Steam Generator Cleanness Management
A Comprehensive Concept for CANDU Plants

C. Stiepani[1], S. Weiss[1], G. Kraemer[1] A. Drexler[1] and J. Fandrich[1]
[1] AREVA NP GmbH, Erlangen, Germany
(christoph.stiepani@areva.com)

Abstract

Steam generator tubes are by far the largest boundary between the primary and secondary side and the overall performance of the plant depends strongly on the steam generators. The steam generator efficiency can be negatively affected by Magnetite deposition on the tubes on either ID or OD. These deposits are a thread to the integrity of the SG due to either ID or OD corrosion. Deposits in the steam generators may promote corrosion phenomena, leading in worst case to a steam generator replacement. A comprehensive cleanness concept, based on optimized water chemistry, chemical and mechanical cleaning processes is mandatory and will be outlined in the following.

1. Introduction

The nuclear power plant asset management strategy must focus on safety, availability and efficiency. Steam generators represent one of the crucial assets. Not only that the steam generator tubes are by far the largest boundary between the primary and secondary sides, the steam generators are also essential in the overall performance of the plant. This calls for an optimization for the steam generators in terms of operating life time and thermal performance by applying cleanness management. It becomes even more interest with respect to a life time extension program.

Accumulation of secondary side deposits is intrinsic for the operation of steam generators in PWRs. However a peculiarity of the CANDU concept is the fact that also the inner diameter surfaces of the steam generator tubes suffer from magnetite deposition. No matter whether ID or OD is affected by deposition of magnetite, such depositions often lead to reduction of thermal performance, in some cases to power restrictions and in particular on the OD (secondary side) can promote corrosion phenomena and consequently may affect component integrity.

Accordingly removal of such deposits is an essential part of the asset management of the steam generators in a nuclear power plant. In order to optimize outages and reduce down time as much as possible it becomes evident that the combination of secondary and primary side cleaning is a potential candidate for significant improvement.

Since there is no "standard" steam generator condition because each plant has a specific operation history, design and construction of steam generators and water chemistry it is obvious that there is also no "standard" cleaning scenario. In order to address these individual conditions, AREVA has developed a cleanness management program that allows tailoring the cleaning measures to the specific site conditions.

2. Evaluation of the steam generator condition

2.1 Evaluation of the steam generator secondary side

A holistic view on all areas is necessary for a cleanness evaluation. Besides the performance considerations, which are applicable for primary and secondary side of a nuclear steam generator also corrosion issues have to be considered on the secondary side. This is due to the fact that primary side has very defined water chemistry conditions while on the secondary side impurities from possible condenser leakages may be involved and the fact that due to evaporation all dissolved and solid matter in the feed water is concentrated in the steam generator. Due to the high mass flow even very low concentrations add over time to significant amounts.

There are several possibilities to assess the secondary side condition of a steam generator spanning from evaluation of water chemistry data like iron content in the feedwater and removed iron via blow down allow to calculate the total amount of iron accumulating in the steam generator over time. While this method is purely quantitative it does not provide information over sludge distribution in the SG nor whether this sludge is loose and fluffy or whether it generating hard sludge formations. To gain such information visual inspections as well sludge mapping technologies based on ECT are applied.

Figure 1 Pictures from hard sludge and tube collars formation on a tube sheet [1]

Typical pictures from visual inspections are shown in Figure 1. The problem with visual inspection is the fact that only a very limited area can be evaluated. Another new method that is applied by AREVA is the sludge mapping using ETC technology. This method allows visualize the distribution and the thickness of sludge layers in the steam generator. A typical lot of such sludge mapping evaluation is shown in Figure 2. The different colours in the plot show different thickness of the sludge layers. This new technique is an excellent tool to assess the condition in the steam generators and support the decision about adequate maintenance or remedial measures.

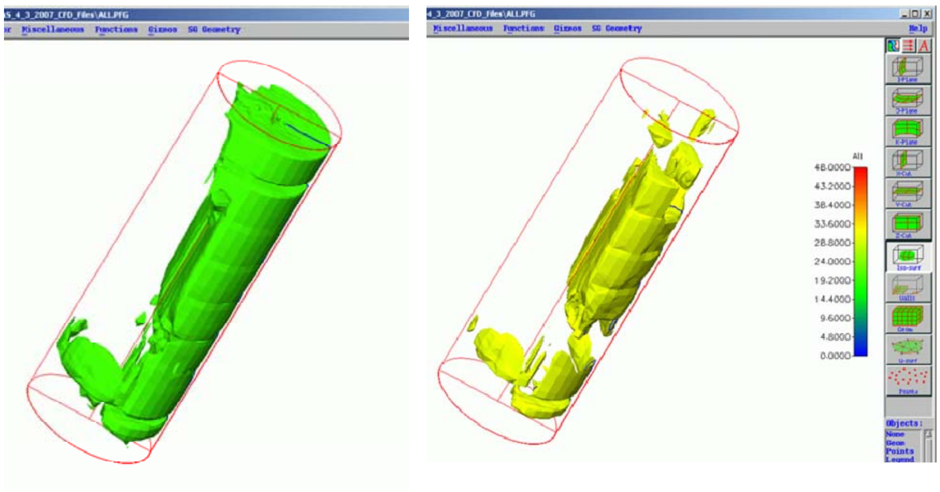

Figure 2 Picture of sludge mapping plots different colors indicating different thickness of sludge layers

A typical result of the accumulated sludge in the steam generator is fouling of the tubes which cause a reduction in performance. A relationship between sludge ingress and evolution of the fouling factor is shown in Figure 3. The fouling factor is the difference between measured and as-designed overall heat transfer resistance of the tubes. This graph demonstrates the improvement of the fouling factor after a full scale cleaning of a steam generator.

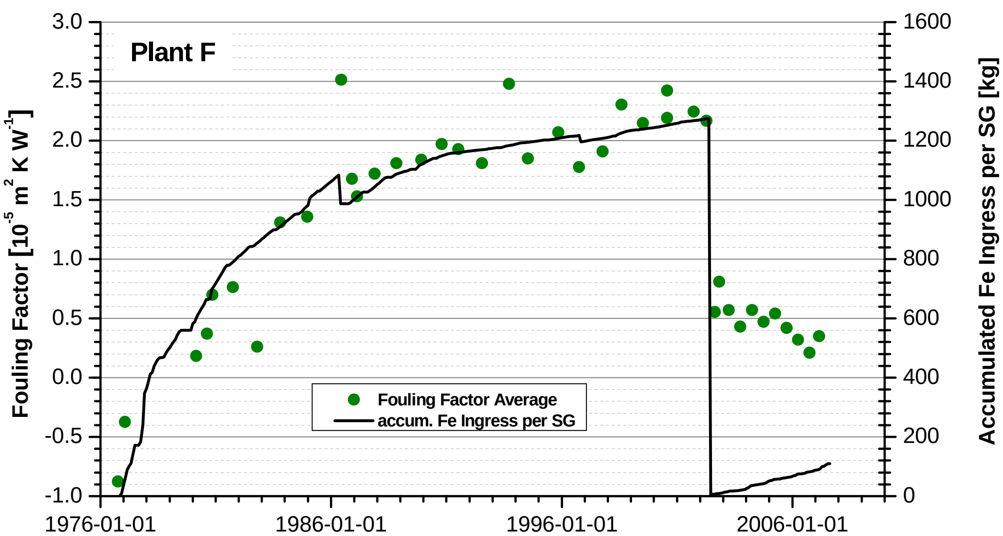

Figure 3 Development of sludge ingress and fouling factor [2]

The effects and observations provide only a portion of the steam generator threads because they do not consider corrosion or corrosion promoting effects. In order to gain a complete picture of the cleanliness condition for each steam generator in a plant, all suitable plant operational and SG inspection data should be evaluated collectively. These data serve as "fouling indicators", which may be categorized as given in Table 1.

Table 1: Fouling Indicators

Water Chemistry Data	**Inspection Results**	**SG Heat Transfer Calculation**
Corrosion Product mass balance	Visual inspections	Design Data (heating surface, number of plugged tubes, etc.)
Impurity ingress (sulphate, chloride and other salts)	Tube sheet lancing results	Process parameter (mass flow rates, temperature, pressure)
Out of specification conditions, e.g. condenser leaks	Tube scale thickness measurements	
Calculation of local conditions (hide-out and hide-out return)	Sludge mapping	

After data compilation, weighting factors are applied in order to normalize the fouling indicator parameters for comparison [1]. As per definition, the sum of all weighting factors is 100. Based on field experience, heat transfer performance and water chemistry data have been found to be the most important parameter category. Within each category the individual indicator parameters are separately weighted. From the sum of the weighted individual indicator parameters an overall fouling index of the SG can be calculated which can, as per the above definitions, have values between 0 and 100, where 0 represents "clean" and 100 is "severely fouled" [2].

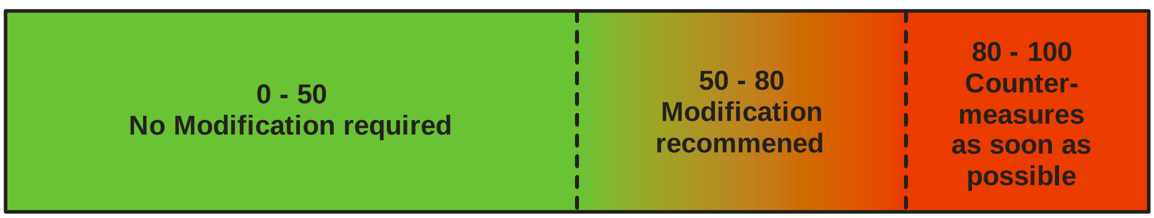

Figure 4 Range of AREVA's Fouling Index

As a general rule it can be stated that with increasing sludge load not only the thermal performance of the steam generators suffers over time but also the risk of other threads have to be considered. This can include tube corrosion and also blockage of broached holes with subsequent vibration or denting problems.

Hence, steam generator shall be kept as clean as possible to ensure safe and reliable operation.

2.2 Evaluation of the steam generator primary side

In CANDU plants the feeder pipes of the fuel channels are made from carbon steel. During operation of the plant feeder pipe thinning occurs. This causes magnetite deposition on the ID surface of the steam generator tubes. These magnetite depositions change the hydrodynamic conditions in the primary heat transport system. This can affect (RHI) reactor header inlet temperature and also decrease of the RHI pressure generally leading to a reduction in heat transfer efficiency. The plot in Figure 5 shows the evolution of the fouling factor of the primary side of a CANDU unit and the significant improvement after a primary side cleaning. Not only is the thermal performance affected by this deposition but also the testability of the tubes and also duration of the actual testing.

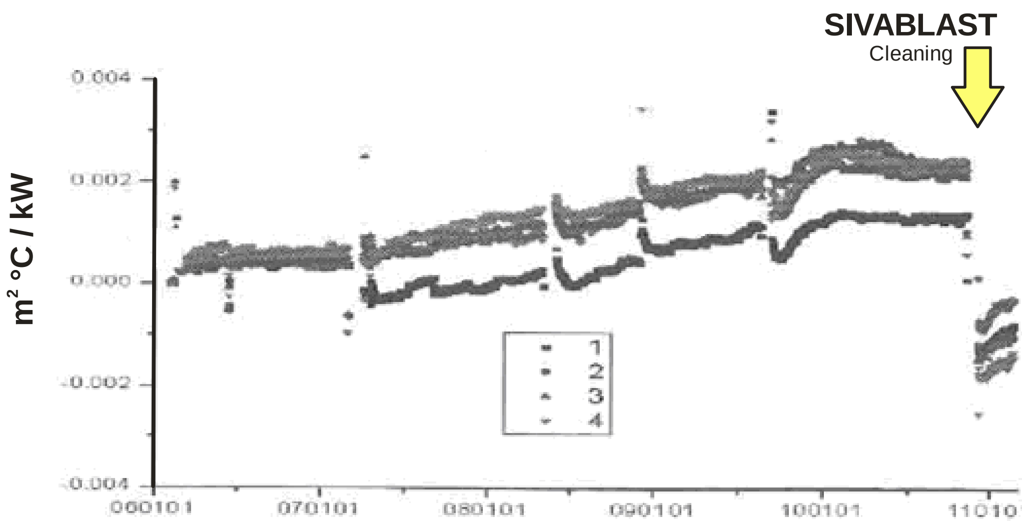

Figure 5 Development of fouling factor in a CANDU plant (from 2006 to 2011) due to SG tube ID magnetite deposition [4]

3. Strategies for the secondary side chemical cleaning of steam generators

Based on the steam generator assessment the most suitable countermeasure is elaborated, if required at all. Theses measures range in general from modification of chemistry treatment to full scale hard chemical cleaning. Since each plant and steam generator has its own history and particular condition it is obvious that the applied cleaning scenario should take these aspects into considerations as well as application constraints like outage schedule critical path etc. Therefore AREVA has developed the Customized Chemical cleaning Concept C³ concept (see Figure 6). This concept comprises a variety of chemical cleaning technologies which allow tailoring the chemical cleaning exactly to the plants needs.

Depending on the assessment result it has to be decided whether a preventive or a curative cleaning is the most beneficial approach. Figure 7 shows the simplified development of SG sludge inventory with different maintenance cleaning strategies. It demonstrates that cleaning methods removing only the range of the yearly input will at the best maintain the actual level in the SG but are not able to reduce the inventory. This is an acceptable strategy for new or recently fully cleaned steam generators. For steam generators with an already long life span only a cleaning method with a removal capacity of at least several yearly iron inputs per SG will provide a real improvement of the SG condition in terms of total sludge inventory.

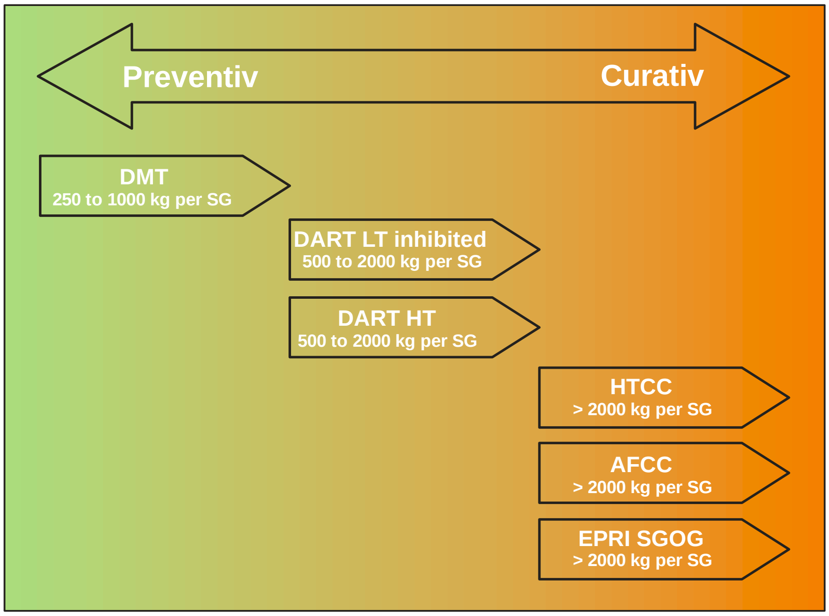

Figure 6 AREVA customized chemical cleaning concept for steam generator cleaning

This also shows that in case of planning any cleaning for older plants it is important that the applied cleaning method reduces the sludge load significantly in order to avoid too many repetitions of chemical cleanings. As shown in Figure 7 only cleaning methods that are capable of removing a multiple of the yearly input are efficient to achieve this goal.

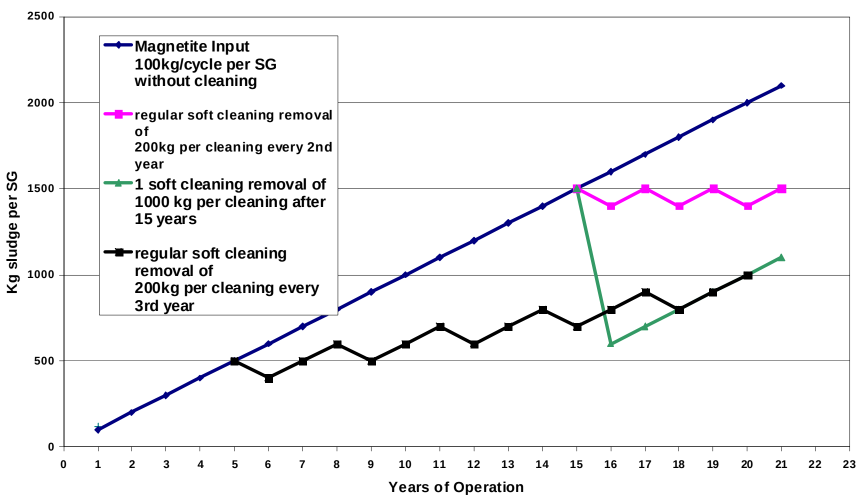

Figure 7 Development of sludge inventory with different cleaning strategies

Recently preventive chemical cleanings for steam generators are being advocated. Reason for this is that such preventive cleanings are less intrusive to the plant and thus can save outage time and cost. Nevertheless it is important that such cleanings remove as much as possible sludge per campaign. Since such preventive cleanings are intended to be applied repeatedly the corrosion behaviour of such a cleaning is not only relevant from a general material compatibility point of view but also from an efficiency point of view. Since metal from base material corrosion is part of the total iron removed it is obvious that lower corrosion rates increase the efficiency of the cleaning agent.

Part of the AREVA C³ concept is the proprietary DMT (Deposit Minimization Treatment) process. This process utilizes a new chemistry in the SG cleaning business. This new chemistry increases the cleaning efficiency compared to the commonly used EDTA chemistry. In particular DMT excels with its self-inhibiting property which reduces the average corrosion rates of the process to < 10 µm on carbon steels. Thus > 95 % of the removed iron originates from dissolved magnetite, while the commonly applied 1% EDTA cleaning without inhibitor yields only approx < 60 % of the iron from magnetite. In Figure 8 the ratio of magnetite dissolved to iron from carbon steel corrosion for the DMT process and a cleaning solvent using 1% EDTA is depicted. The increase of efficiency due to the extreme low corrosion rates can clearly be seen.

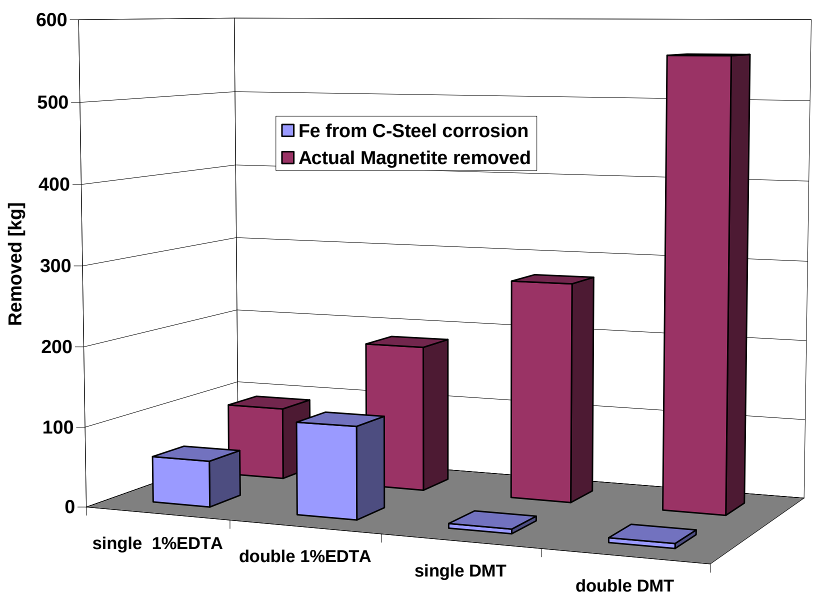

Figure 8 Comparison of cleaning efficiency of oxalic acid (i.e. DMT) with 1% EDTA cleaning agent

This data are corroborated from a field experience data obtained during a recent DMT application in a 4 loop unit that had corrosion coupons in the steam generator during the cleaning. During this campaign a total of 3830 kg sludge was removed from the 4 steam generators were removed and only a total of approx. 88 kg iron was dissolved from the base material of the 4 steam generators.

4. Strategies for the primary side cleaning of steam generators

At first for a cleaning of the primary side of a steam generator the same considerations are valid as for the secondary side. However for the secondary side the contamination of the magnetite if of major importance since such waste will be highly radioactive and thus is difficult to handle and store accordingly the generated waste volume is directly affecting the price. Furthermore not only the volume but also whether the generated waste is liquid or solid affects drastically the cost. Taking these facts into consideration AREVA developed already in the mid nineties a regenerative mechanical cleaning process that effectively removes the magnetite from the tube ID surface without negatively affecting the tube material. The advantage of this process in terms of waste generation is the fact that the pure magnetite can be collected in waste drums hence the generated waste volume is the lowest possible. In the latest application in Wolsong Unit 2 A recent application yielded only 9 drums with a volume of 253 ltr for more than 2200 kg Magnetite removed from the steam generators [4] A part of this SIVABLAST® system is the so called suction header a patented device that allows a higher flow rate of the cleaning material in the tubes and thus enhances efficiency drastically.

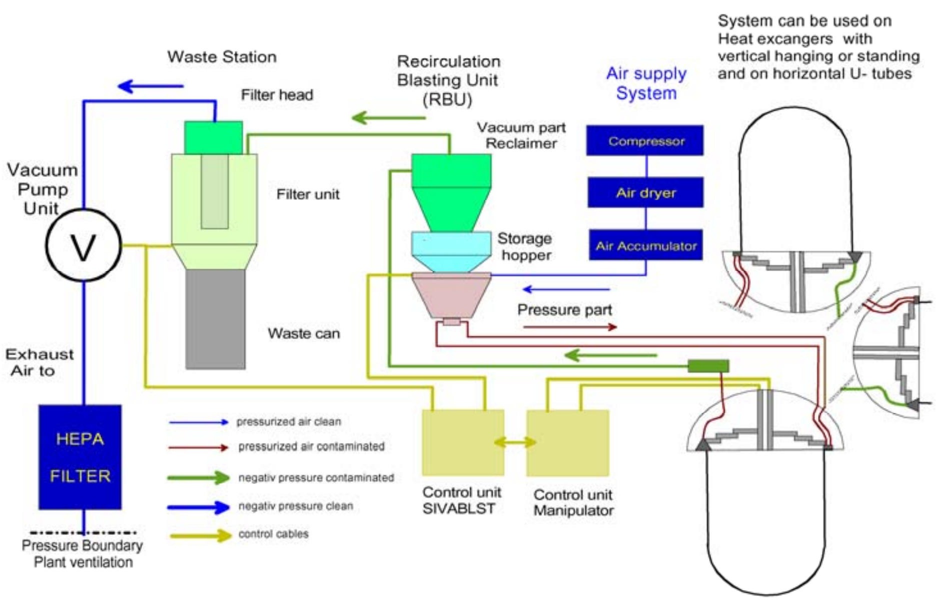

Figure 9 Outline of the SIVABLAST® mechanical cleaning system

The SIVABLAST® technology has successfully been applied to all types of heat exchangers with straight tubes, horizontal, upright and hanging U bend tubes with different materials including brass, carbon steel and typical SG materials like Inconel 600 and Incoloy 800. Typical results from steam generators cleanings in CANDU units worldwide are listed in Table 2 below. Based on schedule restrictions in Darlington only 60 % of the SG tubes of each SG have been cleaned, this may be one reason why the reduction of the RHI Temperature is less than at the CANDU 6 units; also Darlington is a CANDU 8 unit which may have also influence.

Table 2 Results of SIVABLAST® application in steam generators at CANDU stations

Main Application and Improvement Data	**PLGS 1995**	**G2 1999**	**CNE 2000**	**Wolsong 1 2003**	**Darlington 1 2004**	**Wolsong 2 2010**
Total Magnetit removed (kg) from SG 1 to 4	**789**	**3045**	**2603**	**2574**	**1433**	**2204**
Magnetit g/Tube Range of SG 1 to 4	**96**	**234**	**198**	**194,5**	**127**	**164**
Total amount of used blasting material (kg) SG 1 to 4	**1925**	**475**	**650**	**675**	**515**	**300**
Litre Waste Volume / kg Magnetit	**4,1**	**1,1**	**1,1**	**1,1**	**0,9**	**1,1**
Amount of waste drums used (each 235 litre incl. filter)	**14**	**14**	**12**	**13**	**6***	**9**
Reduction of RHIT Reactor Header Inlet Temperature (°C)	**n.d.**	**- 2,75°C**	**- 4,5°C**	**- 1,8°C**	**- 0,8°C**	**- 2,1°C**
Increase of PHT Flow Primary Heat Transfer Flow (%)	**n.d.**	**+ 3 - 6 %**	**+ 5 %**	**n.d.**	**+ 2,5 %**	**+ 0,4 %**
At all CANDU 6 applications ≥ 95% of the tubes have been cleaned and at the Darlington application about 60%; * 205 litre without filter						

The positive effect of this cleaning measure on the plant performance can be taken from the decrease in fouling factor as shown in Figure 5 but also reactor header inlet temperature and pressure showed significant improvement as shown in Figure 10 from the last application at Wolsong 2.

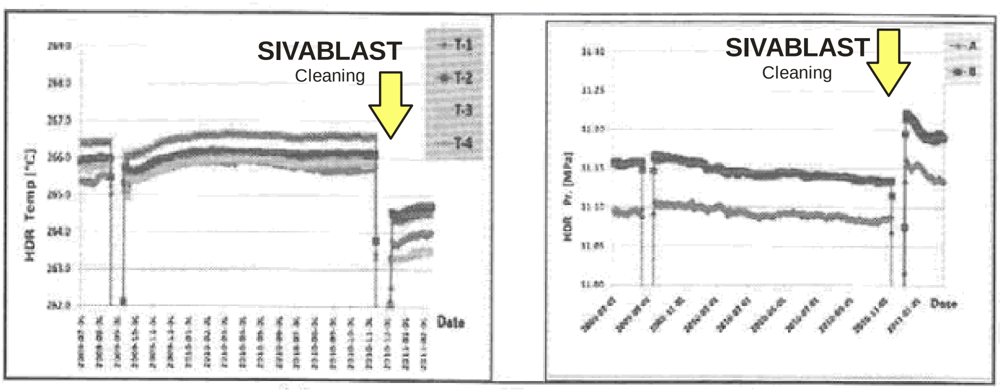

Figure 10 Evolution of RHI temperature (°C, left side) and RHI pressure (MPa, right side) [4]

In every case where SIVABLAS® has been applied for the removal of magnetite deposits from the inner diameter of SG tubes, significant and measurable benefits have been observed. While the results vary from application to application, here are some typical observations:

- Thermal Performance – The removal of deposits invariably leads to a significant improvement in thermal performance for the SG. The end result is an observed reduction in Reactor Inlet Header Temp (RIHT), ranging up to 4.5°C

- Flow Increase – The removal of the deposits clears a major constriction for the primary heat transport system, resulting in improved core flow in the range up 6% depending on evaluation method.
- SG Tube Inspection Quality – Magnetite deposits present a major problem for SG In-Service Inspection (ISI) techniques. Removal of the deposits results in improved inspection signal quality, duration of testing and prolonged probe life.
- Dose Rate Reduction – The removal of deposits from the SG tubes have resulted in significant reductions in the general gamma dose rate in working areas around the SGs. Localized Decon Factors (DF) of up to 4.6 have been observed.

5. AREVA Integrated approach to steam generator cleanliness management

As outlined above the steam generators are one of the most important parts of a nuclear unit whereas it is not only the thermal and with this the monetary performance, but also the steam generator tubes represent by far the largest boundary of the primary circuit. Due to their importance for reliable and safe plant operation, a thorough and unitary SG maintenance concept is important.

In order to establish a steam generator cleanliness management program it is important to define as exact as possible the actual condition of the steam generator. In order get a complete picture it is important to gain as much as possible information about sludge inventory and distribution as well as the consistency of the sludge. Beside the typical inspection methods like endoscopy and videoscopy AREVA has an ECT based sludge mapping technology that allows a detailed analysis of the sludge distribution and can also provide information about broached-hole opening ratios.

In addition to these inspection methods AREVA can provide comprehensive support in the assessment of the steam generators from a water chemistry point of view. This includes the chemical environment inside the steam generator and also the conditions and the materials of the entire water steam cycle. Such evaluation is a major part of the steam generator cleanliness management since not only reaction on existing conditions is mandatory but also proactive measures may become necessary. This can include changing in water chemistry and also materials used in the water steam cycle. The principle of such an assessment is shown in Figure 11.

As it can be taken from Figure 11 a thorough evaluation of the SG condition is mandatory in order to decide about possible countermeasures. Once the necessity is of a cleaning is recognized it has to be integrated into the outage management. This makes clear that SG cleanliness management is very complex it is highly advantageous to combine as much as possible actions in one hand the most preferable possibility is to establish a turn key project - AREVA has a long history and the most comprehensive experience in servicing nuclear power plants world wide. Furthermore AREVA owns several technologies for cleaning of steam generators for primary and secondary side. The availability of such technologies in one company allows applying the most beneficial process or combination of processes. As a typical example for such an integrated application a combination of primary and secondary cleaning is outlined below.

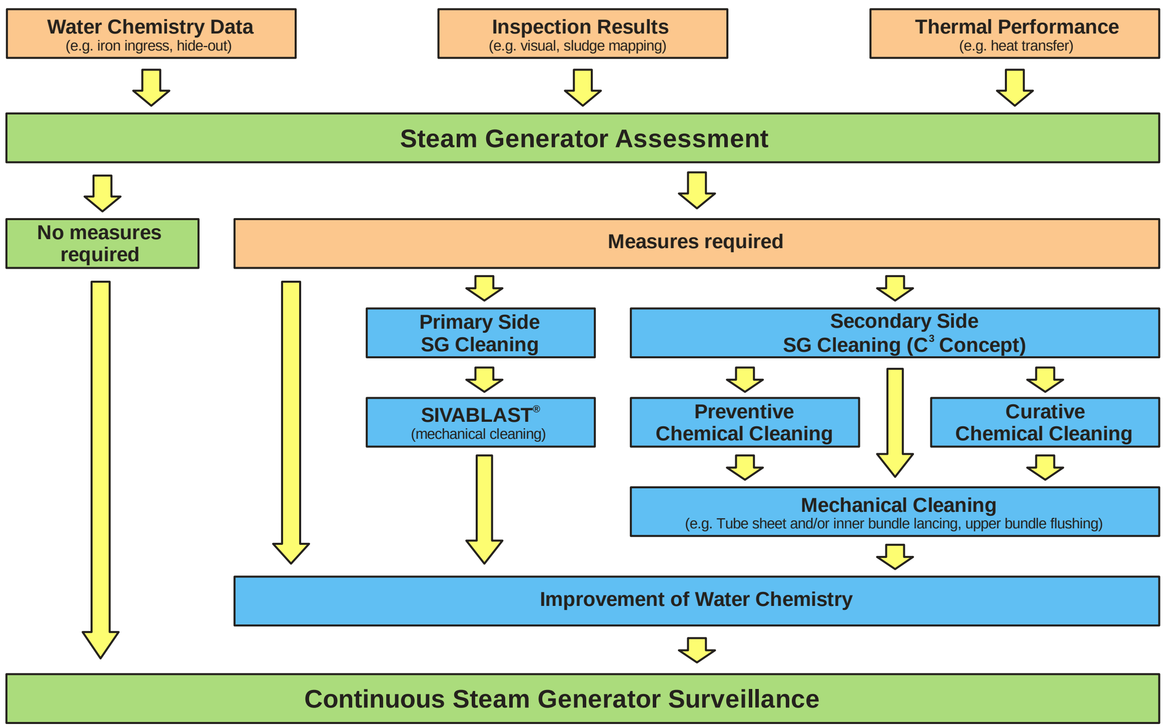

Figure 11 Principle of steam generator assessment

In order to successfully apply a mechanical cleaning of the primary side of CANDU SGs it is mandatory that the SGs are completely drained and dried. Due to the fact that AREVA owns the SIVABLAST® process as well as preventive CC technologies a recommended approach is for example to combine the SIVABLAST® process with a DMT / DART preventive chemical cleaning. The AREVA DMT process can be easily applied with an external heat source due to the low application temperature. Thus the process is performed using only very few plant systems and especially without plant internal heat source (i.e. heat from primary side). Therefore the secondary side CC can be applied in a way that during the CC the primary side is perfectly dried. Doing so, the efficiency and the duration of the SIVABLAST® application are significantly improved.

6. Conclusion

The SG condition is a key factor for plant performance, high plant availability, possible life time extension and is important to NPP safety [3]. The major safety function of SGs is to act as a barrier between the radioactive primary side and the non-radioactive secondary side. Any degradation mechanism, which impairs this barrier function, is a significant safety concern. The main reason for SG tube failure is known to be the accumulation of deposits contributing to formation of local aggressive conditions. Furthermore deposits on primary as well as secondary side of SG tubes reduce the heat transfer performance. A SG cleanliness management program is therefore mandatory to ensure high plant performance regarding efficiency as well as component integrity. Due to the interdisciplinary and unitary nature of the program a harmonisation between all involved sector and specialist is required. Therefore a minimization of the interfaces among the participating parties becomes of special importance.

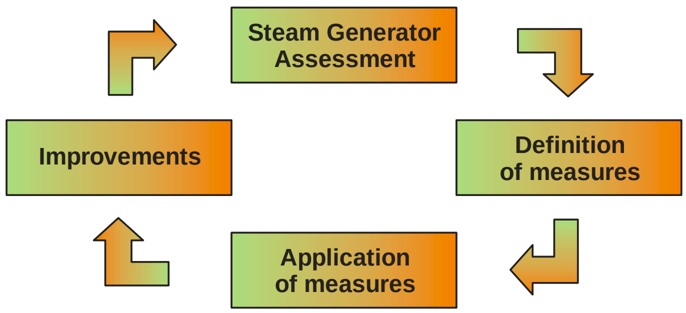

Figure 12 Steam generator cleanliness management

Such a cleanliness management program (Figure 12) is in principle a closed cycle process that first assesses the current SG situation. In the subsequent steps appropriate measures which improve the current status or counteract on identified serious issues are identified, defined and applied. These measures include possible changes in the water chemistry and materials concept to minimize unfavourable conditions in order to reduce the effort for later remedial measures.

7. References

[1] S. Odar, V. Schneider, T. Schwarz, R. Bouecke, “Cleanliness Criteria to Improve Steam Generator Performance”; International conference on water chemistry of nuclear reactor systems, Jeju Island Korea, October 23 – 26, 2006

[2] A. Drexler, F. Boettcher, H. Barth, B. Markgraf, H. Neder, H.-R. Sauer, S. Schuetz, “Steam generator performance update for German PWRs”, Nuclear Plant Chemistry Conference 2010, Quebec, Canada, October 3 -7, 2010

[3] IAEA TecDoc 1668, “Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: Steam Generators”, Vienna, 2011

[4] Y. S. Kang and D.-M. Shin “Evaluation of steam generator primary side cleaning effects on Wolsong NPP’s 2011 Proceedings of intern. symposium of radiation safety management.

8. Abbreviations

C^3	Customized Chemical Cleaning
CANDU	Canada Deuterium Uranium
CC	Chemical Cleaning
CNE	Central Nuclear Embalse
DART	Deposit accumulation reduction treatment
DF	Decon Factor
DMT	Deposit Minimization Treatment
ECT	Eddy Current Testing
EDTA	Ethylenediaminetetraacetic acid
G2	Gentilly Unit 2
ID	Inner Diameter
ISI	In-Service Inspection
NPP	Nuclear Power Plant
OD	Outer Diameter
PHT	Primary Heat Transfer
PLGS	Point Lepreau Generating Station
PWR	Pressurized Water Reactor
RHI	Reactor Header Inlet
RIHT	Reactor Inlet Header Temperature
SG	Steam Generator