Proceedings of the ASME 2013 Pressure Vessels and Piping Conference
PVP2013
July 14-18, 2013, Paris, France

PVP2013-97269

PWR AND WWER STEAM GENERATOR TUBE INTEGRITY ASSESSMENT

Roman Krautschneider
Institute of Applied Mechanics Brno, Ltd. (IAM Brno)
Veveri 95, Brno 611 00, Czech Republic
Email: krautschneiderr@uam.cz

ABSTRACT

Paper is describing and comparing degradation mechanisms and integrity assessment of PWR and WWER type of steam generator tubes. Because of different design, different used materials and also different operating conditions, there are significant differences in degradation mechanisms. Therefore both steam generator types have their specific codes dealing with inspection, monitoring and maintenance.

INTRODUCTION

Ageing management of main primary components of a nuclear power plant (NPP) has been in major focus for many years.

The steam generators (SG) in the pressurized water reactor (PWR) and Russian water moderated, water cooled energy reactor (WWER) plants are large heat exchangers that use the heat from the primary reactor coolant to make steam in the secondary side to drive turbine generators. A typical plant has two to six steam generators per reactor. The steam generators are shell-and-tube heat exchangers each with several thousands of tubes. The primary reactor coolant passes through the tubes and boils water on the outside of the tubes (secondary side) to produce steam. The design confines radioactivity from neutron activation or fission products to the primary coolant during normal operation.

Tube degradation in steam generators can be due to corrosion mechanisms, mechanical wear, and fatigue. Further, corrosion degradation may develop at locations of local discontinuities such as dings, dents, scratches or other mechanical marks.

There will be described mechanisms and places of damage of steam generator tubes in tube bundle. First part will be dedicated to PWR SGs (vertical SG) and second part to WWER SGs (horizontal SG). Because of different SG's design, tube's material, SG's position, fluid flow and thermal-hydraulic conditions, there are also differences in observed tubes damage on both SG's types.

PWR STEAM GENERATORS

PWR SGs are pressure vessels which are oriented in vertical position. Inside is tube bundle formed of U-tubes placed in tubesheet (Fig. 1). Support system of the tube bundle is formed of baffles.

Initially, the heat exchanger tubing in most of the PWR steam generators placed in-service in the western countries (except Germany) was made from nickel based alloy Inconel 600. The first German steam generators designed by Siemens used also Inconel 600 MA, but due to leaks in steam generators after two cycles caused by stress corrosion cracking (SCC), those SGs were replaced by SGs with alloy Inconel 800NG tubing. Since the early 1970s all German SGs were tubed with Inconel 800 NG (I 800NG) material. Now, most steam generators designed by Westinghouse, AREVA NP, Babcock & Wilcox and Mitsubishi-Heavy Industries, Doosan Heavy Industries are being fabricated with thermally treated Inconel 690 (Inconel 690TT). AREVA NP and Babcock & Wilcox Canada are also supplying replacement steam generators with Inconel-800NG tubing or Inconel 690TT.

Inconel alloys are nickel alloys which are oxidation and corrosion resistant materials well suited for service in environments subjected to pressure and heat. Material compositions of frequently used Inconel alloys are shown in Table 1.

Typical locations and forms of degradation on PWR SGs are shown in Fig. 1. The following is a listing of potential degradation mechanisms (it is not intended to be an all-inclusive list).

- Intergranular Attack (IGA) and Outside Diameter Stress Corrosion Cracking (ODSCC)
- Primary Water Stress Corrosion Cracking (PWSCC) and Intergranular Attack
- Tube Fretting and Wear
- Other Wear Damage
- Pitting
- High Cycle Fatigue
- Impingement
- Wastage/Thinning

TABLE 1 FREQUENTLY USED PWR SG TUBE MATERIALS COMPOSITION

Material	Element (% by mass)														
	C	Mn	Si	P	S	Cr	Ni	Mo	W	Ti	V	Cu	Co	Al	Fe
Inconel 600	≤ 0.15	≤ 1.0	≤ 0.50	≤ 0.020	≤ 0.015	14.0 ÷ 17.0	≥ 72.0	-	-	-		≤ 0.50	-	-	6.0 ÷ 10.0
Inconel 690	≤ 0.05	≤ 0.50	≤ 0.50	-	≤ 0.015	27.0 ÷ 31.0	≤ 58.0	-	-	-		≤ 0.50	-	-	7.0 ÷ 11.0
Inconel 800	≤ 0.10	≤ 1.5	≤ 1.0	-	≤ 0.015	19.0 ÷ 23.0	30.0 ÷ 35.0	-	-	0.15 ÷ 0.60	-	≤ 0.75	-	0.15 ÷ 0.60	≥ 39.5

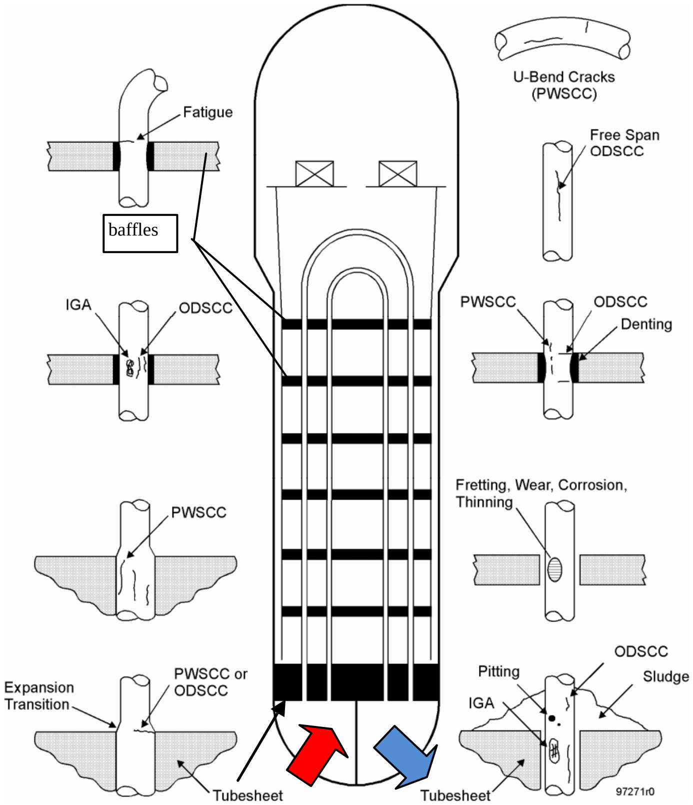

FIG.1 PWR RECIRCULATING STEAM GENERATOR DEGRADATION MECHANISMS [2]

Degradation mechanisms on PWR SGs are very well described, well observed and also have good Fitness For Service (FFS) assessment. EPRI [2] provides guidance for evaluating the condition of SG tubes based on nondestructive examination (NDE) or in situ pressure testing. This integrity assessment is normally performed during a reactor refueling outage. This document has guidelines to satisfy requirements for condition monitoring and operational assessment as defined in the NEI initiative, Steam Generator Program Guidelines, NEI 97-06 [3].

Damage to steam generator tubing can impair its ability to adequately perform required safety functions in terms of both structural integrity and leakage integrity. Therefore, assessing tube integrity is an important component of a steam generator program, which is required by NEI-97-06.

EPRI also maintains the Steam Generator Degradation Database (SGDD). SGDD is a place to collect, store and report relevant steam generator information. Mainly it's a good place to see statistic information about PWR SG tube degradation on various power plants all over the world.

WWER STEAM GENERATORS

WWER NPP horizontal steam generators have different design than PWR SGs. WWER SGs are pressure vessels placed in horizontal position. Tube bundle is formed of "U-tubes" (tube shape is similar to U-tube) and tube ends are fixed to "hot" (inlet) and "cold" (outlet) collector. Collector is like circular shape tubesheet (Fig. 2).

Tubes in WWER SG tube bundle are made of austenitic steel 08X18N10T (also 08Ch18N10T). In Table 2 is shown material composition of the 08X18N10T steel.

TABLE 2 FREQUENTLY USED WWER SG TUBE MATERIAL COMPOSITION

Material	Element (% by mass)														
	C	Mn	Si	P	S	Cr	Ni	Mo	W	Ti	V	Cu	Co	Al	Fe
08Ch18N 10T	≤ 0.08	≤ 2.0	≤ 0.8	≤ 0.035	0.020	17.0 ÷ 19.0	9.0 ÷ 11.0	-	-	5 * %C ÷ 0.7	-	-	-	-	-

Unfortunately degradation mechanisms on WWER SGs tubes are not so well described as by PWR SGs. One of the reason is that WWER SGs are not so frequent as PWR, and thus the statistical data are not many.

In many publications dealing with WWER SG tube degradation is only mentioned Stress Corrosion Cracking (SCC) as the main reason of tube damage during operation. Sometimes is also mentioned pitting to be found.

Steam generator secondary side water is like corrosion-active medium, containing activators and oxidants. In our case the SCC occurs in places of higher concentration (small gaps and sedimentation on tube's outer surface) of dissolved impurities such as chlorine ions (Cl^-) which are working like activators. Like oxidant appears oxygen (O_2).

Usually places with creation of sediments e.g. the narrow gap area between tube outer surface and collector, can be a possible place of SCC. There are two major types of sediments found on outside diameter of WWER SG tubing. It's hard sediments and soft sediments, both can be often found on lower positioned tubes and having high corrosion potential.

In Fig. 3 are shown typical areas of tube bundle damage on both main WWER SG types - PGV-1000 and PGV-440. More frequently some tube defects occur on so called "HOT side" of the tube bundle (in figure is shown hatched) and especially the area around hot collector (HC) (usually up to four baffles far from HC) is the most critical one. In PWR SGs is the "hot" side (the first half-turn part of U-tubes) also the side with more frequently found defects .

In Fig. 4 is shown statistics of plugged tubes depending on position in tube bundle. It can be seen that most frequently are damaged low position tubes.

Cracks are mostly oriented in tube axis direction and have intergranular character, but sometimes also transgranular or coupled character. Inspection of tube integrity is done same way as by PWR SGs and that is using eddy current testing (ECT).

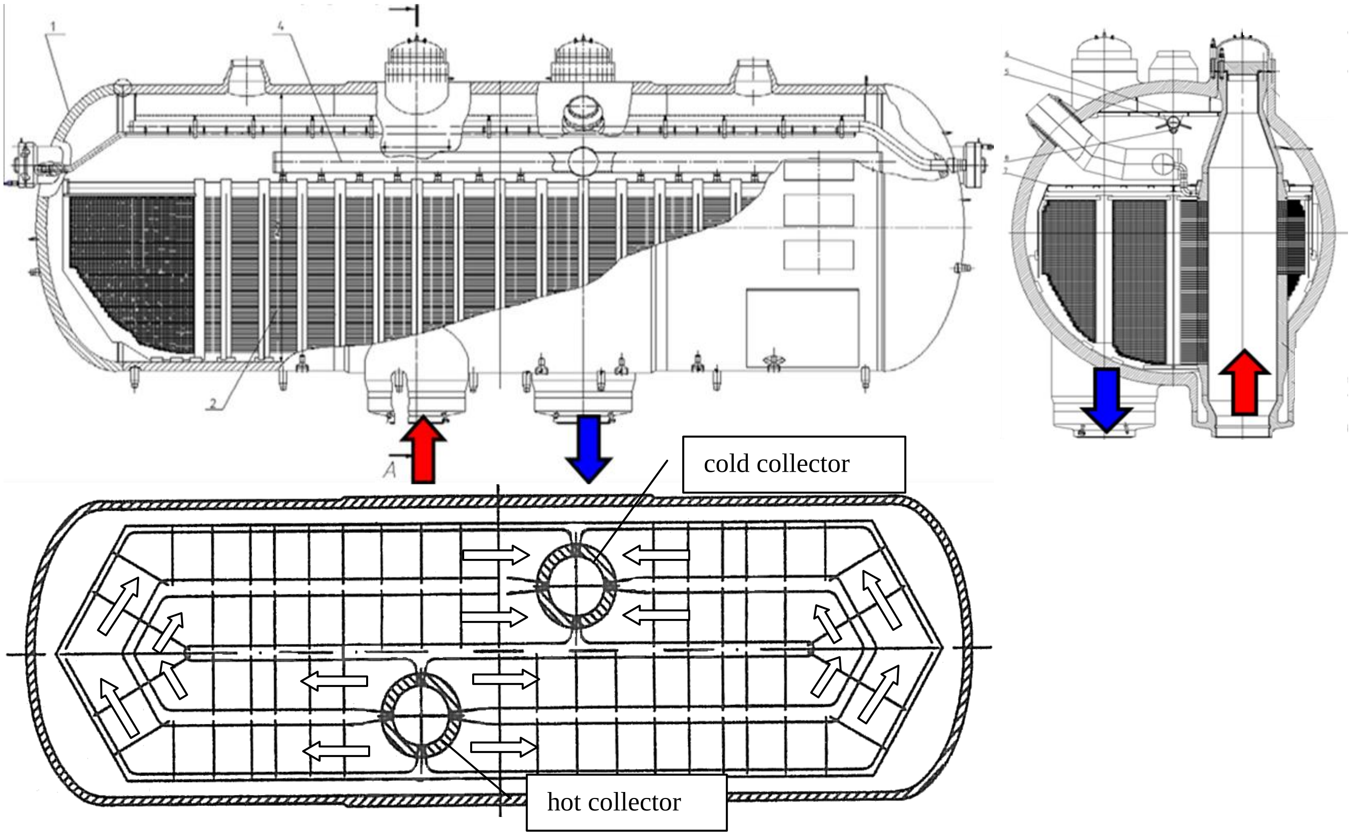

FIG.2 WWER 1000 STEAM GENERATOR WITH SHOWN TUBE BUNDLE SHAPE [7]

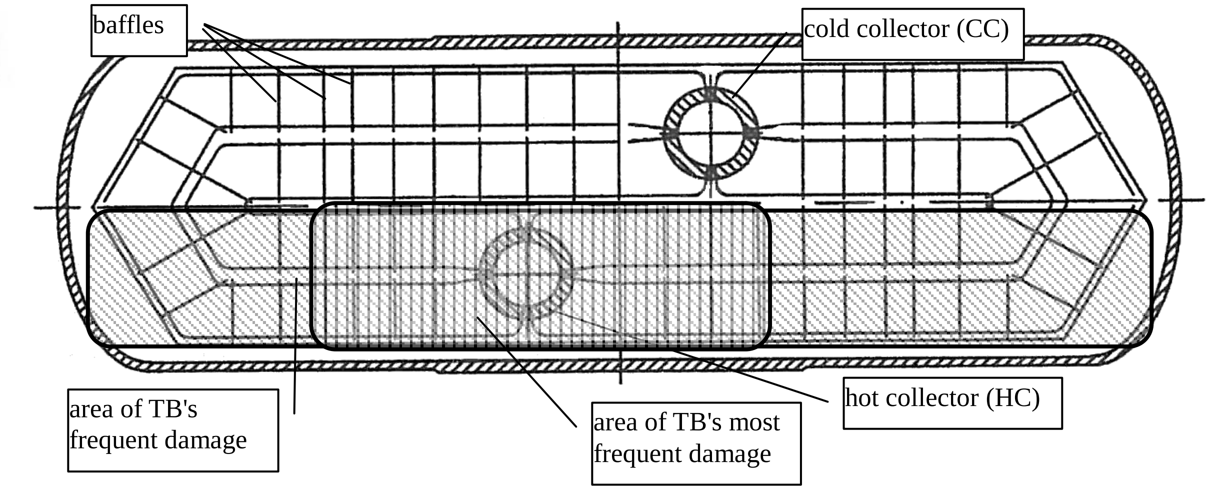

FIG.3 WWER STEAM GENERATOR TUBE BUNDLE FREQUENT DAMAGE LOCATIONS

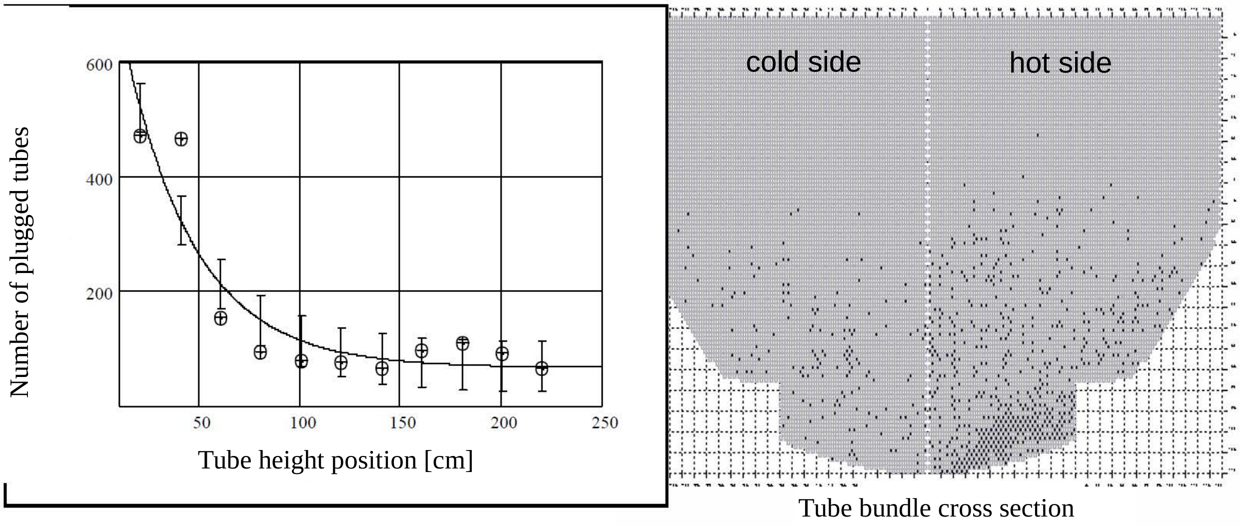

FIG. 4 STATISTICS OF WWER SG PLUGGED TUBES - TUBE POSITION(HEIGHT) DEPENDENCE (WITH TOLERANCE INTERVALS) [9]

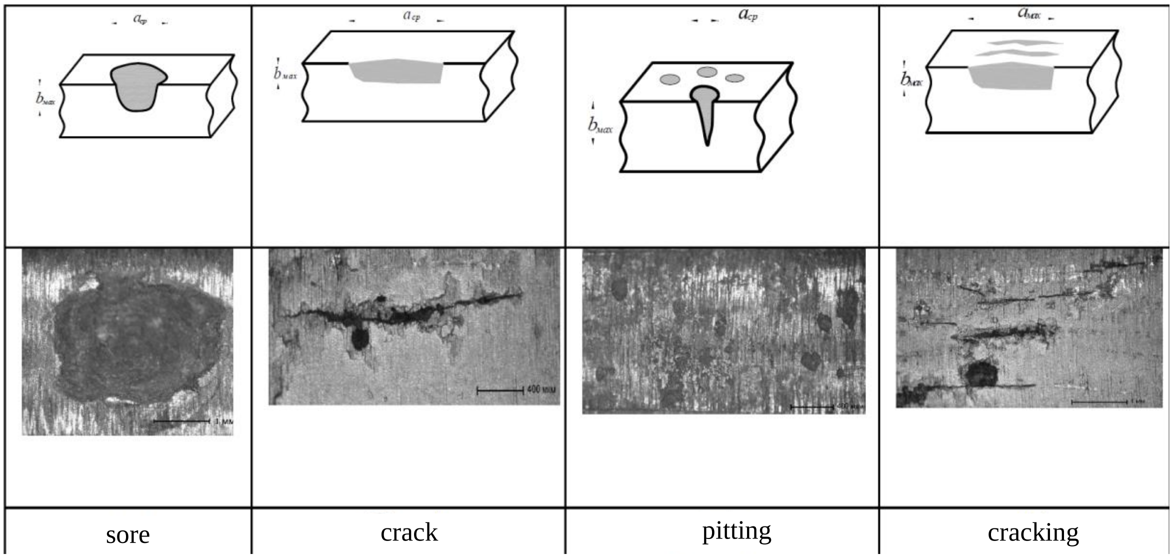

FIG. 5 DEFECTS FOUND ON WWER SG TUBES [9]

In connection with SCC there are 3 factors for tube defects rising in WWER SGs (this can be also applied to PWR SGs of course):

- local sedimentation on tube's surface
- local heat flow on tube's surface
- local concentration of dissolved impurities (chlorides) in SG water

In Fig. 5 are shown some examples of defects found on WWER SG tubes. When the NPP has a condenser made of copper it leads to intensification of corrosion processes in SG, because Cu has a high corrosion potential.

SUMMARY AND CONCLUSION

There were shown different types of tube degradation mechanisms for PWR and WWER steam generators. Because of long history of PWR SGs and because heat exchanging tubes are frequently damaged and well observed part by PWR SGS, there exist a large database of plugged tubes from NPPs all around the world, where are also identified causes of plugging of each tube. Such large statistical data are missing by WWER steam generators.

Generally said tube degradation is not so big problem on WWER SGs that is on PWR. Major cause of tube plugging by WWER is Stress Corrosion Cracking (SCC) mechanism. That's why on WWER SGs it's important to keep tube bundle clean of deposits. If the SG's chemistry is on high level, there is no need for tube plugging on WWER SG's.

Comparing PWR and WWER steam generators, there seems to be missing some PWR's frequent non-chemical degradation mechanisms like fretting, thinning, denting, wear or fatigue on WWER's.

From the point of view of tube inspection, for both PWR and WWER steam generators are used same Eddy Current Testing (ECT) inspection methods. Used are either standard bobbin probes or advanced rotating probes. Using ECT is still quite new on WWER NPPs comparing to PWRs, where it was started to use much sooner. But between WWER and PWR SGs is still a big gap on the field of Fitness for Service assessment (FFS). One important area is the tubing repair criteria, where is now quite a large difference in how different countries decide when the tube should be repaired (plugged or sleeved). Some the earliest guidance on this subject was publish in the US Code of Federal Regulations and the ASME Pressure Vessel and Boiler Code. The ASME code states that for U-tube steam generators, the allowable outside diameter flaw shall be less than 40% of the tube wall thickness. This criterion was initially implemented in most countries with PWR and CANDU NPPs. However, alternative criteria are allowed by the ASME code if accepted by the regulatory authority. In recent years, a number of countries have found out the original ASME criterion overly conservative and inflexible and have developed revised or new FFS criteria, often in conjunction with revised inspection requirements. So that's why although the new FFS criteria used in most countries follow the general technical basis, there are still substantial differences in implementation. In Table 3 are shown SG tube plugging criteria in some countries.

TABLE 3 TUBE PLUGGING CRITERIA IN DIFFERENT COUNTRIES

Country, type of NPP reactor	Tube plugging criteria damage level *d* (% of wall thickness)
USA, PWR	>40
France, PWR	>40
Brasilia, PWR	>40
Slovenia, PWR	>45
Germany, PWR	>60
Canada, CANDU	>40
Bulgaria,WWER	>40
Czech Republic, WWER	>80

In Table 4 are listed SG tube inspection rules for different countries. It can be seen there is a substantial difference in number of inspected tubes and inspection intervals. In connection with this, there is another big gap between WWER and PWR SGs in degradation assessment. For PWR SGs there exist very good guidelines elaborated by EPRI [2] for SG integrity assessment, where are also mentioned statistical methods for degradation growth assessment with examples. Because such document was missing for WWER SGs, there were written at least some simple strategies for WWER SG tube integrity assessment by IAEA [5]. This document was based on experiences on WWER and the existing EPRI PWR SG guidelines [2]. Some statistical approach for WWER SGs was also proposed by Gulina et. al. [9]. Their proposed method for degradation growth assessment is based on Kalman linear stochastic filter. But even when there already exist some guidelines for statistical approach by WWER SGs tubes FFS assessment, it's not widely used yet. The reason can be quite low number of damaged tubes on most WWER SGs even after many years of operation. So as it can be seen in Table 4, it's maybe more practical to inspect 100% of tubes in full length in fuel cycle period interval, than trying to implement some statistical approach. But for example for Czech Republic (WWER) it can be seen from Table 3 and 4 that the tube plugging criteria is >80% of wall thickness damage but the inspection interval is quite long. So in this case it is very advisable to implement some degradation growth assessment method.

REFERENCES

1. Krautschneider, R.: Steam generator tubes degradation mechanisms of vertical and horizontal types of steam generators, New Methods of Damage and Failure Analysis of Structural Parts, Ostrava, September 2012
2. EPRI, Steam Generator Integrity Assessment Guidelines, Revision 2, 1012987, Final Report, July 2006
3. NEI, NEI-97-06 Rev.3, Steam Generator Program Guidelines, NEI, Washington D.C., 2011
4. IAEA, Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: Steam Generators (2011 Update), IAEA-TECDOC-1668, Vienna, 2011
5. IAEA, Strategy for Assessment of WWER Steam Generator Tube Integrity, IAEA-TECDOC-1577, Vienna, 2007
6. Kupca, L., Kang, S.: IAEA CONTRIBUTION TO ASSESSMENT AND MANAGEMENT OF STEAM GENERATOR AGEING, 8th International Seminar on Horizontal Steam Generators, Podolsk, 2010
7. TRUNOV, N.B. et al.: Hydrodynamic and thermal-chemical in NPP WWER steam generators, Energoatomizdat, Moscow, 2001 (in Russian)
8. TRUNOV, N.B. : Development and improvement of NPP WWER Steam Generators based on thermal and mass-transfer investigation, Dissertation Thesis, Podolsk, 2003 (in Russian)
9. Gulina, O. M., et al: NPP Equipment Lifetime Management under Ageing, Journal of Reliability and Statistical Studies, Vol. 5, Issue Special 2012, p.27-36
10. Diercks, D. R., Shack, W. J., Muscara, J.: Overview of Steam Generator Tube Degradation and Integrity Issues, 24th Water Reactor Safety Meeting, Bethesda, US, 1996

TABLE 4 SG TUBE INSPECTION IN VARIOUS COUNTRIES [4]

Country	Baseline inspection	Number of tubes to be inspected	Inspection intervals
*USA	All tubes prior to service and after any major change in secondary water chemistry	First inspection, 3% of the total steam generator tubes at a unit. Subsequent inspections Suggestion: All American plants follow the EPRI Guidelines for Examination of SG tubes maybe the document could be mentioned as a reference and used for definition of number of tubes.	First inspection, 6–24 months. Subsequent inspections, 12–24 months. If less than 5% of inspected tubes with indications and no defective tubes, 40 months. If more than 10% degraded and more than 1% defective, <20 months.
Canada	25% of the tubes prior to service	At least 10% of the tubes in one steam generator per unit.	First baseline inspection interval 4–6 years. Second inspection interval since first net power at 10–12 years, third inspection interval 16–18, fourth inspection interval 22–24 years, fifth inspection interval at 28–30 years.
Czech Republic	All tubes prior to service	100% of the tubes in each steam generator must be inspected full length. There are inspected all the tubes from the hot and cold collectors.	ISI intervals are gradually extended from 4 to 6 years/fuel cycles.
France	All tubes prior to service All tubes every ten years (1st after 30 months)	If susceptible tubing, all of the tubes are inspected in the hot leg roll transition, tube support plate and sludge pile regions, and the U bend region of the first row in service, with an appropriate probe. If less susceptible tubing: Sample of tubes inspected full length. All tubes in service with a previous defect indication.	Every outage for roll transition and small radius U bend regions. Every other outage for TSP and sludge pile regions. Sample every two years. Each outage.
Germany	All tubes prior to service	10% of the tubes per steam generator per inspection	Every five years all steam generators Every two years, one half of the steam generators
Japan	All tubes prior to service. Insertion depth of antivibration bars.	If no leakage and no defects: 30% If any leakage or defects: 100%	If no leakage and no defects, every other year. If leakage or defects, every year.
Republic of Korea	All tubes prior to service 20% of total number of tubes each SG	If a potential degradation area (expansion region, U bend, denting or inside the tube sheet) is not verified by the bobbin probe, an additional inspection by RPC is required. The periodical inspection depends on materials (Alloy 600MA/TT, Alloy 690TT), operating years, and degradation status.	Each refuelling outage
Slovakia	All tubes prior to service	100% of the tubes in each steam generator must be inspected full length. There are inspected all the tubes from the both hot and cold collectors.	ISI intervals are gradually extended from 4 to 6 years/fuel cycles.
Slovenia	All tubes prior to service	100% using bobbin coil and all reported indications, roll transitions and inner bends with pancake coil. (Probably, after SG replacement in 2000 the scope of inspection is changed).	Each refuelling outage
Spain	All tubes prior to service	If susceptible tubing: 100% using bobbin coil and all indications and roll transition regions with rotating pancake coil. If less susceptible tubing: 9 to 20%	Each refuelling outage
Sweden	All tubes prior to service	Random sample of 15–17% full length 100% hot leg tube sheet. 20–100% of other selected regions.	Each year
Switzerland	All tubes after one year of operation	If susceptible tubing: inspect the hot leg side up through the U bend region to the top tube support plate on the cold side-full inspection. If less susceptible tubing: random sample of 5.5% of all tubes.	Every outage Every three years

*): If more than 10% of inspected tubes show indications, additional 3% in that steam generator and 3% in remaining steam generators. If more 10% of second batch show indications, inspect additional 6% in area of indications.