TECHNICAL LETTER REPORT

Evaluation of Possible Examinations for Pulled Steam Generator Tubes

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Introduction

The US Nuclear Regulatory Commission (NRC) is interested in the causes of steam generator (SG) tube degradation, including wear and cracking. One of the best ways to gain information about degraded SG tubes is to examine tubes that have been removed from operating generators, i.e. a “pulled tube.” However, pulling a tube from an operating or retired SG has high financial costs and can result in high radiation dose to personnel; therefore, pulling a tube is a rare event. To better capitalize on these rare events, the NRC researched the types of information that can be gained from the various methods used to examine pulled tubes. An initial literature review found some studies that reviewed the tests which are performed on pulled tubes. This report, in addition to reviewing tube examination methods and their benefits, discusses two guidelines on SG pulled tube examination: the Canadian Nuclear Safety Commission (CNSC) Guidelines [1] and the Electric Power Research Institute (EPRI) Guidelines [2]. Actual SG pulled tube examination results are also available in the appendix of the EPRI Guidelines [2] and other open literature [3-7].

Most currently operating SGs contain tubes made from more corrosion resistant materials, such as Alloy 690 or Alloy 800. Therefore, the incidence of cracking in current SGs is low. In fact, as of the time of publication, there have been no reported stress corrosion cracks in Alloy 690 tubes anywhere in the United States. Consequently, the majority of flaws in newer SGs are wear flaws. However, this report on examination techniques is focused on flaws that initiate as a result of stress corrosion cracking or fatigue cracking, since the root causes of wear defects would most likely be found from design review, analyses, or visual inspection rather than destructive examination of pulled tubes.

CNSC Guidelines

The CNSC Guidelines for the examination of pulled SG tubes [1] are discussed below.

Table 1 shows the elements of a SG tube material surveillance examination suggested by CNSC. The primary elements are mandatory although some elements, such as the identification of root causes, are only required when degradation is present. The secondary elements are considered, based on the results from the primary elements.

Table 1. Elements of a steam generator tube material surveillance examination [1].

	Element Description	Comments
Primary Elements	Manner of tube removal	Required for all exams
	Suitability of locations examined and examination methods used	Required for all exams
	Identification of significant flaws and conditions	Required when degradation is present
	Identification of root causes	Required when degradation is present
	Estimation of rates of growth of flaws	Required when degradation is present
	Flaw size determination	Required when degradation is present
	Deposit characterization	Required when

		degradation is present

Secondary Elements	Use of plastic straining	None
	Use of additional methods to check for aggressive species	None
	Gathering and analysis of deposits	None

EPRI Guidelines

Also considered were the EPRI guidelines for tube removal and examination [2]. The EPRI test and examination methods are categorized into three main areas: Nondestructive Evaluations (NDE), Pressure Tests, and Metallurgical and Local Chemical Examination. Five main reasons for tube removal are identified: Condition Monitoring and Operational Assessment, NDE Verification, Support of Alternate Repair Criteria (ARC), Chemistry Evaluation, and General Condition Assessment. Table 2 shows the recommended tests and examinations for SG pulled tubes for each tube removal reason. Some evaluations, such as visual inspection, bobbin and rotating probe eddy current tests, and base material characterization (by destructive methods or other NDE methods), are recommended for all pulled tube sections. Base material characterization procedures include tensile testing, microstructural examination by optical or electron microscopy, hardness tests, chemical assay, and sensitization tests. NDE includes use of all techniques used in SG tube evaluation: Eddy current (EC), ultrasonic testing (UT), tomography, and radiography. Pressure testing may also be performed for information on leak rates and critical crack opening displacement.

Table 2. Recommended tests and examinations for SG pulled tubes per each tube removal reason [2].

Reason for Exam	Exam Methods	Description
All Tube Sections	Nondestructive Evaluations	• Performed prior to any cleaning or decontamination • Unmagnified & magnified visual inspection • Dimensional measurements • Bobbin coil EC testing and rotating probe EC testing
	Base Material Characterization	• Tensile test using materials from undeformed area with no detected flaws • Microhardness of base materials across wall thickness • Chemical composition & Microstructure of base material • Sensitization test
Condition Monitoring and Operational Assessment	Nondestructive Evaluations	• NDE using all techniques used in situ • Radiography of flaw area • Helium leak test if there is a question about the possible presence of a small throughwall flaw
	Pressure Tests	• Leak and burst tests of areas with significant flaws • Burst tests of areas with no detected flaws and no significant deformation
	Metallurgical and Local Chemical Examination	• Determine the extent of the major flaws • Determine the morphology of major flaws

NDE Verification	Nondestructive Evaluations	• NDE using all techniques used in SG • Radiography of areas with significant NDE indications • Additional NDE techniques for which verification data are desired • Helium leak test if there is a question about the possible presence of a small throughwall flaw
	Pressure Tests	• Leak and burst tests of areas with significant flaws • Burst tests of areas with no detected flaws to establish a baseline
	Metallurgical and Local Chemical Examination	• Consider a method for opening up the flaws and assisting in their detection (swelling, bending, etc.) • Stereovisual and Scanning Electron Microscopy (SEM) examination of burst test ruptures and other areas (flaws size, morphology, etc.) • Sectioning followed by optical metallography and/or SEM examination
Support of ARC	Nondestructive Evaluations	• NDE using ARC technique
	Pressure Tests	• Leak test if the maximum flaw depth by NDE is >80%TW, followed by visual examination to record flaw size opening, if leakage occurs • Burst test of flaw area • Burst tests of areas with no detectable flaws (not mandatory) • Tensile tests (alternate to burst test for a circumferential flaw)
	Metallurgical and Local Chemical Examination	• Stereovisual and SEM examination of ARC area (flaw size, morphology, etc.) • A full SEM montage of the burst crack face at about 40X and a crack profile. • Sectioning followed by optical metallography and/or SEM examination
Chemistry Evaluation	Metallurgical and Local Chemical Examination	• Swelling, axial extension, flattening, and/or bending of flaw areas and examination using SEM, optical metallography, and local surface chemical analysis techniques • Stereovisual and SEM examination of ARC area (flaw size, morphology, etc.) • Sectioning followed by optical metallography and/or SEM examination • Chemical analysis of deposits at freespan and crevice areas that are still attached • Chemical analysis of deposits from freespan and crevice areas that were removed • Tube surface chemical analysis after the removal of the deposits • Fracture surface chemical analysis • Possibly, chemical analysis of leachates from tube surfaces

General Condition Assessment	Nondestructive Evaluations	• Examination using as sensitive NDE techniques as available
	Plastic Straining to Open Up Flaws	• Tensile tests • Bending • Pressure testing • Mechanically roll expanding the ID (suitable for OD axial or volumetric flaws)
	Metallurgical and Local Chemical Examination	• Swelling, axial extension, flattening, and/or bending of the most susceptible areas and examination using SEM, optical metallography • Longitudinal sectioning followed by stereovisual examination of ID surfaces • Stereovisual and SEM examination of any visual flaws (morphology, fracture type, etc.) • Sectioning followed by optical metallography and/or SEM examination to define morphology of IGA • Sectioning followed by optical metallography and/or SEM examination of potentially susceptible areas • Chemical analysis of deposits at freespan and crevice areas that are still attached • Chemical analysis of deposits from freespan and crevice areas that were removed • Tube surface chemical analysis after the removal of the deposits • Fracture surface chemical analysis • Possibly, chemical analysis of leachates from tube surfaces

Discussion of Examination Purposes

Non-destructive and destructive examinations serve many purposes, including: 1) identification of flaws, 2) sizing of flaws, 3) base material characterization, 4) characterization of deposits, 5) tube integrity characterization, and 6) root cause identification.

The six examination purposes listed above are discussed below.

1) Flaw Identification: Destructive or NDE methods may be applied to a pulled tube to identify flaw types and characteristics. Also, testing may be used to verify results of eddy current inservice inspections (ISI).

   Some appropriate examination procedures for flaw identification are optical microscopy (metallography) for large size (i.e. visible) flaws, scanning electron microscopy to view fracture surfaces or to view cross sections of crack-like flaws in polished and etched samples, and EC, UT, radiography, and tomography to employ as an NDE technique for flaw location or depth below the material surface.

2) Flaw sizing: All of the techniques mentioned above for flaw identification also apply to flaw sizing. Again, physical examination may give true flaw size information, which may be used to verify the ISI eddy current scan measurements. Also, a comparison of the pulled tube eddy current data to ISI data on the same tube may be valuable for noise and masking effects from tube supports or the tubesheet.

3) Base material characterization: The properties of the base material may be examined for signs of change. Any significant changes in base material properties could be indications of issues with the material itself, or the effects of operating conditions or local environment.

   Metallography, electron microscopy, and the other macro- and microstructural examination techniques listed in Table 2 may be employed. Structural integrity changes may be assessed with tensile, fatigue, leak, or burst testing.

4) Characterization of foreign deposits: Many chemical analysis methods exist to characterize deposits on pulled tubes. Atomic absorption spectrophotometry, x-ray or UV fluorescence would be ideal for a quick identification of elemental composition. For more detailed information on the possible compounds, electron microscopy, energy dispersive and wavelength dispersive x-ray analysis, transmission electron microscopy, auger analysis, and atomic force methods may be used.

5) Tube integrity characterization: Pressure or leak rate tests may be performed on pulled tubes, or sections thereof, to assess the integrity of the tube. Also, mechanical tests, such as tensile or fracture toughness, may be performed for evaluating mechanical properties.

6) Root cause analysis: Root causes of cracking includes vibrations, foreign matter, operator error, or other possible causes. Use of any or all of the above mentioned procedures could yield information about the type of defect, local chemistry, or any deposits. Use of that information, combined with the operating history, conditions, and human factors could yield a root cause determination.

In addition to the above methods, other methods to consider in evaluating pulled tubes are discussed below.

NDE is often used to gain interior and exterior surface information, without altering, damaging or destroying the material of a specimen. For a pulled tube specimen, some additional NDE techniques are discussed here:

Radiography is sometimes used to examine cracks in SG tube sections. Radiographs can show interior defects and structures. Synchrotron X-ray micro Computed Tomography (μCT) can provide a better spatial resolution with 3-dimensinal (3-D) crack imaging than conventional radiography. Intergranular stress corrosion cracking has been observed by in situ Synchrotron X-ray μCT [8]. This method permits seeing a 3-D crack morphology without sectioning the pulled tube. It is noted, however, that there will be a limit to the volume of interest that can be analyzed at any one time. Synchrotron X-radiation may be used not only to obtain tomographic information of cracks but also to obtain a better spatial resolution than conventional phase analysis using in-house X-ray sources or residual stress measurement by X-ray diffraction.

Stress corrosion cracking has been a cause of defects in SG tubes. The chemistry of the water environment on the secondary side (and primary side) is an important factor in cracking control. Some contaminants, i.e. lead, may contribute to SG tube cracking. Therefore, a chemical analysis may be very beneficial. 3-D Atom Probe Tomography (3-D APT) is another advanced technique to characterize the local chemistry. When the local chemistry (e.g., along

grain boundary or at the crack tip) needs to be evaluated, 3-D APT can provide information on the elemental distribution with atomic resolution [9].

Atomic Force Microscopy (AFM) is one of the emerging analysis tools in materials science and engineering field. Sectioned tube samples examined using AFM can provide various microstructural information on a nano-meter scale. Although AFM provides topological information, it is not limited to just topology. AFM can be run in various modes: conducting, work function, magnetic, nano-indentation, or tapping (elastic modulus mapping). One of advantages of AFM is that analysis is performed in an ambient condition so that a vacuum system is not required.

Cracking may occur along grain boundaries if the material has had diffusion of components (chromium depletion, for example) away from boundaries, or deposits of foreign elements (e.g. lead) at grain boundaries. Orientation Image Microscopy (OIM) is often used to analyze grain orientation and grain boundary mismatching. More recently, OIM has been used as a tool to obtain residual strain distribution in grains. The strain mapping near the crack tip can be performed using OIM [7].

Summary

A main objective of this report was to evaluate the information gained by various methods which are used to examine pulled SG tubes. The intent was to understand how to examine pulled tubes to enhance understanding of root causes of defects and to ensure tube integrity.

Many examination techniques for pulled SG tubes were reviewed, along with the types of information gained from each examination technique. The CNSC and EPRI guidelines for pulled tube examinations were discussed to provide insights and procedures used in industry. Combinations of many existing analytical apparatus and techniques may be used to explore physical characteristics, defect parameters, tube integrity, and possibly contribute to determination of the root causes of defects.

References

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