STEAM GENERATOR AGING IN CANDUS: 30 YEARS OR OPERATION AND R&D

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INTRODUCTION

The early years of operation of CANDU reactors, with the exception of the Douglas Point reactor, was characterized by relatively few operational problems associated with steam generators. During the same period PWR reactor steam generators (SGs) were experiencing tubing degradation associated with denting of tubes at intersections with drilled hole support plates; these types of degradation were followed by other forms of corrosion-related degradation. Figure 1 shows the evolution of the various SG degradation mechanisms observed to date with time for the first 30 years of operation, with stress corrosion cracking (SCC), either primary side SCC (IDSCC) or secondary side SCC (ODSCC) dominating the degradation. This history is essentially that of degradation of SGs tubed with Alloy 600.

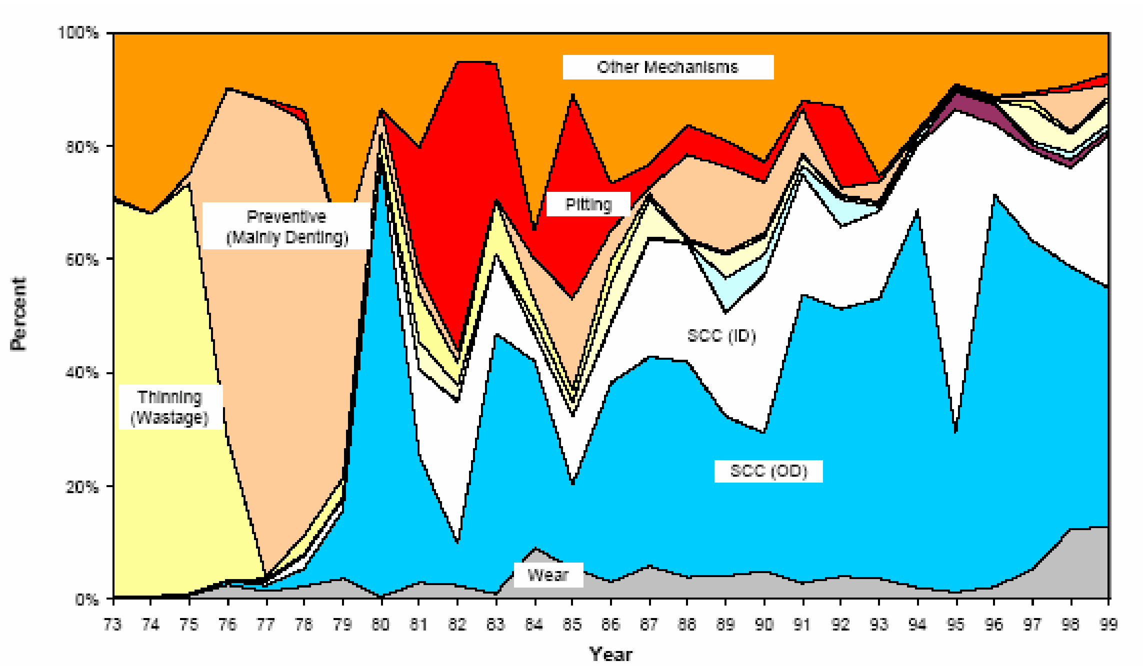

Figure 1: Evolution of Causes of SG Tube Degradation with Time [1]

CANDU SG degradation experience with SGs tubed with Alloy 600 (Bruce A and B) has followed this PWR experience, although with much lesser impact at Bruce B to date and, to date, longer times to crack initiation at Bruce B in the absence of accelerants such as Pb. No cracking has been detected at Bruce B after approximately 20 years of operation, although there has been some localized intergranular attack (IGA) detected. For PWRs SG degradation has accounted for about 0.3% of in-service tubes being plugged per year, on average, and for significant incapability factors until recently. In addition to improved SG management practices, many of the high risk SGs have been replaced, thus taking these degraded Alloy 600-tubed SGs out of the database. The impact of SG degradation on Canadian CANDU plant incapability factors has been significant at some stations, notably Bruce A and Pickering B. The contributions of SG degradation on Ontario Hydro reactors (now OPG and Bruce Power reactors) until the late 1990’s is illustrated in Figure 2.

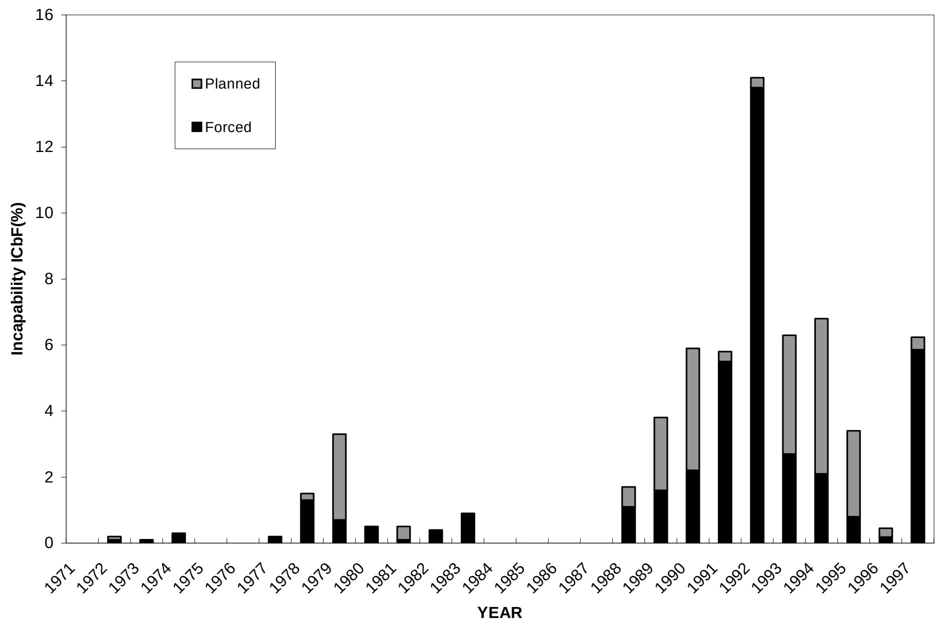

Figure 2: Incapability Factor Associated with Ontario Hydro SGs up to 1998 [2]

Thus, there has been a history or legacy of SG degradation, dominated by Alloy 600 issues, that has affected operation of all types of SGs, and has impacted regulatory and design decisions, as well as operational practices.

CANDU SG design has evolved differently from that of PWRs. Typically, PWRs employed a small number of large SGs per reactor, one for each loop. The early days of CANDU reactor design and construction emphasized a "made in Canada" approach, where feasible, and for SGs this resulted in a larger number of small SGs, compared to typical PWRs, for Pickering and Bruce; 12 for Pickering and 8 for each Bruce reactor. The Douglas Point and Pickering sizing and tube material selection were based on experience with fossil-fuelled plant feedwater heaters, and cost [3]. All CANDU SGs have had preheaters, all integral preheaters except Bruce A and B, which have external preheaters. Despite PWR experience to the contrary, CANDU experience is that there has been relatively little negative impact of the integral preheaters on SG performance; in fact, the preheaters permit more efficient design and operation of the SGs. Each evolution of CANDU reactors was marked by a decrease in the number of SGs per reactor, and an increase in size. Figure 3 illustrates this trend. Current CANDU 6 and Darlington reactors each have four SGs with stainless steel supports and Alloy 800 tubing, with relatively little history of corrosion-related degradation. For the Advanced CANDU Reactor (ACR), the SG size is comparable with the larger PWR SG designs.

As reactors age, decisions are being made about extended plant life (long term operation), which is usually associated with a refurbishment plan (following a condition assessment and remaining life assessment of major components) and outage, and, for CANDU reactors, an extended life of 25 to 30 years. The refurbishment decision is an economic one. For CANDU reactors the minimum requirement is to retube the calandria vessel (new pressure tubes and calandria tubes). Refurbishment of other major components, which include the feeders and steam generators, is based on remaining life decisions and projected future maintenance costs. SG replacement is a major cost item, and in some cases, SG degradation has resulted in premature permanent reactor shutdown (for instance Trojan in the USA; Bruce Unit 2 in Canada) because of escalating SG maintenance and downtime costs. For CANDU 6 reactors planning retubing or refurbishment (Point Lepreau, Gentilly-2, Wolsong-1), the steam generators are currently in good condition and should perform well for the extended life period. Other CANDU reactors undergoing retubing are replacing steam generators (Bruce Units 1 and 2), and other potential Bruce Power and OPG refurbishments may also replace the SGs.

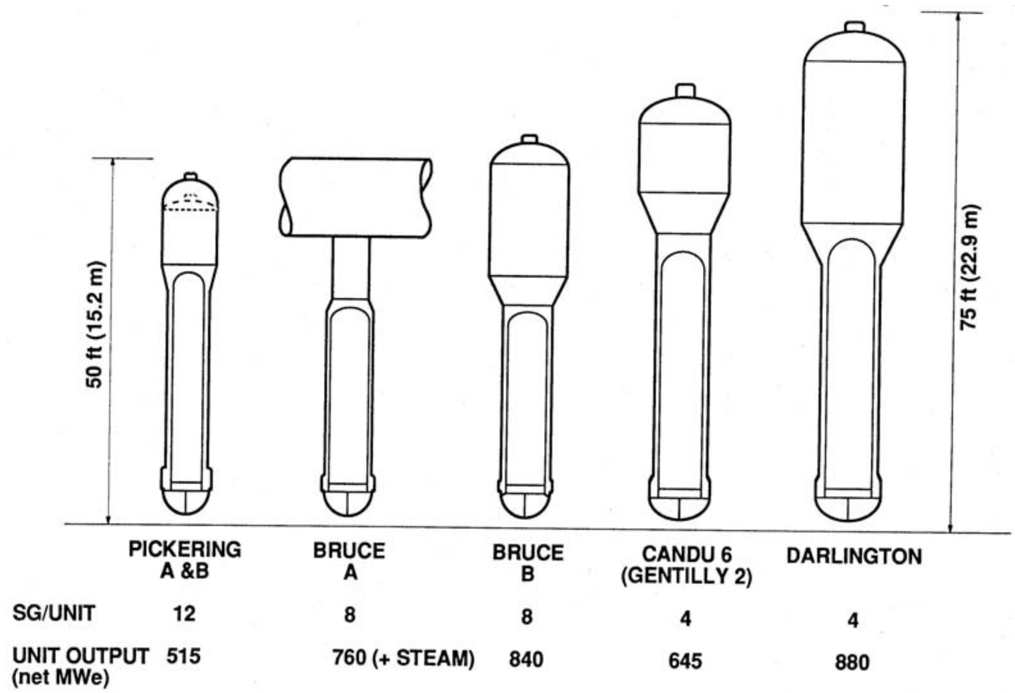

Figure 3: Size Evolution of CANDU SGs

The R&D emphasis in support of CANDU SGs has evolved in line with the operating experience and life extension decisions, and typically has evolved in parallel with (but complementary to) R&D carried out elsewhere. Initially R&D focussed on denting, SG chemistry (especially crevice chemistry) and SCC, then moved to an integrated SG program that included all aspects of SG technology (thermalhydraulics, inspection, repair, cleaning, vibration and fretting), and has now evolved to consider possible future long term degradation mechanisms (Pb cracking, for instance) and remaining life estimation. For SGs tubed with Alloy 800, with very little degradation has been observed to date with up to 30 years' service, and thus there is no large operational database upon which to base a deterministic remaining life prediction, although it is generally assumed that a further 30 years' service is a reasonable expectation if appropriate life management practices are followed [for instance, see references 4 and 5]. Similar considerations apply to new SGs, which are required to operate economically and without replacement for up to 60 years, regardless of whether they are tubed with Alloy 800 or with Alloy 690.

This paper provides an overview of the CANDU SG operating experience (OPEX), the R&D response and a projection of the next 30 years' operating experience and requirements.

WHAT WAS NOT FORSEEN BY EARLY SG R&D

As Figure 1 illustrates, a number of different SG degradation mechanisms has been experienced, many of which were neither anticipated by designers nor expected by operators. This paper will not discuss these mechanisms in detail; there are a number of publications that do so [for instance references 6 and 7 and references therein], but a brief overview of the historical evolution of the degradation mechanisms serves to highlight the key factors responsible for the degradation. The first point to note is that although it was recognized that stainless steels would not provide adequate service if chloride contamination could occur, and thus was used for SG tubing in only a few early SG designs, the successor material in PWR SGs, Alloy 600, was shown by the early 1960s to be susceptible to SCC in pure water if stressed sufficiently [for instance, see reference 8], and in contaminated caustic solutions which were believed to be possible in secondary side crevices [9]. Thus it perhaps should not have been surprising that after a few years' service, SCC of Alloy 600 SG tubes was detected in areas with high residual stress (dented areas, rolled joints at the tubesheet, tight radius U-bends, etc.), starting in the late 1970's.

Wastage is usually associated with concentration of phosphates in crevices, especially tube-to-tubesheet and tube-support crevices, and with off-specification application of the Na/PO_4 ratio. Phosphate chemistry, derived from fossil boiler use, was designed to complex and suspend impurities in the SG to facilitate their removal by blowdown. Some wastage, typically in cold leg portions, was associated with acidic chloride or sulphate buildup under deposits. Most stations converted to a volatile amine chemistry, called all-volatile treatment (AVT) using ammonia, and then morpholine and other amines, to eliminate phosphate wastage as a concern. In Canada, the only station to use phosphate SG chemistry, PLGS, remained on phosphate chemistry until 2000, when it converted to AVT [4].

Denting, which was not anticipated at the time reactor SGs were designed, is typically associated with acidic (chloride or sulphate) chemistry in tight crevices between carbon steel supports and the SG tubing, and was originally primarily associated with seawater ingress into the feedwater. The corrosion of the carbon steel supports resulted in the expanding corrosion product crushing the tube in the confined spaces between the tubes and supports and, occasionally, the tubesheet. The stresses induced by this tube crushing action were sufficient to initiate IDSCC of the tubing. This has been seen only with Alloy 600 SG tubes and carbon steel support plates. Early CANDU 6 SGs were designed with stainless steel supports, and broached-type flow holes, to eliminate this concern.

Over the next decades, SCC became more prevalent in SGs tubed with Alloy 600. As noted above, this was perhaps predictable based on some early R&D results, but what was probably not anticipated was the extensive nature of the SCC, and some pitting, that was observed on the secondary side, and the wide range of environments found to cause this degradation, including reduced sulphates (thiosulphates and tetrathionates, for example), copper compounds, oxidants, chlorides and Pb. These contaminants can concentrate in heat transfer crevices at factors up to 10^6 [7]. Included in this concern is the need to reduce fouling associated with ingress of corrosion products from the feedwater system; such ingress has been reduced with improved amine selection and improved feedwater piping materials. These concerns have resulted in the need for stringent chemistry control requirements such that the impurity levels of key corrosive or fouling contaminants must be maintained at the low ppb level or below. Related to this was the need to eliminate copper-containing materials from the feedtrain and any auxiliary system that feeds into it, the need for much improved water treatment plant operation, exclusion of oxygen from the feedwater prior to startup, maintaining the SG in a deoxygenated state during shutdowns, and the need for improved condenser designs and materials such that leak tightness can be assured.

Finally, for some PWR and CANDU SGs, another unexpected degradation has been flow-accelerated corrosion (FAC) of some carbon steel secondary side internal components. This has included steam separator components, support plates (U-bend and straight leg) and feedwater inlet components. Although FAC of carbon steel is now a well-known phenomenon, it was not as well-understood 40 years ago when early SGs were designed, and even today, the FAC experience is highly variable, with frequent observations of variability between otherwise identical SGs and within a given SG. This variability may be a consequence of small variations in the Cr content of the carbon steel, and thus is difficult to predict, although the use of stainless steels for supports and other susceptible areas eliminates this concern.

EVOLUTION OF CANDU SG DESIGNS AND MATERIALS

As Figure 3 shows, the most obvious design evolution for CANDU SGs has been size; the size increasing as the manufacturing capability has increased, to the stage where the ACR (Advanced CANDU Reactor) SGs are of similar size to the larger PWR designs. However there has also been an evolution in other key areas, which include tube material, support material, support design and feedwater/steam cycle piping design and materials.

Tube material evolution was from Monel 400 (Alloy 400) used for Douglas Point, Kanupp, early Indian PHWRs and Pickering SGs, through Alloy 600 selected for Bruce, to Alloy 800 selected for CANDU 6 and Darlington SGs, as well as for replacement SGs for Bruce A. As noted earlier, the selection of Alloy 400 was based on available Canadian technology derived from fossil plant feedwater heaters, where the material has had an excellent service record. In CANDU-type reactors the early Alloy 400 used at Douglas Point and in some Indian SGs experienced fatigue cracking at the very tight radius bends (“hairpins”) of the early designs, but has given excellent service at Kanupp, Pickering A and several other Indian SGs. The slightly modified Alloy 400 (change in Ni to Cu ratio to improve inspectability with eddy current [3]) used at Pickering B has been shown to be susceptible to under-deposit corrosion in the presence of oxidizing impurities [10]. AECL and Ontario Hydro moved away from Alloy 400 because of operating experience at Douglas Point, and because of the activity transport issues there associated with Cu-64 following oxidizing transients[11]. Ontario Hydro elected to use Alloy 600 at Bruce A and B, based on early PWR experience at the time design decisions were made and because of concerns with early experiments with Alloy 800 which showed that the material was susceptible to cracking in concentrated hydroxide solutions, especially if not made with carefully controlled Ti/C ratio (nuclear grade or “modified” Alloy 800) to prevent sensitization. These early decisions were based on the assumption that SG crevices could become highly alkaline under certain chemistry upset conditions [12].

For CANDU-6 SGs, AECL, after careful review of early Alloy 600 laboratory data showing the susceptibility to PWSCC, and in consultation with developments elsewhere that led to the modified Alloy 800 tubing specification, specified Alloy 800M with a Ti/C ratio >12. This ratio has changed slightly since the late 1970’s, but Alloy 800M is used in current CANDU 6 SGs, as well as at Darlington.

CANDU SG support plates, including U-bend supports, were fabricated from carbon steel in early SGs, but all CANDU-6 SGs, except Embalse, have stainless steel supports (Wolsong-1 has Alloy 600 supports). The move away from carbon steel was driven by the early experiences with denting in PWRs, but has also provided an additional benefit with the resistance to FAC. Table 1, which shows various operating parameter comparisons for some PWR and PHWR SG designs, includes this information.

Table 1: Geometric and Material Data and Operational Parameters for PWR and CANDU Steam Generators

Reactor Design	**AP600**	**AP1000**	**ACR 1000**	**System 80**	**N4**	**Candu 6**	**Darlington**
	Westinghouse		AECL	CE	Framatome	AECL	AECL
Electrical output MWe gross/net	619/600	/1090	1165/1085	1389/1350	1450	680/650	881
No of SGs	2	2	4	2	4	4	4
Thermal MW transfer/SG	970	1707.5	802	1957	1065	516	664
Heat transfer area, m²/SG	**6986**	**11477**	**8454**	**14660**	**7300**	**3205**	**4830**
No of tubes	6307	10025	7234	12580	5599	3550	4663
Tube pitch, mm	24.9	24.9	24.79	25.4	27.4	24.13	24.5
Tube diameter/wall, mm	17.5/1.00	17.5/1.00	17.4/1.07	19.05/1.07	19.05/1.09	16/1.13	16/1.13
Pitch/Diameter for tube	1.42	1.42	1.42	1.337	1.44	1.52	1.54
Max outer dia, mm	4500.8	5842	4650	5890	4780	3862	4730
Total height, mm	21051	22536	24000	23000	21940	19333	22211
Weight (tonnes)	480		422	748		215	334
Tube material	I690 TT	I690 TT	I800M	Inconel 600	I690TT	I800M	I800M
Steam flow rate, kg/s/SG	531.5	943.73	430	1100	600	258.25	329.2
Steam temperature, °C	272.7		275.5	289.7	288.5	260	264.75
Steam pressure, MPa (abs)	5.74	5.764	6	7.38	7.3	4.7	5.07
Feedwater temp, °C	226.6	226.6	217	232C	229.5	187	176.7
Tube support design	broached trefoil	broached	lattice grid	egg crate	broached hole	lattice grid	lattice grid
Tube suppport material	405 SS	405 SS	410 SS	409 SS	13% chrom steel	410 SS	410 SS
Primary flow rate, Mg/s/SG			3.26	10.33	4.17	1.925	2.48
Primary inlet pressure, MPa (abs)	15.5	15.5	11.1	15.5	15.5	9.89	9.88
Primary SG inlet temp, nom/max, °C	315.6	322/325	318.6	327.3	329	309	309.2
Primary SG outlet temp, °C	279.5	279.72	274	296	292	266	265
Primary quality, %	0	0	0	0	0	4.4	3.4
Integral preheater	no	no	yes	yes	yes	yes	yes
Design fouling factor, hr-sqft-F/Btu		0.00011	0.00015			0.0002	0.0002
Circulation ratio			6.2			6	5

Similarly, certain secondary side components which may be susceptible to FAC are now specified to be made from either Cr-enriched carbon steel (Cr > 0.2 wt. %) or stainless steel. Steam cycle piping sections and components that are susceptible to FAC in single phase flow or two-phase flow, and thus which may contribute to high feedwater iron and particulate ingress to the SG, are now also specified to be stainless steel. Early BOP piping was fabricated entirely from carbon steels, and much of the high-energy portions of this have been replaced over the years because of FAC.

As noted earlier, current CANDU designs have eliminated the use of copper components that might contribute Cu contamination to the feedwater; this has led to the elimination of copper-alloy condensers and feedwater heaters, which were the primary sources of copper. This is to eliminate the risk of copper-induced corrosion of the SG tubing, but provides an additional benefit of improved chemistry control by eliminating mixed-metal systems. Support designs have also evolved, from “solid” U-bend support structures at Bruce A to a more open design at

Bruce B, and the early CANDU 6 units, to lattice bars at recent CANDU 6 units and at Darlington. R&D has also shown that the flat bar designs are more open to flow than broach plate (or drilled hole) designs, and thus are the appropriate choice for optimal thermalhydraulic performance (Table 2).

Table 2: Qualitative Comparison of Support From a Fouling Perspective [6]

A Fouling-Resistant Design Will Have:	Bruce Broached Plate	CANDU 6 Broached Plate	Darlington Lattice Bars		Wolsong-1 Formed Bars
			High	Low	
Low flow resistance	X	O	X	√	√
Low potential for particle trapping upstream	X	X	O	√	√
Low potential for particle deposition downstream	X	X	O	√	√
Uniformity in subchannel size	√	√	X	√	O
Design asymmetry for flow mixing	X	X	√	√	X
NET ASSESSMENT	XXX	XX	√ √		√ √

legend: X = bad; O = o.k; √ = good

CANDU SG OPERATIONAL DRIVERS

Over the past 30 years, the SG-related operational drivers affecting CANDU stations have evolved from initial optimism, in the absence of inspection (especially of the secondary side) that the SGs were performing well and were thus not significantly impacting operation and maintenance, to the realization that SG management is a core component of safe and economic plant operation. The major impacts of SG degradation on plant operation began to be seen in the 1990’s and primarily at Bruce A with cracking of the Alloy 600 SG tubing, and at Pickering B, with Alloy 400 SG tubing. Table 3 provides a summary of this history.

Table 3: Summary of CANDU SG Degradation Experience

PERIOD WHEN FIRST NOTED	DEGRADATION TYPE	COMMENTS
1970’s and 1980’s	Fatigue cracking	Found only in a few outer row tubes at Bruce A; early in life.
	Fouling	Primary side fouling generic to all SGs and resulted in contribution to RIHT increase and less efficient operation/reduced margins. Secondary side fouling varies with chemistry management practices; Pickering A and Bruce A units experienced significant fouling. In both cases, lack of inspection up to late 1980’s to quantify rate and extent; in late 1980’s fouling began to impact SG operation/thermalhydraulics.
	Pitting	A few tubes affected at Point Lepreau at first support plate location; phosphate wastage may also have been involved.
	Carbon steel corrosion	Bruce A U-bend supports (attributed to crevice corrosion, unprotective chemistry and flow accelerated corrosion)
1990’s	Cracking (SCC)	Bruce A U-bends Bruce A top-of-tubesheet
	Phosphate wastage	Limited to Point Lepreau (arrested after switch to AVT); approximately 40 tubes directly affected. Some pitting also as a consequence of condenser leaks
	Denting	Bruce A U-bends (cause of some of the SCC there); resulted in U-bend support damage Pickering A; a few hundred tubes affected at lower supports (carbon steel lattice bar supports)
	Fretting wear	Bruce B U-bends Darlington U-bends and hot leg supports Minimal impact at CANDU-6 SGs, Bruce A, Pickering A/B

PERIOD WHEN FIRST NOTED	DEGRADATION TYPE	COMMENTS
	Pitting	Bruce Units 3 and 4; significant numbers of tubes affected (approximately 2000 tubes plugged); attributed to inappropriate layup practice. Pitting in other SGs may be a consequence of oxidizing conditions during shutdowns.
	Flow accelerated corrosion (FAC) of carbon steel primary side components	Primarily associated with segmented divider plates; FAC of bolts, plates and channel supports led to divider plate bypass and loss of thermal efficiency. Mitigated by replacement with solid plates fabricated from FAC-resistant materials, or by application of a stainless steel "skin"
Late 1990's and 2000's	Flow accelerated corrosion of secondary side components	Major impact has been on upper supports; Bruce B and Embalse. Feedwater component wall loss at Pickering. Separator wall loss at Bruce B (variable extent). Monel 400 SG tube wall thinning in upper broaches at Pickering B SGs

This experience has led to SG life management plans that include extensive inspections, and the need to develop disposition arguments that can ensure economic plant operating intervals. Currently fretting wear rates and SCC crack growth rates can have a significant impact on the length of the operating interval that can be justified before tube integrity is compromised. Thus, R&D has been carried out to improve inspection capability (sizing and probability of detection), and to better understand the root causes of the observed degradation. Corrosion-related degradation is best managed by improvements in chemistry control, in particular to ensure no deposit buildup and to ensure non-oxidizing conditions are maintained, especially during shutdowns and startups. Examples of the effectiveness of this approach are the arresting of FAC degradation of carbon steel supports by improving at-temperature pH control [for instance see 13], and the minimization of top-of-tubesheet pitting at Bruce Units 3 and 4 by eliminating oxidants and the likelihood of generating corrosive species such as reduced sulphate compounds.

The R&D has had to evolve to address this progression of degradation, and because much of the CANDU SG degradation is specific to CANDU SG tube materials, and CANDU SG tubing is smaller in diameter than PWR tubing, it has not been possible to simply apply R&D results or operational experience generated outside Canada. However external OPEX and R&D results have been incorporated where possible, including those related to feedwater chemistry specifications, shutdown chemistry guidelines, etc..

THE R&D RESPONSE

Early R&D, before significant degradation was observed in CANDU SGs, followed PWR R&D that was co-ordinated by EPRI, and R&D carried out in Europe. Thus, the early focus was on crevice chemistry and denting, and corrosion-related degradation of SG tubing in secondary-side faulted feedwater and under off-specification HTS conditions. This work included studies of Alloy 800 (nuclear grade) as well as comparisons with Alloy 600. Much of the work was related to specifications for SGs, especially the heat treatments of tubing materials, vibration and fretting wear requirements, and tube-to-tubesheet expansion joint studies. Table 4 summarizes the major components of the CANDU SG-related R&D carried out over the past 30 years.

Table 4: Overview of Major SG R&D Activities Carried out by the Canadian Nuclear Industry

TIME PERIOD OF CANDU R&D EMPHASIS	PRIMARY CANDU R&D AREAS INVESTIGATED
1970's	Denting and crevice chemistry/hideout Primary side cracking Phosphate chemistry Vibration and fretting wear Rolled joint technology
1980's	Primary and secondary side cracking Crevice chemistry/hideout

TIME PERIOD OF CANDU R&D EMPHASIS	PRIMARY CANDU R&D AREAS INVESTIGATED
	Fouling Vibration and fretting wear Inspection technology Thermalhydraulics (THIRST code development)
1990's	Secondary side cracking Secondary side corrosion (pitting, IGA) Crevice chemistry SG chemistry/chemistry mitigation strategies, alternative amines and dispersants Inspection technology (eddy current and UT) Vibration and fretting Thermalhydraulics (THIRST code development) Fatigue Cleaning (primary and secondary side technologies) Tooling for SG inspection, repair/mitigation strategies Lead (Pb) chemistry
2000's	Crevice chemistry (including effects of crevice geometry) Lead (Pb) cracking and Pb chemistry Inspection technologies (eddy current and UT) Cleaning of hard deposits (secondary side) Secondary side cracking, IGA and pitting (susceptibility mapping) Fatigue SG chemistry (hydrazine chemistry)

This paper will not address in detail what has been covered by the R&D outlined in Table 4 [see, for instance, Reference 13], but examination of the table reveals that, after the early R&D carried out before the late 1960s, the R&D has tended to follow, rather than predict, the SG operational issues experienced by the stations, and that "themes" or paradigms have evolved and been replaced as the issues changed. Thus in the 1960s and into the early 1970s the major R&D activities were driven by design-related needs [for instance, see Reference [14]. The initial PWR experience with Alloy 600 degradation (denting, phosphate chemistry), which led to R&D in these areas in Canada [15], was followed in the 1980's by a growing impact of fouling on SG function, especially in Canada. However, inspections of CANDU SGs, especially of the secondary side, were not extensive and thus the growing fouling, and associated corrosion, problem was not fully realised until the late 1980's (for instance thermalhydraulic instabilities, under-deposit corrosion, denting). In fact it was widely assumed that SG designs would prevent SG fouling because blowdown would be effective in removing suspended particulate (hence the initial applications of phosphate chemistry). By the late 1980's and early 1990's fouling and corrosion-related degradation, particularly at Bruce A, had had a major operational impact on reactor operation, in common with the PWR experience with Alloy 600.

This was to continue through the 1990's. Unique to CANDU was the "wastage" or "pitting" of the Alloy 400 SG tubing at Pickering B, along with "erosion" of the Monel 400 tubing in the upper broach plate flow holes [9]. During this time, it was recognized that SG fouling was the major contributor to the corrosion-related degradation and thermalhydraulic instabilities, and significant cleaning development, qualification and field campaigns took place. Also critical during this period was the development of CANDU-specific inspection technologies that provided the operators and regulators with confidence that the degradation could be confidently detected and operating intervals defended. During this time Ontario Hydro removed more than 100 tubes from Bruce A for detailed examination, and this database enabled development of good probability of detection (POD) curves for the C3-4 and C3-8 eddy current probes, which provided the dispositions for maintaining the units in service. The inspection technologies for the small diameter Bruce A SGs and the large Alloy 600 cracked tube database for Bruce A were not available from the PWR industry, and thus was addressed by CANDU industry. Similarly, inspection technology for other small diameter SG tubing (compared to PWR tubing), and the need to understand the degradation of Alloy 400 and Alloy 800 SG tubing, required a CANDU-specific R&D activity.

During this period, there was also emphasis on fouling, on both the primary and secondary sides for CANDU SGs, and for the secondary side at EPRI. This work led to an improved understanding of fouling mechanisms and predictability, and to the development of dispersants and alternative amines for SG application [13]. This work was linked with R&D activities oriented at improving SG secondary side cleaning, including a better understanding of deposit consolidation that enables operators to better schedule cleaning activities, and the application of ultrasonic energy to improve tubesheet cleaning,

It is also important to note that the Bruce A SG tubing cracking was complicated in the mid-1980s by the inadvertent introduction of a lead blanket into an operating Bruce Unit 2 SG, which resulted in severe SCC of that SG and significant contamination of the other SGs in that unit, and eventually, in 1995, in shutdown of the Unit (Unit 2 is to be restarted with new SGs and other components). This event drove some significant R&D activity in Pb transport and Pb-assisted cracking, with the realization that not only does Pb accelerate SCC of Alloy 600 SG tubing, and that most, if not all SGs are contaminated with Pb, but also that very low levels of Pb may impact Alloy 600 SCC. This is illustrated by Figure 4. Recently, the realization that Pb may be responsuible for much of the Alloy 600 SG tube cracking detected to date, and that most, if not all, SGs are contaminated with Pb, has begun to cause some concern in the SG community, in particular with respect to the possible susceptibility of Alloy 690 SG tubing to Pb-assisted SCC [7, 16], with EPRI, AECL and COG all initiating studies of the effects of Pb on SG chemistry and corrosion. Thus, for the 2000's there are several collaborations by CANDU industry with SG technology and R&D with EPRI related to Pb. This is currently a major R&D activity, focussed on ensuring that Alloy 800 will not be susceptible to Pb-assisted cracking over the next 30 years, or for a total of 60 years in-service. The other R&D activities are complementary to this goal, and there continues to be interest in cleaning of primary side deposits (now a mature technology) and in the removal of remaining hard tubesheet deposits using new solvent-based approaches. The major industry focus is now moving towards more effective life management and preventive maintenance, and the integration of the past 30 years of knowledge, both R&D and operational, to achieve this and hence meet retubed/refurbished and new reactor requirements.

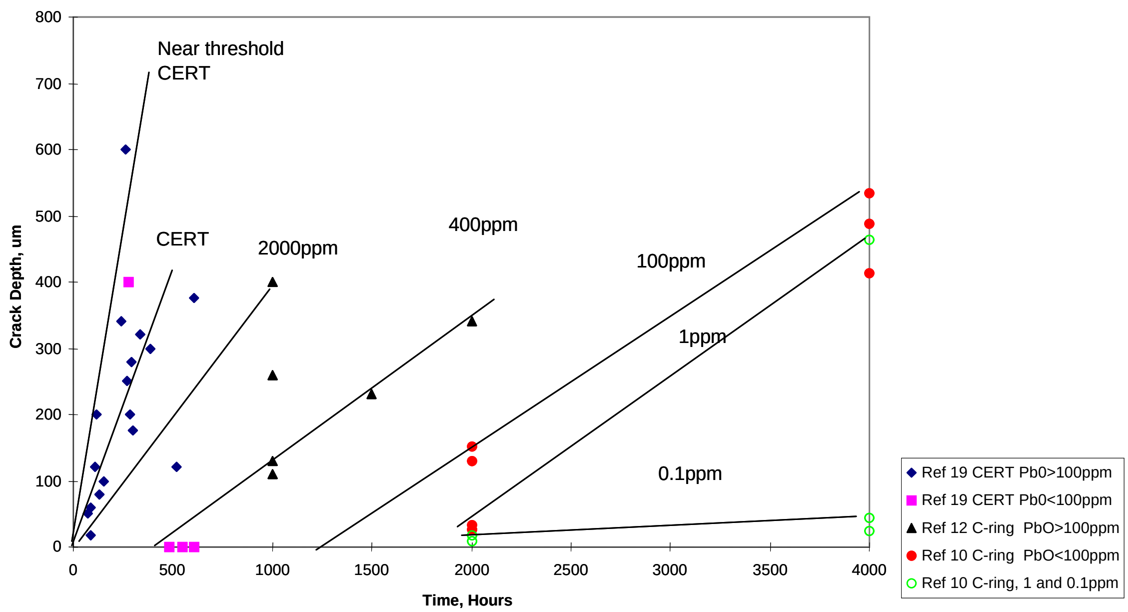

Figure 4: Effect of Varying Pb Concentrations on Stress Corrosion Cracking of Alloy 600 SG Tubing [17].

The R&D activities, whilst still addressing new or as-yet still difficult issues, are indeed starting to consider the needs for the next 30 years. Typically, the R&D data are being incorporated into tools that are more readily available to SG operators, and more clearly address their needs. For instance, "smart" SG monitoring technologies can link corrosion susceptibility data with operating chemistry parameters to provide a tool that advises when chemistry is out-of-specification and could impact SG integrity if not corrected. Figure 5 illustrates this approach [18]. Although it is recognized that the accelerated tests used to create these types of diagrams may not accurately reflect actual field corrosion susceptibility, especially for SCC susceptibility, they provide a useful operating guide.

Past experience has shown that laboratory data may be a better predictor of qualitative susceptibility than often thought, even if this realization has been in hindsight.

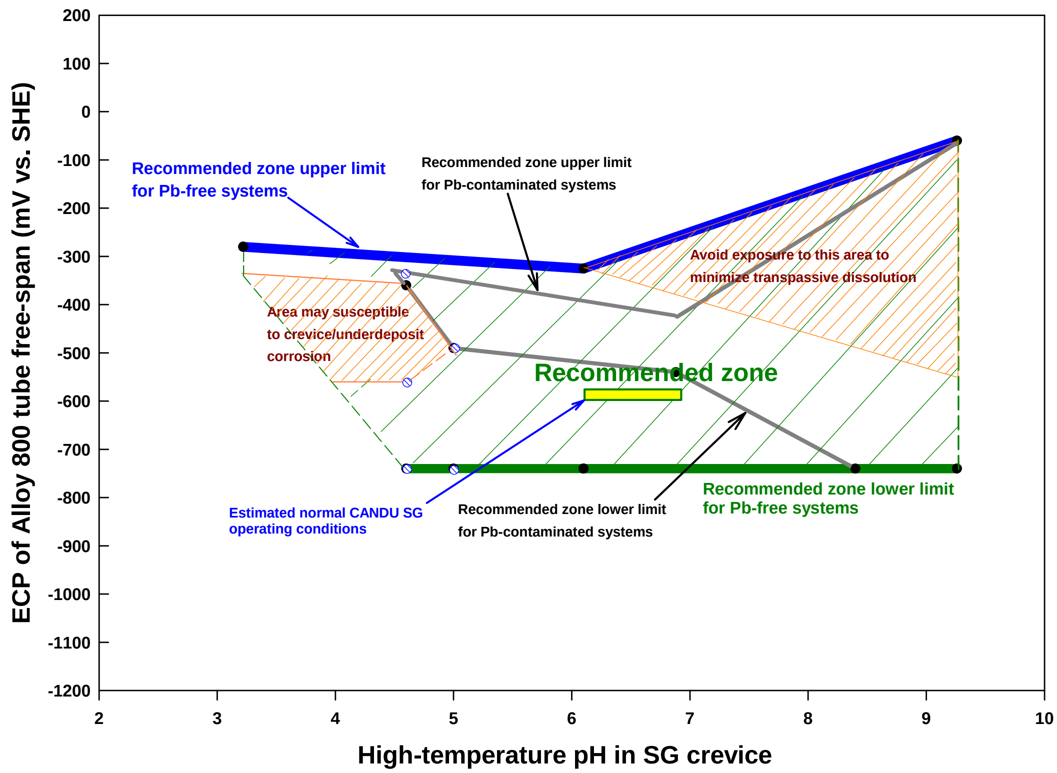

Figure 5: Schematic Showing Recommended Operating Zones for Alloy 800 SG Tubing [18]

THE NEXT THIRTY YEARS

Over the next 30 years, a number of CANDU (and PWR) SGs will achieve a 60-year life if they are able to remain in economic service, and if plant operation is also economic and safe. New SGs are promised to have a 60-year life, largely based on knowledge from nearly 30 years of service and R&D. The first 30 years of service has been obtained with the knowledge and expertise of a generation of engineers and scientists who are now retiring. Thus the path forward, and especially the integration of the past knowledge with that required for the future, requires a knowledge transfer to the operators, the R&D community, and the service providers of the current state-of-the-art. Within the CANDU community much of that knowledge has been transferred into improved technologies for predicting, monitoring and diagnosing SG performance, improved inspection probes and data analysis, improved chemistry monitoring, diagnostics and control, an integrated heat transport system aging management perspective and improved technical and operating specifications designed to ensure the possibility of 60-year life.

There is insufficient scope in this paper to fully address all the key advances R&D has made that, if appropriately implemented, should ensure that steam generators can achieve these extended, compared to the original “design life”, service lives. Compared to 30 years ago, the existing OPEX and the following advances (not in any particular order) derived from CANDU-related R&D, including international collaborations, are providing, or have provided, the technologies that have increased 30 year life to confidence that 60 years is achievable:

- Continued confirmation that Alloy 800M is the appropriate choice for SG tubing and identification of the optimal operating conditions to ensure SG tube life, and identification that shutdowns, layups and startups may constitute the times of greatest risk to SG integrity. It is also clear that minor surface imperfections, such as scratches, weld spatter (for instance see [4]), etc., can initiate degradation of any SG tube material, including SCC degradation;

- Development of a versatile chemistry codes (such as AECL's ChemSolv [19]) to predict SG/feedwater/steam cycle chemistry, including evaluation and prioritization of dispersants and alternative amines to improve SG chemistry control;
- Identification of the design, chemistry and materials requirements to eliminate FAC in the SG secondary side and in the feedwater system;
- Development of a thorough understanding of SG fouling, and its impact on SG thermalhydraulic function, fouling margins, alternative amines and dispersants, support plate fouling and contributions to CANDU reactor inlet header diagnostics;
- Development of fast multi-purpose eddy current probes for SG tube inspection (X-probe), and of high resolution UT probes (TRUSTIE);
- Identification of the design requirements needed to minimize vibration and fretting wear and to optimize SG thermalhydraulic function (support design requirements);
- Development and application of the THIRST code [20] for 3-d thermalhydraulic analysis of SGs, including chemistry predictions, applications of CFD codes to analyse localized corrosion problems at supports, and application of EPRI's CHECWORKS code to evaluate SG FAC susceptibility;
- Development and qualification of cleaning technologies for the primary and secondary sides of the SG tube bundle, in particular for hard tubesheet deposits;
- Development and application of operator-friendly prediction and diagnostic codes, and fitness for service guidelines, to aid in-service decision making.

However, the CANDU industry is not stopping at this stage, but is continuing to maintain key capabilities such as inspection, which is essential to all plant management strategies, chemistry control, tubing corrosion, and thermalhydraulics. Key areas of interest in inspection are to improve the speed of analysis of the increased data stream that is a consequence of using faster and more comprehensive probes. This may include new approaches to applications of probabilistic methods for handling data, and to innovative approaches that may involve combinations of NDE techniques. In the chemistry area, future challenges include the continued drive to reduce hydrazine additions and the use of alternative amines (compared to ammonia and morpholine). There will be a continuing challenge to assure operators and regulators that there are no unforeseen degradation mechanisms that could significantly impact Alloy 800 SG life, especially in light of concerns about the role of Pb in accelerating SG tube corrosion.

In this light, it is important to continue the move away from focussing on the latest problem towards a proactive approach. There has been a tendency to assume that R&D knowledge and plant experience is sufficient to address any future problems that might occur; this has led to the cessation of R&D in vibration and fretting wear, for instance. Even if there are no issues related to SG vibration and fretting wear anticipated for the next few years, there is a need to invest in capability maintenance should an issue arise, and to provide expert assistance for new designs that will be required should the new reactor build plans become a reality.

Overall however, the primary issue is that further operating life of SGs in refurbished plants, and the expectation of a 60 year life of new SGs, will require a very proactive chemistry control program, including regular cleaning of both the primary and secondary sides to ensure that deposit buildups are always maintained at the minimal acceptable level to prevent unacceptable crevice chemistries. In the opinion of this author, this will likely require more stringent SG chemistry management than is usually practised, especially during periods of shutdown or layup, and during startups.

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