PREDICTING AND MANAGING STEAM GENERATOR PERFORMANCE

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ABSTRACT

To efficiently manage the life of the steam generators (SGs), utilities require 'tools' to monitor and assess the effects of degradation and aging, as well as to predict the impact of such degradation on SG performance. To assist utility staff in these areas, AECL has developed a comprehensive 'tool set' for steam generator life cycle management. The toolset includes THIRST, a code originally developed to model two-phase flow within a Recirculating Steam Generator (RSG) but now modified to calculate SG bulk water chemistry and the impact of fouling on the SG thermalhydraulic conditions, and SLUDGE, a code developed to predict the SG fouling rate and deposit distribution as a function of operating conditions. Work is currently in progress to map the deposit distribution as part of the normal SG Non-Destructive Examination (NDE) inspections, thus closing the loop between THIRST/SLUDGE predictions and the results of tube-bundle inspection. To ensure that chemistry conditions are optimal throughout the steam cycle, ChemSolv was developed to calculate pH in SG crevice regions and on wetted surfaces throughout the steam cycle. Investigations using electrochemical methods have defined 'safe zones', regions of pH and electrochemical corrosion potential where the risk of localized corrosion of the SG tubes is minimized, that in combination with ChemSolv provide a powerful tool for managing steam cycle chemistry.

1. INTRODUCTION

Good performance of nuclear steam generators (SGs) is a key factor in maintaining a high plant capacity factor. Because steam generators are expensive and difficult to replace, careful life cycle management is important throughout the original 40-year planned life, and for any additional operation following station refurbishment. Good performance begins with the design and material selection, and is maintained through effective chemistry control, inspection and maintenance programs. Even very low levels of suspended solids and ionic impurities present within the feedwater can have a deleterious effect on SG performance. Corrosion products transported with the feedwater deposit within the steam generator, impairing heat transfer and forming regions of restricted flow at the tube sheet and tube/tube-support intersections. Concentration of ionic impurities in such restricted regions can result in aggressive localized water chemistry. Deposition on the tube-support structure can cause changes in the flow-velocity profiles and affect fretting wear of steam generator tubes and cause flow accelerated corrosion of steam generator internals.

The aim of the present paper is to review the AECL recommendations for good SG as-built performance, examine the factors that can contribute to the loss of performance during normal operation, and describe a 'tool set' based on laboratory experimentation, in-service inspection results, field monitoring and mathematical modelling that can be used by utilities to optimize operating and maintenance strategies to manage steam generator lifetime performance.

2. FACTORS AFFECTING STEAM GENERATOR AS-BUILT PERFORMANCE

2.1 Design

Good SG performance starts with a good design. Atomic Energy of Canada Limited (AECL) has been very proactive in this regard, and has developed computer models to predict thermalhydraulic performance for a given SG design (THIRST), to predict the vibrational response of the SG tube bundle to a given flow field (PIPO) and to predict the fretting wear rate of the tubes at the points of contact with the tube-support structure (VIBIC). All three codes are used extensively by AECL engineers to provide input to design specifications for CANDU SGs and to predict the SG design lifetime performance.

THIRST [1] solves three-dimensional, coupled equations for mass, momentum and heat transfer to predict two-phase thermalhydraulic conditions in a recirculating SG. Detailed information on gap cross-flow velocity, density and void fraction calculated by THIRST [2] is used by PIPO to calculate the tube excitation forces and damping values under two-phase flow conditions [3] and assess the susceptibility of the tube bundle to flow-induced vibration. By taking account of the details of the individual tube-support sliding/impact dynamics, VIBIC calculates the average and peak-value contact forces, contact durations and work-rates of the selected tube-support and U-bend support designs. Work-rates combined with wear coefficients are then used to predict fretting-wear damage by turbulence excitation to ensure that the SG will meet or exceed its design lifetime [4].

CANDU SGs are designed to achieve a high recirculation ratio (>5) to minimize local steam qualities and to achieve good mixing and tube-bundle penetration of the secondary-side water; conditions that have proven to be beneficial for mitigating the adverse affects of corrosion, fouling and fretting wear. Guidelines have been compiled by AECL for optimal materials selection, tube-support gap thickness and other design parameters, such as tube dynamic stiffness and the tube pitch/diameter ratio, that minimize vibration and fretting wear. It is strongly recommended that new SGs undergo post-installation eddy current (EC) inspection to demonstrate that tube-support clearances meet the design specifications.

2.2 Materials

Equally important to good design is the selection of corrosion-resistant materials to ensure good SG performance throughout the design life and beyond. AECL has had good success with its choice of Alloy 800NG[1] U-tubes for the SG tube bundle. There is only one report world-wide of an Alloy 800NG SG tube that has cracked in service, although it is susceptible to phosphate-wastage and to pitting under oxidizing conditions. The performance of the 410 stainless

[1] Alloy 800 has a nominal composition of 22 wt% Cr, 34 wt% Ni and 42 wt% Fe. Nuclear Grade (NG) Alloy 800 has a Ti/C ratio > 12 to minimize susceptibility to stress corrosion cracking.

steel (SS) tube supports has also been very good in CANDU SGs, although 410 SS will undergo pitting under oxidizing conditions and is susceptible to flow-accelerated corrosion (FAC) if the water chemistry becomes acidic. Some plants that installed carbon steel tube-support structures instead of 410 SS have experienced high rates of tube-support degradation that has been attributed to FAC.

The performance of materials used throughout the steam cycle will also have an impact on SG performance because of the transport of corrosion products and the ingress of impurities introduced by condenser leaks into the SG. Stainless steel for fresh water and titanium for sea-water or brackish-water conditions are the recommended materials for the condenser tube bundle. Carbon steel is an acceptable material for the heat exchangers and piping in the steam-cycle, although a minimum chromium content of 0.2 wt% is preferable to minimize the rate of FAC [5]. In locations where the rate of FAC has been observed to be high, e.g., wet steam lines, drains, elbows, reducers, an FAC-resistant material such as 304 SS or a low-chrome alloy steel (e.g., 2.5% Cr 1% Mo) is recommended to minimize both corrosion product transport and the risk of failure of the pressure boundary [6].

Finally, copper-bearing alloys should not be used in either the condenser or in the low-pressure feedwater heaters. Copper alloys corrode in the presence of trace concentrations of dissolved oxygen, and not only increase the rate of corrosion product transport but also introduce an oxidizing agent (i.e., Cu^{2+}) to the SGs. Steps should also be taken to exclude the use of lead-bearing greases, valve packings, seals, and, especially, alloys (e.g., lead-alloy bushings have been used in the condensate extraction pumps in some plants) to minimize the transport of lead to the SG and, therefore, the risk of lead-induced stress corrosion cracking of the SG tubes [7].

2.3 Chemistry

Although good performance starts with a good design and the selection of robust materials, it has long been recognized that the chemistry control program is key to maintaining good performance of the SG throughout its life cycle. To ensure optimal SG water chemistry and minimize the transport of corrosion products and impurities to the SG, AECL recommends:

- on-line sodium and conductivity monitors to detect condenser leaks and to monitor the quality of the makeup water,
- all-volatile treatment (AVT, i.e., a volatile amine and reducing agent) to maintain alkaline pH throughout the steam cycle and reducing conditions in the steam generator.

The AVT currently recommend by AECL is morpholine and hydrazine added to the steam cycle in sufficient quantities to ensure:

- a $pH_{25°C}$ of 9.5 to 10 in the low-pressure part of the feedwater system.
- A high-temperature pH of at least 1 pH unit above the high-temperature neutral point throughout the high-pressure part of the steam cycle.
- a hydrazine/dissolved oxygen ratio >5 in the final feedwater (outlet of the high-pressure heater) and/or a residual concentration of 25 to 50 μg/kg hydrazine in the SG blowdown, whichever is greater.

Table 1 lists the calculated ΔpH_N, i.e., the high-temperature pH, pH_T, minus the high-temperature neutral point, pH_N, for several volatile amines that are in common use in the nuclear industry. Calculations were done for several key locations in the steam cycle at temperatures typical of the steam cycle in a CANDU 6 unit. Of the four amines listed, only morpholine maintains the high-temperature pH at least 1 pH unit above the high-temperature neutral point for a pH of 9.5 at the condensate extraction pump (CEP) discharge, although ethanolamine is nearly as good as morpholine at the final feedwater (FW) and provides better protection in the SG and the moisture-separator drain (MSD).

Table 1
Calculated ΔpH_N Through the Steam Cycle for Amines Commonly used for AVT

Amine	pH	$\Delta pH_N = pH_T - pH_N$		
	CEP Discharge*	Final FW	SG	MSR Drain
Morpholine	9.5	1.2	1.0	1.3
Ammonia	9.5	0.92	0.40	0.70
Ethanolamine	9.5	0.97	1.1	1.5
Dimethylamine	9.5	1.1	0.50	0.80

* Calculated at 25°C. All other entries are calculated at the temperature of interest.

3. AN INTEGRATED APPROACH TO STEAM GENERATOR LIFE MANAGEMENT

3.1 Modes of SG Performance Degradation During Operation

During full power operation, corrosion products are transported with the feedwater to the SG where they either remain suspended where they can be removed by blowdown or they accumulate on the tubesheet, the tube bundle and the tube-support structure. A plant with a steaming rate of 1 000 kg/s and as little as 1 μg/kg of corrosion product in the feedwater will still transport about 25 kg of corrosion product to the SGs per year during full-power operation. This number can easily be doubled once account is taken of 'crud busts' on start-up[2]. Of the total corrosion product transported to the SGs, typically 75% ends up on the tube-bundle, 15% is removed by blowdown, and the remainder accumulates on the tubesheet and the tube-support structure.

Fouling of the SGs, i.e., the accumulation of corrosion products on vertical and horizontal surfaces, will ultimately have a deleterious effect on SG performance. For example, deposit that accumulates on the tube-support structure will increase the hydraulic resistance of the support structure, and result in a decrease of the recirculation ratio. In some cases, blockage of the tube-support structure has become severe enough to cause serious operational issues, such as density-wave oscillations in RSGs with trefoil [8] and quatrefoil [9] tube-support structures, and flooding of the steam-aspirating nozzles in Once-Through Steam Generators (OTSG) [10]. In each case, the plants had to operate at a reduced power level until such time as the blockage could be removed to restore flow through the support structure. The accumulation of deposit on the tube bundle has an impact on SG thermal performance, with the performance showing an initial period of improvement while the tube-bundle is first covered with a thin layer of deposit followed by a period of declining performance as the deposit thickens [11]. Soluble impurities, introduced to the feedwater from the water treatment plant or from condenser leaks, accumulate

[2] The corrosion product concentration in the feedwater during a crud burst on start-up is typically >100 times greater than during normal operation. Thus, one day on startup can be equivalent to >100 days of normal operation in terms of corrosion product transport to the SGs.

in flow-occluded regions by a process known as 'hideout' [12]. Hideout can lead, under some circumstances, to the formation of chemistry conditions that are aggressive to both the tube-bundle and to the tube support structure. In extreme cases, localized corrosion can ultimately result in tube failure by pitting and/or stress corrosion cracking [13].

Thus, unless properly managed, the transport to the SG of trace quantities of corrosion product and impurities in the feedwater can eventually lead to the loss of thermal performance, increased hydraulic resistance that can result in plant power de-rating and expensive remedial measures, and SG tube failures resulting from localized crevice or under-deposit corrosion. To help manage these issues, AECL has developed a set of 'tools' that can be used to monitor and assess the effects of fouling on SG performance and to optimise operating and maintenance strategies to minimize these effects and ensure good performance over the lifetime of the SG.

The current state of development of these tools and their amalgamation into a 'tool set' to manage SG lifetime performance is discussed in the following subsections.

3.2 Managing the Impact of SG Fouling

The AECL 'toolset' to manage the impact of SG fouling includes numerical analysis tools to model fouling of an RSG and its impact on the SG recirculation ratio and thermal performance, as well as inspection probes to measure the SG downcomer flow velocity and the distribution of deposit throughout the SG. The models and probes together provide the means to predict the rate of fouling and performance degradation of the SG and to assess the effectiveness of operating and maintenance strategies at restoring and maintaining performance.

AECL models the fouling of RSGs using SLUDGE [14], a three-dimensional transient analysis of SG fouling based on the thermalhydraulic output from THIRST and a model of particle fouling developed on the basis of high-temperature loop tests of particle fouling under flow-boiling conditions [15]. SLUDGE allows the user to select from one of several fouling scenerios (i.e., magnetite vs. haematite, various AVTs with and without dispersant) to examine the impact of water chemistry and operating parameters such as the SG blowdown rate, moisture carry-over rate, and feedwater iron concentration during both startup and full-power operation on the SG fouling behaviour. The output from SLUDGE includes a predicted blowdown efficiency as well as deposit distribution on the tube bundle and the tubesheet. Figure 1 shows the effect of the fouling rate on the blowdown efficiency predicted by SLUDGE for two different blowdown rates. The figure suggests that blowdown efficiency should increase with increasing blowdown rate and that relatively high blowdown efficiencies can be achieved if the fouling rate is made sufficiently low; for example by the addition of a dispersant. Field experience with addition of a dispersant demonstrated that such high blowdown efficiencies can, indeed, be achieved [16].

The tube-bundle deposit distribution calculated by SLUDGE can be combined with a model of the effect of deposit on the rate of heat transfer under flow-boiling conditions to generate a fouling-factor distribution for the tube bundle and account for the impact of secondary-side fouling on SG thermal performance. The formation of a thin, porous deposit on a clean boiler tube initially improves the rate of flow-boiling heat transfer by reducing the wall superheat required for bubble nucleation [17]. As the deposit grows thicker, however, the deposit adjacent to the heat transfer surface consolidates to form a dense inner layer that impedes heat transfer, so that thermal performance eventually declines, typically after about 5 years of operation [11].

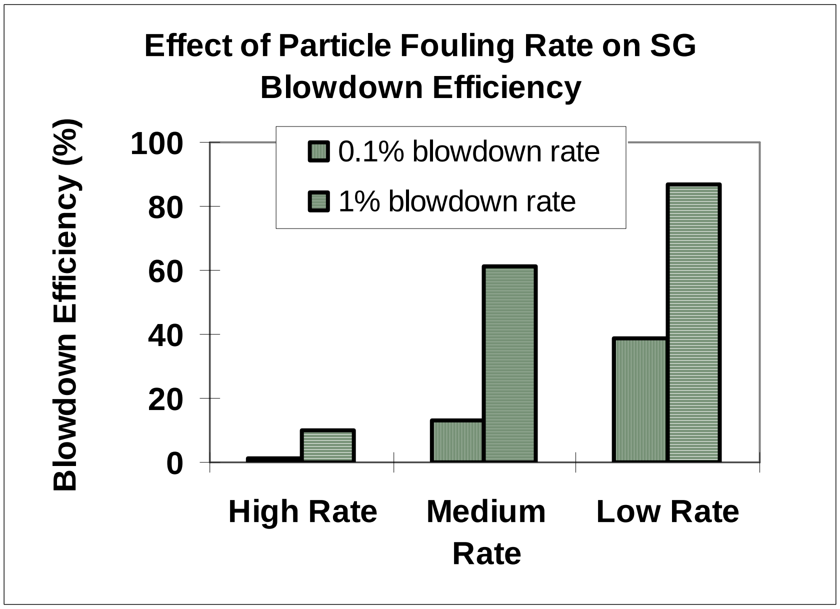

Figure 1 Predicted effect of fouling rate and blowdown rate on SG blowdown efficiency.

Results from SG inspections can be used in combination with THIRST and SLUDGE to assess the impact of fouling on SG performance and to predict the effectiveness of proposed remedial measures. For example, eddy-current probes that have been developed to detect fretting wear, crack growth and pitting corrosion of the SG tubes are also being used to detect aging-related effects that will change the hydraulic resistance of the tube-support structure, such as degradation caused by FAC [18] or fouling of the supports. The latter will eventually manifest itself in a reduced SG recirculation ratio and downcomer flow rate [19], and if left un-checked could eventually lead to the density-wave oscillations mentioned previously. Eddy current probes have also been adapted to measure the magnetite deposit distribution on the tube bundle (primary and secondary side) to better quantify the impact of tube fouling on SG thermal performance degradation. There is good agreement between the measured and predicted distribution of magnetite on the primary-side of the tube bundle [2], but there are still challenges to be met to improve the quantification of the measured deposit on the secondary-side [20].

The results from the analysis codes and SG inspections on the effect of fouling-related degradation can be used as input to THIRST to predict the impact of aging on SG thermal performance [21][3]. By accounting for the individual degradation mechanisms in the modelling, supported by inspection results, the user is able to assess the impact of operating and maintenance strategies, e.g., the impact of changing water treatment chemistry to reduce fouling, changes in blowdown rate or changes that could affect the level of corrosion product transport in the feedwater system and the impact of chemical cleaning of the secondary side, on the management of SG aging and performance.

[3] In addition to the degradation mechanisms discussed here, thermal performance analyses of aging SGs have also taken account of separator fouling, divider plate leakage, pressure-tube creep, the impact of primary-side fouling on hydraulic resistance in the primary heat transport circuit and changes to operational parameters, such as feedwater temperature and steam pressure [21].

3.3 Managing SG Chemistry and Corrosion

A key element of the SG life management strategy must include managing the chemistry and its impact on the corrosion of system materials, particularly the SG tube bundle and tube support structure and the corrosion of materials in the rest of the steam cycle.

Recently, a chemistry model was incorporated into THIRST to calculate the high-temperature pH as a function of steam quality throughout the SG tube bundle [22]. Account is taken in the model of the base strength and volatility of the amine used for pH control, as well as the thermal decomposition of hydrazine. The model can be used to optimise the selection and concentration of amine in the feedwater system to ensure that all parts of the tube-bundle and tube-support structure are adequately protected against corrosion. This is particularly necessary for plants that use carbon steel tube supports that will suffer flow-accelerated corrosion if the at-temperature pH is not sufficiently elevated above the neutral point.

A separate chemistry model, ChemSolv™, was developed to predict localized water chemistry within SG crevice regions as well as on wetted surfaces throughout the steam cycle. The results of ChemSolv predictions of high-temperature pH relative to the neutral point for selected amines and locations in the steam cycle are listed in Table 1. These results are complementary to the detailed modelling of pH throughout the SG using THIRST, and together provide a means to optimise the AVT to protect wetted carbon steel surfaces throughout the steam cycle.

The chemistry that develops within the crevice regions is affected by the 'hideout' of impurities that are transported to the SG with the feedwater. These impurities concentrate within flow-occluded regions, such as in crevices and the top of the sludge pile, and form precipitates. The pH of the concentrated solution in equilibrium with the precipitate can range from being acidic to alkaline, depending on the concentrations of individual impurities in the system. The chemistry that develops as a result of hideout and precipitation has been the subject of an intensive investigation at AECL's Chalk River Laboratories and at other nuclear laboratories throughout the world [23]. Simulations using ChemSolv and other chemical equilibrium analysis codes have been used to assess the impact of condenser leaks and impurity concentrations in the system during startup and normal operation on crevice chemistry. Recently, attention has turned to the chemistry of lead within the SG crevice regions because of its negative impact on SCC of SG tubing. Lead is transported to the SG absorbed onto corrosion products [24], but its behaviour within the SG crevice is not well understood. Experimental programs have been undertaken by the Electric Power Research Institute (EPRI) and AECL to investigate the solubility of lead compounds [25] and the absorption/desorption behaviour of lead under SG crevice conditions [26]. The results of these investigations will be used to update ChemSolv to take account of lead chemistry and its impact on SG corrosion.

The impact of localized crevice chemistry on the integrity of SG tubing has been thoroughly investigated using electrochemical methods [27], [28]. The results are reported as recommended zones of pH and electrochemical corrosion potential (ECP) in which the risk of pitting and stress corrosion cracking of SG tubes is minimized under various operating conditions, i.e., full power, startup (intermediate temperature) and layup. ChemSolv is currently being upgraded to calculate ECP in addition to crevice pH so that the code can be used in conjunction with the 'recommended' pH/ECP zones to assess the impact of operating chemistry, including the impact of excursions during startup or layup, on the risk of SG tube bundle degradation.

Final confirmation of the effectiveness of the chemistry control program is obtained through inspection (eddy current) and monitoring (ultrasonic) aimed at the timely detection of degradation and for assessment of the need for remedial measures such as repair or chemical cleaning.

4. SUMMARY

Management of SG performance starts with a good design, the selection of robust materials and the specification of a rigorous chemistry control program to protect materials throughout the steam cycle against corrosion. Performance management during the operational phase of the plant requires a vigorous program of monitoring and inspection to detect the early onset of degradation and to develop appropriate operations and maintenance strategies to mitigate further degradation and restore lost performance.

AECL has developed a suite of 'tools' to provide input to design specifications and to help manage SG performance during operation. The 'toolset' combines the results of inspection probes with numerical analysis models to quantify the impact of fouling and corrosion on SG performance. Results from a comprehensive experimental program using electrochemical methods and high-temperature loop tests are used to define chemistry control regimes where fouling and corrosion are minimized.

Measurements of downcomer flow rate, for example, can be used to detect the onset of tube-support fouling and flow-accelerated corrosion of the tube-support structure. The results of this measurement can be confirmed by eddy current and visual inspection of the tube-support region to verify the type of degradation that is occurring, while codes such as THIRST and ChemSolv are used to do further diagnostic analyses to identify the cause of the degradation and to develop remedial solutions. AECL maintains an on-going R&D effort to continue to improve its non-destructive inspection capabilities and to further refine its numerical analysis codes in support of the SG life management programs at CANDU utilities.

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