The Effect of Steam Generator Tube Temperature on the Stress Corrosion Cracking of Alloy 600

F.P. Vaccaro, G.J. Theus, and B.P. Miglin
Babcock & Wilcox
Research & Development Division
Alliance, Ohio
S. Roy

Abstract

This review of the stress corrosion cracking (SCC) of Alloy 600 tubing assesses the relative importance of steam generator operating temperature in contrast to other factors. Although temperature is the most important environmental factor affecting primary side high-purity water SCC, the individual effect of stress and the combination of stress and microstructure are far more important. In regards to secondary side crevice-related SCC, other environmental factors are of greater importance than temperature. The use of stress-relieved tubing, low design stresses, stringent water chemistry control, and non-stagnant working fluids are the major reasons for the absence of SCC in many nuclear steam generators (SG). This includes the Babcock & Wilcox Canada (B&WC) recirculating steam generator (RSG) designs and the B&W USA once-through steam generator (OTSG) designs. This is in contrast to other SGs that have experienced SCC. The afflicted units usually have the following characteristics: low-temperature mill-annealed tubing, highly stressed areas in the tubing, poor water chemistry control, stagnant regions, and low recirculating ratios. An analysis of laboratory data demonstrates that the use of stress-relieved (621°C (1,150°F)/10 hrs) or thermally-treated (704°C (1,300°F)/16 hrs) tubing stressed (total stress, i.e., applied plus residual) to no higher than 70% of the yield strength will survive 33 times longer at 343°C (650°F) than mill-annealed tubing stressed to 125% of the yield strength. This improvement is at least an order of magnitude larger than the increase in mill-annealed tubing life obtainable by reducing the operating temperature from 327°C (620°F) to 304°C (580°F).

Résumé

Cette étude de la fissuration par corrosion sous tension (FCT) des tuyaux en Alliage 600 évalue l'importance relative de la température de fonctionnement du générateur de vapeur par rapport à d'autres facteurs. Bien que la température soit le plus important des facteurs de milieu qui affectent la FCT dans l'eau très pure du côté primaire, l'effet particulier de la tension et la combinaison de la tension et de la microstructure sont beaucoup plus importants. En ce qui concerne la FCT du côté secondaire liés à des crevasses, d'autres facteurs de milieu ont une plus grande importance que la température. L'emploi de tuyaux soumis à un traitement de détente des tensions, des tensions nominales faibles, un contrôle rigoureux de la chimie de l'eau, et des liquides de travail non stagnants sont les principales raisons de l'absence de FCT dans de nombreux générateurs de vapeur (GV) nucléaires. Ceci inclut les concepts de générateur de vapeur à recirculation de Babcock & Wilcox Canada et les concepts de générateur de vapeur sans recyclage de Babcock & Wilcox USA. Ceci s'oppose aux autres GV qui ont été atteinte de FCT. Les unités affectées ont généralement les caractéristiques suivantes: tuyaux recuits en usine à basse température, zones de tension élevée dans les tuyaux, mauvais contrôle de la chimie de l'eau, régions stagnantes, faibles taux de recirculation. Une analyse des données de laboratoire démontre que l'emploi de tuyaux ayant subi un traitement de détente des tensions (621° C (1,150° F)/10 hr) ou traités thermiquement (704° C (1,300° F)/10 hr) soumis à des tensions (tension totale, c. à d. appliquée plus résiduelle) maximum de 70% du seuil de plasticité dureront 33 fois plus longtemps à 343° C (650° F) que des tuyaux recuits en usine soumis à des tensions de 125% du seuil de plasticité. Cette amélioration est supérieure d'au moins un ordre de grandeur à l'augmentation de la durée des tuyaux recuits en usine qu'on peut obtenir en réduisant la température de fonctionnement de 327° C (620° F) à 304° C (580° F).

Introduction

Previously published work showed that the temperature of the environment is a factor in the SCC of Alloy 600 tubing on the primary side of U-bends and on the primary and secondary sides in tubesheet regions [1].

Keywords: stress corrosion cracking, steam generator designs, Alloy 600 tubing, heat treatment, activation energy, operating experience, residual stress, water chemistry.

Table 1: PWR and PHWR Steam Generator Operating Experience through December, 1984[a]

Manufacturer	*Number of plants*	*Number of tubes in operation*	*Tube years accumulated (× 10^6)*	*Total tubes removed from service*	*Defects per tube – year (× 10^4)*
B&W Canada[b]	15	405,930	2.195	33	0.15
B&W USA (OTSGS)[c]	8	248,052	1.319	820	6.22
Mfr C	29	294,756	0.713	613	8.59
Mfr D	11	124,376	0.806	832	10.32
Mfr E	6	50,099	0.282	293	10.38
Mfr F	9	77,668	0.347	2,206	63.49
Mfr G	13	211,485	1.000	8,204	82.01
Mfr H	49	527,758	2.481	21,729	87.59
World totals[f]	147	2,083,156	9.691	34,730	33.59 (Avg)

[a]Based on data from AECL 8268 (1984) and AECL 9107 (1986).
[b]Excluding NPD reactor – 1 horizontal SG for 22 MWe, used mainly for research.
[c]Excluding number of tubes plugged at TMI-1, per US NRC NUREG-1063.

This current report reviews the effect of temperature on SCC in relation to the effects of other important variables such as stress state, material condition, alloy type, water chemistry, and SG designs.

Stress corrosion cracking in SG tubing is a complex function of the following parameters: temperature, time, tube material composition, tube material microstructure, total stress (applied plus residual), environment and interactions of these factors. Sufficient data and information are available to separate semi-quantitatively these interactive effects and to demonstrate their relative importance.

Both operating experience and laboratory results were used to evaluate the relative importance of each variable. Factors other than temperature should be considered in ascertaining the reasons for the excellent performance of some SGs as opposed to the relatively poor performance experienced by others. As Table 1 and Figures 1 and 2 show, the improved performance of some of these SGs is not restricted to the absence of SCC but includes an extremely low incidence of other tube degradation problems. A more detailed categorization of reasons for tube plugging in OTSGs is presented in Table 2. At present there is a remarkable accumulation of over 3 × 10^6 effective full-power tube years (EFPTY) in B&W RSGs[1] and over 1.5 × 10^6 EFPTY in B&W OTSGs without in-service SCC.

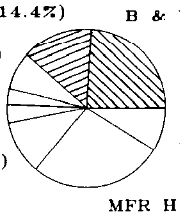


Figure 1: PWR and PHWR operating experience. Accumulated tube-years (×10^6).

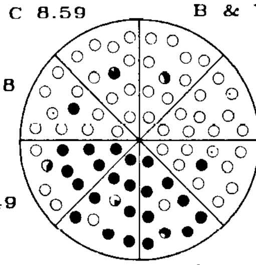


Figure 2: PWR and PHWR operating experience. Number of tubes plugged/10^4 tube-years. Each tube represents 10 tubes.

Operating Experience

There are several examples from operating experience which demonstrate that other factors are more important than temperature in controlling the incidence and severity of SCC.

Point 1 – Lack of Correlation of SCC with Temperature in Individual Steam Generators

For SG designs susceptible to SCC there exists a higher incidence of primary side cracking in the U-bend regions than in the appreciably hotter straight tube hot leg regions. This is an example where tube material condition in combination with the stress state, and not temperature, are the primary controlling factors of SCC. Two examples are Cook 2 and Farley 1, which are of similar SG design (W-51). These two units reported U-bend cracking at 302°C (575°F) in 140 and 30 weeks, respectively, but no hot leg cracking at 318°C (605°F) and 322°C (611°F), even after 360 weeks of operation [2, 3, 4].

Point 2 – Lack of Correlation of SCC with Temperature for Equivalent Steam Generator Designs

Not all SGs of similar design, operating characteristics, and time in operation are susceptible to SCC, although temperatures are essentially equivalent. In some cases,

Table 2: Secondary Side Damage Mechanisms Requiring Tube Pluggage or Removal (through 11/20/85)

	Maximum one OTSG		*All OTSGs*[a,b]	
	Number of tubes	*Percent*	*Number of tubes*	*Percent*
Corrosion fatigue – lane region	27	0.17	111	0.05
IGA – upper span/tubesheet	184	1.18	257	0.12
Corrosion/erosion – peripheral tubes	218	1.40	287	0.13
Fretting	11	0.07	28	0.01
Waterhammer[c]	10	0.06	26	0.01
Unknown	25	0.16	106	0.05
Not Service Related	79	0.51	278	0.13
Total			1,098	0.50
Total service-related			820	0.37

[a]Includes seven operating plants, excludes TMI-1 and TMI-2.
[b]Based upon approximately 217,000 tubes.
[c]Only three operating plants contained internal auxiliary feedwater headers which were associated with waterhammer damage to the tubes because of the deformed header.

some units free from SCC operate at even higher temperatures than those which are experiencing SCC. Such an example is Cook 2 compared to Salem 1, both of which are W-51 SG designs. Cook 2 has experienced U-bend cracking in 140 weeks, whereas Salem 1 has been operational for over 400 weeks with no observed U-bend problems. The temperature profiles are similar in that the primary inlet temperatures are 319°C (607°F) and 321°C (609°F), respectively [2, 3, 4].

Point 3 – The Importance of Stress and Deformation

In-service primary side SCC is invariably associated with areas characterized by high plastic deformations and high residual or applied stresses [5, 6]. These include U-bend, transition zones, and denting affected areas (i.e., U-bend and crevice areas). These deformed areas are undoubtedly under high residual stress, which is believed to approach the yield strength of the deformed material. Furthermore, dynamic straining occurs during denting and is probably producing strain rates known to cause more severe tendencies for SCC than equivalent, but constant stress conditions.

Non-deformed Alloy 600 tube sections adjacent to U-bend and transition areas displaying SCC have performed well in some cases for over 20 years. For these cases, where SCC has occurred in less than 1–2 years in deformed regions, it may be concluded that deformation produces an effect that is at least 20 times that of temperature. Furthermore, the temperature differentials between the non-deformed hot leg region and the U-bend area, and between the non-deformed hot leg region and the cold leg transition region are typically 22°C (40°F) and 28°C (50°F), respectively. This translates into an even greater difference between the effect of deformation and stress versus temperature on SCC.

Point 4 – The Importance of Water Chemistry

In many steam generators experiencing secondary side SCC, crack propagation was arrested and initiation of SCC reduced after improved water chemistry practices were introduced. These practices included conversion from phosphate chemistry (PO_4) to all-volatile treated (AVT) secondary water, the avoidance of condenser leaks, the use of demineralizers, and the removal of copper alloys from feed streams. These successes were obtained for many cases in which the operating temperatures remained unchanged [2, 3]. Controlling the sodium to phosphate ratio to between 2.0 and 2.6 reduced the incidence of SCC in phosphate-treated generators. Unfortunately, the conversion from phosphate to AVT secondary water chemistry also caused SCC to occur as a result of denting [7]. The sequence of events leading to this SCC involved chloride ingress from condenser leaks, which concentrates at tube/support structure crevices, causing accelerated growth of non-protective magnetite. The resultant stresses were in some cases sufficient to cause both primary and secondary side SCC in the tube/support structure areas, and U-bend primary side SCC. One ameliorating practice includes adding boric acid to reduce the corrosion rates of the carbon steel support plates.

Point 5 – The Importance of Thermal Treatment

The increased susceptibility of low-temperature mill-annealed Alloy 600 tubing to SCC is widely recognized [8]. In addition to suggesting conservative water chemistry practices, the Steam Generator Owner's Group of the Electric Power Research Institute considers the substitution of thermally treated Alloy 600 for mill annealed as another means of reducing the likelihood of SCC [2]. This recommendation is made without corresponding requirements for reducing op-

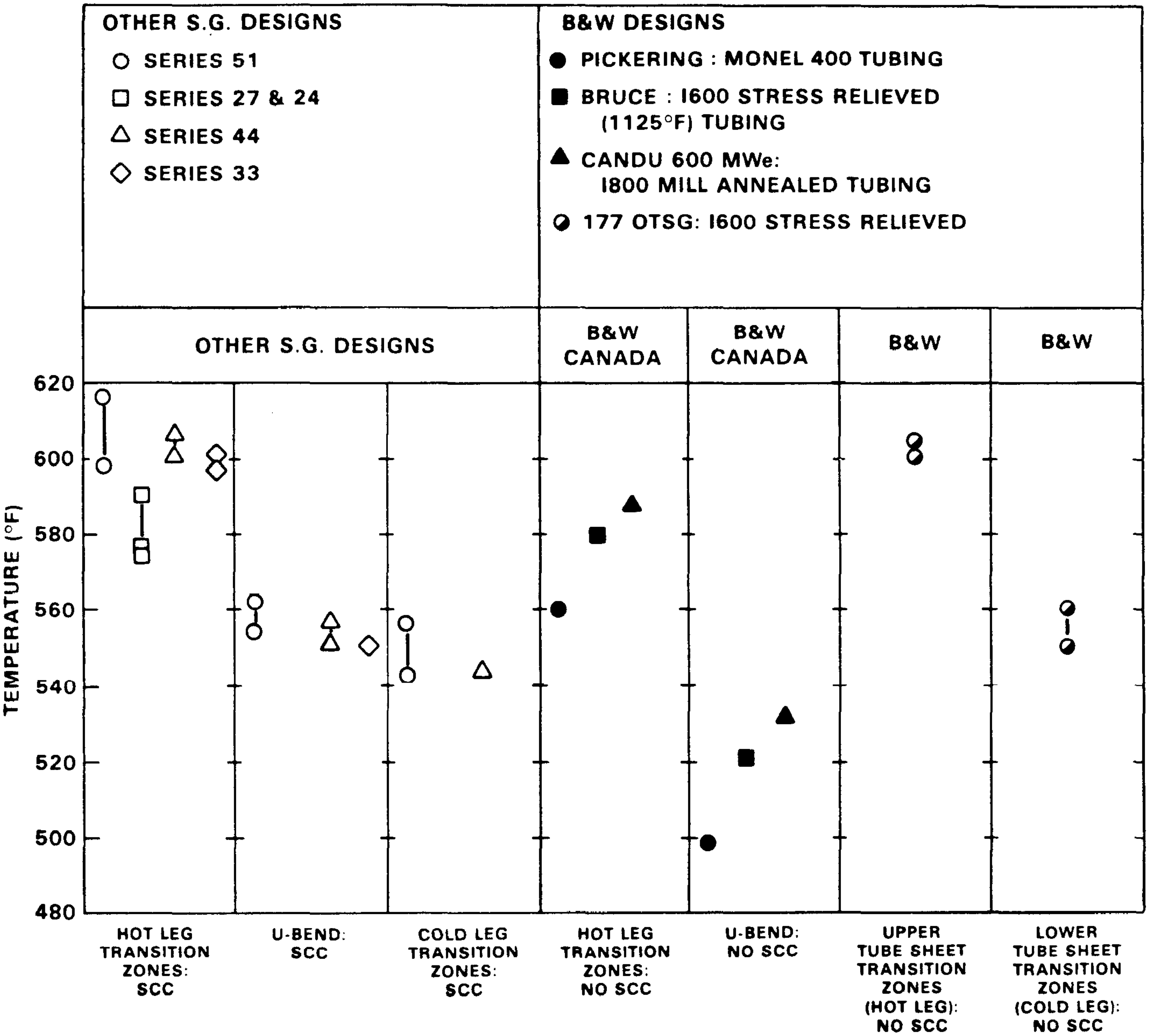


Figure 3: Temperature profiles and primary side scc incidence.

erating temperatures. Furthermore, thermally treated base Alloy 600 tubing is used in nickel-clad sleeving operations to reduce the risk of scc for members known to be placed in regions already possessing critical conditions [9]. It should be noted, however, that these thermal treatments must produce appropriate grain boundary carbide structures as well as reductions in residual stress to fully obtain the improved properties relative to the mill-annealed condition.

Point 6 – Steam Generator Design Effects

As emphasized earlier, stress-relieved or alternative-material SG tubing in both recirculating and once-through designs has performed extremely well in terms of high-temperature water scc. A significant portion of this tubing operates at temperatures equivalent to or in excess of those encountered in failed tubing of other designs, as seen in Figures 3 and 4. These figures illustrate, for example, that the primary side operating temperatures of hot leg transitions in non-susceptible designs are typically 11°C to 17°C (20°F to 30°F) higher than U-bend and cold leg transition temperatures for designs susceptible to scc. Furthermore, there is as little as a 11°C (20°F) differential in hot leg transition temperatures between non-susceptible recirculating designs and those experiencing extensive scc. Similarly, there is only a 17°C (30°F) differential in U-bend temperatures [2, 3]. Activation energy predictions of failure times indicate that this

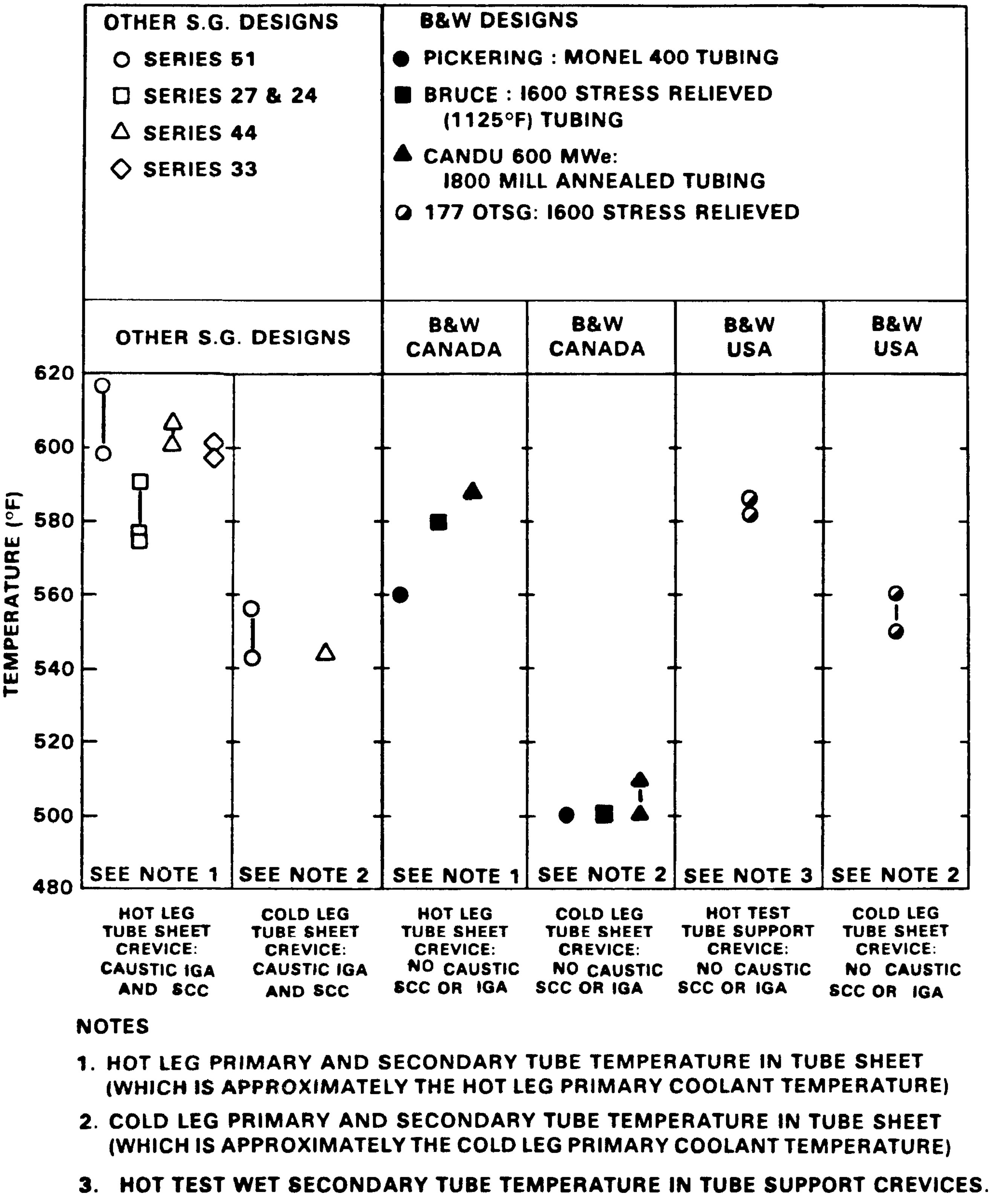


Figure 4: Temperature profiles and secondary side scc incidence.

large divergence in performance cannot be attributed to this small variation in operating temperatures.

Another important feature of SG design affecting secondary side scc is tube support crevice design. The use of open flow tube support designs eliminates the tight crevice conditions which create a vulnerability to the buildup of contaminants and sludges. Furthermore, the improved fluid flow precludes changes in the local secondary side crevice environments, which in turn can lead to either high acidic or caustic conditions conducive to denting and SCC.

In conjuntions with tube support crevice design, circulation ratios[2] can greatly affect the concentration of contaminants. Because OTSG designs do not include recirculation of secondary water, there exists a reduced tendency to build up contaminants in the liquid phase. In addition, the typically higher circulation ratios for some RSG designs (i.e., 5–6) versus others (i.e., 2–4) results in higher fluid flow velocities, which in turn improves the stripping action of the fluid, reducing the tendency for crud deposition and vapor pocket formation.

On the basis of these observations, it seems reasonable that the improved performance of these non-susceptible SGs can be attributed to the use of stress-relieved (or thermally-treated) tubing, better water chemistry control, lower applied and residual stress designs, and better fluid flow conditions. Indeed, incorporation of some, if not all, of these improvements may be necessary to guarantee that SG lives will be at least 30 years.

Laboratory Experience

Laboratory studies show thermal treatment to be a means of markedly improving resistance to both caustic and primary water SCC [1, 2, 4, 10–14]. Although service experience is scarce concerning the success of replacing damaged mill-annealed tubing with thermally treated material, laboratory results are abundant. They conclusively demonstrate the importance of these metallurgical factors in reducing the tendency for SCC, to the extent that this replacement practice was followed in a number of cases [15]. This improvement in resistance to SCC is greatest when thermally-treated material is substituted for cold-worked material typical of U-bend or roll transition regions. Furthermore, it is almost certain that future steam generator designs will avoid recommending temperature reductions, but will vary other design characteristics to avoid SCC, and yet maintain or even increase operating temperatures to produce equivalent or enhanced power ratings and efficiencies.

There is only one incidence of SCC of non-deformed mill-annealed Alloy 600 in high-purity water 365°C (689°F) when loaded to below the room temperature 0.2% offset yield strength [16]. Indeed, this one sample was loaded to 90% of the room-temperature yield strength of the non-deformed material, which will produce a substantial plastic strain at test temperature (i.e., near yield). Failure occurred in only 90 days. Two other SCC failures occurred in high-purity water at 343°C (650°F) in the laboratory in deformed Alloy 600 at stresses below the room-temperature yield strength of the deformed material [17]. One specimen prestrained 5% failed in 19,700 hours (2.24 years) when tensile

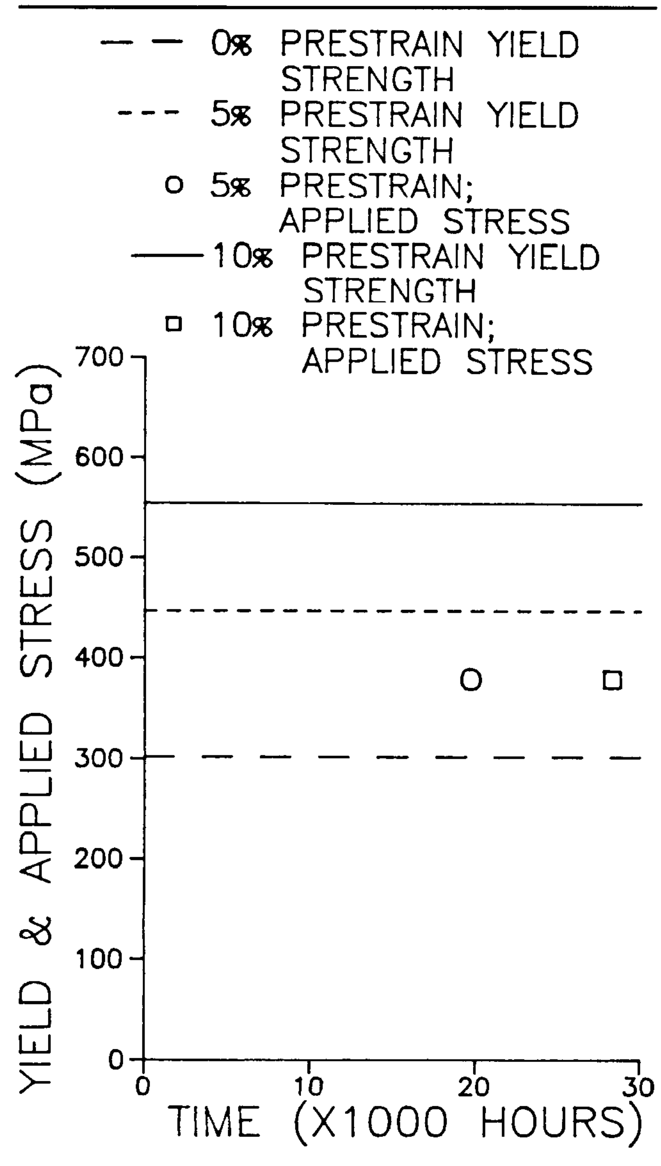
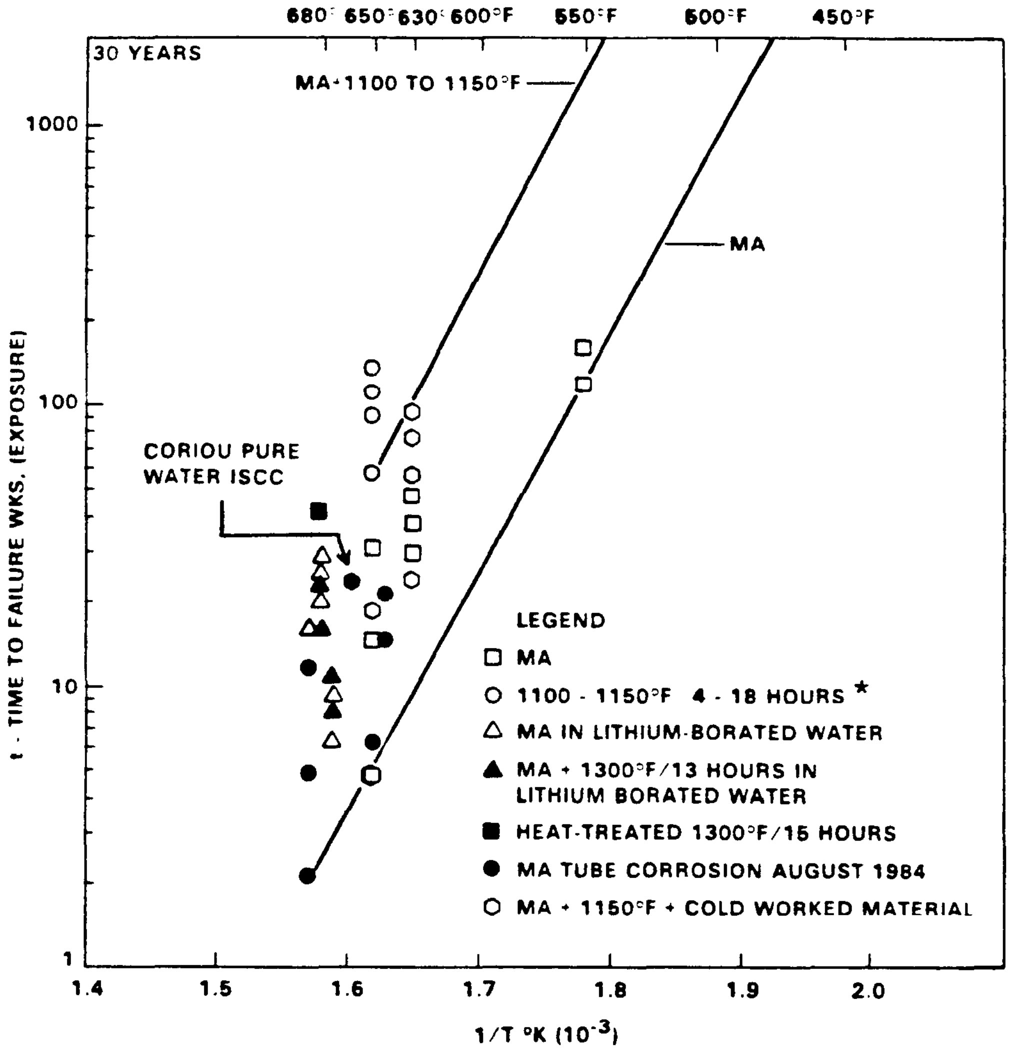


Figure 5: High-purity water tests 343°C (650°F). Applied stress must be near to or grater than the 0% prestrain yield strength to cause SCC.

loaded to 84% of the prestrained material yield strength (i.e., 379 MPa (55 ksi), YS = 448 MPa (64.9 ksi)). The second specimen prestrained 10% failed in 28,300 hours (3.23 years) when loaded to 67% of the prestrained yield strength (i.e., 379 MPa (55 ksi), YS = 555 MPa (80.5 ksi)). Evaluating these results, as shown in Figure 5, demonstrates that stresses must be near if not above the mill-annealed material yield strength (determined at operating temperature) in order to produce SCC in high-purity water.

Recently, attempts have been made to estimate activation energies for initiation of SCC based upon laboratory studies [4, 18, 19]. The activation energy is determined from the slope of an Arrhenius curve, which is a plot of the logarithm of time to failure as a function of the reciprocal temperature. These estima-



*For the 2 stress relieved U-bend failures (Temperature 1150°F for 18 hours) the loads were appreciably higher than the yield strength. Furthermore there were an additional 35 U-bend and split ring tensile stress-relieved samples which did not fail with exposures of at least 279 weeks.

Figure 6: scc of Alloy 600 U-bends in high-temperature water (from reference 4).

tions in turn are compared to actual service data to develop models for remaining life prediction. In one such effort [4] it is assumed that the activation energy for initiation of scc is about 40 Kcal/mole – K°, and is basically independent of tube material condition (i.e., whether it is low- or high-temperature mill-annealed, thermally treated, stress-relieved, or even highly cold-worked). This estimation is made for the minimum failure times as a function of temperature for the most sensitive material condition, i.e., low-temperature mill-annealed. Therefore, the Arrhenius plot for the more resistant material condition should be of equal slope to the reference curve for low-temperature mill-annealed material, but displaced to longer times to failure, as shown in Figure 6.

It should be noted, however, that thermal treatments (i.e., 621°C (1,150°F) for 10 hours and 704°C (1,300°F) for 15 to 16 hours) produce grain boundary decorated microstructures similar to those resulting from stress relief treatments (i.e., 593°C (1,100°F) to 621°C (1,150°F) for 10 to 18 hours) which are extremely resistant to high-purity water scc. Indeed, detailed inspection of laboratory results reveals that only four scc failures occurred out of a total of 117 stress-relieved tests. Many stress-relieved specimens were tested for as long as 93,750 hours (10.7 years) with scc [20]. Furthermore, failures occurred in stress-relieved samples only for loads well in excess of the room temperature yield strength, and only for temperatures of at least 343°C (650°F). Therefore, the results presented in Figure 6 must be carefully interpreted, recognizing that the vast majority of stress-relieved or

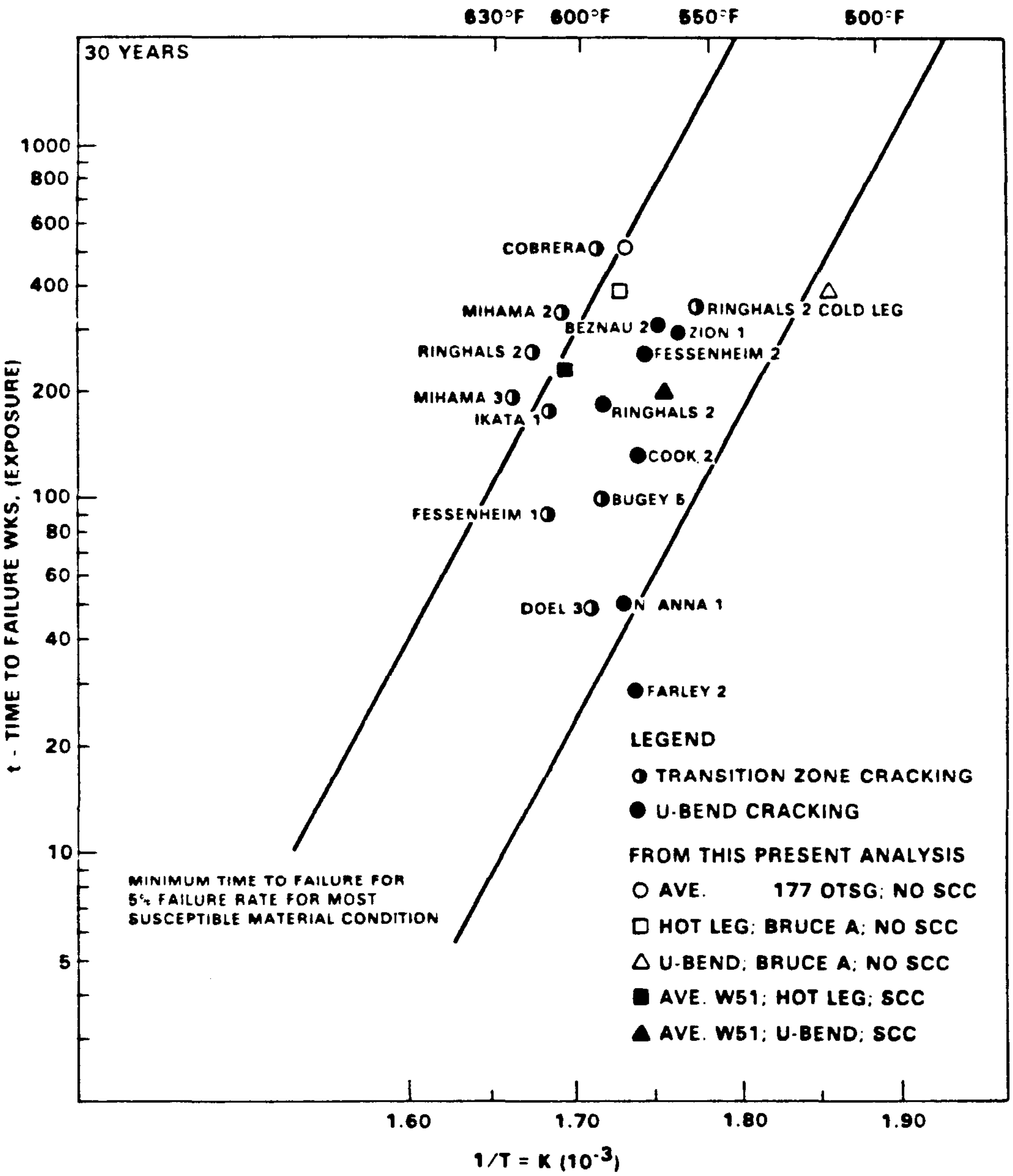


Figure 7: Steam generator operating experience. Note: No scc for B&W designs (from reference 4).

comparably heat-treated test samples lasted more than approximately five years, and some for as long as about 11 years, or until the program was terminated, without incidence of scc. These laboratory tests are being confirmed even today with operating plants that use stress-relieved Alloy 600 tubing, in that there are no reported high-purity water scc problems.

One conclusion reached in the cited activation energy analysis [4] was that thermal treatments for 593°C (1,100°F) to 621°C (1,150°F), for as short a time as four hours to more typically 18 hours, or 704°C (1,300°F) for 15 to 16 hours, greatly improved potential life, whereas other treatments (i.e., low-temperature mill-annealed or cold-worked) reduced life expectancy. However, another study showed that 10 hours of heat treatment at 621°C (1,150°F) will insure the formation of microstructures extremely resistant to caustic and high-purity water scc [10]. Nevertheless, the former analysis [4] showed that a 12-fold improvement in life can be obtained for thermally treated material versus annealed, even when heat treated for only 4 hours (Figure 6).

Another conclusion which can be drawn from the data is that there exists extensive scatter at any one specific temperature, which strongly suggests effects of other uncontrolled but important parameters. Higher temperature tests for thermally activated phenomena are normally prescribed to accelerate the processes, to allow for practical laboratory investigation. However, an additional effect often desired when testing at higher temperatures is a reduction in the scatter of the data. That this effect of scatter is probably occurring in the scc of steam generator tubing is apparent from the data presented in Figure 7. The scatter in times-to-fail

Table 3: Activation Energy Predictions of Time to Fail Compared to Actual Experience

Location	*Temperature* °C	(°F)	*Predicted minimum time to fail using activation energy approach (ΔE = 40 KCAL/mole-°K) (weeks)** 50% failure rate	5% failure rate	*Observed Minimum time to fail (weeks)*
Hot leg transition zones					
B&W RSGS (Bruce A)	304	(597)	155	42	No failure (364)
B&W OTSGS	318	(604)	75	21	No failure (501)
Cobrera	313	(595)	95	29	500
Mihama 2	318	(605)	75	21	320
U-bends					
B&W RSGS (Bruce A)	272	(522)	1100	375	No failure (364)
Ringhals 2	294	(562)	270	90	190
Cold leg transition zones					
B&W RSGS (Bruce A)	263	(506)	2000	750	No failure (364)
B&W OTSGS	314	(598)	90	27	No failure (501)
Ringhals 2	293	(560)	270	90	350

*Note: These predictions are based upon the data plotted in Figure 6 and on the assumption that SCC is strictly a function of temperature and independent of material condition, water chemistry, etc. It should be emphasized that there are no known high-purity water SCC failures in service in stress-relieved 600 tubing.

for operational steam generators is appreciably greater than the scatter in laboratory data, which were generated at higher temperatures and plotted in Figure 6. It is recognized that an appreciable amount of this increased scatter may be attributed to the greater number of variables present in service vs laboratory conditions, or perhaps to the thoroughness of the eddy current inspections. However, it was suggested that increased scatter in failure times will occur with decreased temperature [1].

The implications of this scatter upon the present issue are noteworthy. The fact that some SGS are SCC-free while operating within the temperature ranges characterized by a high incidence of SCC and a large scatter in failure times for other designs, is extremely significant. If it is assumed there will also be a large scatter band for failure for the SG's designs that are presently performing without SCC, it may be concluded that the lower end of the scatter band for failure has not been reached as yet. Therefore, it is likely that the vast majority of these SGS will continue to perform without the development of SCC.

It was previously pointed out that activation energy analyses are being used to predict initial design and remaining SG lives. Applying this approach to service data further demonstrates that temperature is only one of several factors affecting SCC. Table 3 contains temperature profile data and predicted times-to-fail for different SG designs, compared with actual field experience. For these examples, there is an obvious discrepancy between predicted values and actual experience. The reasons for this discrepancy is that the method assumes temperature is the primary controlling factor for SCC.

Empirical Correlation Life Predictions

An empirical life prediction technique was formulated by performing tensile tests on highly susceptible material (i.e., low-temperature anneal and a severe pickle) in AVT water at 343°C (650°F) to evaluate the effect of temperature [1, 17]. The effects of stress and heat treatment were determined by electro-chemical caustic tests at 288°C (550°F). As a result, the times to failure can be predicted for both mill-annealed and heat-treated material as functions of stress and temperature. This correlation method was used to predict successfully service failure times for mini-sleeves at Doel 3.

Table 4 presents predicted lives and multiplying factors for mill-annealed and heat-treated Alloy 600 ring tensile specimens in 343°C (650°F) AVT water as a function of load (in terms of per cent room temperature yield strength). As Table 4 shows, the prediction technique is highly accurate at the one condition for which failure occurred (i.e., as received, 125% YS). Due to the absence of failures of non-deformed specimens stressed below the yield in high-purity water tests, the accuracy of the correlation method has not been assessed at these lower stresses. Although high-purity water tests were performed for exposures as long as 93,750 hours (10.7 years), the program was unfortunately terminated before predicted times for failure were achieved. However, it is believed that the estimations are conservative.

Table 4: Predicted Failure Times in High-Purity Water at 343°C (650°F) and Multiplying Factors from References 1 and 17

	As-received		*Heat treated*		*Heat treatment multiplying factor***	*Stress multiplying factor***	
% RTYS	*Hours*	*Years*	*Hours*	*Years*		*As-received*	*Heat-treated*
125	35,000*	4.0	136,000	15.5	3.9	1.0	1.0
90	102,500	11.6	451,000	51.5	4.4	2.9	3.3
70	185,000	21.1	1,171,000	133.7	6.3	5.3	8.6
60	245,000	28.0	–	–	–	7.0	–

*Two of three specimens have failed at 36,300 and 39,900 hours. The rest have not failed after 93,750 hours of testing.
**Derived from electrochemical caustic tests.

Table 5: Predicted Lives (Years) and Stress Multiplying Factors for Mill-Annealed and Heat-Treated Alloy 600

	Stress multiplying factors		*Temperature*					
			650°FF/343°C		*630°F/332°C*		*550°F/288°C*	
% RTYS	*As-recd*	*Heat treat*	*As-recd*	*Heat treat*	*As-recd*	*Heat treat*	*As-recd*	*Heat treat*
125	1.0	1.0	4.0	15.5	8.0	31	32	124
90	2.9	3.3	11.6	51.5	23.2	103	93	–
70	5.3	8.6	21.1	133.7	42.2	266	169	–
60	7.0	–	28.0	–	56.0	–	224	–

Note: Times to fail at 332°C (630°F) should be 2 times those at 343°C (650°F). Times to fail at 288°C (550°F) should be 8 times those at 343°C (650°F). From AVT water tests on highly susceptible material, i.e., low-temperature anneal with a severe pickle [1, 17].

Table 6: Temperature Multiplying Factors[a]

Temperature, °F/°C	*Empirical correlation method [1, 17]**	*Activation energy method [4]***
680/360	0.27	0.4
650/343	1.0	1.0
630/332	3.6	1.8
620/327	4.8[b]	3.0
610/321	5.9[b]	3.8
600/315.6	7.0[b]	5.0
580/304	9.5[b]	10.0
550/288	13.0	24.0

[a]Normalized relative to 650°F.
[b]Estimated.
*Factor = (avg. time to fail at T_1)/(avg. time to fail at 650°F).
**Reference 4 assumed thermal treated and annealed material had same activation energy (40 Kcal/mole-°K) for scc.

This predictive technique incudes the effect of stress, microstructure (i.e., heat treatment), as well as temperature. Table 5 presents the predicted lives and multiplying factors of mill-annealed and heat-treated Alloy 600 ring tensile specimens as functions of load and temperature. Similarly, Table 6 compares the temperature multiplying factors from the empirical correlation method [1, 17] to those from the activation energy method [4]. It should be noted that the correlation method temperature multiplying factors were derived from failure data of highly susceptible material (i.e., low-temperature (927°C/1,700°F) anneal with a severe pickle). However, multiplying factors from the activation energy approach [4] on mill-annealed material are not appreciably different, as is shown in Table 6. Both methods assume that the temperature multiplying factors are the same for heat-treated and mill-annealed material. In fact, the largest variation in temperature multiplying factors was at 288°C (550°F), where the value from the correlation method was 55% of the value from the activation energy method. It is emphasized that the stress multiplying factors for thermally treated and stress-relieved material are estimations, and are not based upon actual failures. Only a small per cent of test samples failed in high-purity water, and only when loads were appreciably higher than the yield strength.

Table 7 contains a comparison between temperature multiplying factors and those for the combined effects of stress and heat treatment (i.e., microstructure). Whereas only a 2 (9.5/4.8) [1, 17] to 3.3 (10/3) [4] increase in steam generator tube life is predicted if the operating temperature is decreased from 327°C (620°F) to 304°C (580°F), an improvement of at least 33 times is predicted if stress-relieved or thermally treated tubing is stressed (total stress = applied plus residual) to no more than 70% of the yield strength. Therefore, the combined effects of stress and heat treatment are 10 to 16.5 times that of temperature. Even individually the effects of stress and microstructure are larger than the effect of temperature. The effect of microstructure (i.e., heat treatment excluding stress relaxation) ranges from 3.9 to 6.3 for stresses at 125% to 70% of yield. The effect of stress for mill-annealed material ranges from 2.9 at 90% yield through 5.3 at 70% yield to 7.0 at 60% yield. These individual factors are equivalent or slightly higher than the factors for temperature (i.e., 2.0 to 3.3).

Table 7: Comparison of Temperature Multiplying Factor vs Stress, Heat Treatment (Microstructure) and Combined Stress Plus Microstructure

% YS	*B&W temperature factor* [1, 17]*	*Stein temperature factor* [4]*	*Stress multiplying factor mill-annealed***	*Heat treatment multiplying factor*	*Combined stress plus heat treatment multiplying factor*
125	2 (9.5/4.8)	3.3 (10/3)	1.0	3.9	3.9
90	–	–	2.9	4.4	12.8
70	–	–	5.3	6.3	33.4
60	–	–	7.0	–	–

*For temperature reduction from 327°C (620°F) to 304°C (580°F).
**343°C (650°F).

Conclusions

It may be concluded that the use of alternative alloys (e.g., titanium-stabilized Alloy 800 or Alloy 690), thermally treated or stress-relieved Alloy 600 tubing, with low stress and low cold work designs, stringent water chemistry control, and high fluid flow, in concert, far outweighs the influence of temperature on SCC. The combined effects of these other more important factors, and not lower operating temperatures, are the primary reasons for the improved resistance of some SGs to SCC. Controlling these design variables is a preferred approach for avoiding SCC to reducing operating temperatures, in that it allows for maximizing operating temperatures (which is desirable for reasons of efficiency) without the incidence of SCC.

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Notes

1. Canadian Deuterium Uranium Plants.
2. Definition: Circulation ratio – ratio of total mass flow in riser/steam flow (as opposed to recirculation ratio, which is the ratio of water in the downcomer/steam flow).

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