TOP OF TUBESHEET CRACKING IN BRUCE A NGS STEAM GENERATOR TUBING – RECENT EXPERIENCE

M. A. Clark, O. Lepik, M. Mirzai,* and I. Thompson

ABSTRACT

During the Bruce A Nuclear Generating Station (BNGS-A) Unit 1 1997 planned outage, a dew point search method identified a leak in one steam generator(SG) tube. Subsequently, the tube was inspected with all available eddy current probes and removed for examination. The initial inspection results and metallurgical examination of the removed tube confirmed that the leak was due to intergranular attack/stress corrosion cracking (IGA/SCC) emanating from the secondary side of the tube at the top of the tubesheet location. Subsequently, eddy current and ultrasonic indications were found at the top of the tubesheet of other Alloy 600 SG tubes. To investigate the source of the indications and to validate the inspection probes, sections of 40 tubes with various levels of damage were removed. The metallurgical examination of the removed sections showed that both secondary side and primary side initiated, circumferential, stress corrosion cracking and intergranular attack occurred in the BNGS-A SG tubing. Significant degradation from both mechanisms was found, invariably located in the roll transition region of the top expansion joint between the tube and the tubesheet on the hot leg (304^0C) side of the tube. Various aspects of the failures and tube examinations are presented in this paper, including presentation of the cracking morphology, measured crack size distributions, and discussion of some factors possibly affecting the cracking.

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1.0 INTRODUCTION

During the planned 1997 outage of Bruce NGS Unit 1, a low level primary to secondary side leak was located in a SG tube (in steam generator 3,BO3) by a helium/dewpoint leak detection procedure. Eddy current (ECT) inspections of the suspected leaking tube and several adjacent tubes detected possible degradation of the Alloy 600 tube material in the vicinity of the top of the tubesheet (TTS) on the hot leg side. The leaking tube and one adjacent tube (with a significant indication) were removed in July 1997 and submitted to Ontario Hydro Technologies (OHT) for identification and analysis of the *degradation*. Preliminary results indicated that through wall intergranular cracks were present in both tubes.

After the discovery of through-wall TTS cracking in the first two tubes from U1 BO3, the inspection scope was expanded to 100 % of the tubes in BO3 and BO5. Similar TTS crack indications were detected in 59 tubes from BO3 and 25 tubes from BO5. Since the initial results suggested that these were the steam generators most affected by the cracking, tubes for removal were selected from these two steam generators. As results from these removals became available, Units 3 and 4 were shut down and an inspection program initiated. Eventually a 100 % inspection of the hot leg TTS region was performed in all 16 steam generators from Units 3 and 4. Cold leg inspections were carried out in two of the steam generators but detected no defects. Tubes were removed from the two Unit 4 steam generators with the largest number of significant indications. Only one TTS indication was detected in Unit 3, therefore, no tubes were removed from Unit 3. Eventually regulatory permission was obtained to restart Units 3 and 4. The final results of all the 1997 inspections are summarized in Table 1.

Table 1 – Summary of 1997 ECT Inspection Results

	Unit 1		Unit 3		Unit 4	
	135,500 Operating hours		136,600 Operating hours		133,800 Operating hours	
SG	No of tubes inspected with C3/4 probe	No of TTS crack indications	No of tubes inspected with C3/4 probe	No of TTS crack indications	No of tubes inspected with C3/4 probe	No of TTS crack indications
1	64	0	4200	0	4196	5
2	0	-	4170	0	4198	4
3	4118	59*	4199	0	4172	0
4	3210	10	4200	0	4199	48*
5	4119	25*	4199	0	4200	7*
6	0	-	4198	0	4170	2
7	3956	11	4197	1	4198	0
8	0	-	4197	0	4199	6*
Totals	16070	106	33528	1	33540	72

* tubes removed from these steam generators

2.0 HISTORY

Design

Bruce A NGS consists of four 760 MWe reactor units, each equipped with eight recirculating steam generators (SGs) and four separate preheaters. Each SG has 4200, 0.5 inch (12.7 mm) nominal OD U-bend tubes. The hot leg inlet operating temperature is 304^{0}C (580^{0}F). The tubing material is mill annealed Alloy 600 with nominal carbon *contents* in the range of 0.03 to 0.06 wt%. A final hydrogen furnace anneal was conducted at 1093°C (2000°F). The annealed tubes were then straightened, OD surface ground, cold bent, and assembled into the tube bundle. Tubes were mechanically rolled at two locations with the upper joint located just below the secondary face of the tubesheet (Figure 1). The tubes were seal welded to the primary side of the tubesheet with a fillet weld. The completed tube bundles were heat-treated to relieve the stresses at the carbon steel shell closure welds at a nominal temperature of 607°C (1125°F). Heat was applied to the lower half of the vessel while the upper portion of the bundle shell was insulated/1/. The hard rolled joints saw a partial stress relief as part of this operation, and tubing microstructure was moderately sensitized at the tubesheet region (as confirmed by ASTM G28 testing).

Early History

Between 1978 and 1983, there were a total of eight tube leaks in Units 2, 3 and 4, all located in the large-radius U-bends at either the top horizontal support plate (the 7th support plate), or the 40° hot-leg U-Bend (HLUB) support. Metallurgical examination of removed leakers identified high cycle, low-stress amplitude fatigue with flow-induced vibration as the most likely cause of failure. In recent years, leaking SG tubes resulted in significant unavailability of the BNGS-A Units. The major degradation was identified as OD-initiated circumferentially oriented stress corrosion cracking (SCC) of the tubes in the 40^0 HLUBS/2/. In 1986 a lead shielding blanket, inadverently left after a maintenance outage in one of the Bruce Unit 2 SGs, dissolved in the secondary side water and exacerbated the SCC problem in one bank of SGs. The severity of the SG tube cracking contributed to the shutdown and lay-up of BNGS-A Unit 2 in October 1995.

Recent History –top of tubesheet

An in-service Inspection (ISI) program has been in place to provide information on the overall condition of the SGs and to assist in the early identification and ongoing monitoring of SG tubing degradation mechanisms. Until recently, only a small sampling of tubes in any steam generator had been inspected for potential TTS degradation but none had been detected. Several survey tubes had been removed from the top of tubesheet area for metallurgical characterization. No significant damage other than some slight intergranular attack on the OD was discovered.

In 1995, the ISI program did detect TTS defects in the form of general wall loss/pitting just above the tubesheet. One tube was removed from Unit 1 BO5 to explore the source of these indications. The source of the signals was found to originate with OD initiated, general corrosion and pitting in a band about 12-15 mm above the top of the tubesheet to a maximum depth of 22 % through wall (TW). The tube also was found to contain multiple, shallow, intergranular circumferential cracks in the top roll transition region to a maximum depth of 10 % TW. In response to these findings, a partial TTS inspection program with three tube removals was performed in Unit 3 in 1996, but no significant corrosion or cracking was detected.

3.0 METALLURGICAL EXAMINATION METHODOLOGY

A total of 40 tubes sections were removed and examined from Units 1 and 4 in 1997. The purpose of the examinations was:

1. To identify the degradation mechanism (s),
2. To provide information to assist in the root cause determination of the degradation mechanism(s), and to
3. To characterize and measure the extent of the degradation for nondestructive inspection probe evaluation and detection/sizing validation.

All tube sections were removed from the primary side of the steam generators with the tubes being cut about 75 mm above the TTS and pulled through the tubesheet after relaxing of the rolled joints and removal of the seal weld. The rolled joint relaxation was accomplished by the TIG (tungsten inert gas) process. This process essentially applies a small weld bead to the inside surface of the tube within the rolled joint in a helical pattern. The heat associated with the welding effectively relaxes the residual stresses in the rolled joint permitting extraction of the section. The process was generally controlled to be confined to the rolled joint region so that the welds did not usually intersect the area of interest (the upper roll transition region).

A schematic of the tubesheet area of the steam generators is shown in Figure 1. In all the tubes, the degradation was located either in or just above the upper transition region of the upper roll expansion (Figure 1). This transition region is formed by the upper tapered portion of the rollers used to form the expansion joint. The top of the roller leaves a distinct burnish mark that is readily discernible on the ID surfaces. This mark was used as a reference for the axial location of the defects. The last point of contact between the tube and the tubesheet hole was not always apparent on the outside surface.

The examination procedures employed the basic metallurgical techniques of metallographic sectioning and fractography, augmented by other techniques such as chemical analysis, microhardness testing, energy dispersive X-ray analysis (EDX) in the scanning electron microscope (SEM) or secondary ion mass spectroscopy (SIMS). For each tube, a detailed quality assurance (QA) test plan was developed and implemented prior to any work being done. The degree of sensitization of the material was assessed using the ASTM G28 method.

4.0 RESULTS

ODSCC

The first two tubes from Unit 1 were removed and examined to investigate the source of the identified leak and the nature of ECT signals in an adjacent tube; these were tubes R16C90 (suspected leaker) and R18C90 from Unit 1 SG3.

After removal, visual examination showed that both tubes contained apparent circumferential cracks on the outer surfaces in the rolled joint region. In R16C90, two large circumferential cracks were found located between the end of the contact region with the tubesheet hole and the top of the rolled transition region (Figure 2). The cracks were offset from each other about 1 mm axially but were overlapped circumferentially. The total circumferential extent was about 190^0. In R18C90 the cracks were finer and slightly less extensive (100^0) but had also progressed through the tube wall over part of the length. In addition to the cracks, the OD surfaces in the area of the roll transition and slightly above had some wall loss in the form of general corrosion and minor pitting attack in a band around the circumference and extending from 2-5 mm above the last contact point. Typical general wall loss was about 5% with pit depths to about 12% through wall (TW).

Metallographic and fractographic examinations were used to characterize the crack features. The cracks were progressing by an intergranular path accompanied by extensive intergranular attack (IGA) around the main cracks. The IGA was contained in narrow bands that were 1- 2 mm wide in axial extent. General metallographic features are shown in Figure 3 which illustrates the intergranular attack and grain dropping as well as the axial location of the defects.. The IGA was located between the burnish mark made by the rollers and the contact point of the roll expansion i.e. in the roll transition region. The degradation mechanism was established in these first tubes as secondary side intergranular attack and stress corrosion cracking (OD IGA/SCC) in the upper roll transition region. This form of degradation is also known as top of tubesheet (TTS) cracking.

After these initial examinations, a further 21 tubes were removed from Unit 1, primarily for NDE probe validation. They were selected, based on the NDE results, to provide a range of defect sizes for probe validation. Fifteen of the 21 tubes had cracks or IGA of depths varying from 33 to 100% TW. Only four contained no IGA or cracks. Similar damage was also found in 17 tubes later removed from Unit 4. The measured crack depths in all these tubes are summarized in Figure 4. In most of these tubes, in addition to the IGA/SCC, the band of general corrosion and pitting damage, above the roll transition region, was apparent to a maximum depth of about 20% through wall (TW).

The degradation features were similar to the first two tubes and were characterized by extensive IGA, grain dropping and circumferential cracking. In some cases, the end result of the degradation was not really crack-like but a wide-mouthed trough with a rounded bottom or tip. In other tubes, the IGA formed symmetric elliptical-shaped patterns (Figure 5). In all cases, the IGA areas and cracks were located in the roll transition, i.e. below the burnish mark but above the tubesheet contact point. The other significant observation from this set of tubes was the circumferential extent of the damage. Circumferential extents in some cases were up to 340^0.

PWSCC

As a result of the discovery of OD-initiated IGA/SCC in Unit 1, the other two operating Bruce A units were shutdown for inspection to ascertain if similar damage was present. Unit 4 was shutdown initially because it also had a very low level chronic leak in one steam generator (SG8). The inspection program quickly identified several potential defective tubes as candidates for removal. Eventually a total of 72 tubes were found with TTS indications in Unit 4.

The initial two tube removals from this steam generator included one tube (R23C35) that fractured during the tube removal attempt. Examination of the fracture surface indicated that the small remaining ligaments were located on the OD. Sectioning and fractography of the other tube (R18C30) confirmed that a through-wall crack was present for about 80^0 of the circumference but in the remainder of the circumference the crack clearly initiated from the ID surface (Figure 6). In both tubes, the crack path was intergranular but was not accompanied by the extensive IGA found on the OD of the U1 tubes. After this initial discovery of circumferential cracking in the first two tubes, 15 additional tubes were removed from Unit 4. These tubes were again selected to verify the probes, but now for ID initiated indications.

Examinations of the additional tubes showed that the ID-initiated, intergranular cracking was present in 7 of the 9 tubes from SG8 and 5 of the 6 tubes from SG4. None of these cracks were through-wall and depths ranged from 11 to 94% (Figure 7). Circumferential extents of the ID cracking could be up to 360^0. The crack features and locations suggested that the ID cracks were due to primary water stress corrosion cracking (PWSCC).

OD initiated cracking was also present in several of the tubes (7 of 15) but was generally offset axially from the primary side cracking, being slightly higher up in the roll transition region. In one case the ID and OD cracks were in the same axial position (Figure 8). The depth of the OD cracking seemed to be generally less than the ID cracking although one tube had an OD crack depth of 85%. OD damage in the form of general corrosion and pitting was also present in these tubes with wall losses up to 29% in some cases in the same area as the ID cracks. These results show that both OD and ID degradation mechanisms are affecting the tubes from the Unit 4 steam generators and can, in fact, be present in the same tube.

DISCUSSION

The ISI program on three Units and the series of tube removals from four Bruce A steam generators in two Units has shown that two main degradation mechanisms are affecting the steam generator tubes :

- Top of tube sheet OD initiated intergranular attack and stress corrosion cracking (OD IGA/SCC)
- Top of tubesheet ID initiated cracking (PWSCC).

The degradation is confined to the top transition of the upper expansion joint on the hot leg side of the tubes. The ODSCC mechanism has been confirmed in two units (Unit 1 and Unit 4); the third unit (Unit 3) appears not to be affected at this time (Table 2).

Table 2 - Summary of Removed Tubes, Bruce A, Units 1 and 4

Unit and Steam Generator	Number of Removed Tubes	Purpose	Mechanisms
U1 SG3	13	Identify leaker and mechanism, probe validation	**OD IGA/SCC** OD corrosion and pitting PWSCC?
U1 SG5	10	Probe validation	**OD IGA/SCC** OD corrosion and pitting PWSCC?
U4 SG8	11	Identify mechanism and probe validation	**PWSCC** OD SCC
U4 SG4	6	Probe validation	**PWSCC** OD SCC OD corrosion and pitting
TOTALS	40		

Initially it appeared that the PWSCC was present only in Unit 4 tubes, however this may only be a result of the sequence of events. The initial removed tubes from Unit 1 were selected based on analysis of ECT signals for OD defects. The laboratory examinations were also focussed on OD defects. One tube from Unit 1 did contain an ID crack but it was attributed, at the time, to the TIG tube removal process. After the initial discovery of PWSCC in Unit 4, emphasis shifted to ID defect detection and the subsequent tube removals were selected for ID probe validation. It is now felt that both mechanisms are probably operative in tubes from both units.

A preliminary investigation of contributing factors was initiated as soon as the top of tubesheet ODSCC mechanism was identified. The focus was on obtaining information on the three main factors important to any SCC mechanism: material, stress and environment. The thrust of the initial investigations was to identify possible contributing factors so that the scope of the inspection program might be restricted with the aim of returning the units to service as soon as possible. It was hoped that an "area of risk" might be defined by such an analysis. For instance, it is likely from the axial location of the cracking that either residual stresses or cold work from the rolling process were important contributors. If the manufacturing records could show that some tubes had been over-rolled or re-rolled so that residual stresses were altered or more cold work was introduced, the apparent confinement of the cracking to certain tubes might be explained. Several of these manufacturing variables were analyzed but yielded no clear contributing factors. Similarly, heat treatment histories of the various steam generators were obtained but no definitive differences were found that could account for the restriction of damage to specific steam generators.

The initial observations of OD damage suggested that the secondary side environment was important in the mechanism. The locations of the damaged tubes in Unit 1 relative to the typical sludge pile are shown in Figure 9. The majority of the damaged tubes were within the sludge pile which suggests that the sludge pile environment or the interaction stresses between the sludge pile and the tubes might be important. As the sludge piles contained significant concentrations of copper, which as CuO is known to increase the propensity and depth of SCC in mill annealed Alloy 600 /3/, it is likely that this sludge constituent played a significant role in the observed OD IGA/SCC.

Material factors such as material bulk composition, microstructure (ie. grain size, carbide distribution, grain boundary microchemistry and orientation), strength, and cold work are known to be important to the SCC mechanism. Analyses of some of these material factors for selected tubes removed from Units 1 and 4 revealed no appreciable differences in bulk chemical composition, microstructure (grain size and carbide distribution), degree of sensitization and hardness in the roll transition. In general, the tube material exhibited a grain size less than ASTM 8 and partial to near-continuous grain boundary carbide decoration with few intergranular carbides - both of which are known to confer a lower susceptibility to PWSCC. The work hardening brought about by the roller expansion process increased the hardness of the tube material in the roll transition region. The maximum hardness measured in the roll transition ranged from 211 to 303 VHN, compared to a hardness in the base metal that ranged from 165 to 198 VHN. This elevation in cold work is known to increase the material's susceptibility to SCC, however no definitive differences could be discerned between each removed tube. Other material factors such as grain boundary microchemistry and orientation are presently being explored in an ongoing program.

SUMMARY AND CONCLUSIONS

Two main degradation mechanisms are affecting the steam generator tubes at the TTS in Bruce A:

- Top of tube sheet OD initiated intergranular attack and stress corrosion cracking (OD IGA/SCC)
- Top of tubesheet ID initiated intergranular cracking (PWSCC).

The degradation is confined to the top transition of the upper expansion joint on the hot leg side of the tubes. The OD IGA/SCC mechanism has been confirmed in two units (Unit 1 and Unit 4); the third unit (Unit 3) appears not to be affected at this time.

The PWSCC degradation has only been found in the Unit 4 tubes, but it is suspected that it is also present in Unit 1 tubes as well.

Some relatively minor general corrosion and pitting attack also is occurring on the OD surfaces in the same locations and can extend further up the tube above the tubesheet. The relationship between this degradation and the top of tubesheet IGA/SCC is not known but implies that the corrosive environment in this location is a key contributing factor.

The location and characteristics of the IGA/SCC degradation are similar to that experienced by PWR's tubed with Alloy 600 and, as such, is a consequence of this material's inherent susceptibility to stress corrosion cracking in this environment.

The details of the factors, i.e. stress, corrosive species and material susceptibility, which, in combination, produced the degradation are not yet well understood and have only been assessed in a preliminary fashion in the removed tubes, but will be the subject of ongoing work.

REFERENCES

1. N. Simpson, "Bruce A Steam generator Tubing History", Attachment 17 - " Bruce A Root Cause of Cracking - Summary Report 1" - December 1995.

2. P.J. King et al., "Stress Corrosion Cracking Experience in SGs at Bruce NGS", Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems, San Diego CA. p. 233-240, Pub. TMS, August 1-5 1993.

3. R.J. Jacko, "Corrosion Evaluation of Thermally Treated Alloy 600 Tubing in Primary and Faulted Secondary Water Environments", EPRI Report NP-6721-M, June 1990.

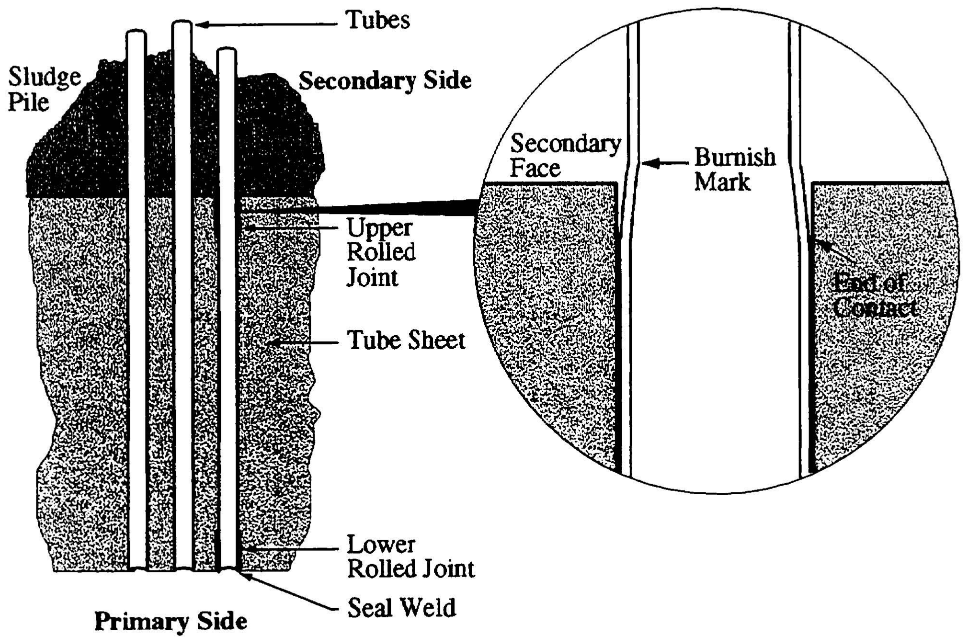


Figure 1 Schematic of cross-section of tubesheet and upper roll transition of tube

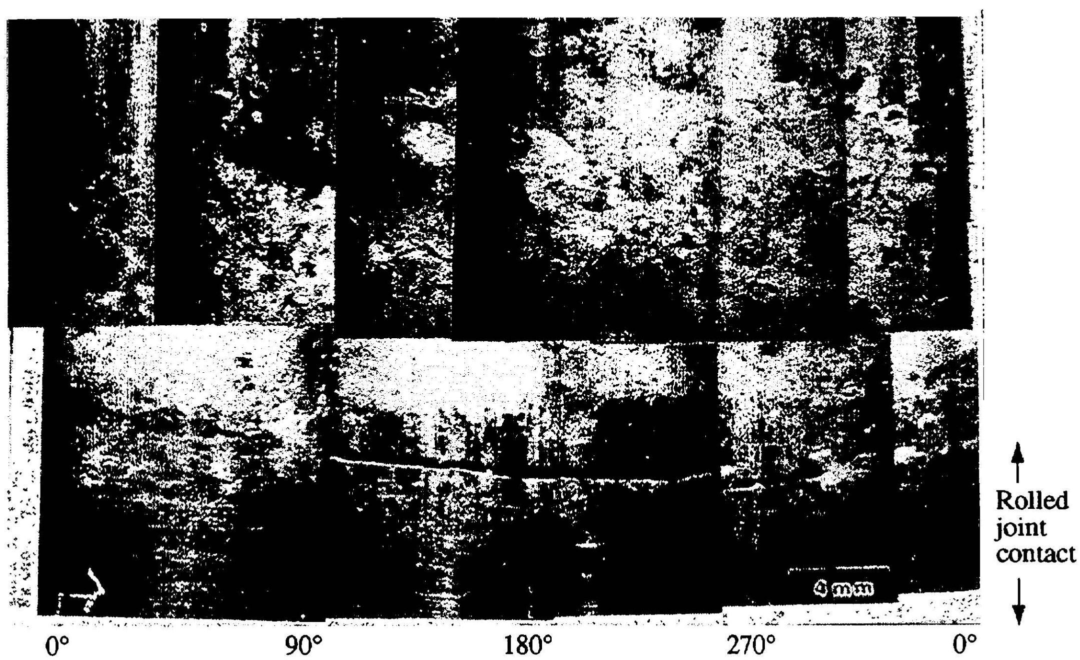


Figure 2 Surface features around circumference in upper roll transition of tube R16C90 removed from Unit 1, SG 3

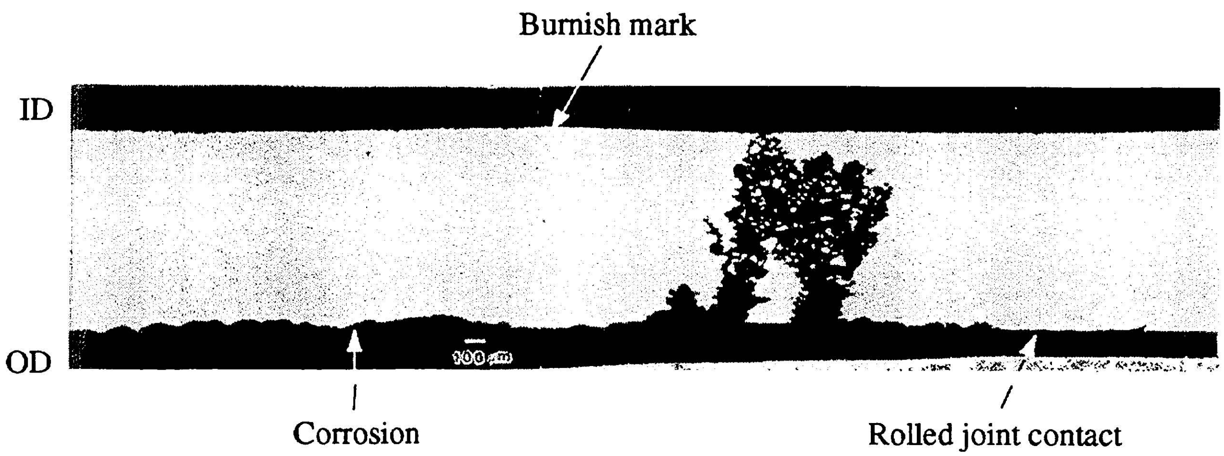


Figure 3 Features of damage in upper roll transition in tube R18C90 removed from Unit 1, SG 3

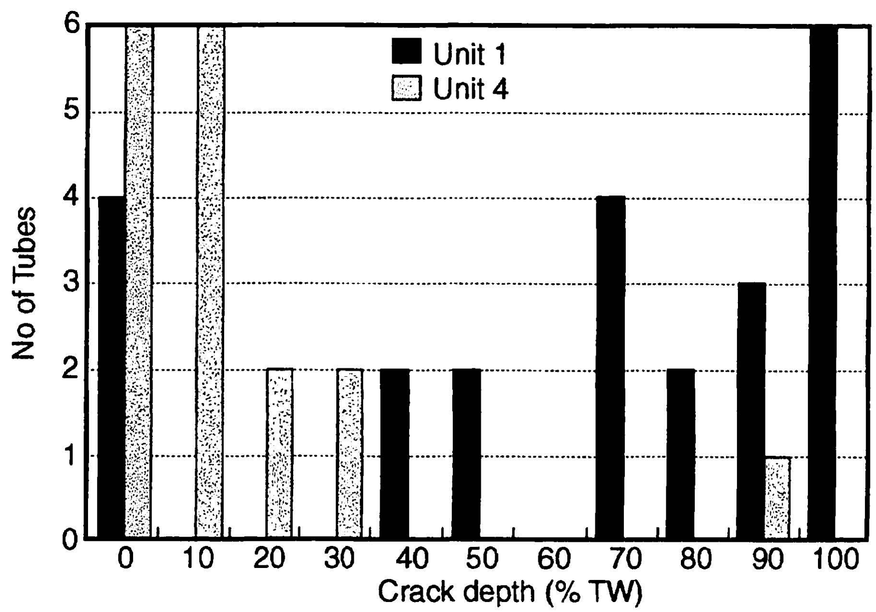
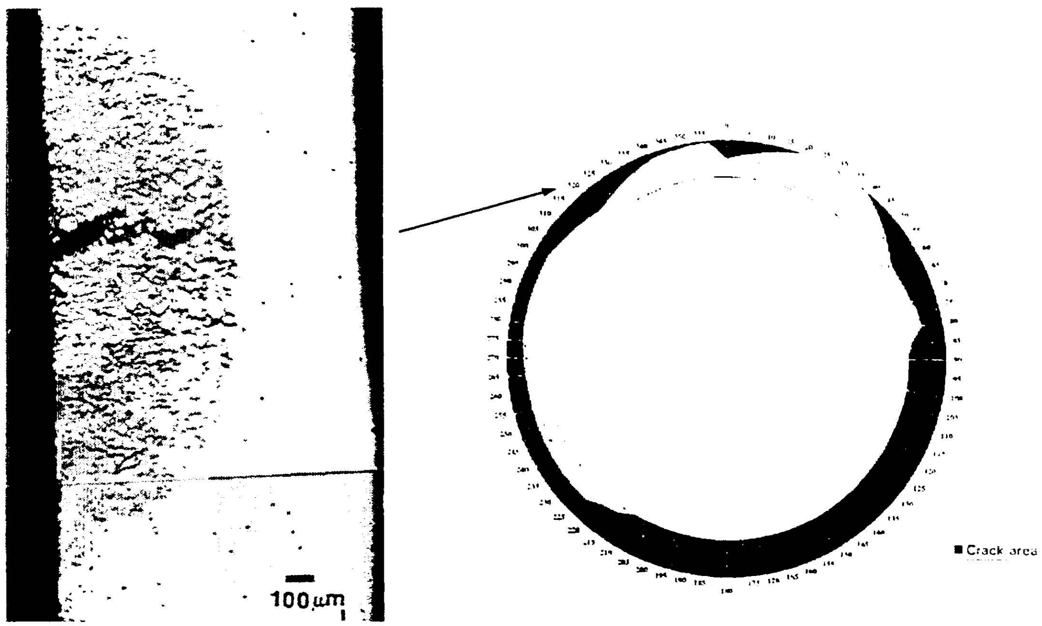
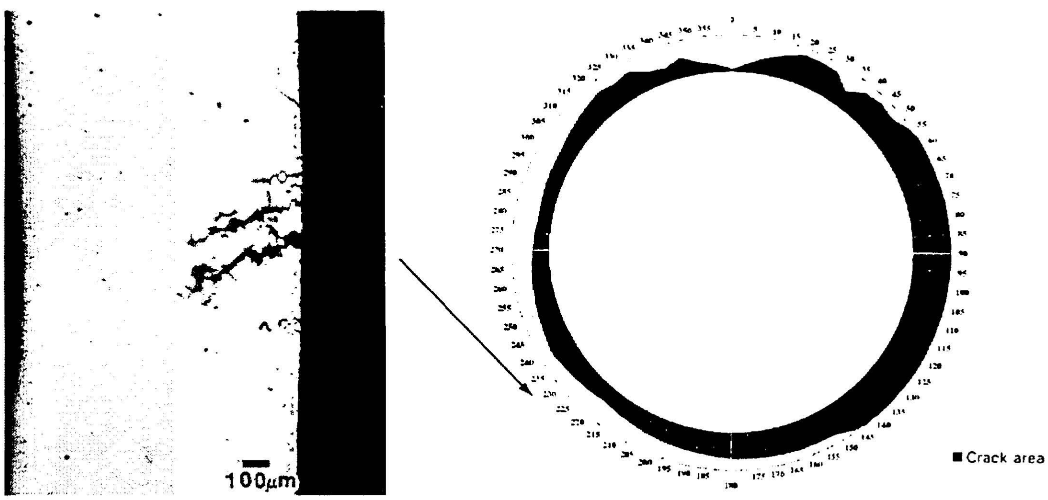


Figure 4 Distribution of maximum depths of OD initiated cracks in 40 tubes removed from Units 1 and 4



OD ID

Figure 5 Features of OD corrosion in tube R30C56 removed from Unit 1, SG 5



OD ID

Figure 6 Features of ID corrosion in tube R18C30 removed from Unit 4, SG 8

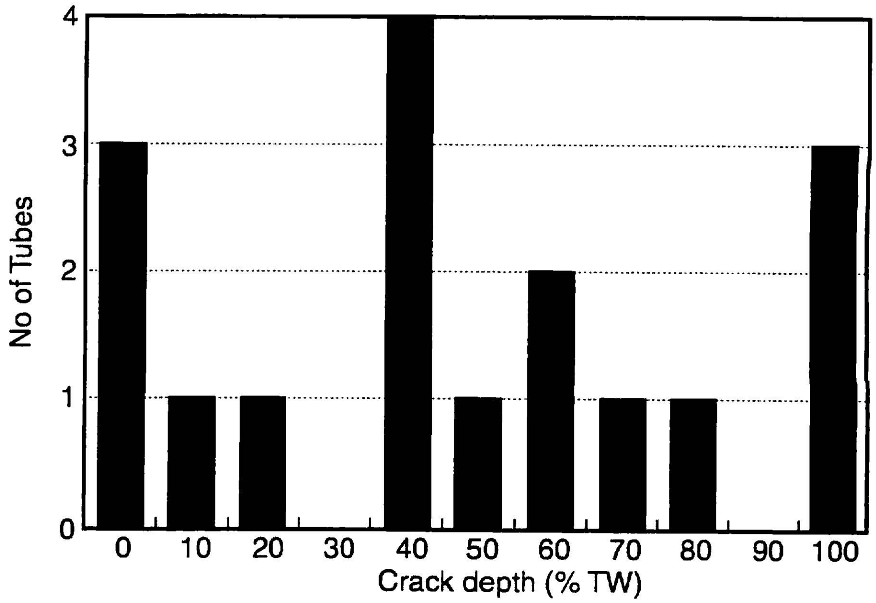


Figure 7 Distribution of maximum depths of ID initiated cracks in 17 tubes removed from Unit 4

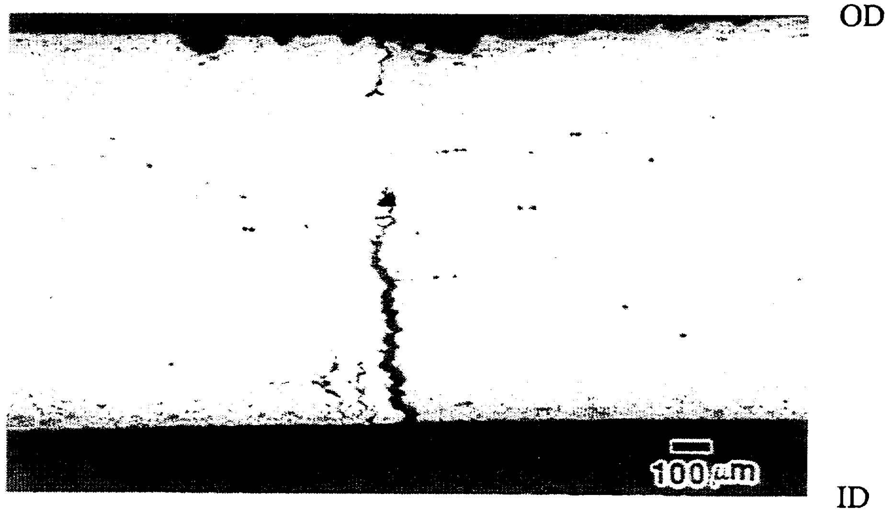
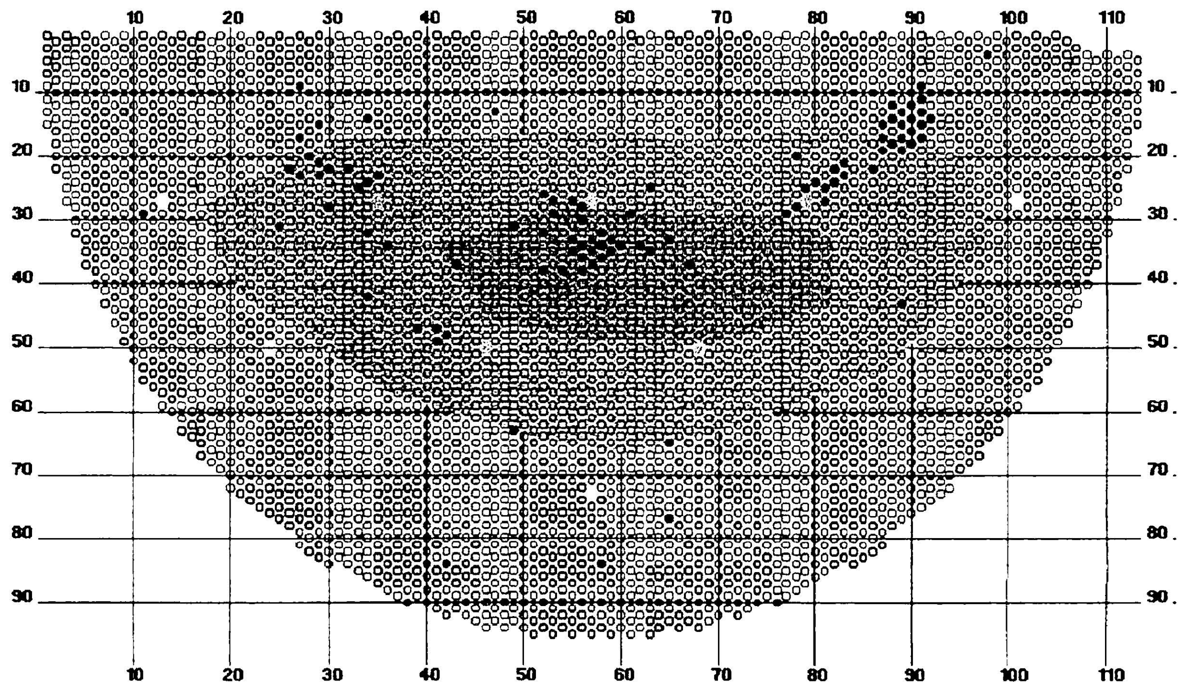


Figure 8 Features of corrosion in tube R32C78 removed from Unit 4, SG4



● Tubes with indications

○ Typical sludge pile

Figure 9 Location of all hot leg tubes containing TTS indications in Unit 1 SGs, also showing typical location of sludge pile

DISCUSSION

Authors: M.A. Clark, O. Lepik and I. Thompson, Ontario Hydro Technologies

Paper: Top of Tube Sheet Boiler Tube Cracking at BRUCE-A NGS - Recent Experience

Questioner: R.W. Staehle

Question/Comment:

(1) With respect to the BASCC observation, you might consider (a) effects of surface preparation (similar to Bergé suggestions) and (b) stress ripple (high R ratio effects).
(2) With respect to OD SCC, a major part of the "cause" is lack of definition of the effects of principle variables. In general, the regions of SCC are narrow especially in the pH and potential domains. Therefore, "surprises" often occur when the local environments impinge on these narrow zones.

Response:

We are planning to explore the effect of residual cold work on the PWSCC which may be a surface finish or "preparation" effect. We will also consider your comments in attempting to better define the local OD environments.

Questioner: R.F. Voelker, Lockheed Martin

Question/Comment:

Could you clarify what the relationship between sludge buildup at the tubesheet and tube stress levels is?

Response:

We are not certain about the details of stresses but they may be due to interaction with the first horizontal support plate and/or thermal expansion/contraction differences between the tubes and hard sludge.

Questioner: M. Wright

Question/Comment:

Listing possible sources of axial stresses, you didn't mention forces resulting from degradation of the C-steel support structure at the U-bends - have you been able to rule this out?

Response:

It was considered as a factor but the inspection results showed that ODSCC was present in tubes not passing through the U-bend supports as well as supported tubes; therefore, any effect seems unlikely.

Questioner: J. Gorman

Question/Comment:

(1) Has denting at TTS been investigated as a possible contributor?
(2) Is the microstructure typical of sensitized tubes?
(3) How will you determine the extent of problem - number of tubes affected with small cracks - if decide to restart?

Response:

(1) Denting was considered early on in the investigation. Preliminary assessment from eddy current probes indicated no denting. Metallographic examinations also showed no evidence of major denting.
(2) Yes, fairly high percentage of intergranular carbides, also GB sensitization testing indicated partial sensitization.
(3) This will be done on a probabilistic basis. The assumption will be that everything larger than 50% TW cracked has been removed. The probe detection limits are about ~50%.