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Technical note

CANDU steam generator life management

R.L. Tapping [a,*], J. Nickerson [b], P. Spekkens [c], C. Maruska [c]

[a] *AECL, Chalk River Laboratories, Chalk River Ont., Canada K0J 1J0*
[b] *AECL, Sheridan Park Research Community, 2251 Speakman Drive, Mississauga Ont., Canada L5K 1B2*
[c] *Ontario Hydro, Chemistry and Metallurgy Department, 700 University Avenue, Toronto Ont., Canada M5G 1X6*

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Abstract

Steam generators are a critical component of a nuclear power reactor, and can contribute significantly to station unavailability, as has been amply demonstrated in PWRs. Canadian Deuterium Uranium (CANDU®) steam generators are not immune to steam generator degradation, and the variety of CANDU steam generator designs and tube materials has led to some unexpected challenges. However, aggressive remedial actions, and careful proactive maintenance activities, have resulted in a decrease in steam generator-related station unavailability of Canadian CANDU reactors. AECL and the CANDU utilities have defined programs that will enable existing or new steam generators to operate effectively for 40 years. Research and development (R&D) work covers corrosion and mechanical degradation of tube bundles and internals, chemistry, thermalhydraulics, fouling, inspection and cleaning, as well as provision for speciality tool development for specific problem solving. A major driving force is development of CANDU-specific fitness-for-service (FFS) guidelines, including appropriate inspection and monitoring technology to measure steam generator condition. This paper will also show how recent advances in cleaning technology are integrated into a life management strategy. Longer-range work focuses on development of intelligent on-line monitoring for the feedwater system and steam generator. New steam generator designs have reduced risk of corrosion and fouling, are more easily inspected and cleaned, and are less susceptible to mechanical damage. The Canadian CANDU utilities have developed programs for remedial actions to combat degradation of performance (Gentilly-2, Point Lepreau, Bruce-A/B, Pickering-A/B) and strategic plans to ensure that good future operation is ensured. The R&D program, as well as operating experience, has identified where improvements in operating practices and/or designs can be made in order to ensure steam generator design life at an acceptable capacity factor.

1. Introduction

Until recently Canadian Deuterium Uranium (CANDU) steam generators had an enviable record; virtually no tubes plugged because of corrosion (Dyck et al., 1990). Since then several Ontario Hydro reactors have experienced steam generator corrosion, fouling degradation, and fretting of the upper bundle. This has led to thermal and hydraulic inefficiencies as well as tube integrity concerns. To date most CANDU-6

* Corresponding author.
E-mail address: tappingr@aecl.ca (R.L. Tapping)

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(C-6) steam generators have not experienced significant corrosion degradation, although reactor inlet header temperature (RIHT) increases have required remedial action at both Gentilly-2 and Point Lepreau NGS, and Point Lepreau has had some minor steam generator tube corrosion.

Hence CANDU steam generators are subject to many of the same problems that have plagued pressurized water reactor (PWRs) for the past 20 years. This has led to a concerted effort to restore the health of those steam generators that have been degraded, and to proactive measures to ensure that all CANDU steam generators, current and future, meet their design lifetimes. Supporting these efforts is a research and development (R&D) program aimed at providing the knowledge necessary to understand, predict and prevent steam generator degradation.

CANDU steam generators are smaller and different in design than those used in PWRs. Also there are differences in materials, primary and secondary side chemistries, and they operate at lower temperatures than those in PWRs. AECL and the CANDU utilities have had to develop their own solutions to steam generator degradation to ensure an effective steam generator service life. Table 1 summarizes the Canadian CANDU design and chemistry features.

This paper will briefly outline the CANDU utility experience with steam generators, the various CANDU steam generator life management strategies that have been put into place, and the supporting R&D program. As well, the paper provides design recommendations for new steam generators.

2. CANDU utility experience

Until the mid 1980s fouling of the secondary side of long service Ontario Hydro Nuclear (OHN) CANDU steam generators was significant but with little apparent loss of function. By 1990 the support plate flow holes at Bruce-A NGS were(80% blocked (Malaugh and Ryder, 1990; Roy, 1994). This led to flow instabilities (boiler level oscillations) and a program of secondary side cleaning was initiated. Soon after this, under-deposit corrosion of steam generator tubes in the sludge pile region was found at Pickering-B NGS. At approximately the same time the effects of lead contamination on the Bruce Unit 2 steam generator became evident. Later, sludge pile pitting was discovered at Pickering-1, and fretting became a concern at Bruce-B NGS. This information is briefly summarized in Table 2, along with C-6 data. It indicates that prolonged neglect of fouling of CANDU steam generators will lead to thermal performance and corrosion degradation. Repeated detection of fretting wear also indicates that the fabrication of some CANDU steam generators leads to some susceptibility to fretting damage in the U-bend.

In addition to tube degradation, a concern with degradation of primary side divider plates, leading to excessive leakage from inlet to outlet, has emerged recently. Divider plates have been replaced recently at Point Lepreau and Gentilly-2 in 1994/95, and this has had a significant positive impact on steam generator thermal performance.

Despite these problems, the CANDU utilities were able to restore steam generator performance in most units using a program of extensive cleaning, often accompanied with refurbishment. Fig. 1 illustrates the improvement since 1992, in terms of steam generator contributions to incapacity factor, for OHN stations. The intent of the refurbishment was to remove copper alloys from the feedwater train, and to reduce the risk of impurity ingress. The remedial actions are also summarized in Table 3. (It is now anticipated that, with the exception of Bruce Unit 2, and with an appropriate life management strategy in place, steam generators should not become the station life limiting component in CANDU stations). At Bruce Unit 2 the extent of lead-induced stress corrosion cracking, and lead contamination, was such that the unit was shut down in September 1995. Low demand for electricity in Ontario and the projected uncertainty in tube life led to a decision to cease operation. It is anticipated that, should electricity demand, and economics, permit, the Unit 2 steam generators and fuel channels will be replaced and the unit returned to power.

Concerns about U-bend vibration and stress, which have led to fretting, fatigue and stress

Table 1
Summary of design and chemistry specifications for Canadian CANDU stations

Plant history	Pickering-A (4 × 542 MWe)	Pickering-B (4 × 540 MWe)	Bruce-A (4 × 904 MWe)	Bruce-B (4 × 915 MWe)	Darlington (4 × 935 MWe)	CANDU 600	
						Point Lepreau (680 MWe)	Gentilly-2 (685 MWe)
Commercial operation	U1 July 1971	U5 May 1983	U1 September 1977	U5 March 1985	U1 November 1992	February 1983	October 1983
	U2 December 1971	U6 February 1984	U2 September 1977	U6 September 1984	U2 October 1990		
	U3 June 1972	U7 January 1985	U3 February 1978	U7 April 1986	U3 February 1993		
	U4 June 1973	U8 February 1986	U4 January 1979	U8 May 1987	U4 January 1993		
Number of tubes/SG	2600	2573	4200	4200	4663	3550	3550
Thermal output/SG (MWt)	138	138	280	280	664	516	516
Tube material	Monel 400	Monel 400	Inconel 600	Inconel 600	Incoloy 800	Incoloy 800	Incoloy 800
Tube size (OD) (mm)	12.7	12.7	12.7	12.7	15.9	15.9	15.9
T_{hot}/T_{cold} (°C)	293/249	290/249	304/265	304/265	309/265	310/266	310/266
Steam temperature (°C)	252	252	256	256	265	260	258
Tube supports	C-steel lattice bars	C-steel trifoil broached TSP	C-steel trifoil broached TSP	C-steel trifoil broached TSP	410S SS lattice bars	410S SS trifoil broached TSP	410S SS trifoil broached TSP
U-bend supports	C-steel (Cu bearing) lattice bars	Staggered C-steel scallop bars	Stacked C-steel scallop bars	Staggered C-steel scallop bars	Flat 410S AVBs	410 S SS staggered scallop bars	410S SS staggered scallop bars
Tube expansion	Hard roll, near secondary face				Hydraulic, near secondary face	Hydraulic	Hydraulic
Secondary system	Ferrous/copper	Ferrous/copper (Cu being removed)	Ferrous/copper (Cu being removed)	All ferrous	All ferrous	All ferrous; full flow deep bed polishers	Ferrous/copper
Feedtrain heaters	LP: admiralty brass, HP: 90/10 Cu/Ni, reheater: carbon steel	LP: admiralty brass, HP: 90/10 Cu/Ni, reheater: carbon steel	LP: admiralty brass, HP: 90/10 Cu/Ni, reheater: carbon steel	LP: stainless steel, HP: stainless steel, reheater: carbon steel	LP: stainless steel, HP: stainless steel, reheater: carbon steel	LP: stainless steel, HP: stainless steel, reheater: carbon steel	LP: stainless steel, HP: carbon steel, reheater: carbon steel
Preheater	Integral	Integral	Separate	Separate	Integral	Integral	Integral
Condenser tubes	Admiralty brass (304SS outer)	Unit 5 titanium; Unit 6 to be changed to titanium; Units 7/8; admiralty brass (304SS outer tube)	Admiralty brass (304SS outer)	304L SS	Titanium	Titanium	Admiralty brass (316 outer)
Secondary chemistry	AVT/morph/N_2H_4	AVT/morph/N_2H_4	AVT/morph/N_2H_4, boric acid	AVT/NH_3/N_2H_4	AVT/NH_3/N_2H_4	Phosphate and morph/N_2H_4	AVT/morpholine
Condenser water	Lake Ontario	Lake Ontario	Lake Huron	Lake Huron	Lake Ontario	Seawater (Bay of Fundy)	St Lawrence River
Condensate polishing	No	No	No	No	No	Full-time, full-flow	No

corrosion cracking of tubes in the U-bend of various steam generators, have led to improvements in U-bend support structures and designs. At Bruce-A, anti-vibration bars (AVBs) were added to stabilize the structure to reduce the risk of mechanical fatigue, stress corrosion cracking and corrosion fatigue. Similarly, at Bruce-B, the installation of AVBs was required to reduce fretting degradation. More recent designs (DNGS, Wolsong-2, -3, -4) use stainless steel flat bar U-

Table 2
Summary of degradation mechanisms found in CANDU steam generators to date

Unit	Problem	Cause	Comments
Pickering-A	Pitting/wastage in sludge piles	Deep sludge piles; poor chemistry control (for all Pickering units) for some time	Crevice cleaning carried out in Units 1 and 2; SG visually clean; residual tube sheet sludge pile; pitting mainly in Unit 1
	RIHT increase	Primary side fouling? Divider plate leakage	Primary side cleaning of straight legs in unit 1 produced no improvement in RIHT
Pickering-B	Pitting/wastage in sludge piles and first support-plate broaches, RIHT increases	Sludge piles; heavy deposits; condenser in-leakage; secondary/primary side fouling; poor chemistry control (for all Pickering units) for some time	Feedwater chemistry upgrading taking place, Cu in sludge; chemical cleaning of Units 5 and 6 resulted in no improvement in RIHT but left SGs visually clean
Bruce-A	IGSCC/IGA in U-bend at scallop bars	Denting of tubes at scallop bar intersections and 'jacking' of scallop bars; lead (Pb) contamination in Unit 2 accelerated cracking; some fatigue/corrosion fatigue involvement	Feedwater chemistry upgrading taking place, Cu and Pb in sludge; secondary side chemical cleaning carried out in Units 1, 3 and 4
	Shallow pitting in sludge pile	Possibly acidic sulphate conditions	Sulphuric acid ingress from water treatment plant in 1985
	Boiler level oscillations	Fouling of upper support plate	Lancing effective in stopping oscillations
	Fatigue	Excessive vibration	
	Scallop bar corrosion	Unknown: possibly related to crevice corrosion under deposits/acidic conditions	May be some flow assisted corrosion also
Bruce-B	Fretting at U-bend and top support plate	Excessive clearances of U-bend supports	
	Shallow pitting in sludge pile	Possible acid and caustic excursion (WTP in 1989)	
	RIHT increasing	Divider plate leakage; primary side fouling?	Secondary side visually clean; unit 6 has most significant increase
Point Lepreau	U-bend fretting/minor pitting in sludge pile/first support area	U-bend support design? Underdeposit corrosion	Secondary side clean carried out
	RIHT increasing	Divider plate leakage; primary or secondary side fouling?	Recovered $\approx 2°C$ in RIHT; floating one-piece divider plate installed; primary side clean carried out on 60% of tubes
	Emergency water system header erosion	Material loss by flow assisted corrosion	Replacement with low alloy steel
Gentilly-2	RIHT increasing	Divider plate leakage; primary or secondary side fouling?	Recovered $\approx 2.5°C$ in RIHT; floating one-piece divider plate installed; did not carry out large scale primary side cleaning

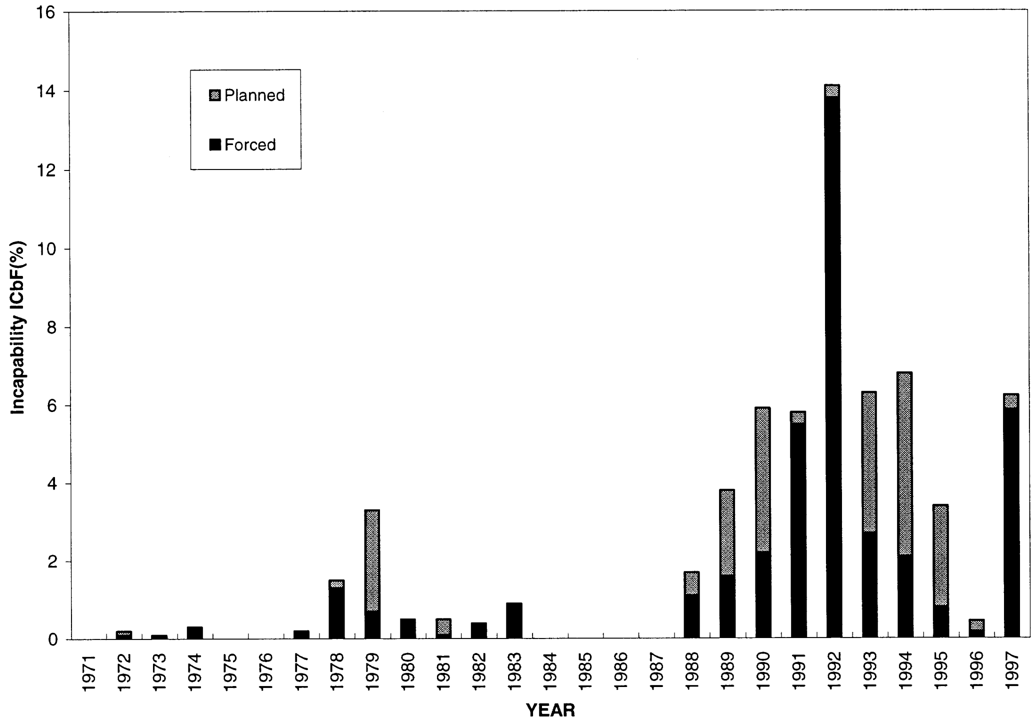

Fig. 1. Forced and planned incapability due to steam generators: OHN, all units.

bend supports, to provide a greater margin against support-induced stresses on the U-bend tubes than do scallop bar supports. However, the effect on fretting wear, compared to correctly installed scallop bar supports, has not yet been determined.

3. Canadian CANDU life management strategies

All Canadian CANDU utilities have a steam generator life management strategy. Those which have experienced degradation (Bruce-A, Pickering-A and B, Point Lepreau, Gentilly-2, Bruce-B) have already carried out remedial actions, as indicated in Table 3, and Darlington has initiated a proactive maintenance strategy. Many of these stations have developed a formal strategic planning document which has been peer reviewed, and the others have operational and maintenance plans which address the same need. Table 3 summarizes the key components of each station's steam generator life management strategy. It may be noted that all address the current Electric Power Research Institute (EPRI) recommendations (Tapping, 1995) where they are relevant for each individual station. The major goals of these plans are to:

1. avoid surprises,
2. learn from experience, and
3. manage the investment in steam generators.

Fig. 2 summarizes the key components needed to implement a life management strategy.

The methodology necessary to put a life management strategy in place is first to establish the station objectives with respect to expected service life and required reliability. It is then important to characterize the plausible degradation mechanisms that may affect steam generator life and reliability, and how these may affect station life and reliability. Important here is a sound fitness-for-service (FFS) plan, and good inspection capability. Steam generator life and reliability is then a function of available remedial actions and a pre-

Table 3
Summary of life management strategy highlights for Canadian CANDU steam generators

Unit	Life management plan highlights
Bruce-A	*Manage existing degradation mechanisms and maximize SG life* Cleaning to remove deposits on tubes, supports, tubesheets Replace all copper components on secondary side Improve water treatment plant Boric acid Wet lay-up recirculation system High hydrazine chemistry Refurbishment of steam generator internals to remove stresses and reduce flow-induced vibration Extensive tube inspection/plugging Tube removals for metallographic assessments and FFS evaluations Hot soaks implemented New water treatment plant Reduction of condenser and air in-leakage Optimization of pH/amine control
Bruce-B	*Manage existing fretting* *Proactive means to prevent corrosion and RIHT increase* Enhance in-service inspection to determine fretting extent/severity Evaluation of effectiveness of prototype U-bend modifications Preparation of enhanced ISI for non-fretting degradation Tube removals for metallographic assessments and FFS evaluations Monitor deposit buildup Evaluate cleaning options
Pickering-A	*Manage existing degradation* Secondary side cleaning Condenser retube of air removal zone Improve condenser in-leakage detection and repair High hydrazine chemistry Routine blowdown Improve water treatment plant Hot soaks Primary side cleaning (Unit 1) Tube removals for metallographic assessments and FFS evaluations
Pickering-B	*Manage pitting degradation* Extensive inspection/plugging Tube removals for metallographic assessments and FFS evaluations Replace copper in feedtrain (including condenser) High hydrazine chemistry Improve water treatment plant Tube sleeving development Water lancing and chemical clean of all steam generators Improved condenser and air in-leakage detection and repair
Darlington NGS	*Proactive program of maintenance, inspection and good chemistry control* Enhanced in-service inspection to detect degradation as soon as possible Water lancing of all steam generators every 4 years Process qualification and conceptual design work for chemical cleaning
Point Lepreau NGS	*Manage existing degradation* Secondary cleaning to control corrosion Improve chemistry control (move to AVT?) Remove primary side deposits Replace divider plate
Gentilly-2	*Maintain clean steam generator and good chemistry control* replace divider plate

ventive maintenance strategy. This may require equipment modifications, cleaning strategies, effective monitoring programs, and improved chemistry control. Clearly cost effectiveness is important, and may vary with time depending on station economics and power demand. Each of the plans summarized in Table 3 has these elements, with the ratio of remedial action to proactive maintenance varying from station to station. Currently Bruce-A is still in the remedial action mode, whereas Gentilly-2 and Pickering-B are transitioning to the proactive maintenance stage, and Darlington is in the proactive maintenance stage.

Remedial programs have paid particular attention to chemistry control, with upgrading of water treatment plants and condenser upgrades (or upgraded operating procedures such that condenser leaks are no longer tolerated) a major consideration. Chemistry specifications have been tightened, and Ontario Hydro stations place heavy emphasis on maintaining secondary chemistry specifications within guidelines.

The steam generator remedial actions have largely been based on extensive cleaning campaigns, including the use of specialized water lance equipment and low and high temperature chemical cleaning, and crevice cleaning methods. All of these had to be specifically tailored to the CANDU designs, materials and sludge characteristics. CANDU-specific cleaning developments are described in Semmler et al. (1998).

For CANDU reactors to benefit fully from their on-power refueling capability, steam generator maintenance must be carried out during the annual, or in some cases, biannual, maintenance outages. There may be a need to have an extended maintenance outage for chemical cleaning every 10 years or so, depending on the fouling situation. Many CANDU stations are currently carrying out remedial and rehabilitative actions to redress years of accumulation of deposits. It has been noted that the cost of these activities is similar to the cost of putting this into place, after degradation has occurred, and maintaining effective long-term maintenance strategies designed to avoid future serious degradation (Talbot, 1995). The Darlington steam generator life assurance plan notes that the cost of an extensive proactive maintenance strategy designed to avoid serious degradation will be about 10% of the cost, over the 40 year station life, of rehabilitating the steam generators after they have been subjected to chronic fouling and impurity ingress. Thus it is evident that routine, frequent and, as necessary, enhanced inspection is an essential part of any effective maintenance strategy; along with a good proactive plugging policy. The past measure that no steam generator leaks implied good performance, with little or no knowledge of the actual condition of the steam generator, is now unacceptable and costly.

Coupled with inspection, is the need for a sound and flexible FFS program that addresses plausible station degradation mechanisms. For current CANDU steam generators the variability of designs implies that fouling and corrosion degradation mechanisms will vary from station to station and hence each station will require a different FFS guideline as well as station specific life management plans.

An important part of the OHN FFS is tube removal to validate degradation mechanisms and assist with root cause analysis. In one case, at Bruce Unit 2, sufficient tubes ((100) were removed that the metallographic analyses could be used to validate the inspection results. This provides considerable confidence, both for the utility and the regulator, in the FFS and life management strategies.

From a design perspective there are several factors to consider when striving for a 40 year steam generator life. Perhaps the most important, after good chemistry control (and specifications and equipment to assure this), is the need for a leak-tight condenser. For seawater-cooled sites a titanium-tubed condenser with leak-tight tube-to-tubesheet joints (for instance Wolsong-1) is recommended to minimize any risk of impurity in-leakage, although few utilities have these. It is often assumed that on fresh water sites the condenser requirements can be relaxed, but experience at CANDUs and PWRs indicates that this assumption is false (Stipan and Tapping, 1995). Although the risk of chloride ingress from lake-water in-leakage may be lower, the concentration over time of chloride in steam generator crevices will eventually reach the same levels as seawater in-leakage. Thus leaktight condensers for fresh water-cooled sites should be as high a priority as at seawater-cooled sites. Other issues related to improved designs for long-term steam generator reliability are briefly outlined in the next section.

4. Research and development activities

Within the CANDU Owners' Group (COG) there is an R&D program aimed at improving current steam generator reliability and operability, and some of this information is used to improve future steam generator designs, which would include replacement steam generators if applicable. AECL has a smaller program focused on design improvements. The entire program covers all aspects of steam generator and balance-of-plant technology, with the primary focus on corrosion, fouling, cleaning, vibration, specialized tooling and non-destructive inspection. Table 4 summarizes the important activities currently underway. Major goals are to put in place the data and tools needed for effective FFS guidelines, to provide effective support for CANDU secondary system chemistry specifications, and to provide input into design requirements, in particular the data needed to ensure that steam generator design life is economically achievable. There is consider-

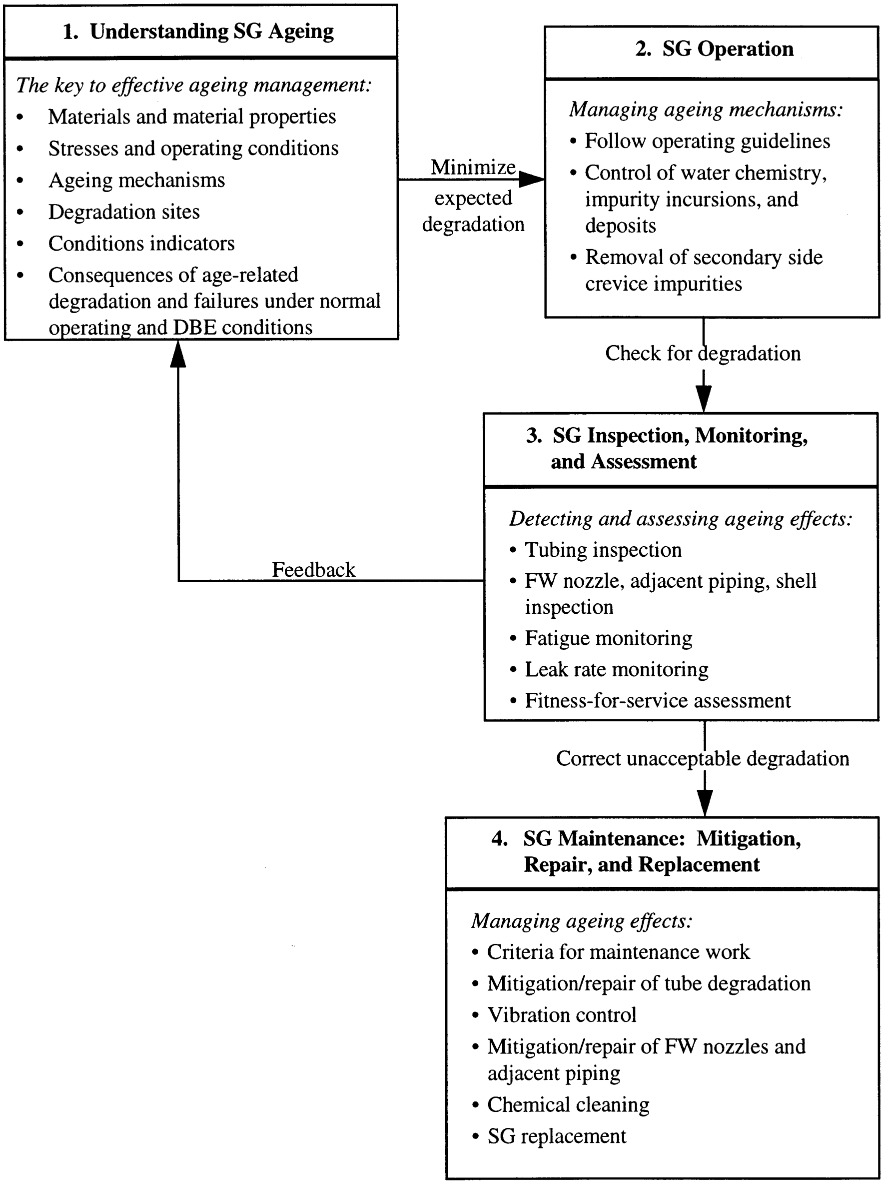

Fig. 2. Key elements of a steam generator life management program and associated interfaces. (From IAEA document 'Assessment and Management of Ageing of Major Nuclear Power Plant components Important to Safety: Steam Generator', published 1996).

Table 4
Summary of R&D activities in the COG steam generator program

Technology	Applications
Chemistry	Crevice chemistry/hideout/hideout return for CANDU SGs Sludge pile chemistry Molar ratio control studies for CANDU Boric acid addition to the secondary side Zinc additions to the primary circuit (primary side fouling/outlet feeder FAC) Amine chemistry ECP correlations
Corrosion/ fatigue	IGA/IGSCC of Alloys 400, 600, 800, 690 under CANDU conditions Pitting of CANDU SG tubing Corrosion fatigue/fatigue of CANDU SG tubing, especially in U-bend Corrosion of carbon steel supports Corrosion inhibitors Corrosion monitoring
Fouling	SG fouling mechanisms and predictions (SLUDGE code development) Corrosion product transport characterization, prediction and assessment (on-line CPT monitor development, control system development, oxide solubility measurements) Applications of CHECWORKS to assess FAC contribution to primary and secondary SG tube fouling Additives for reduction of deposition In-situ sludge characterization (laser Raman, X-ray fluorescence) Sludge chemistry RIHT prediction code Thermal properties of tubes and deposits
Cleaning	Improvements to chemical cleaning processes for CANDU sludge chemistry On-line and dilute cleaning developments Ultrasonically-assisted chemical cleaning Primary side cleaning technology Corrosion monitoring (for cleaning) technology
Vibration and fretting	Vibration and fretting assessments of all CANDU SG designs (PIPO, VIBIC and H3DMAP codes) Fretting fatigue evaluation Underlying vibration and fretting mechanisms
Thermalhydraulics	Thermalhydraulic evaluations of CANDU SG designs (THIRST code) Evaluation of effects of supports on thermalhydraulics Downcomer flow monitoring technology
Inspection and tooling	Eddy current probes and ultrasonic for CANDU SG tubing degradation Eddy current data handling development Validation of eddy current and ultrasonic response (development of probability of detection curves) Qualification of NDE analysts Specialized tooling for SGs (plug leak detector, tube slitting tool, tube sampling tool, sludge sampling tool, i.d. replication tool)
Technology transfer	FFS guidelines development and database generation World-wide steam generator survey (in collaboration with EPRI) Specialized symposia on topics of interest to SG owners

able effort aimed at providing steam generator operators with the rationale and tools to improve steam generator performance, especially corrosion, fouling and fretting mechanisms and inspection tooling. This knowledge, combined with that learned from steam generator tube removals, also provides FFS arguments, an important contribution to life management activities. In what follows, some recent R&D developments that contribute to design and life management strategies are outlined.

Downcomer flow is a measure of steam generator health. In a recirculating steam generator it indicates steam generator support structure fouling by providing an estimate of the recirculation ratio. Comparison with Thermalhydraulics of Recirculating Steam Generators (THIRST) code thermalhydraulic predictions can then be made and an assessment of overall thermalhydraulic efficiencies derived. Downcomer flow measurements can be made in situ during operation over the entire power range with a non-invasive ultrasonic technique developed by AECL. This technique also detects the presence of void in the downcomer and hence separator efficiency or other steam leak paths can be inferred. Downcomer flow measurements have been made at Bruce-A and Darlington, and others are planned.

These measurements suggest that cleaning of the Bruce-A upper support plates has restored thermalhydraulic behaviour there, and that Darlington is operating as designed.

As noted earlier, chemical cleaning is now part of the CANDU steam generator life management strategy, both for existing and new stations. R&D in cleaning technology has been oriented towards optimizing available low and high temperature processes for CANDU steam generators, and more recently towards developing dilute or mild cleaning for routine, low-cost and non-corrosive cleaning, probably during shutdowns. This work includes the development of cleaning technology for primary side steam generator fouling, which may be a contributor to increasing RIHT. This fouling also increases radiation fields in the vicinity of steam generators and negatively impacts NDE inspection campaigns.

The NDE work has led to the development of eddy current probes capable of detecting axial or circumferential cracks in 0.5 and 0.625 in. tubes (C-5 and C-3 probes, respectively), of rotating probes for detection of pits in Monel 400 (Carter probes), and, more recently, of dual purpose probes for rapid detection of cracks and volumetric defects. In parallel with this are developments of ultrasonic probes for more detailed analysis of degraded areas, especially those at the detection limit (or below) of eddy current.

There are also projects to improve data handling, since the C-3 and C-5 probes generate significant data that impacts on the ability of the analyst to complete the analysis quickly, and hence on overall inspection time. If life management is to be successful, more rapid, and accurate, steam generator inspections are required.

Part of the NDE work, in collaboration with FFS, is validating NDE response and qualifying analysts; both activities essential to an effective, and cost-efficient, life management program.

Hideout return studies are an important component of steam generator life management, and provide a direct measure of chemistry control. Such studies at a number of Ontario Hydro stations have shown that good chemistry control has reduced fouling and hideout of impurities (Balakrishnan et al., 1995). Older units had considerably more impurities 'hidden out' than newer ones, which is indicative of the greater degree of fouling in the older units. It also suggests that it is important to maintain a clean steam generator. CANDU stations typically do not operate under molar ratio control guidelines, but analysis of chemistry data for Ontario Hydro stations indicates an operating molar ratio of 0.6:0.8. At Bruce-A, where boric acid additions are made to inhibit scallop bar corrosion, hideout return studies show that boric acid is indeed penetrating the crevices and deposits, as desired.

As Table 4 shows, there is considerably more R&D that is having an impact on steam generators, much of it aimed at improving inspection technology, and at quantifying design requirements and operating specifications. Changes in these requirements and specifications can be made only if there is a good understanding of the science and engineering behind them, so that their impacts can be properly assessed.

5. Summary

While CANDU steam generators had an enviable record until 1988, recent experience has shown that they are not immune to some of the problems that have plagued PWR plants. To address these, the CANDU utilities have put in place aggressive steam generator life management programs. AECL and COG have undertaken proactive R&D work aimed at both supporting these life management programs and providing knowledge to lead designs for future units. It is recommended that a rigorous and detailed life management program be put in place at all CANDU stations. A detailed assessment of all potential degradation mechanisms is a key ingredient of the program.

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