5th International Conference on CANDU Maintenance
November 19-21, 2000, Toronto, ON, Canada

CANDU PLANT LIFE EXTENSION: STEAM GENERATOR CONSIDERATIONS

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ABSTRACT

Life Management planning and its effective implementation is essential for reliable and competitive power plant operation. Lack of timely implementation of plant life management (PLIM) in many Nuclear Power plants worldwide, particularly for steam generators, has forced many operators into a remedial repair mode, and sometimes steam generator replacement, particularly steam generators with Alloy 600 tubing. Maintaining economically competitive nuclear power plant operation requires high capacity factors. This requires a high degree of component reliability and an innovative approach to maintenance and outage planning. If these are achieved NPPs offer a competitive and environmentally sound product, making the option of plant life extension (PLEX) an attractive one.

Point Lepreau Generating Station (PLGS) has been in operation since 1983, with an average lifetime capacity factor to date of 84% and a good safety track record. Hence the option of extending its service life can be considered. The viability of PLEX depends heavily on the state of key systems, structures and components (SCCs). Steam generators (SGs) are one key component while considering the PLEX option. For CANDU 6 PLEX decisions, the timing of a potential fuel channel replacement is also a primary decision-making activity, and steam generator replacement or may need to fit with any fuel channel replacement activity.

This paper presents some of the aspects currently under consideration for a life extension of CANDU 6 steam generators to a 50 year life (design life is 30 years), and makes recommendations to address these aspects. Tube bundle life, although a significant factor, may not be the most important factor in determining the probability of achieving 50 year life. Steam generator internal structures, for instance, present a challenge in estimating current condition as well as future life. The life assurance of the internal structures needs to be assessed with an appropriate inspection program. The excellent corrosion resistance of the PLGS (and Alloy 800M world-wide) tube bundles so far requires a novel approach to predicting future performance. This approach is based on extensive laboratory data and involves defining a minimal set of tubes that can be predicted to be susceptible to degradation.

INTRODUCTION

A number of Canadian CANDU reactors have now reached mid-life, and are carrying out programs to maintain or improve plant capacity factors. Plant life management strategies for maintaining efficient operation until end of life (typically 30 years at 80% capacity factor for CANDU 6 units and all Ontario Power Generation (OPG) units except Pickering A, which is 40 years) are in place at most Canadian CANDU stations. These plans are designed to maintain the asset and minimize outage time in order to provide competitive electricity production costs in an increasingly deregulated electricity market.

Although the CANDU 6 units (Point Lepreau, PLGS, and Gentilly-2, G-2) in Canada have been in operation since 1983, and thus are only at mid-life, part of an effective life management strategy must involve considerations for life extension. This is because strategies to maintain the asset to design life may differ from strategies to maintain and extend asset life. Additionally, if replacement of major components is required, and cost-effective, for life extension, then sufficient time for this replacement must be provided.

CANDU reactor life extension decisions will be dominated by fuel channel replacement. Since this requires an extended outage, any other major components that need replacement in order to achieve significant life extension should be replaced at that time, if they also require an extended outage. This, then, can add an economic constraint to life extension considerations.

In many pressurized water reactors (PWRs), SGs have had to be replaced because of severe degradation of the steam generator tubing. In 5 of the 6 US PWR plant closings, steam generator problems were a primary factor in the decision to shut down. Generally where SG replacement has occurred the SG replacement has been required to continue efficient plant operation, and not for plant life extension. In most of the CANDU reactors, the SGs have not experienced significant corrosion degradation, and hence plant life extension considerations will require decisions to be made on the probability of the SGs to continue to function without significant degradation for a total life of 50 years, or possibly more.

This paper provides a summary of the steam generator issues that need to be addressed for any proposed life extension, with specific relevance to CANDU steam generators.

BACKGROUND

CANDU steam generators are smaller than most PWR steam generators, but are otherwise similar in design. Some notable differences are:

- CANDU SGs are designed with a recirculation ratio close to 5; this is are typically higher than PWR SGs
- CANDU SGs have integral preheaters (except the Bruce units, which have external inverted U-tube preheaters)
- CANDU SGs typically use different tubing and internal materials than most PWR SGs, and have smaller diameter tubing (5/8", 16 mm, in CANDU 6 SGs and Darlington NGS; ½", 13 mm, in other OPG units).
- CANDU SGS operate at lower temperatures and pressures.

Table 1 summarizes typical CANDU 6 SG materials. CANDU SG degradation is largely limited to SGs in units operated by OPG. Typically those units experiencing significant corrosion are those at Bruce A (tube cracking; Alloy 600 tubing) and Pickering B (tube wastage/pitting; Alloy 400 tubing), which are earlier designs than those currently in use in CANDU 6 and Darlington units. Table 2 summarizes the typical SG degradation noted to date for CANDU units. It can be noted that the experience with the Bruce A units is typical of that in PWRs with Alloy 600-tubed SGs. The Pickering B tube wastage/pitting, which contrasts with the lack of corrosion noted in the older Pickering A units, appears to be a consequence of subtle differences in the Alloy 400 tubing composition between the A and B SGs, and is associated with the presence of oxidizing impurities.

CANDU 6 SGs, which are all tubed with Alloy 800M (modified, or nuclear grade, with controlled carbon content), have experienced relatively little SG tube corrosion to date. Table 3 presents a summary of SG tube plugging experience for these units, which shows that CANDU 6 SG performance to date is excellent. Based on this performance it would not be anticipated that SGs, or at least the tubing, would be a life-limiting component in a plant life extension evaluation.

SPECIFIC EXPERIENCE WITH POINT LEPREAU SGs

Point Lepreau Generating Station has operated since 1983 and provides a good example of CANDU 6 SG performance to date, as well as the strategy required for life extension. Although the PLGS SGs have had more SG tube plugging that any other CANDU 6 unit to date, overall the rate of tube plugging is very low, and relatively little of the plugging is a consequence of corrosion (see Table 4 for a summary); and most of the corrosion is a consequence of the use of phosphate secondary side chemistry control. PLGS currently operates with a combination of morpholine and congruent phosphate secondary side pH control. Conversion to morpholine-based AVT is planned for 2000. There has been no primary side tube degradation at any CANDU 6 unit, nor any secondary side intergranular attack/stress corrosion cracking (IGA/SCC).

Thus, as summarized in Table 4, there is little evidence for any significant SG tube degradation mechanism. Nevertheless any life extension strategy will have to evaluate the likelihood that this experience will continue, especially following the conversion to AVT secondary side chemistry treatment and evaluate the susceptibility to any degradation experienced elsewhere, but not yet at PLGS.

Laboratory data, and in-service experience at other utilities, forms the basis for predicting Alloy 600 SG tube life, and also for defining the optimal set of tubes for inspection and monitoring (less than 100%). In effect, the combination of this database with the existing experience (world-wide) with Alloy 800 SG tube degradation, provides the basis for specifying which tubes should be inspected and monitored.

In addition to the tubing, there are a number of other components in a SG that could compromise life. These include components that can be grouped into the following categories:

- primary side pressure boundary
- secondary side pressure boundary
- external supports
- primary side internals
- secondary side internals

Furthermore, the first 3 CANDU 6 units (PLGS, Gentilly-2 and Embalse) all required a SG tube bundle rebuild; the consequence of a vessel heat treatment that resulted in tube support movement that dented the tubing [1]. The SGs were re-built at site; this adds a level of complexity to the life extension considerations. Any impact of the SG rebuild has to be assessed. Each of the following sections deals with the major groupings outlined above, as well as the tube bundle itself.

TABLE 1: CANDU 6 STEAM GENERATOR INFORMATION

	Point Lepreau	Gentilly 2	Embalse	Wolsong 1
Reactor Size (MWe) gross	680	685	648	679
Date of First Operation	Feb-83	Oct-83	Jan-84	Apr-83
Chemical Control Chemical Additive	Congruent Phosphate Hydrazine, Morpholine Converting to morpholine-based AVT in 2000.	AVT Morpholine (in 1999 Hydrazine was added)	AVT Hydrazine, Morpholine	AVT Hydrazine, Morpholine
Number of SG's	4	4	4	4
Number of Tubes/SG	3542	3542	3542	3542
SG Tube Material	Alloy 800 M*	Alloy 800 M*	Alloy 800 M*	Alloy 800 M*
SG Tube Support Plate Material/Type	SS/Broached	SS/Broached	CS/Broached	Alloy 600/Grid Support
SG Tube Treatment	Stress Relief in U-bends	OD glass bead peened above tubesheet	Stress Relief in U-bends	Vessel Stress Relief
SG Manufacturer	Babcock & Wilcox (Can)	Babcock & Wilcox(Can)	Babcock & Wilcox (Can)	Foster Wheeler (Can)
Condenser Tube Material	Titanium (Aluminum bronze D tubesheet)	Admiralty with 316SS outer tubes	Admiralty with304SS outer tubes	Titanium
Condensate Polishing in place	Full-time, Full-flow (retrofit)	No	No	No
Feed Train Materials	LP heaters - stainless steel HP heaters - stainless steel Reheater - carbon steel Piping - carbon steel with some stainless steel	LP heaters - stainless steel HP heaters - carbon steel Reheater - carbon steel Piping - carbon steel	LP heaters - carbon steel HP heaters - stainless steel Reheater - carbon steel Piping - carbon steel	LP heaters - stainless steel HP heaters - carbon steel Reheater - carbon steel Piping - carbon steel

*Ti/C ≥ 12

TABLE 2: SUMMARY OF CANADIAN CANDU STEAM GENERATOR DEGRADATION AND COUNTERMEASURES TAKEN (LOOSE PARTS AND PRE-SERVICE PLUGGING NOT INCLUDED)

UNIT	DEGRADATION	CONTRIBUTING FACTORS	COUNTERMEASURES
Pickering-A	Pitting/wastage in top of tubesheet area mainly in Unit 1.	Deep sludge piles. Impurity ingress due to condenser in-leakage.	Waterlancing and crevice chemical cleaning carried out in Units 1 and 2. Inspection and plugging of tubes.
	RIHT rise (loss of thermal performance).	Primary side fouling. Divider plate leakage.	Primary side cleaning of straight legs in Unit 1 (produced no improvement in RIHT; cleaning may not have been effective).
Pickering-B	Pitting/wastage in top of tubesheet area and at support-plate broaches.	Sludge piles; heavy deposits; impurity ingress due to chronic condenser in-leakage. Secondary/primary side fouling. Mixed Cu/Fe secondary side system. Condenser in-leakage.	Manage pitting degradation by inspection and plugging. Large scale inspection and plugging in Unit 5. Tube removals. Chemistry upgrading in all units. Chemical cleaning and waterlancing of deposits in all units. Removal of all Cu components in secondary system, including condenser . Sleeving developments.
	RIHT rise (loss of thermal performance).	Primary side fouling; divider plate leakage.	Hot quadrant divider plate replacements.
	Shallow erosion of tubes at supports (Unit 8).	Unknown at this time; FAC-related mechanism.	Inspection trending.

UNIT	DEGRADATION	CONTRIBUTING FACTORS	COUNTERMEASURES
Bruce-A	Intergranular stress corrosion cracking/intergranular attack (IGSCC/IGA) in U-bend at scallop bars.	High induced stresses due to locked tube supports, denting of tubes at scallop bar intersections and "jacking" of scallop bars due to carbon steel corrosion. Lead (Pb) contamination in Unit 2 accelerated cracking. Some fatigue/corrosion fatigue involvement.	Large inspection and plugging campaigns. Tube removals. Release of stresses by unlocking supports. Feedwater chemistry upgrading. Secondary side chemical cleaning and waterlancing carried out in Units 1, 3 and 4. Removal of Cu components including condenser in Units 3 and 4. Lead control and monitoring measures. Boric acid addition. Water treatment plant (WTP) improvements.
	IGSCC/IGA @ tubesheet on secondary side (discovered in 1997).	Unknown at this time. Tube stresses, hard sludge piles and acid excursion may have contributed to mechanism.	Inspection and plugging campaign. Tube removals for metallography.
	PWSCC at tubesheet.	Unknown at this time.	Inspection and plugging.
	Shallow pitting at top of tubesheet area.	Presence of sludge pile and possibly acidic sulphate conditions due to WTP excursion.	Inspection trending.
	Boiler level oscillations.	Fouling of upper support plate.	Lancing to remove fouled broach plate blockage.
	Fatigue.	Excessive vibration.	Additional supports installed to reduce vibration in some units.
	Scallop bar corrosion.	Unknown. Possibly crevice corrosion under deposits/acidic conditions. May be some flow assisted corrosion also.	Inspection and additional supports installed in Units 1, 3 and 4.
Bruce-B	Fretting of tubes at U-bend and top support plate.	Excessive clearances of U-bend supports.	Manage degradation by inspection and plugging. Additional supports installed in some steam generators.
	Shallow pitting.	Possible acid and caustic excursion (WTP in 1989) or may be due to start-up oxygen transients.	Inspection trending. Chemical environment monitoring. Deposit monitoring. Evaluation of cleaning options. Tube removals for metallographic assessments.
	Primary separator wall loss and perforation.	Appears to be FAC-design related (under investigation)?	Selective replacement with austenitic stainless steel.
Darlington	U-bend fretting.	Support alignment/clearances (?)	Manage by inspection and plugging.
PLGS	U-bend fretting.	U-bend support design?	Manage by inspection and plugging
	Minor pitting in tubesheet area and at lower supports.	Underdeposit corrosion. Condenser in-leakage in early life.	Secondary side clean. Waterlancing. Plans to improve to all volatile treatment (AVT) chemistry control. [Currently use phosphate chemical control.]
	Reactor Inlet Header Temperature (RIHT) increasing.	Divider plate leakage. Primary/secondary side fouling?	Floating one-piece divider plate installed. Primary side clean carried out in 60% of tubes. Recovered ~2°C in RIHT.
	Emergency water system header erosion.	Material loss by flow assisted corrosion.	Replacement with higher Cr content steel.
Gentilly 2	RIHT increasing.	Divider plate leakage. Primary/secondary side fouling?	Floating one-piece divider plate installed. Recovered ~2.5°C in RIHT. Large scale primary clean in 1999 recovered ~2°C RIHT and 4 to 5% core flow.

TABLE 3: SUMMARY OF CANDU 6 SG TUBE PLUGGING (NO TUBES SLEEVED)

	Tubes Plugged In-Service (to 1998)
PLGS	48
Gentilly-2	3
Embalse	29
Wolsong-1	1

TABLE 4: SUMMARY OF TUBE PLUGGING FOR PLGS SGS (TO 1999)

Reason	# of Tubes	Comments
Pre-inservice	51	manufacturing defects
Pitting/Wastage	38	mostly phosphate-related
Fretting (U-bend)	4	
Loose parts	42	38 in 1999
Other	3	2 seal weld

PRIMARY SIDE PRESSURE BOUNDARY

Significant concerns are the potential for cracking of the primary head-to-tubesheet weld and local head wall thinning. So far there has been no evidence for either in CANDU SGs; all welds were heat treated following welding and should not be susceptible to weld cracking. Similarly, although flow assisted corrosion (FAC) of carbon steels in steam generators is possible (note that the primary head in CANDU SGs is unclad carbon steel), to date no FAC or wall thinning of the primary side pressure boundary of CANDU SGs has been observed. Low cycle thermal fatigue cycles expected for 50 years are less than the design requirements for 30 years, so thermal fatigue is not expected to be an issue. Thus a life extension of at least 20 years, in addition to the original 30-year design life, would be anticipated, with an appropriate inspection program.

SECONDARY SIDE PRESSURE BOUNDARY

As with the primary side pressure boundary, the concerns are weld cracking, for instance girth weld cracking, and FAC in the downcomer annulus. Although girth weld cracking has been seen in some PWR SGs [2], this was a consequence of incorrect post-weld heat treatment (PWHT). CANDU SG vessels were given an appropriate PWHT, and to date no cracking has been detected. Minor cracking has been detected under some seismic lugs and is being successfully managed in current inspection and maintenance programs. This cracking is considered to have occurred during fabrication. Inspections for wall thinning, although limited, indicate no i.d. wall thinning of the SG vessel, although instances of FAC of SG internals have been reported elsewhere [3]; thus this degradation mechanism cannot be excluded from life extension considerations.

Again, a life extension of at least 20 years beyond design life seems reasonable, with an appropriate inspection and maintenance program.

EXTERNAL SUPPORTS

The potential ageing mechanism for external SG supports is general corrosion; however the environment in the vicinity of the supports is very dry air and no degradation would be expected. A visual examination of the PLGS external supports, where accessible indicated no degradation. Thus life extension for 20 years seems reasonable with periodic visual inspection to verify condition (and re-coat support cables as necessary).

PRIMARY SIDE INTERNALS

There are two life-limiting concerns here. One is the primary divider plate and the other loose parts. Both have been issues for CANDU 6 SGs in the past. In the older CANDU 6 SGs (PLGS, G-2, and Embalse), the divider plates were assembled inside the primary head and bolted together to form a solid plate. This plate was held in place with seat bars on the primary tubesheet and the primary head. FAC of the bolts holding the plate sections together, as well as FAC of some of the plate-to-plate joints, resulted in unacceptably high leakage rates. At PLGS and G-2, these divider plates were replaced with a floating all-welded plate. Embalse will be replacing their primary divider plates shortly. All subsequent CANDU 6 SGs have either a floating all-welded plate, or an all-welded plate welded into the SG primary head. FAC of the joints between the floating divider plate design and the seat bars is precluded by the use of Alloy 690 cladding material on the seat bars. The only potential area for FAC is the gap between the divider plate and the vessel head-tubesheet intersection. This will be monitored to ensure no degradation is occurring.

Design allowances are such that these all-welded plates should comfortably provide for a 20-year SG life extension, again with an appropriate inspection program.

Loose parts are always a concern for SGs. On the primary side there have been several instances of large parts entering (or being left in) the primary head and causing damage to the tube ends. In CANDU 6 SGs, there has been no evidence of tube end cracking resulting from loose parts, but, for instance, at G-2 prior to service (commissioning), an errant manway cover hinge caused considerable tube end damage to the hot leg side of the tubesheet in one SG, which resulted in all tube-to-tubesheet welds being re-done. An on-going requirement of any SG life management program, whether it includes life extension or not, is to put in place an effective program to prevent loose parts from entering the steam generators.

SECONDARY SIDE INTERNALS

From a life extension perspective, the secondary side internals pose perhaps the greatest challenge. Many of these components in CANDU 6 SGs are difficult to inspect (for instance the feedwater box, tie-rod turnbuckles), but can have life limiting consequences if they fail. Many are repairable, but for some of these components repair will be difficult. Examples of this are the feedwater box and associated components. An example of a repairable item is the emergency water supply/reheat condensate header (EWS/RCH) located above the tube bundle. At PLGS, severe wall thinning (thought to be a consequence of FAC) of parts of this system led to replacement in 1996. This FAC is not a life limiting concern here because the component is readily inspectable and replaceable. However, failure of the system could result in significant loose parts damage to the tube bundle, and might compromise primary to secondary containment. Thus inspection of this component becomes a life management and life extension issue, as well as a safety concern, for any CANDU 6 SGs with a similar design.

Similarly, the recent (1998) detection of separator wall loss/perforation in several Bruce-8 SGs suggests that other CANDU SG separators be inspected for such wall loss (thought to be a consequence of FAC), in particular those with a similar design (PLGS, G-2, Embalse). To date, inspections of PLGS and G-2 separators have revealed no evidence of FAC or wall thinning.

CANDU SG secondary side internals, in particular those at PLGS, have been examined reasonably frequently, probably more than at most other CANDU or PWR stations. However, such inspections are limited to readily-accessible components (tubesheet area, downcomer annulus, steam drum, tube supports, for instance), and usually this is a visual inspection. For life extension some assurance, and analysis, that these components are currently in good condition is required, and/or a commitment to inspecting components that to date may not have been inspected. Frequently a visual inspection will be sufficient to establish that the components are in good condition. For instance, at PLGS visual inspection of components in the downcomer area revealed that machining marks could still be discerned, suggesting that no significant degradation has occurred. For critical components, such as the feedwater box, provision for a hand hole located in the area will allow for visual inspection. Review of the design analyses of critical components such as the feedwater box may be required for life extension.

GENERAL CONSIDERATIONS FOR LIFE EXTENSION

Any life extension strategy requires an assessment of current condition. In CANDU 6 SGs, current condition is generally very good and SG life extension requirements are based on an inspection/maintenance plan, with some component re-analysis or review (i.e., for fatigue life) if there is any concern about current condition (for instance, if a component is critical in the sense that its failure could compromise SG life or operation, and inspectability is limited).

Table 5 gives an assessment of risk to the tube bundle for CANDU 6 SGs, of not attaining design life/life extension due to the various types of degradation mechanisms that have occurred in the nuclear SG industry. Because there is so little evidence for Alloy 800 SG tube corrosion world-wide (for example, only 1 tube crack in 25 years of service; Biblis B, early 1980's), there is no database on which to carry out a probabilistic risk of failure assessment. The risk factors in Table 6 are based on laboratory data, with field experience added when available. Currently the Canadian CANDU 6 SG tube performance, based on percentage of tubes plugged per effective full power year (EFPY), is 0.036 (including tubes plugged prior to in-service). Given that a value ≥1 typically means the SG will have to be replaced (or the plant shut down), and that a value ≤0.1 indicates excellent performance, there is considerable margin for a 20-year life extension of CANDU 6 SGs (the offshore CANDU 6 SGs have an even lower rate of percent tubes plugged/EFPY; ≤0.01). One caveat here is that, typically, units not experiencing tube degradation do not remove surveillance tubes very often. A good life management and life extension program would include periodic removed tube examinations.

AECL has an extensive database of Alloy 800M corrosion behaviour in various SG chemistries, based on more than 30 years of laboratory work. This database, plus available literature data, enable an estimation to be made of the most critical areas of the tube bundle that may be susceptible to fouling and corrosion. Based on this estimation, an optimized inspection and cleaning strategy can be developed for each CANDU-6 SG.

Table 6 gives a generalized assessment of SG life attainment/life extension capability for CANDU 6 SGs. Specific units may have slightly different risk assessments based on varying levels of inspection (in particular inspection of non-tube components) and operating practice, but Table 6 can be considered a generic statement based on current condition, world-wide experience, and data from laboratory testing. For CANDU 6 SGs, it is important, particularly for secondary side internals, to assess current condition, followed by a proactive maintenance (cleaning) and inspection program that should assure at least a 20-year life extension.

TABLE 5: SUMMARY OF PWR/PHWR SG TUBE DEGRADATION MECHANISMS, AND RELEVANCE TO CANDU 6

MECHANISM	STRESSORS	SITE	FAILURE MODE	INSPECTION METHOD	RELEVANT TO CANDU 6?	RISK
Secondary side (OD) SCC*	tensile stress, material susceptibility, concentrated acidic or alkaline chemistry in crevices/under deposits, temperature	• tube-to-tubesheet crevice • tube-to-support crevice • under freespan deposits • sludge pile • U-bend supports	• axial or circumferential cracking • axial crack • axial crack • circumferential crack • axial and circumferential cracks	• Motorized Rotating Pancake Coil (MRPC or Cecco 5 • MRPC or Cecco 5 • MRPC or Cecco 5 • MRPC or Cecco 3 • MRPC or Cecco 3 • MRPC or Cecco 5	Possible; Alloy 800M can crack in highly acidic or alkaline solutions when highly stressed, especially if lead contamination is present. Only 1 SCC occurrence of Alloy 800M in service to date. (Biblis B)	Low
Intergranular Attack	Deposits, crevices, oxidizing impurities	• tubesheet sludge pile, supports, free-span tubes under deposits	• dissolution of grain boundaries; • grain dropout	• bobbin, Cecco-4	Possible on AVT. Not yet detected on Alloy 800M in service under any chemistry control.	Low

MECHANISM	STRESSORS	SITE	FAILURE MODE	INSPECTION METHOD	RELEVANT TO CANDU 6?	RISK
Primary side SCC	tensile stress, material susceptibility, temperature	• U-bend inside surface • tubesheet transition • dents	• axial and circumferential cracks • axial and circumferential cracks • circumferential cracks	• MRPC or Cecco 5 • MRPC or Cecco 5 • MRPC, Cecco 4, Cecco 5	Alloy 800M highly resistant to PWSCC (none observed to date).	Very Low
Fretting, wear, thinning	flow-induced vibration, loose parts	• contacts between tubes and supports (AVBs) • contact between tubes and loose parts • tube-to-tube contact	• local wall loss • local wall loss • local wall loss	• bobbin or Cecco 4 • bobbin or Cecco 4 • bobbin or Cecco 4	Yes. Scallop bar and AVB fretting has been detected; loose parts damage always a risk	Medium - Low (likely very limited in extent)
High cycle fatigue	high mean stress and vibration; initiating defect	• inadequately-supported tubes	• transgranular circumferential cracking	• MRPC or Cecco 5; leak detection	Unlikely; however cannot be entirely ruled out.	Very Low
Denting	oxidizing impurities (copper oxides, oxygen), chlorides, low pH, crevices (drilled-hole supports), temperature	• tube supports, sludge pile, tubesheet cracking	• flow blockage, circumferential cracking	• profilometry, bobbin, Cecco-4, UT	Unlikely, but requires maintaining clean SG and good feedwater chemistry.	Low
Dinging	Likely same as denting	• typically found in U-bend tubes	• unknown, but in extreme, circumferential cracking	• profilometry, bobbin/UT/ Cecco 4	Dinged tubes present	Very Low
Pitting	chlorides, oxidizing impurities, deposits, crevices, resin intrusions	• sludge pile, fouled supports, tube defects (i.e.,weld slag)	• local attack	• bobbin, Cecco-4, ultrasonics	Yes, already detected. Possible unless impurity ingress carefully controlled.	Medium
Wastage	phosphate	• sludge pile, fouled supports, tubesheet crevices	• localized patches of wall thinning	• bobbin, Cecco-4, ultrasonics	Yes, already detected and attributed to phosphate chemistry (PLGS, German plants).	High (while maintaining phosphate chemistry) Low on AVT.
Fouling	Poor chemistry control; transients, startups	• primary and secondary sides of tubing; tubesheet	• loss of thermal performance (primary side fouling); increase corrosion susceptibility (secondary side)	• bobbin (primary side); visual (secondary side) or bobbin (tubesheet sludge pile)	Yes. Both primary and secondary sides are fouled.	High. Requires periodic primary and secondary side cleaning.
Loose Parts	Loose parts entering SG	• tube bundle, primary head	• tube perforation; primary tubesheet damage	• bobbin/Cecco-4, UT	Yes, on tube bundle secondary side.	Medium. Must control loose parts that could enter SG

*SCC = stress corrosion cracking

TABLE 6: GENERALIZED ASSESSMENT OF CANDU 6 SG LIFE ATTAINMENT/LIFE EXTENSION CAPABILITY

COMPONENT	ASSESSMENT		COMMENTS
	Design Life Achievable?	20 Year Extension?	
Tube bundle	✓	✓	• U-bend fretting limited and will not compromise life • wastage a concern at PLGS, but will be managed there by move to AVT to reduce risk • pitting a concern; manage with improved chemistry control to minimize risk • SCC unlikely to be a concern • monitor routinely at-risk selection of tubes and maintain clean tubesheet/supports to lower risk
Primary side pressure boundary	✓	✓	• no degradation observed to date; low risk for not achieving design life/extension • periodically monitor to maintain low risk
Secondary side pressure boundary	✓	✓	• no degradation observed to date; low risk for not achieving design life/extension • periodically monitor to maintain low risk
External supports	✓	✓	• no significant degradation observed to date; low risk of not achieving design life/extension • periodically inspect to maintain low risk; cables should be re-coated every 10 years
Secondary side internals	✓	✓	• relatively few inspection data available; baseline data insufficient for low risk assessment • based on available data, components should achieve design life and life extension; moderate risk • lack of corrosion allowance in some components may limit secondary side chemical cleaning applications • increased inspection and monitoring required to reduce risk
Thermalhydraulics/ Fouling	✓	✓	• SG fouling contributes to ROP/CCP margin erosion; ensure primary side of tube bundle is periodically cleaned to minimize this • periodically monitor downcomer flow, separators to ensure thermalhydraulic function meets design; periodically clean tube bundle/supports to maintain function

SUMMARY

A brief overview of CANDU 6 SG issues relating to life extension has been provided, using PLGS SGs as an example. Because the current condition of CANDU 6 SGs appears to be good, with little evidence of corrosion of the Alloy 800M tube bundles, and only occasional deterioration of a few (replaceable) internal structures, life extension to at least 20 years beyond the 30-year design life appears feasible. The significant recommendations for such life extension are for an assessment of current condition prior to a life extension decision (primarily for secondary side SG internals), and to maintain, or put in place, a sound maintenance and inspection program. The key maintenance activities are to eliminate loose parts from entering the SGs and to prevent or manage the accumulation of deposits on the secondary and primary side surfaces.

ACKNOWLEDGMENTS

The authors would like to acknowledge inputs from B&W Canada, Siemens Canada, and a number of AECL staff who have contributed to steam generator life management studies, in particular N. Subash.

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