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Characterization and structural integrity tests of ex-service steam generator tubes at Ontario Power Generation

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ABSTRACT

The Canadian Nuclear Standard CSA N285.4 requires the periodic metallurgical examination of removed ex-service steam generator tubes. This paper describes the practices used for the characterization and structural integrity tests of ex-service steam generator tubes at Ontario Power Generation (OPG). It shows that there is no degradation of mechanical properties of Monel 400 tubes after 7–18 effective full power years (EFPY) of operation and Incoloy 800 tubes after more than 10 EFPY of operation.

1. Introduction

To ensure the safe operation of ageing reactors, a variety of plant and component life management plans have been proposed and implemented in the CANDU®[1] industry. A key requirement in any life cycle management plan is the material surveillance program of in-service components to: assess whether materials degrade from known or unknown mechanisms; to estimate the remaining life; and to determine appropriate mitigation, when required. This paper describes recent developments in the steam generator tube material surveillance program at Ontario Power Generation (OPG).

OPG has 10 operating CANDU units. The oldest unit began commercial operation in 1971. For the Pickering Units, which began operation before 1990, the steam generator tubes were fabricated using Monel 400 (M400) 1/2-in. tubing. For the Darlington units, which began operation after 1990, the steam generator tubes were fabricated using Incoloy 800 (I800) 5/8-in. tubing. Compared with the M400 tubing, which has experienced several degradation mechanisms (see Fig. 1 for illustration), minimal material degradation has been experienced in the I800 tubing at Darlington. The main degradation experienced in the Darlington steam generators is: tube fretting at the U-bend supports, tube debris fretting, and some minor tube pitting. Table 1 compares the nominal properties of these two tubing materials.

OPG periodically removes surveillance tubes from their steam generators for metallurgical examinations. These are done to: meet the requirements of the Canadian Nuclear Standard CSA N285.4-94 (CSA, 1994); to characterize observed degradation, and to validate non-destructive examination (NDE) inspection techniques, and in some cases to support fitness-for-service assessment. As of 2007 December, a total of 142 steam generator tubes have been removed from OPG plants:

61	M400 tubes from Pickering Units 1 and 4;
64	M400 tubes from Pickering Units 5, 6, 7 and 8; and
17	I800 tubes from Darlington Units 1, 2, 3 and 4.

OPG has not performed all the testing or characterization described in this paper on every one of the 142 removed tubes. The criteria for metallurgical examinations and structural integrity testing depend on the nature and severity of the degradation, the number of flaws on the tube, and whether the degradation has been previously observed. Characterization and structural integrity (burst pressure) tests of two defect free ex-service I800 tube sections removed from the Darlington steam generators, and two defect-free M400 tubes from Pickering steam generators have recently been completed. The bubble test (or leak test), proof test (applying specified internal pressure), and metallurgical examination of one ex-service M400 tube with an axial flaw have also been completed.

This paper summarizes the practices and results for the characterization and structural integrity tests of ex-service steam generator tubes at OPG.

2. Characterization of as-received tubes

Three methods of characterization are generally performed to collect essential information to support the decision making process used for metallurgical examination and the structural integrity

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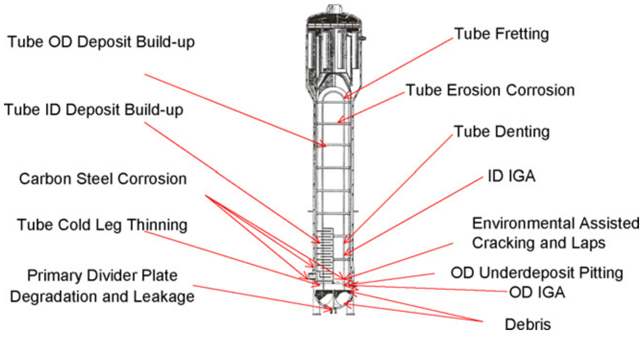

Fig. 1. Degradation mechanisms observed in Pickering A and B steam generators.

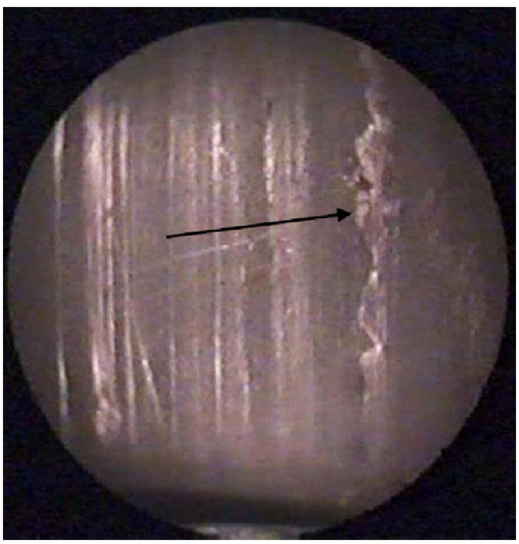

Fig. 2. Optical image captured from boroscope inspection of an inside diameter lap-like flaw.

testing. These characterizations include the following:

- Laboratory ultrasonic testing (UT) to confirm the field non-destructive examination (NDE) measurements. The normal practice at OPG is to use a range of NDE techniques in situ prior to removing tubes; these include bobbin probe, X-probe eddy current, and UT. Comparison of the in situ and post removal NDE signals is used to ensure that the tube was not inadvertently damaged during the removal process.
- Measurements of the outside diameter and wall thickness. A minimum of four measurements is usually conducted in one cross-section. The purpose is to compare the measurements against the nominal tube dimensions.
- Visual surface examination using low-power magnification for the tube outer surface to confirm the absence or presence of flaws. Boroscope inspection has been used to confirm the absence or presence of flaws on the inside surface of the tube. Fig. 2 shows a picture from the boroscope examination of a tube with an inner lap defect, which is attributed to the tube drawing process. Boroscope examination is not routinely used for examination of removed tubes.

3. Material characterization

When warranted, the following additional material characterization is performed on surveillance tubes:

- Orientation imaging microscopy (OIM) measurements. OIM is a valid tool to determine the residual plastic strains in the vicinity of flaws. OIM is also used as a means for characterizing the structure of grain boundaries used to establish the limits on crack propagation and the likelihood of through-wall propagation. This information is used to support models used to predict the growth of flaws in service. The measured strain information can also be used to validate finite element analysis. Fig. 3 shows the OIM measurements of the plastic strain distribution at the tip of a 71%tw (through-wall) flaw in a removed M400 tube (Lehockey et al., 2007). In this example, 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 is evidence that the flaw did not propagate along its depth under the influence of intense plastic strain from manufacturing and transients encountered in service.
- Micro hardness measurements. Through-thickness Vickers hardness measurements are used to characterize the variations of local mechanical properties in both the axial and the transverse directions. This information has been used together with the heterogeneous finite element method to quantify the structural margins on load and flaw size (Pagan et al., 2007). For the two I800 defect free tubes subjected to structural testing, the measured Vickers hardness (200 g) varies from 168 to 185. It is also found that a slightly higher hardness exists near the surface. The hardness measurement of M400 ex-service tubes subject to structural testing has not been performed.
- Chemical analysis. Chemical analysis using scanning electron microscopy (SEM) equipped with an energy dispersive spectrometer (EDS) is performed to obtain semi-quantitative elemental composition of the surface deposits. In certain cases, more detailed surface analysis may also be performed using secondary ion mass spectrometry (SIMS). This information is used in the root cause analysis of the flaw initiation and propagation. Wet chemical analysis is also performed to confirm that all examined ex-service tubing conforms to the ASME specification for seamless nickel and nickel alloy condenser and heat-exchanger tubes (SB-163).
- Metallurgical examination. Metallurgical examination establishes the mode of failure and the microstructure, e.g., grain size, as well as the distribution of second phase particles. For I800

Table 1
Nominal tube properties.

	M400	I800
Outside diameter	12.60 mm	15.88 mm
Wall thickness	1.24 mm	1.12 mm
Code specified yield strength at 288 °C	152 MPa	171 MPa
Code specified tensile strength at 288 °C	483 MPa	514 MPa
Tube degradation observed in OPG steam generators	Pitting, intergranular attack, environmental assisted cracking, erosion corrosion, thinning, fretting	Fretting, pitting
Number of tubes removed as of 2007 December	61 from for Pickering Units 1 and 4; 64 from Pickering Units 5–8	17 from Darlington Units 1–4