ASSESSMENT OF CRACK-LIKE FLAW IN EX-SERVICE MONEL 400 STEAM GENERATOR TUBE REMOVED FROM PICKERING UNIT 4 STEAM GENERATOR 12

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Abstract. This paper documents the considerable efforts to characterize and assess an axial crack-like flaw on the outer surface of Monel 400 steam generator tube R41C52, which was removed from service from Pickering Unit 4 Steam Generator (SG) 12 in 2005. Metallurgical examination showed that this flaw had a maximum depth of 81% through-wall (tw), and was at least 65-mm long. The flaw initiated at a manufacturing defect on the outside surface. Orientation Imaging Microscopy (OIM) showed that no organized plastic strain fields are present at the crack tip. This implies an absence of plastic deformation as a driving force for crack propagation. These observations, along with others such as the blunt nature of the crack tip and intergranular attack (IGA) ahead of the advancing crack tip, suggest the crack growth rate is therefore very slow. The flaw in tube R41C52 did not pass the Condition Monitoring Assessment of the Ontario Power Generation Steam Generator Fitness-for-Service Guidelines (FFSG) when the non-mandatory FFSG axial flaw model was applied. If an alternative heterogeneous finite element model (HFEM) were used, it can be demonstrated that sufficient margin on load does exist to meet the "prohibiting leakage" acceptance criteria of the FFSG and hence result in an acceptable Condition Monitoring Assessment. The calculated plastic strain agrees well with that from OIM analysis. The initial operational assessment based on statistical analysis showed no crack depth in all of the Pickering Unit 4 steam generator tube population would exceed the maximum tolerable flaw size after a 1.24 year operating period following the 2005 outage.

1. Introduction

ASME alloy UNS N04400 (Monel 400) is a solid solution alloy that may be hardened only by cold working. It has high strength and toughness over a wide temperature range and excellent resistance to many corrosive environments. Due to the inherent resistance of Monel 400 to cracking, many laboratory test environments have been unable to initiate stress corrosion cracking under typical exposure times. Monel 400 was selected as the steam generator tubing material in the earliest CANDU® reactors, such as Pickering Units 1 to 8 of Ontario Power Generation (OPG).

In recent years, a variety of Monel 400 degradation mechanisms have been observed at ageing plants, including pitting, thinning, erosion corrosion, fretting, denting, intergranular attack and cracking

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[1], [2], [3]. To assist with steam generator life cycle management, OPG has developed *Fitness-For-Service Guidelines* (FFSG) for steam generator tubes [4], [5]. The FFSG are intended to provide standard acceptance criteria and evaluation procedures for assessing the

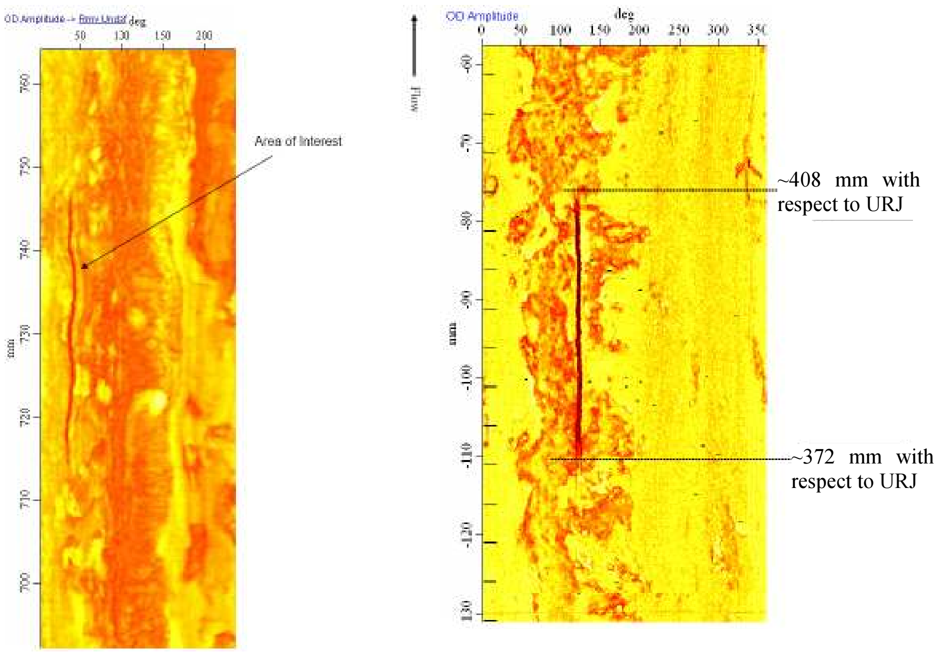
condition of steam generator tubes for structural integrity, operational leak rate, and consequential leakage during an upset or abnormal event. Based on inspection results in conjunction with representative, postulated distributions of flaws in the un-inspected tubes,

the FFSG provide an acceptable method of satisfying the intent of CSA-N285.4 [6] and justifying the continued operation of degraded steam generator tubes.

The occurrence of Outer Diameter (OD) cracking has posed considerable short-term challenges to the Pickering A steam generator life cycle management. Cracking was first observed in Monel 400 in 2004 on the OD of steam generator tube R25C52 in Pickering Unit 2 steam generator 11. A second crack was found in 2005 on the OD of steam generator tube R41C52 in Pickering Unit 4 steam generator 12. This paper summarizes the considerable effort invested over the last couple of years on the characterization and assessment of this previously unobserved degradation mechanism. Taking the tube R41C52 as an example, these efforts include:

- Field and laboratory ultrasonic inspection.
- Material characterization to investigate the chemical composition, hardness distribution and microstructure.
- Metallographic examination by a series of cross sections to show the crack morphology.
- Orientation Imaging Microscopy Analysis to characterize the texture, grain size distribution, plastic deformation, and the through-wall crack propagation resistance.
- Development of a new flaw model and application of Heterogeneous Finite Element Method for assessing the structural integrity of axial cracks in Monel 400.
- Statistical operational assessment.

FIG. 1: Ultrasonic inspection results from field and laboratory



Field UT Laboratory UT

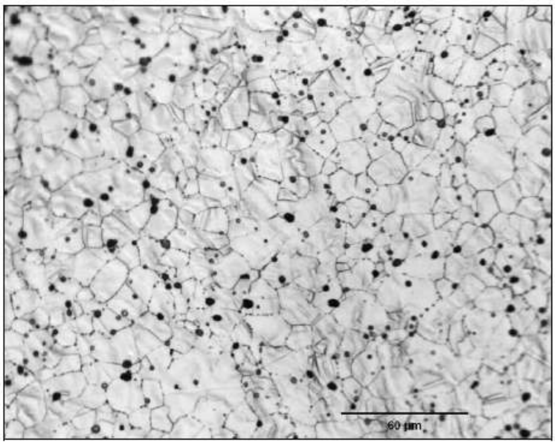
2. Field and Laboratory NDE Examinations

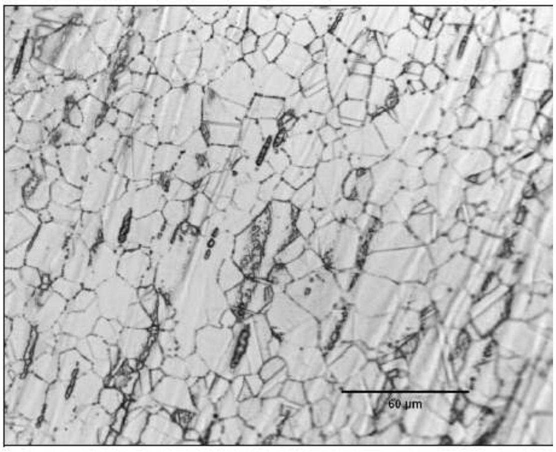
The crack like indication in tube R41C52 was detected by eddy current- using both the bobbin probe and a crack detection probe (X-probe) during the Pickering Unit 4 2005 inspection

outage. The detection threshold for X-probe for an open axial crack-like flaw is 30%tw on the free span, within the sludge pile, and on longer radius U-bends. The term "open" refers to the crack width on the tube OD surface and is consistent with the observed morphology from metallurgical examination. The established probability of detection (POD) for open axial cracks on the free span (the location of R41C52) is 90% for cracks having depths of 30%tw or deeper for both the X-probe and bobbin probe. The POD for both probes is assumed to approach 100% for open cracks with a depth greater than 70%tw.

FIG. 1 shows the field UT axial indication of tube R41C52. Laboratory UT of the removed tube confirmed the NDE results. The axial length is about 36 mm, extending from 372 mm to 408 mm above the upper roll joint (URJ).

FIG. 2: Representative microstructure of tube R41C52 shown along the transverse and axial directions

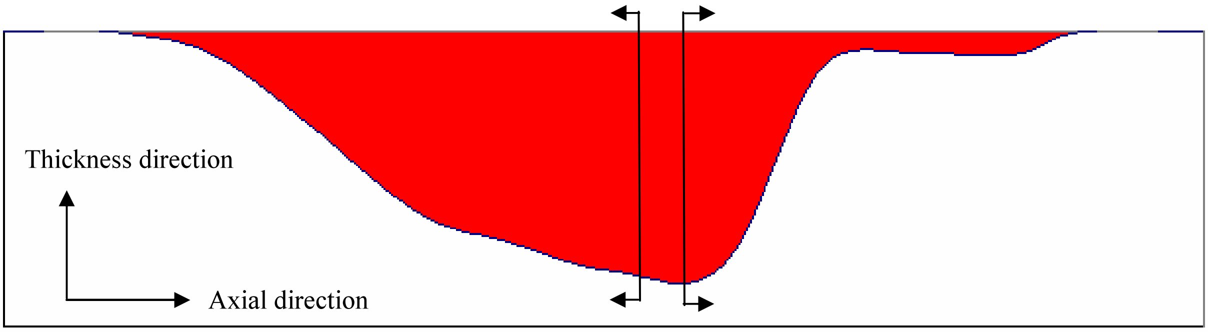




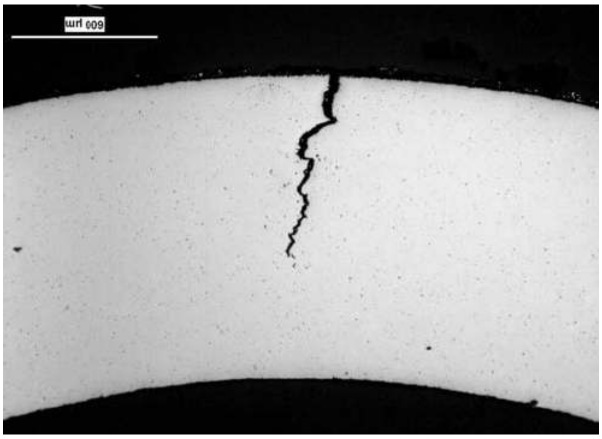
Transverse section (radial-circumferential plane)

Axial Section (axial-radial plane)

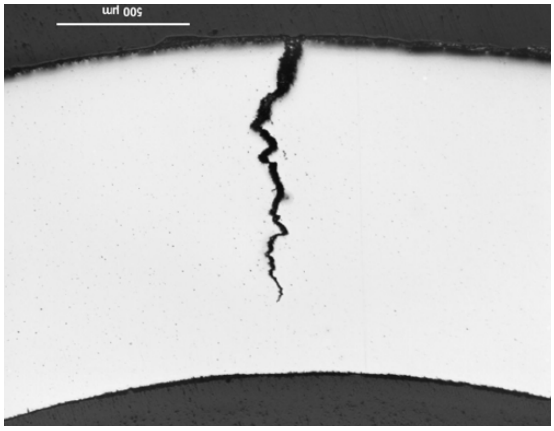
FIG. 3. Crack profile and two cross sections from Tube R41C52



Schematic illustration of crack profile



Crack depth of 71%tw

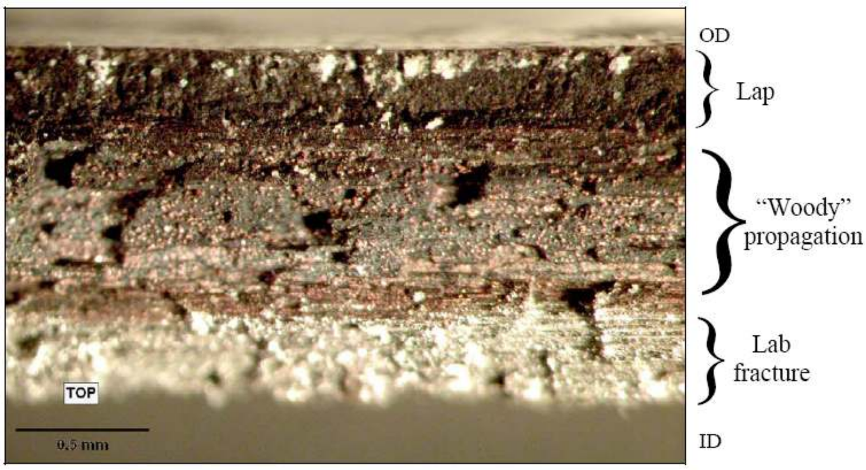


Crack depth of 81%tw

3. Material Characterization

The Pickering steam generator tubes have a nominal outside diameter of 12.7 mm, a nominal wall thickness of 1.24 mm and the lower bound wall thickness of 1.12 mm. Actual chemical analysis of tube material from tube R41C52 machined from an area between the roll joints indicates that material's composition generally conforms to the ASME specification: 61.8% Ni, 34.9% Cu, 0.11% C, <0.005% Al, 0.133% Si, <0.005 P, 0.025% S, 0.01% Ti, 0.01% Cr, 1.05% Mn, 1.83% Fe, 0.02% Mo, and 0.26% Co. The measured micro-hardness of the tube material located 424 mm above the URJ ranges from 164 HV to 170 HV (Vickers Hardness). The average yield strength and ultimate strength obtained from the Certified Materials Test Reports (CMTR) for Pickering A steam generator tubing are 238 MPa and 561 MPa, respectively. These values are greater than the ASME Class 1 specified room temperature yield strength of 198 MPa and ultimate strength of 482 MPa. The representative grain structure is shown in FIG. 2. The material contains relatively equi-axed grains and inclusions that are elongated in the drawing (axial) direction.

FIG. 4. Fracture surface at the locations 382 mm to 391 mm above the URJ



4. Metallurgical Examinations

A series of cross-sections are cut to examine the crack morphology, see the schematic illustration in FIG. 3. Metallurgical examination shows that the deepest portion of the flaw is 81%tw deep having initiated at an OD manufacturing defect (lap).

FIG. 4 shows the fracture surface between the two cross sections in FIG. 3. Analysis by Energy Dispersive Spectroscopy (EDS) indicates the presence of Al, Cu, Cl, Si, and S on the "woody" propagation part of the fracture surface. This is consistent with secondary side water contaminants. This woody fracture surface is related to the elongated inclusions, as shown in the axial-radial plane of the microstructure presented in FIG. 2.

5. Orientation Imaging Microscopy Analysis

Orientation Imaging Microscopy (OIM) was conducted to characterize the material grain size distribution, texture, residual plastic strain, and their impact on the resistance to through-wall crack propagation at the crack region and away from the crack.

OIM is based on collecting electron back scattered diffraction patterns from an array of points within a selected scan area. The intensity and spatial distribution of plastic strain is determined from the area density of intragranular, low-angle misorientations (<5°) representing cellular substructure that evolves in response to plastic deformation [7]. The color scale in

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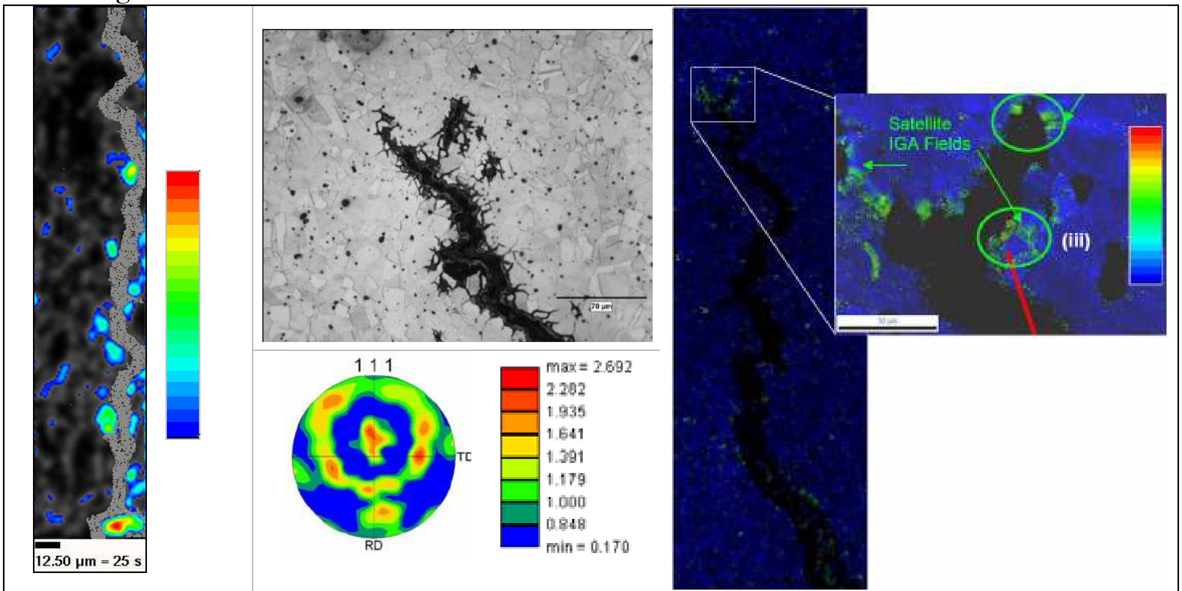
FIG. 5 indicates the relative magnitude of plastic strain ranging from low (blue) to high (red) found along the cross section of the 71%tw deep portion of the crack. No evidence exists for the presence of localized strain fields (above background levels) along the overall crack length even at locations associated with abrupt changes in crack direction. Rather, very weak but localized strain fields are confined to the "branched" crack tip and along adjacent grain boundaries associated with "satellite" Inter Granular Attack (IGA) fields as indicated in the encircled areas of the strain image. This implies that this defect did not propagate along its length under the influence of intense plastic strain or transients encountered in-service. This point is emphasized by contrast to a typical Stress Corrosion Cracking (SCC) crack produced in the lab where very intense plastic strain fields develop along the propagation length at triple junctions in response to abrupt changes in the crack direction.

FIG. 5. Micrograph, pole figures and plastic strain distributions from the OIM analysis at the tip of the crack in tube R41C52. Also shown for comparison is the typical plastic strain morphology surrounding SCC cracks.



Plastic strain	Texture and microstructure	Plastic strain
SCC crack	R41C52	

Collectively, the results imply that that there is a weak stress concentration due to the global loading, e.g. internal pressure differential in this case but it is unlikely that the defect propagated substantially in-service. The blunt crack tip, the skewed crack path and the discrete IGA sites indicate that the crack grows slowly by corrosion, rather than by a stress corrosion cracking mechanism. The weak (<2.7×random) <111> fibre texture is indicative of the tube forming process by drawing. The grain boundary analysis indicates that there are a sufficient number of grain boundaries, with a character that would allow such grain boundary cracking, that it is possible to grow a through wall crack (with a maximum possible propagation depth of 834 µm ±438 µm) in structures like this, see References [8] and [9] for detailed description of this calculation. In other words, the crack could develop into a through-wall flaw for this steam generator tubing material.

6. Fitness-for-Service Guidelines (FFSG)

Two different acceptance criteria are used in the FFSG [5] to ensure steam generator tube structural integrity is maintained during the evaluation period.

- *Acceptance Criteria Prohibiting Leakage* requires safety factors on load against through-wall penetration of the flaw for all loading events. Therefore, there will be no leakage when these acceptance criteria are satisfied. The *Maximum Tolerable Flaw Size* (MTFS) is the acceptance standard associated with this *Acceptance Criteria Prohibiting Leakage.* The MTFS defines the maximum size of the part-through-wall flaw that satisfies the acceptance criteria for flaw stability using the specified safety factors on load.
- *Acceptance Criteria Permitting Leakage* allows leakage during one or more loading events provided that specified safety factors on load against tube rupture are maintained, and that the *consequential leakage* is acceptable in terms of estimated accumulated dose versus applicable site dose limits. The *Flaw At Risk Of Leaking* (FAROL) is the acceptance standard associated with this *Acceptance Criteria Permitting Leakage.* The FAROL

defines the maximum size of the part-through-wall flaw that satisfies the acceptance criteria for flaw stability using a safety factor on load equal to 1.0.

The general practice at Pickering A and other Ontario Power Generation stations is to apply the MTFS for longer flaws to prohibit leakage. FAROL is applied for shorter flaws to permit leakage provided that margin is maintained between the estimated total accumulated dose associated with consequential leakage during accident or upset events and applicable site dose limits.

When tube degradation is detected, a series of mandatory, consecutive periodic assessments of the steam generator tubes are required as follows:

- Evaluation of detected flaws and localized tube deformation. The FFSG provides procedures for determining the criterion that is used to assess whether a tube must be repaired, such as plugging.
- Condition Monitoring Assessment (CMA). This is a current and backward-looking assessment of the entire population of tubes. The CMA evaluates whether the acceptance criteria had been satisfied during the previous evaluation period.
- Operational Assessment (OA). This is a forward-looking assessment of the entire population of tubes. The OA considers the projected future condition of the tubes based on the inspection results and the predicted flaw growth rates to the end of the evaluation period.
- Assessment of Condition Causing Leakage (ACCL). If a reactor unit had primary to secondary side leakage in a shutdown state, and the source of leakage has been located, an ACCL is performed.

The FFSG provide conservative non-mandatory flaw models that can be used to establish the MTFS and FAROL values for axial or circumferential flaws. The technical basis of these flaw models has been documented in Reference [10]. Reference [10] used the results of OPG's Steam Generator Tube Testing Project (SGTTP) to validate that these flaw models are conservative for different tube sizes, different tube materials, and a wide range of flaw morphologies.

7. Condition Monitoring Assessment

Other than the single crack detected on tube R41C52 in SG 12, no other cracks were detected in the approximately 14,400 tubes inspected by the eddy current in the Pickering Unit 4 steam generators during the 2005 outage. Since 100% of all tubes were not eddy current inspected, consistent with the requirements of the FFSG [5], a statistical approach was used to demonstrate that there was an acceptably low probability that undetected cracks were present in the Pickering Unit 4 SGs in 2005 with a depth exceeding an assumed MTFS of 71%tw (this value has been updated in 2007).

Therefore, since the OD axial crack on tube R41C52 did not penetrate through wall and no leakage was detected in-service, only the structural integrity of the removed tube R41C52 needs to be assessed to complete the condition monitoring assessment. In the following, three different structural assessments are considered: the non-mandatory FFSG axial flaw model, a new defect specific axial flaw model developed based on burst-pressure tests, and the heterogeneous finite element method.

Two pressure differentials are used to establish acceptance standards.

8.7 MPa — is the bounding pressure differential for Service Level A&B (normal operating and upset) loading conditions. This pressure differential occurs for only a short time during startup and shutdown when the primary side is pressurized and the secondary side is cold.

9.5 MPa — is the bounding pressure differential for Service Level C&D (accident and faulted) loading conditions. This pressure differential occurs during a main steam line break transient.

For establishing the MTFS acceptance criteria, the minimum failure pressure is defined as the maximum pressure differential for each service level times the specified safety factor specified in the FFSG. For Pickering steam generator tubes, the most limiting case is for Service Level A loading condition; for which a safety factor of 3.0 is specified. This leads to the minimum failure pressure of 26.1 MPa (8.7 MPa×3.0) for establishing MTFS values.

For establishing FAROL, the minimum failure pressure is defined as the maximum pressure differential for loading conditions, as the safety factor equal to unity (1). This results in a minimum failure pressure of 9.5 MPa for establishing FAROL values.

For an axial crack in the steam generator within the free span such as the crack in R41C52, it is the hoop stress due to internal pressure that controls the cracking behavior. Bending moment can be excluded from the structural assessments.

7.1.Non-Mandatory FFSG Axial Flaw Model

For an outer-surface axial flaw, the lower-bound predicted failure pressure (P_{FFSG}) is defined in terms of the dimensions of the flaw and the mechanical properties of the tube in Appendix C of FFSG [11]:

$$P_{FFSG} = \left[-0.743 + 1.825\sqrt{1 - \frac{a}{t}} + 4.322 \left(\frac{a}{t}\right)\left(\frac{a}{2L_{eff}}\right) \right] \times P_f$$

where a is the flaw depth, t is the wall thickness, $2L_{eff}$ is the effective length of the flaw, and P_f is the failure pressure of a flaw free tube. The P_f is defined as $(S_y+S_u)\times R/t$, where S_y and S_u is are the ASME Code specified yield strength and tensile strength for Monel 400, and R is the mean tube radius.

Using this flaw model, the predicted failure pressure is 7.4 MPa (using an effective length of 36 mm and flaw depth 81% tw), which is significantly less than the minimum failure pressure of 26.1 MPa used to establish the MTFS. Therefore with this flaw model using this flaw model, the flaw in tube R41C52 does not pass the Condition Monitoring Assessment of the FFSG.

7.2.SGTTP Axial Flaw Model

In order to reduce the conservatisms of the non-mandatory FFSG axial flaw model [3], a reasonable number of experiments (greater than 25 burst-pressure tests) have been performed under the SGTTP since the finding of the OD cracking in R41C52. These test specimens contained axial slots that were machined into the Monel 400 tube using Electrical Discharging Machining (EDM). The width of these EDM slots (100 µm for OD axial slot and 150µm for axial ID slot) is comparable with the observed width of the open axial crack on tube R41C52 based on metallurgical examinations. The following expression is a 90% lower-bound failure pressure flaw model regressed from the test results.

$$P_{SGTTP} = \left[-0.333 + 1.30\sqrt{1 - a/t}\right] \times \frac{2t}{D} \times \sigma_f$$

where D is the mean diameter, and σ_f is the flow strength of the tube material. At 288°C, the flow strength σ_f is 457 MPa for Monel 400, which is derived from the burst pressure of defect-free tubes.

This new SGTTP axial flaw model is only applicable for crack lengths greater than 25 mm, which was determined based on the flaw lengths currently included in the SGTTP axial slot database. Extrapolation of the model to flaw lengths less than 25 mm might result in overly conservative predictions.

The predicted the failure pressure by the use of this SGTTP axial flaw model is 20.7 MPa for a 36 mm long crack with depth 81% tw. The margins on the failure load are insufficient to meet the “prohibiting leakage” acceptance criteria of the FFSG. Therefore, using this model the flaw in tube R41C52 would also not pass the Condition Monitoring Assessment of the FFSG.

7.3.Heterogeneous Finite Element Method

Alternatively, a heterogeneous finite element model (HFEM) and a failure model was used to predict the failure pressure for the flaw in tube R41C52. The HFEM considers the inherent variation in mechanical properties due to the spatially heterogeneous microstructure, as reflected in the micro-hardness measurements. The FE model (mesh size, element type and time step) and the failure model have been extensively calibrated and validated with respect to a database of burst pressure test results from Monel 400 tubes with a variety of defects as documented in Reference [3].

FIG. 6. Finite element model and the predicted plastic strain distribution at the internal pressure of 8.7 MPa

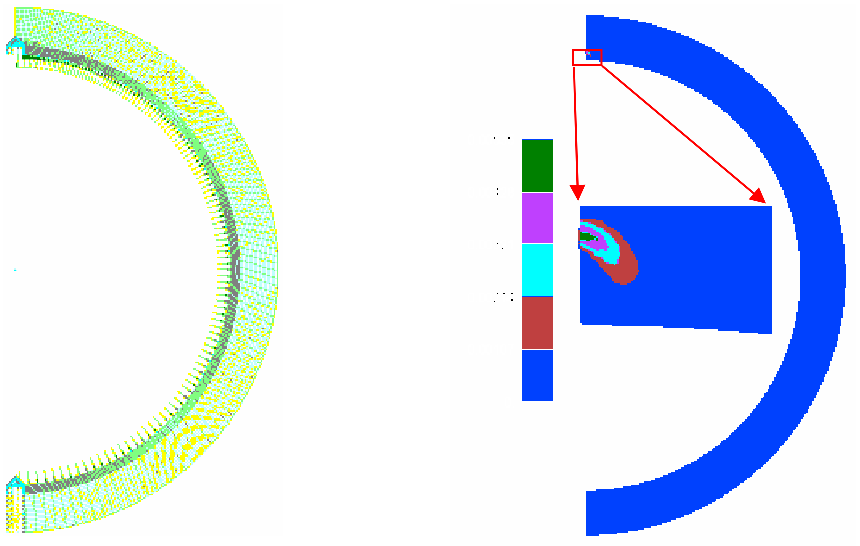


FIG. 6 shows the 2-D plane strain model (infinite crack length), boundary conditions (symmetrical displacement constraints and internal pressure loading), and the calculated distribution of effective plastic strain. The calculated plastic strain at the crack tip for the maximum normal operating pressure differential (8.7 MPa) is limited at the crack tip and the maximum value is 0.005, as shown in the figure. This agrees well with the measured plastic strain distribution from the OIM. It is to be noted that the plastic strain from the OIM analysis is performed at the cross section with 71%tw crack depth. The present plane strain assumption and the 81%tw crack depth in the finite element models indicate that the results from HFEM are very conservative. The actual plastic strain should be less than the 0.0054 calculated by HFEM.

Using the methodology (plastic collapse load) documented in Reference [3], the predicted failure pressure for this flaw is 27.0 MPa, resulting in sufficient margin on load to meet the "prohibiting leakage" acceptance criteria of the FFSG. Therefore the tube R41C52 passes the Condition Monitoring Assessment of the FFSG if this alternative HFEM simulation is used.

8. Operational Assessment

For operational assessment, the determination of crack growth rate is critical. There is little information available on crack initiation and growth rate of Monel 400 in literature. Since only one crack was detected in the Pickering Unit 4 SGs an empirical crack growth distribution cannot be estimated. For the initial operational assessment in 2005, a crack growth rate for Outer Diameter Stress Corrosion Cracking (ODSCC) from a much more susceptible Inconel 600 mill annealed tubing was used to bound a worst case for Monel 400. After reviewing some crack growth rate data for Inconel 600 available in the open literature, such as Reference [12], an upper-bound mean crack growth rate of 4.45%tw/year was determined to be appropriate.

A statistical approach was used to determine the crack depth distribution in all tubes in the Pickering Unit 4 steam generators at the end of next evaluation period, which corresponded to

a1.24 years operating interval. The distribution of crack growth was assumed to follow a gamma distribution, and the current crack depth to follow an exponential distribution. The parameter of the exponential distribution was estimated assuming that the maximum undetected crack depth in the remaining inspected tubes was 30%tw. This value represents the limit where the POD for X-probe is estimated as 90%. After completing the statistical calculations, it was estimated that:

- Potential undetected cracks would not grow to exceed 70%tw (MTFS prior to 2007) over the planned evaluation period of 1.24 years.
- The 95% upper bound on maximum crack depth predicted in the Pickering Unit 4 after 1.24 years of operation was 65.5%tw for the 4.45%tw/year growth rate.

Therefore, the Acceptance Criteria Prohibiting Leakage of the FFSG were met for the evaluation period.

It is to be noted that, at the time of writing this paper, the planned 1.24 operating period has passed. The inspection of all 12 SGs in Pickering Unit 4 after the 1.24 years of operation found no cracks. These latest observations are consistent with the 2005 operational assessment and the metallurgical and OIM examinations, which indicated that the R41C52 crack was associated with an original manufacturing defect (lap) and if there is any in-service corrosion propagation it may be rather slow. The most recent operational assessment of OD axial cracking in the Pickering Unit 4 SGs justified a reduction in the mean crack growth rate to 2.2% tw/yr. This lower crack growth rate in combination with the updated MTFS obtained from the SGTTP axial slot model have supported the next evaluation period of more than two additional years of operation.

9. Conclusions

The OD crack in the steam generator tube R41C52 from Pickering Unit 4 originated from a manufacturing defect. The blunt crack tip and the lack of an organized plastic strain field even at 81%tw indicated that crack had propagated slowly by corrosion. The operating experience to date has supported the Condition Monitoring Assessment and the Operational Assessment documented in this work.

10. Acknowledgement

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