Ultrasonic Inspection of Steam Generators at CANDU Power Plants

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Abstract

TRUSTIE™ has proven to be a valuable tool for inspecting the unique design configuration of CANDU steam generator (SG) tubes. Ultrasonic inspections with TRUSTIE™ offer capabilities that can accurately assess the severity of flaws in SG tubes and monitor their growth. TRUSTIE™ consistently provides exceptional results in detection and sizing of flaws such as pits, frets and cracks. The applications of TRUSTIE™ system effectively supplement Eddy Current techniques for detailed flaw characterization and verify Eddy Current inspection results. Its high resolution capability and sizing accuracy reduce the need for tube plugging, by permitting lower plugging criteria for flawed tubes than that provided by Eddy Current results. The accurate ultrasonic characterization of flaws supports life management programs for SGs. Recent developments in TRUSTIE™ ultrasonic inspection technology continue to produce advanced tooling for SG tube inspection. These developments enhance probe and system performance, and minimize the cost for in-service SG inspections.

This paper will provide an update of our expanded technical experience, including the development of ultrasonic probes and advanced data analysis techniques, field applications and the benefits of ultrasonic testing in SG tube inspections.

*TRUSTIE™: Tiny Rotating UltraSonic Tube Inspection Equipment

1. Introduction

TRUSTIE™ is a high-resolution ultrasonic imaging system that offers the capability to accurately assess the severity of degradation and monitor its growth in SG tubes. The system has been successfully applied for in-service and periodic inspections of SG tubes for flaws such as pits, frets, dents, stress corrosion cracks, and tube deformation. TRUSTIE™ has proven to be a valuable tool in providing critical information for SG life cycle management and fitness-for-service assessments. Accurate information on SG degradation can reduce unnecessary tube pulling and plugging. Although Eddy Current examination is the industry standard for inspecting steam generator tubing, ultrasonic techniques play an important role as a verification method for Eddy Currents and, also provides more accurate sizing and flaw discrimination. The superior sensitivity of TRUSTIE™ provides the capability to detect and size flaws that are below the Eddy Current detection threshold. Inspection techniques with TRUSTIE™ are capable of providing detailed characterization of defects, such as depth, location and overall morphology etc. Detailed flaw information often leads to a better understanding of the degradation mechanisms.

Ontario Power Generation and Kinectrics have been working together for many years to implement TRUSTIE™ technology, and develop advanced ultrasonic techniques for SG tube
inspections. This paper provides an overview of ultrasonic inspections using the TRUSTIE™ system for SG tubes in CANDU nuclear power plants.

2. System Overview

TRUSTIE™ is an ultrasonic imaging system for SG tube inspection applications, which was originally designed to perform ultrasonic testing on sleeved steam generator tubes for unique CANDU configurations.

A TRUSTIE™ system consists of a rotating flexible driveshaft with a detachable ultrasonic probe. It utilizes a manipulating arm such as the Zetec SM-23 to position and deliver the probe. The motion control of the mechanical (axial and rotary drive) system and the acquisition of the ultrasonic data are performed remotely using Winspect (UTEX Inc.), a 32-bit Windows-based data acquisition and motion control software. Figure 1 shows a standard TRUSTIE™ system. Figure 2 illustrates the field operation set-up.

TRUSTIE™ inspection involves both axial (along the tube axis) and rotary (around the tube circumference) motions. The axial drive provides the push and pull motions of the driveshaft to position a probe in the axial direction. The rotary drive provides rotary control of the ultrasonic probe during scanning. The driveshaft provides electrical connections so the ultrasonic signal from the rotating probe can be received by the host receiver at the data acquisition control console. The TRUSTIE™ system provides high-precision scanning capabilities including continuous full 360° helical rotations. In a typical file operation, water is pumped into a tube to build up a water column serving as the ultrasonic couplant between the probe and the tube. The operator, at the control console remotely controls all the functions of the system to perform the data acquisition and the ultrasonic inspection.

Typical characteristics of the TRUSTIE™ system are:

- Inspection of tubes with Inside Diameter (ID) from 0.31” to 0.54”
- Tube lengths up to 50’
- Normal beam and shear wave probes (frequencies ~15 MHz)
• U-bend inspections on 16” radius for 0.5” Outside Diameter (OD) tubes
• A typical probe rotation speed of 600 rpm
• Automated data acquisition and remote analysis

The TRUSTIE™ inspection capability includes:
• Detection, sizing and characterization of flaws (i.e. OD pitting, micro-pits, corrosion, deformation, fretting, and circumferential/axial crack type flaws including ID Inter Granular Attack (IGA) and axial flaws)
• ID Profile characterization
• Inspection of U-bend regions
• Inspection of Preheater regions
• Growth monitoring

3. Ultrasonic Probes

Different degradation mechanisms and SG configurations have led to specific inspection requirements. A number of TRUSTIE™ probes have been developed in response to inspection requirements. The Normal Beam (NB) and Shear Wave (SW) probes are configured to generate sound waves at the tube surface with different incident angles. The straight leg and U-bend probes have different physical lengths. The U-bend probes are shorter to allow tight tube radiiuses to be navigated.

A traditional TRUSTIE™ probe utilizes a single element focused ultrasonic transducer and special mirror/mirrors to direct ultrasonic beam. Recently, probe technology has evolved from the standard single element NB and SW probes (as shown in Figure 3) to multi-element combination probes (as shown in Figure 4) for increased inspection coverage, reliability and productivity. The main function of the combination probe is to provide fast, and reliable UT techniques to characterize various oriented flaws in a single pass inspection. The multi-element probe is currently being evaluated and qualified for field use.
4. Performance Testing with Simulated Flaws

In order to evaluate the performance of the equipment and its associated inspection techniques, various experiments were carried out to demonstrate the inspection capability. Artificial flaw samples were fabricated to simulate field conditions. Several flaw types were investigated, including pits, frets, and more recently, ID and OD cracks oriented circumferentially or axially. The following paragraphs describe results obtained on frets and pits.

Figure 5 shows the result of UT depth measurements versus the nominal values for 92 artificial frets manufactured on SG tube samples. The frets were produced by vibrating the U-bend tubes in contact with mock-ups simulating tube support structures found in nuclear generating stations. The depth range is from 5 to 92% Through Wall (TW). A fretted tube sample is shown in Figure 6. The cross-correlation coefficient between the measurements and the nominal values is 0.98. The standard error is 3.14% TW and RMS is 3.5% TW.

![Figure 5 Measured Fret Depth versus Nominal Values](image)

![Figure 6 A Fretted Tube Sample](image)
Figure 7 shows the UT depth measurements versus the nominal values for 66 artificial pits. The depth range is from 2 to 86% TW. The cross-correlation coefficient between the measurements and the nominal values is 0.995. The standard error and RMS error are 2.15% TW and 2.16% TW respectively.

5. Inspection Experience

The TRUSTIE™ system was developed in 1993 to inspect and qualify Electrosleeves. High-resolution capability made it valuable for characterization and morphological analysis of SG degradations, and for monitoring in-service growth of SG flaws. TRUSTIE™ has since been used in many different CANDU SGs and remains in use today.

The following section provides a brief overview of ultrasonic inspections within OPG and highlights some of the results from different SG tubes. Figure 8 shows the number of SG tubes inspected for CANDU reactors over the years from 1993 to 2007. UT inspections are usually conducted to supplement EC results and provide detailed characterization when required. As a result, the UT inspection scopes vary, depending on ET discoveries and inspection requirements during an inspection campaign.
TRUSTIE™ technology is known for its vivid imaging capability. TRUSTIE™ can produce detailed images of indications for better monitoring and understanding of the defects, especially for inspecting OD & ID surface flaws. Figure 9 shows the comprehensive monitoring characteristics of the UT scans for corrosion pits over years. Figure 10 shows another example of UT imaging capability in terms of fret monitoring. The information is very valuable for SG maintenance and better understanding of degradations. Figure 11 shows ultrasonic images of a fret and an optical image of the fret. The C-scan image of the fret closely resembles its optical view. The metallurgical depth measurement result agrees very well with the ultrasonic measurement.

Recently OPG and Kinectrics collaborated to implement a new probe for axial crack detection. The results were very informative concerning the flaws. A combination of NB, circumferential and axial SW detection information can be integrated to provide a thorough characterization of flaws of various orientations.
Figure 11 Fret Verified by Metallurgy  (a) Optical image of a fret, (b) C-scan image showing the fret, (c) B-scan image showing the maximum depth.

6 Emerging Inspection Capabilities

There are increasing requirements for higher productivity and cost-effective technology for in-service inspections. The limitations of TRUSTIE™ technology are limited scanning speed and time-consuming data analysis. Development of multi-element array probe technology is ongoing for high speed single pass inspections. A feasibility study for Phased Array applications in SG inspection is also being carried out. The major challenges for a Phased Array probe arise from the small diameter of unique SG tubes and the current limitation in manufacturing capability to manufacture an array probe that can meet the unique ultrasonic requirements for sizing and characterization of SG flaws.

Additional work has also been initiated to integrate the TRUSTIE™ system with servo motor drive systems to improve performance in scanning speed, torque and position accuracy. A fiber optic network-based TRUSTIE™ system is being developed. This system is expected to improve the system set-up reliability, mobility and remote operation capabilities.

With emerging probe technology and increased system capabilities in data acquisition and scanning, the amount of information that needs to be processed has increased significantly. This will most certainly require more efficient and sophisticated data processing methods to meet tight outage schedules. Advanced signal processing techniques are also being developed to assist operators in efficient analysis and reporting. The initiatives will enable improvements in data processing efficiency, reliability and information management using computer software, database and communication techniques. They will further provide an essential platform for the development of advanced signal processing algorithms for different types of flaws.
7. Summary

TRUSTIE™ has produced unique quality in defect characterization over many years. Its sizing capability and precise imaging are most valuable and obvious. The inspection technique based on TRUSTIE™ is a reliable verification technique for Eddy Current tube inspections, giving more accurate depth sizing and flaw discrimination. It provides critical information to prevent unnecessary tube plugging and pulling. TRUSTIE™ also helps determine the fitness-for-service of SG tubing. UT is undoubtedly limited by its scanning speed, but its accurate flaw sizing and characterization often outweigh this disadvantage. Over the years, UT inspections associated with ET contribute to thorough and cost-effective inspection programs to ensure SG tube integrity.

As plant outages are scheduled for ever shorter windows to optimize CANDU power production, the need to provide reliable and timely ultrasonic inspection results has become essential to avoid delays in the critical decision making process regarding tube plugging, inspection expansion due to discovery of new degradation mechanisms, and tube removal for metallurgical examinations.

Inspection results from the field have been verified on numerous occasions by removing tubes with flaws for metallurgical analysis. The excellent correlation seen between UT and metallurgy has provided useful performance demonstrated evidence that can be used in qualifying the in-service inspection techniques to satisfy the requirements of the nuclear plant operating license.

OPG and Kinectrics have collaborated to develop new UT techniques, automated data analysis and high-speed systems to meet the challenges present and future, of nuclear industry SG inspection requirements. Advancements in computer technology and development in ultrasonic capability have made it feasible to significantly enhance both the hardware and software for TRUSTIE™ systems.

8. Acknowledgements

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