BABCOCK & WILCOX CANADA STEAM GENERATORS
PAST, PRESENT AND FUTURE

J.C.Smith

ABSTRACT

The steam generators in all of the domestic CANDU plants, and most of the foreign CANDU plants, were supplied by Babcock & Wilcox Canada, either on their own or in co-operation with local manufacturers. More than 200 steam generators have been supplied. In addition, Babcock & Wilcox Canada has taken the technology which evolved out of the CANDU steam generators and has adapted the technology to supply of replacement steam generators for PWR's. There is enough history and operating experience, plus laboratory experience, to point to the future directions which will be taken in steam generator design.

This paper documents the steam generators which have been supplied, the experience in operation and maintenance, what has worked and not worked, and how the design, materials, and operating and maintenance philosophy have evolved. The paper also looks at future requirements in the market, and the continuing research and product development going on at Babcock & Wilcox to address the future steam generator requirements.

Babcock & Wilcox Canada

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INTRODUCTION

Nuclear steam generators in both CANDU reactors and Pressurized Water reactors (PWR's) perform the same function, and are geometrically similar. (See Figure 1). Babcock & Wilcox Canada has supplied more than 200 steam generators to CANDU reactors in Canada, and worldwide, and is also using the same technology which evolved from 40 years of design, manufacturing and operational experience with the CANDU steam generators for supply of replacement steam generators to PWR's, to date entirely in the USA. Including steam generators fabricated in co-operation with local partners such as Hanjung in Korea, B&W Canada has contracted for 223 CANDU steam generators, and 34 PWR replacement steam generators to date. The steam generators designed in the early part of this 40 year history have had a reasonably good operating history, compared to worldwide standards. However, B&W Canada has constantly worked on improvements to the product. The product which has evolved from the 40 years of experience is currently being supplied to the US PWR replacement steam generator market and current CANDU projects. Further evolution is anticipated in the future, and this paper will also address what is seen as future steam generator trends.

HISTORICAL STEAM GENERATOR PERFORMANCE

Some of the earliest steam generator experience by Babcock & Wilcox Canada was at the NPD reactor in Rolphton (shut down in 1987) and at the KANUPP plant in Pakistan (still in operation). However, the most detailed feedback from operation is at the Pickering, Bruce, Darlington, and earlier 600 MWe CANDU plants. The following is a summary of the steam generators and their performance by plant:

Pickering:

Reactor rating: 515 MWe
SG's per reactor: 12
Approx Wt. Per SG: 80 tons
No. of tubes/SG: 2600
Tube size: 13 mm
Tube Material: Monel 400
Tube supports:

Pickering A:	CS Lattice grids	Startup 1971-1973
Pickering B:	CS Broached Plates	Startup 1984-1986

Plugging through end of 1996: (plugged tubes per reactor, out of 31,200 tubes/reactor) (Ref 1)

Unit 1	115	Pitting under sludge: (Phosphate treatment 1st 3 years operation)
Unit 2	3	
Unit 3	1	
Unit 4	0	
Unit 5	1913	Pitting under sludge in tube supports. Stopped by chemical cleaning performed in 1992.
Unit 6	4	
Unit 7	0	
Unit 8	21	

The performance of Pickering has generally been good. The serious chloride pitting problem in Unit 5 demonstrated two things:
1. Sludge will accumulate relatively quickly in broached plates compared to lattice grids
2. Monel 400 is susceptible to chloride pitting. Monel 400 had stood up very well in Pickering A, and the view that it was impervious to corrosive attack was suddenly changed. When pitting was searched out under tubesheet sludge in Pickering 1 in 1994, the resultant plugging (shown above) was essentially the first serious plugging in the 25 year + history of Pickering A.

The Pickering units have integral preheaters. There has been no fretting whatsoever in the preheaters. There has been no U-bend support fretting. It is believed, however that this is partially due to the circulation (Units are designed for a circulation ratio of about 5.5) possibly being lower than predicted due to separator carryunder. Separator carryover is judged as acceptable, although not exceptional. The separators used at Pickering (IMP model) are adapted from fossil fuel boilers.

Bruce:

Reactor rating: 769 MWe (Bruce A) 860 MWe (Bruce B)
SG's per reactor: 8
Approx. Wt. Per SG: 150 tons (Bruce B)
No. of tubes/SG: 4200
Tube size: 13 mm
Tube Material: Alloy 600, HTMA + Stress Relieved
Tube Supports: CS Broached Plates:
Startup: Bruce A: 1977-1979
Bruce B: 1984-1987

Plugging through end of 1996:

Unit 1:	59	
Unit 2:	1861	Lead induced cracking from secondary side at tube supports
Unit 3:	56	
Unit 4:	54	
Unit 5:	107	Fretting at AVB's
Unit 6:	32	
Unit 7:	110	Fretting at AVB's
Unit 8:	61	Fretting at AVB's

In early years of operation, the Bruce SG's have been good, but after some aging, problems have shown up. The broached tube supports are accumulating sludge, and extensive lancing has been required in tube supports, U-bend supports, etc. Although the amount of actual plugging to date appears quite low (except for Unit 2 which experienced a unique lead ingress problem), there is extensive circumferential cracking at the tube roll transitions, from the secondary side in virtually all of the SG's. This leads us to conclude that Alloy 600 will fail eventually, even in a HTMA condition with stress relief, and with relatively low T-hot (T-hot at Bruce is 579 F). The fretting in Bruce B which is not seen in Bruce A is likely contributed to by the use of a newer generation of GXP primary separators in Bruce B, which work better in the carryunder area and hence deliver more flow to the U-bend region. The separators in Bruce B are showing signs of flow-assisted corrosion in several areas. The cracking of the alloy 600 is cause for consideration of replacement of the steam generators at Bruce.

Darlington:

Reactor rating: 881 MWe
SG's per reactor: 4
Approx Wt. Per SG: 380 tons
No. Of tubes per SG: 4664
Tube size: 15.9 mm
Tube Material: Alloy 800
Tube supports: SS Lattice Grids
Startup: 1990-1993

Tube Plugging through end of 1996:

Unit 1:	0
Unit 2:	0
Unit 3:	0
Unit 4:	10

The performance of these units has been quite good. Although it is not yet reflected in the plugging statistics, there is now evidence of some U-bend fretting at Darlington. The Darlington separators, labelled "CAP-1" design, have performed very well (carryover measured at 0.06%) and were the model that later separators ("CAP-2" and "CAP-3") used in the PWR replacement SG's were modelled from. The PWR replacement SG's also use lattice grids and U-Bend supports derived from the Darlington design. The Bruce experience caused B&W Canada to move back to lattice grid tube supports, and non-restrictive flat-bar U-bend supports.

CANDU 6 Units

B&W Canada has supplied (or is in the process of supplying) steam generators for: Pt. Lepreau, Gentilly II, Cordoba (Argentina), Wolsong 2,3, and 4 (Korea), Cernavoda 1&2 (Romania), and Qinshan 1&2 (China). In the case of the Wolsong and Qinshan units, the design is by B&W Canada, and fabrication is split between B&W Canada and Hanjung (Korea).

Reactor rating: 680 MWe
SG's per reactor: 4
Approx wt. Per SG: 240 tons
No. of tubes/SG: 3530
Tube size: 15.9 mm
Tube material: Alloy 800
Tube Supports:

Cordoba: CS broached	Startup 1984
Lepreau, Gentilly II: SS broached plates	Startup 1983
Cernavoda, Wolsong, Qinshan: SS Lattice Grids.	Startup 1996-2002

Tube Plugging through end of 1996:

Pt. Lepreau	48	Primarily pitting
Gentilly II	3	
Cordoba	10	
Cernavoda 1	0	
Others:	Not yet in operation	

Generally, the performance of these steam generators has been good. In the newer units, from Cernavoda onwards, the SS lattice grid design has been adopted, as well as newer generations of CAP separators (CAP-2 and CAP-3). The MWe output of Cernavoda, from startup, has been higher than expected, contributed to by the efficiency increase from the very low carryover from the CAP separators. Similar MWe output increases have been detected at every PWR into which B&W Canada replacement steam generators have been installed. Although the steam separator type used in Pt. Lepreau, Gentilly II, and Cordoba is the same type as used in Bruce B, the flow assisted corrosion detected at Bruce B has not as yet been seen in the CANDU 6 units. There is a level of concern about Pt. Lepreau due to its history of phosphate water treatment, and seawater cooling. There is sludge in the steam generators (tubesheet, first 2 tube support plates) and there has been pitting under the sludge. The problem has mainly been that the pitting has resulted in an unusually high number of leak-related forced outages. Otherwise the CANDU 6 SG's have performed well.

DESIGN SYNTHESIS FOR PWR APPLICATIONS:

The B&W Canada design of replacement steam generators for PWR's is described in detail in another paper in this Conference (Ref 2). The design decisions in the PWR RSG's evolved as follows:

Tubing: All of the SG's being replaced by B&W Canada had either LTMA or HTMA Alloy 600 tubing. The objective in B&W Canada's RSG designs is to provide a RSG with the BWC features but without changing the overall shell geometry. Therefore, drastic changes to thermal performance of tubing (from that of alloy 600) are undesirable. Alloy 690 has a lower thermal conductivity than alloy 600, but equal or higher strength, depending on the exact specification. Alloy 800 has considerably lower conductivity than alloy 600, lower strength, and has shown signs in the laboratory of susceptibility to chloride cracking and pitting, and caustic cracking (cracking in alloy 800 has not been observed in the field). Properly specified, alloy 690 is immune to virtually every imaginable steam generator water chemistry, except some of the most aggressive lead-caustic combinations. B&W Canada therefore elected to use alloy 690 in all PWR replacement steam generators.

Tube Supports: Due to the relatively good performance of B&W's lattice grid SG's compared to the broached plate units, B&W Canada is using exclusively SS lattice grids and flat-bar U-bend supports in its PWR Replacement Steam Generators.

Separators: The latest generation of CAP separators developed by B&W Canada, the CAP-3, have been laboratory tested full scale, full flow in steam and water, to steam flows of 7.5 kg/sec/separator, whereas the most heavily loaded separators in operation see only 5.3 kg/sec/separator steam flow. Therefore, there is a margin of over 40% between actual and tested conditions. The B&W Canada separators in RSG's have performed very well, in some cases showing carryover as low as 0.01-0.015%. All of the PWR's where B&W Canada RSG's have been installed have reported increased electrical output (typically 7-10 MWe) at constant 100% reactor power due to the increased plant thermal efficience from the very dry steam.

Maintainability: On thing learned from past experience with steam generators is that steam generators will always need maintenance, and the best plan is to accommodate maintenance right from initial design. All of B&W Canada's replacement steam generators incorporate:

- numerous large handholes above the tubesheet face.
- numerous inspection ports in the shell from which the tube bundle can be viewed and accessed. In some steam generators there are 2 inspection ports at every tube support elevation, plus U-bend inspection ports.
- manway, handhole and inspection port designs which allow use of automatic stud tensioning equipment.
- permanent access tunnels through the separator modules to allow access to the tube bundle and feedwater header without removing any separators
- permanent row/column markings on the tubesheet for remote video placing of eddy current probes.
- no free-lane obstructions to water lancing at the tubesheet elevation..recessed blowdown headers are used exclusively.
- in some of the more recent RSG's, extensive use is being made of forged shell sections (vs. plate) in order to reduce periodic in-service inspection requirements.

Steam Generators replaced to Date By Babcock & Wilcox Canada

Plant	# of SG's	Startup Date (with B&W RSG's)
Millstone 2	2	1992
Catawba 1	4	1996
Ginna	2	1996
McGuire 1	4	1996
McGuire 2	4	1997
St. Lucie 1	2	1998
Byron 1	4	1998
Braidwood 1	4	1999
D.C.Cook 1	4	2000
Calvert Cliffs 1	2	2002
Calvert Cliffs 2	2	2003

FUTURE TRENDS IN REPLACEMENT STEAM GENERATORS

To date all SG's replaced by B&W Canada have been those with mill annealed alloy 600 tubing. However, there is evidence that steam generators with mill annealed plus heat treated alloy 600 tubing may yet require replacement. This category of steam generators includes:

- Bruce A and B steam generators (HTMA + Stress relief at 1125°F)
- B&W Once Through Steam Generators (OTSG's) at seven operating PWR's in the US.
- Steam generators in 16 other US PWR's where the present SG's have alloy 600 tubing with thermal treatment (7 of which have already replaced SG's once).
- This is in addition to 17 US reactors presently running with alloy 600 MA where no commitment to SG replacement has been made.

In many cases, a commitment to SG replacement in the US will be tied integrally to license renewal. The US NRC has recently begun receiving license renewal applications, and has taken steps to make the process of license renewal both faster and more predictable. As the US Utilities work through deregulation, and stranded cost issues, license renewal will be an more popular way to get the maximum benefit out of the relatively new nuclear plants with thermally treated alloy 600. However, this will result in some additional SG replacements as it becomes apparent that thermally treated alloy 600 has limitations.

CONCLUSIONS:

Based on over 40 years of designing, fabricating, and maintaining nuclear steam generators, B&W Canada has evolved a high reliability design for either new or replacement steam generators. It appears that there is going to be a future demand for such products, in new plants, plants with alloy 600 MA tubing (replacements), and also plants with alloy 600 with either Stress Relief (B&W plants) or Thermally treated tubing. All replacements are anticipated to have Alloy 690 tubing.

REFERENCES:

1. Dow, B.L. Jr., "Steam Generator Progress Report Revision 13", Research Project WO3580-06, EPRI, October, 1997

2. Klarner, R. et al, "Design and Performance of BWC Replacement Steam Generators for PWR Systems", Proceedings of 1998 CNS 3rd International Steam Generator and Heat Exchanger Conference, Toronto, June 1998.

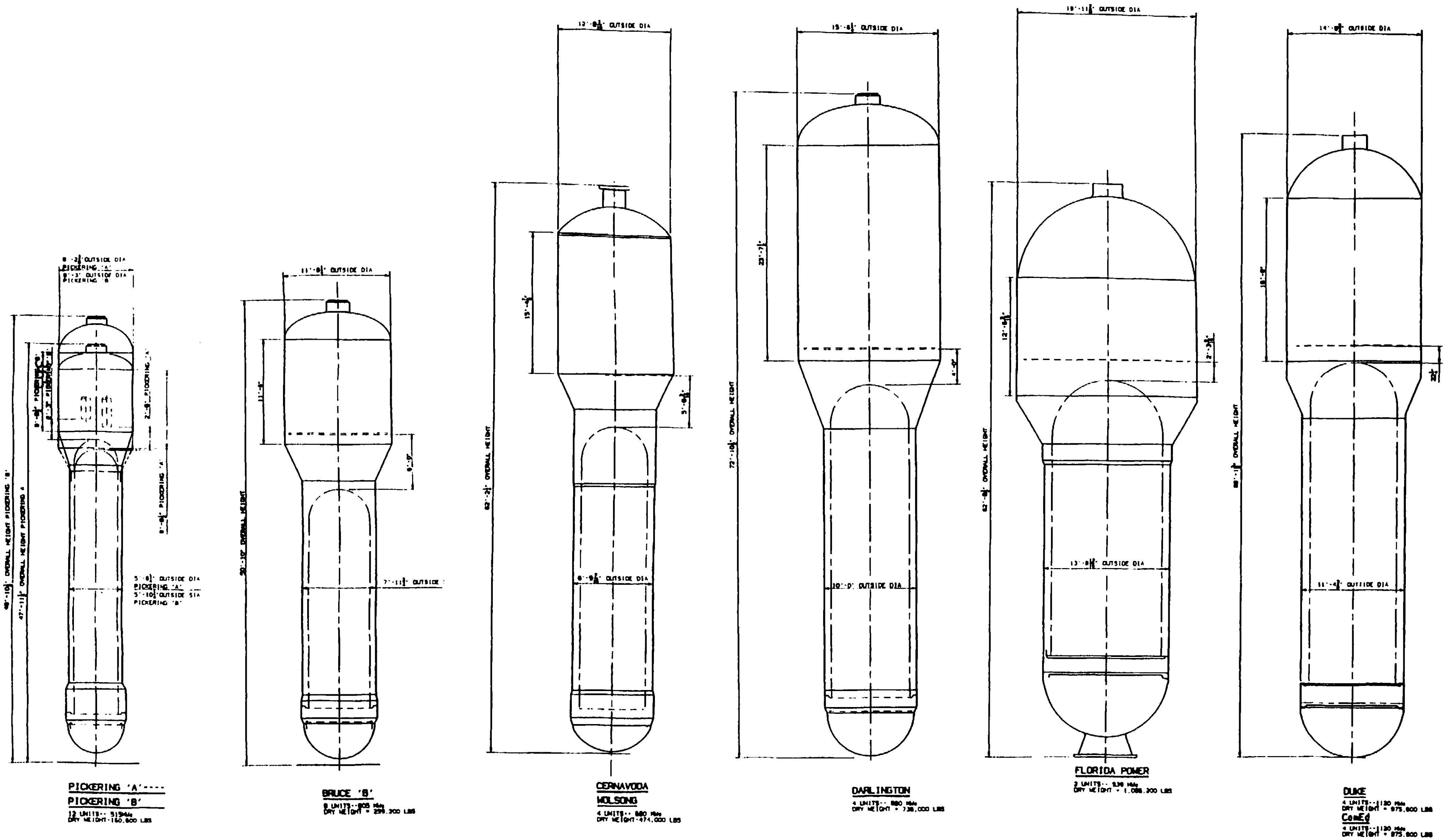
PICKERING 'A'
PICKERING 'B'
12 UNITS-- 515MWe
DRY WEIGHT-160,800 LBS
BRUCE 'B'
8 UNITS--805 MWe
DRY WEIGHT = 299,200 LBS
CERNAVODA
WOLSONG
4 UNITS-- 680 MWe
DRY WEIGHT-474,000 LBS
DARLINGTON
4 UNITS-- 880 MWe
DRY WEIGHT = 738,000 LBS
FLORIDA POWER
2 UNITS-- 936 MWe
DRY WEIGHT = 1,088,200 LBS
DUKE
4 UNITS--1120 MWe
DRY WEIGHT = 975,800 LBS
ComEd
4 UNITS--1120 MWe
DRY WEIGHT = 975,800 LBS

Figure 1

DISCUSSION

Authors: J.C. Smith, Babcock & Wilcox

Paper: Babcock & Wilcox Canada Steam Generators, Past, Present and Future

Questioner: K. Bagli

Question/Comment:

This is more of a comment than a question and it is not fair to address it to B&W alone, since OH is also partly responsible. We have not "stuck to our knitting" and learnt our lessons well. The Bruce-A SG design with the common steam drum and the preheaters is one example. The broached-hole TSPs is another. In hindsight, we have done a poor job in the evolution of the CANDU SG design.

Response:

I assume that the question implies that the Bruce A design, overall is bad. Note that the Bruce A design evolved from Douglas Point (horizontal drum concept) and use of 2-zone reactor (which led to the preheater concept).

By the time we arrived at Bruce B, we got rid of the horizontal drum.

Bruce A and B both use CS broached plate tube supports. The use of broached plates in Bruce A was the result of:

- Some bad fabrication experience with lattice grids at Pickering A. Some repairs to the lattice grids were required at site prior to SG installation.
- AECL's preference was for a Westinghouse or Douglas Point style of drilled-hole tube support. B&W was already using broached plates in SGs in the US and B&W felt broach plates were a better "solid plate" alternative than drilled-hole plates. Alloy 600 tubing was the "material of choice" in the industry by 1970. The whole Bruce A design was a set of compromises between AECL, OH and B&W.

Author's Comment:

There are great resources available in Canada to solve SG problems, but it is possible to have "too many cooks in the kitchen". B&W's experience in the US is very different. In the US, we get a functional specification and B&W must make all the design/material decisions, and then put a very comprehensive warranty on the equipment. There is no question of responsibility.

Questioner: M. Mirzai

Question/Comment:

What was the basis for B&W selecting I-690 over I-800? Was it just lab data, or did you look at all at the good experience of CANDU SGs or KWU?

Response:

Alloy-690 was chosen for replacement SGs to replace SGs with Alloy-600. In a replacement SG, we are trying to work within the original SG geometry. Alloy-690 has a slightly lower conductivity than Alloy-600, but is a stronger material when properly specified. Alloy-800 has a much lower conductivity (than Alloy-600) and is a weaker (ASME S_m) material. Therefore, for equal performance, a bundle with Alloy-800 tubing has to have considerably more surface area (tubes must be thicker due to strength), which sometimes cannot be done within the confined geometry of the original SG.

In addition, despite the good field performance of Alloy-800 (Canada and KWU experience), in side-by-side lab tests we have clearly demonstrated the corrosion behaviour of Alloy-690 to be superior. Alloy-800 can be cracked and/or pitted in chlorides, pitted in aggressive phosphate environments, and cracked in caustic environments. B&W has developed a very restricted specification for Alloy-690 with low carbon content, high mill anneal temperatures and processing (co-developed with a tube mill) which gives

- higher strength than Alloy-600.
- engineered grain boundaries with very high cracking resistance
- enhanced inspectability (very high signal/noise ratio)

We have a material now which we cannot crack, except in extreme lead-caustic mixtures at elevated temperatures which usually crack the autoclave before the tubes! Many of the test chemistries which will not harm 690 destroy both Alloy-600 and 800.

Questioner: F. Boyd

Question/Comment:

I infer different (water) chemistry and even for plants with similar SGs. Is this so? If so, why?

Response:

In the 1970s some plants ran on phosphate water treatment, some ran on AVT (all volatile treatment). Phosphates were mainly a good buffer against chloride ingress. A few plants are still on phosphate chemistry (mainly seawater cooled plants).

Reasons for differences plant-to-plant:

- limitations on what the plant equipment can produce in terms of treated water
- technology which existed at time of plant design. At time of Bruce design, "state-of-the-art" was
    - AVT, big focus on oxygen, less focus on other potentially troublesome elements
    - broached plates
    - Alloy-600 tubing

B&W's current recommendations for water chemistry are very much in line with EPRI Guidelines, Rev. 3. This plus

- Alloy-690 tubing
- SS lattice-type tube supports
- high circulation ratio in the SGs

will result in very long-lasting steam generators. For once-through steam generator plants, we also recommend strongly condensate polishers. Polishers are used extensively in KWU plants, which has contributed to the apparent good overall record of Alloy-800. KWU did experience pitting of Alloy-800 in some of their plants with "high phosphate" treatment, leading to a switch to either "low phosphate" or AVT.