the tubes, it should be removed or a detailed engineering evaluation performed.

(3)Wires are semi-flexible objects.

(4)Rods are stiff objects.

(5)Assumes the object is lying flat against the tube.

(6)Sizes applicable for objects not located in red exclusion zone.

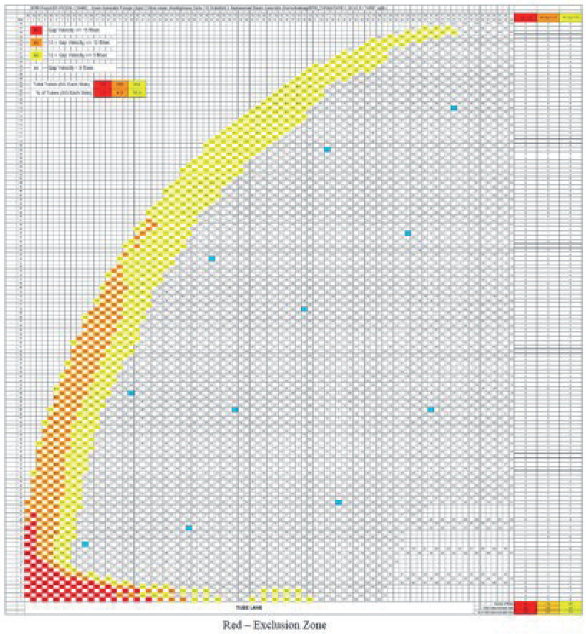

Fig. 13: Classification of foreign objects and the area of high hydrodynamic flow at the periphery of the SG tube bundle - EPRI summary SGMP TR 1020989

6.7 Chemical waste from completed chemical cleaning activity (plus grade)

At benchmarking at Asco NPP in Spain, information was received on the huge quantities of waste chemicals left in the yard after the activity was completed. This was mainly because the waste water showed traces of contamination and the recovery of the waste was not clearly defined in the contract. Therefore, we have included in the technical specification for procurement of the chemical cleaning activity that the contractor is responsible for the recovery and disposal of waste materials. The waste water was not contaminated in our case, so there were no problems in this area. The subcontractor took care of the rapid removal of chemical waste, which also avoided formal complications due to legal requirements for longer storage of this type of waste.

6.8 Removal of hard sludge in the area of DNTs from SG ECT R´18 and ECT reevaluation (2006, 2012, 2018), (SG #1 - minus grade, SG #2 - plus grade)

The primary goal of chemical cleaning was to clean the hard sludge area on the TTS under which the formation of the DNTs is taking place. After the 2018 outage, the ECT data from previous outages was reevaluated to determine when the denting mechanism appeared and with what dynamics it evolved. Statistical analysis of the data revealed that they were most extensively produced in the period 2006-2012, some of them even earlier. By evaluation of 2021 ECT data, it will be able to estimate the combined impact of 2 operational cycles, i.e. OL30 and cycle after chemical cleaning; OL31. Expectation is that we will not notice any progression on the dents around which the ″hard sludge″ has been removed.

Dent re-evaluation statistics also show large difference between the two steam generators. Therefore, it is best to comment on each one individually, but at the same time, it is necessary to evaluate the success of chemical cleaning in the critical area (hard sludge area) where the dents appear, because this can already predict the development or stagnation of this degradation mechanism.

6.8.1 SG #1 Hot Leg

ECT SG #1 in 2018 detected 33 dents on HL, which is essentially a small number based on the size of the ″hard sludge″ area. Interestingly, the 2006 denting mechanism was more developed at SG #1 (29) than at SG #2 (12). Nevertheless, the increment of a new dent at 6 cycles (2006-2012) was lower at SG#1. The right picture of the tube sheet shows the remaining ″hard sludge″ area after the 2019 chemical cleaning. The 2018 dent population has remained trapped in this area, which is not good. Optimistic about SG #1, however, is the fact that we only have 33 dents and that there were no new ones from 2012 to 2018. Since almost all dents have remained in the hard sludge area, we have to say that chemical cleaning on SG #1 HL did not fulfill expectations.

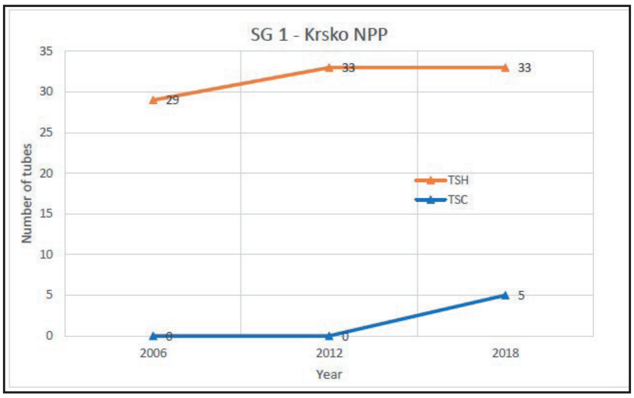

Fig. 14: Hard sludge area and DNT's after CC in SG #1 HL

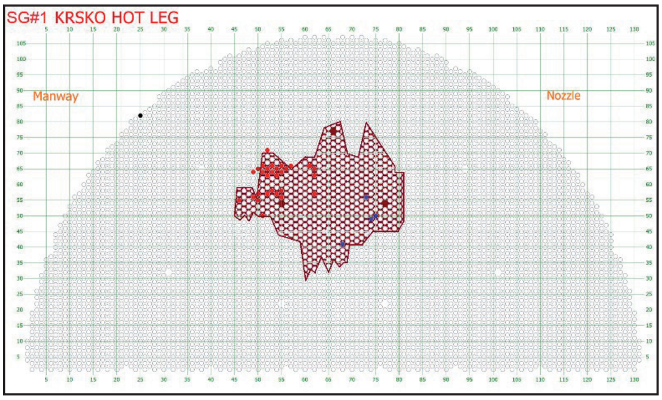

Fig. 15: Dent evolution on SG #1 HL (2002-2018)

6.8.2 *SG #2 Hot Leg*

ECT SG#2 in 2018 detected 83 dents on HL, 2.5 times higher than SG #1, although the hard sludge areas were comparable in size. The denting mechanism started slower than at SG #1, and its result is higher than at SG#1. Chemical cleaning was much more successful at SG #2 because it cleaned > 70% of the area in which the 2018 dents are located. This is far more important because the number of dents at SG #2 is much higher (83) as per SG #1 (33). It is here that we expect that the degradation mechanism will not develop further.

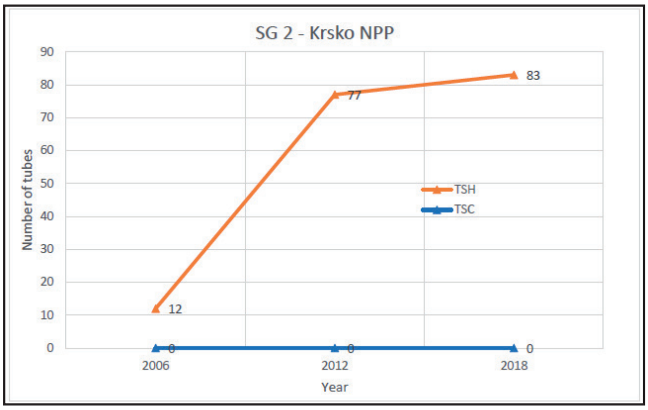

Fig.16: Hard sludge area and DNT's after CC in SG #2 HL

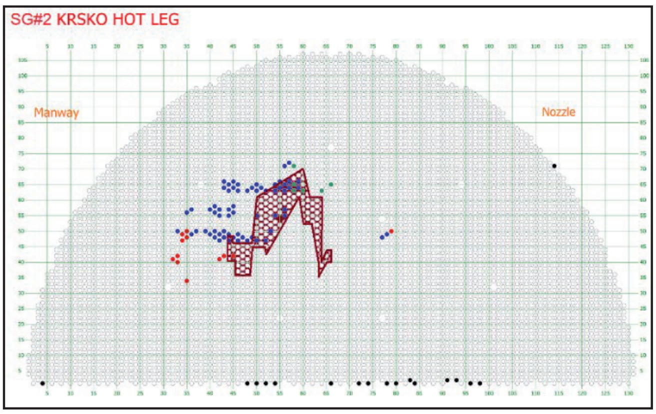

Fig. 17: Dent evolution on SG #2 HL (2002-2018)

With the projects implemented in the past cycle and the results, we have reached a much higher level of understanding of the degradation mechanism of denting, yet we still cannot explain why:

- more dents were generated on SG #2 (83) than on SG #1 (33),
- the number of the newly created dent was lower at SG #1 (4) than at SG #2 (65), in the period from 2006 to 2012
- the rate of newly formed dents decreased on both SG #1 (0 new) and SG #2 (5 new) in the period from 2012 to 2018

Evaluation of 2021 ECT data should provide some new answers. At that time, we will also be re-evaluating the dents from the second set of 50% ECT volumes (2021 – 2015 – 2009 – 2003). For the first time, we will also review the entire dent population - in the 100% scope in the same outage. This data will allow a final assessment of chemical cleaning, as well as an answer to whether the denting process has slowed down or even stopped. Should the trend continue or become even more intense, we can seriously think of repeating such a campaign.

At the moment, the results of statistics and predictions are not too pessimistic. In addition to that, some improvements are also planned that should make a positive contribution to water quality which supplies the FW system of steam generators. The final answer to the question of whether we need to do chemical cleaning in the area between the tube sheet and the first support plate again will be known after the following outages.

VII. Conclusion

In conclusion, the combined chemical cleaning and mechanical cleaning process met the expectations regarding the mass of sediment removed: 223 kg from an estimated 290 kg. The extracted amount equals to 77 % of the estimated, although the NEK goal was set around 80-90 %. The incomparable cleanliness of the hard sludge area especially on SG #2 was satisfactory which shall have a positive effect on the dent growth in the future. For SG #1 HL, the combination of the two cleaning methods fulfilled our expectation to some degree as we expect that due to the difference in the cleaning sequence the results were more visible on SG #2. Additionally, the CL sides of both steam generators were sufficiently cleaned as well. The most negative contributing factors that reduced Chemical Cleaning effectiveness were:

1. Short running time of the chemical cleaning phase (performed in $t = 80$ hours, which would require $t \geq 100$ hours or more).
2. Activity sequence plan: likewise, on SG#1 the activity sequence should start with SL (Sludge Lancing), as it was with SG#2.

References

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[3] "Technical Description SL_VT_IBL_FOSAR" Reference number: F.031071-B-02, February 2019

[4] "DART LT NPP Krško 2019 - Final report" Reference number: D02-ARV-01-149-781, rev. A, December 2019

[5] "MC Technical Document for Final Report" Reference number: D02-ARV-01-149-200, rev. B, December 2019

[6] NEK CC project materials, July 2018 till December 2019