Advancements in Automated Inspection Systems for CANDU Steam Generators and Similar Heat Exchanger Tubes

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Abstract

In 2011 Babcock & Wilcox Canada Ltd. undertook a modernization program for their TRUSTIE[i] steam generator inspection systems, to meet the evolving needs of their customers. A major challenge was to miniaturize the original TRUSTIE motion control, motor drive, and instrumentation systems, so that they could be relocated within the containment building and operated remotely via fibre-optic Ethernet interface. The new control systems and software had to maintain complete compatibility with the original TRUSTIE mechanical systems. This paper will discuss the challenges involved in the development of this novel system. Examples will be given from the new system's first deployment to inspect steam generators at Bruce Nuclear Generating Station A during a planned maintenance outage in early 2012.

Keywords: instrumentation, ultrasonic testing (UT), software, remote control, inspection automation

1 Introduction

CANDU steam generators and related heat exchangers undergo periodic in-service inspections to ensure that they remain capable of performing up to their operational specifications while meeting their regulatory and safety requirements. Both eddy current and ultrasonic inspections are usually performed during planned maintenance. The ultrasonic inspections are particularly useful for detection and sizing of small pits, as well as for detecting fretting and other issues [1]. TRUSTIE™ is an automated tubing inspection system that has been in widespread use by Kinectrics, Babcock & Wilcox and others responsible for maintaining CANDU steam generators.

2 Modernization of inspection system

The TRUSTIE technology was developed in the mid 1990s and used what was then state of the art equipment. The mechanical drive systems remain quite current, but computer and instrumentation technology have evolved dramatically in the interim.

2.1 Description of TRUSTIE Systems

A complete TRUSTIE system consists of two main modules, with an umbilical connection between them, and a Windows PC to run software that controls the entire inspection system.

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[i] TRUSTIE is a registered trademark of Kinectrics. www.kinectrics.com

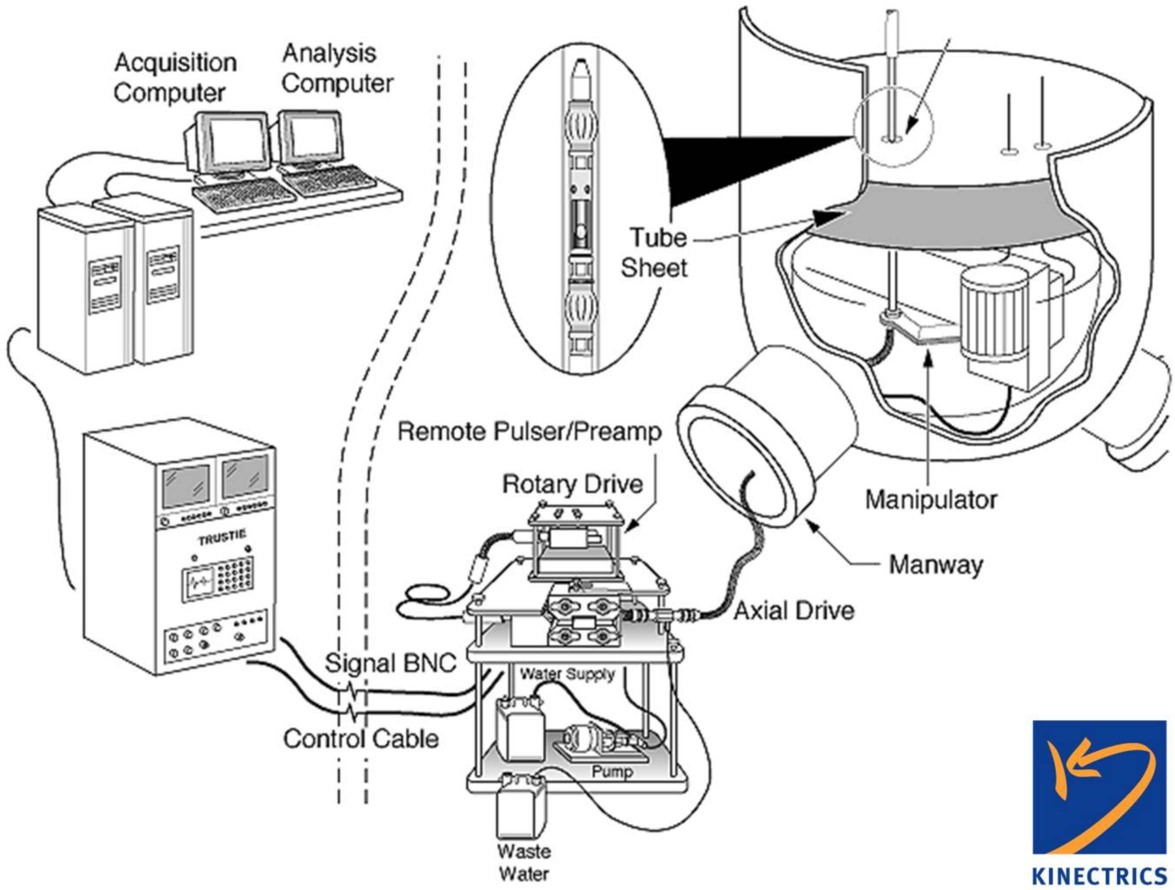

Figure 1: Schematic of TRUSTIE system in the original configuration. Image is courtesy of Kinectrics.

The original control system was housed in a 1.5 m tall electronics rack cabinet containing the axial and rotary drive amplifiers, the motion controller, the ultrasonic instrument, the host PC, and the associated interfacing electronics.

A remote pulser-preamplifier (RPP) was housed in a sealed enclosure mounted on the drive stand. Its purpose was to amplify the weak analog signals for transmission along the 200 m long coaxial cable between the drive stand and the instrument in the rack cabinet.

The connection between the controls cabinet and the drive stand used a proprietary multi-conductor cable that carried all of the control signals and power for the motors.

The drive stand is a modular assembly that includes an axial motor and drive wheels, a rotary motor and drive mechanism, and a couplant delivery and recovery system. These modules are arranged in an interlocking stack to facilitate transport and set up.

The ultrasonic probe is at the end of a flexible drive shaft, which translates and rotates within the tube under inspection. The tube is flooded with water, and an annular space between the drive shaft and its housing also carries water up to the probe.

All of these original mechanical and fluid delivery systems were retained, so the updated electronics needed to mate with the motors, encoders, pumps and valves in the drive stand.

2.2 Evolving Inspection Requirements

The performance of the original inspection tool and the quality of the data it obtained were still meeting expectations, but the electronics were obsolete and there were mounting logistical challenges to setting up and performing the inspection with the old electronics cabinet. Both of these factors were drivers for this upgrade project.

Babcock & Wilcox's inspection services clients wished to:

- eliminate any proprietary penetrations of the containment wall
- standardize on fibre-optic Ethernet for all communications with devices within the containment building
- eliminate the periodic relocation of the inspection services trailers to accommodate the 200 m long umbilical cable

Babcock & Wilcox also wished to streamline the deployment of their equipment to:

- gain efficiency during strict timelines for station outages
- improve operator safety by minimizing exposure times for personnel
- reduce downtime associated with the old electronics and instrument systems

2.3 Instrumentation Upgrades

All of the original instrumentation was replaced with a MicroPulse LT instrument (Fig. 2), which includes the ultrasonic pulser-receiver and signal digitizer in one unit.

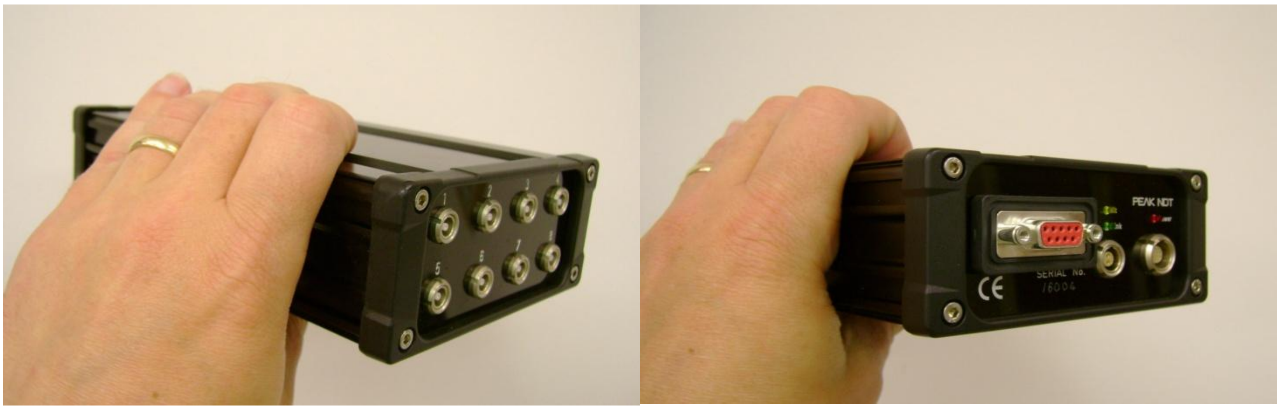

Figure 2: MicroPulse LT Ultrasonic Instrument

The new instrument is housed in the same type of sealed enclosure as the old RPP unit, and connection to the host PC is via the fiber optic Ethernet link in the containment area.

The RPP is not needed. Signal noise is no longer a concern because the A-Scan transmission to the host PC is digital, not an amplified analog signal.

The conduction cooled housing is an important design feature for this application, because the MicroPulse is mounted within a sealed metal enclosure while it is deployed within the containment area. The potential to pick up contaminants is minimized because no air movement is needed to cool the instrument.

2.4 Drive System Upgrades

The drive system electronics and motion controller had to be moved from their original location in the cabinet to a new portable housing that can be placed adjacent to the drive stand within the containment area.

The somewhat opposing goals of portability, high performance, and suitability for use within the vault environment imposed some challenges on the design of the new equipment.

The new drive unit uses a commercial rack mount case for the motion controller and drive electronics. A compressed air purge and 1-way vent system provides cooling air with slight positive pressure to discourage airborne contaminants from entering the enclosure.

The original linear-type stepper motor amplifiers were retained in the new design. Although these amplifiers are bulky and generate significant heat within the enclosure, they are preferable to the more compact switch-mode type of amplifier, because the linear amplifiers impose no RF noise upon the ultrasonic signal.

Figure 3: portable 2 axis stepper drive with embedded controller and ethernet link to host PC

The enclosed design and the remote location required the development of on-board diagnostics for the drive unit. A software program was developed for the embedded controller, to monitor and reports faults from: the stepper drives, a temperature sensor, and a transient suppressor on the AC power supply line. The program includes a watchdog timer that must be reset periodically by the host PC. A light on the reset switch blinks to indicate the status of the drive unit locally, and status messages are sent periodically to the host PC via the Ethernet link.

2.5 Software Upgrades

The original software for TRUSTIE was Winspect: a general purpose non-destructive inspection software package.

Four major benefits were sought from the software update:

1. support for the new instrumentation and motion control hardware
2. a streamlined operator interface that followed the inspection workflow
3. automation of the inspection configuration and scan execution
4. improvement of the data analysis and reporting processes

The primary reason for creating a customized user interface is to make the software workspace follow the user's normal work flow instead of requiring the user to learn how to employ a general purpose software package.

The reasons for automation of the inspection process are typical of any process that benefits from automation. Inspection automation provides improvements in:

1. productivity due to rapid configuration and execution
2. reliability due to standardization of the process and the prevention of errors
3. quality due to the accuracy and dependability of the results

While there are many NDE software packages, none of them can be sufficiently customized to accommodate the unique requirements of this sophisticated inspection. There are also many automation programming platforms that could be used to develop a customized system; however none of these are particularly adept at automation for NDE, and the development times are long.

The new software for Babcock's TRUSTIE system is a customized application created with InspectionWare, a software platform that is specifically designed for developers of automated non-destructive test applications.

2.5.1 Collaborative Design Approach and Rapid Prototyping of Software

Two customized software workspaces were developed: one for data acquisition and another for data analysis and reporting. This follows the optimum division of labour on the inspection team; operators set up and perform scans to gather data, while analysts on separate computer workstations review and process the incoming data and generate reports.

Inspection operators, data analysts and team leaders from Babcock & Wilcox were deeply involved in the workspace design, including the graphical layout and the specification of the automated sequences that would simplify and accelerate their work. Software developers do not have intimate knowledge about the inspection and its requirements; while the NDE experts may not be aware of the capabilities of the software to improve their work in novel ways. Working together, the team can produce a much better result than either group could by working alone.

Because the InspectionWare user interfaces contain no software code, changes to the user interface could be made easily and without incurring any additional changes in the operation of the software underneath. This capability enables a rapid iterative prototyping approach to the workspace design.

The rapid design cycle and the close cooperation significantly reduced the time required to achieve the finished result. The upgraded inspection system was developed and deployed about sixteen weeks after the project began.

2.5.2 Streamlined User Interface

The previous software for the system featured a series of windows and dialog boxes that lacked any visual or operational relationship to the work flow. This is typical for most general purpose software packages.

The customized workspace designed for the upgrade addressed this issue with:

- sequentially tabbed pages that follow the standard inspection work flow
- panels within pages to organize related controls and data
- pop-up windows to reveal supporting displays only when they are required

The result is a more intuitive and comfortable software environment in which to work. This enables more time spent on the work of inspecting, and less time hunting through general menus and control panels. The purpose built software helps to accelerate the work and reduces the risk of errors.

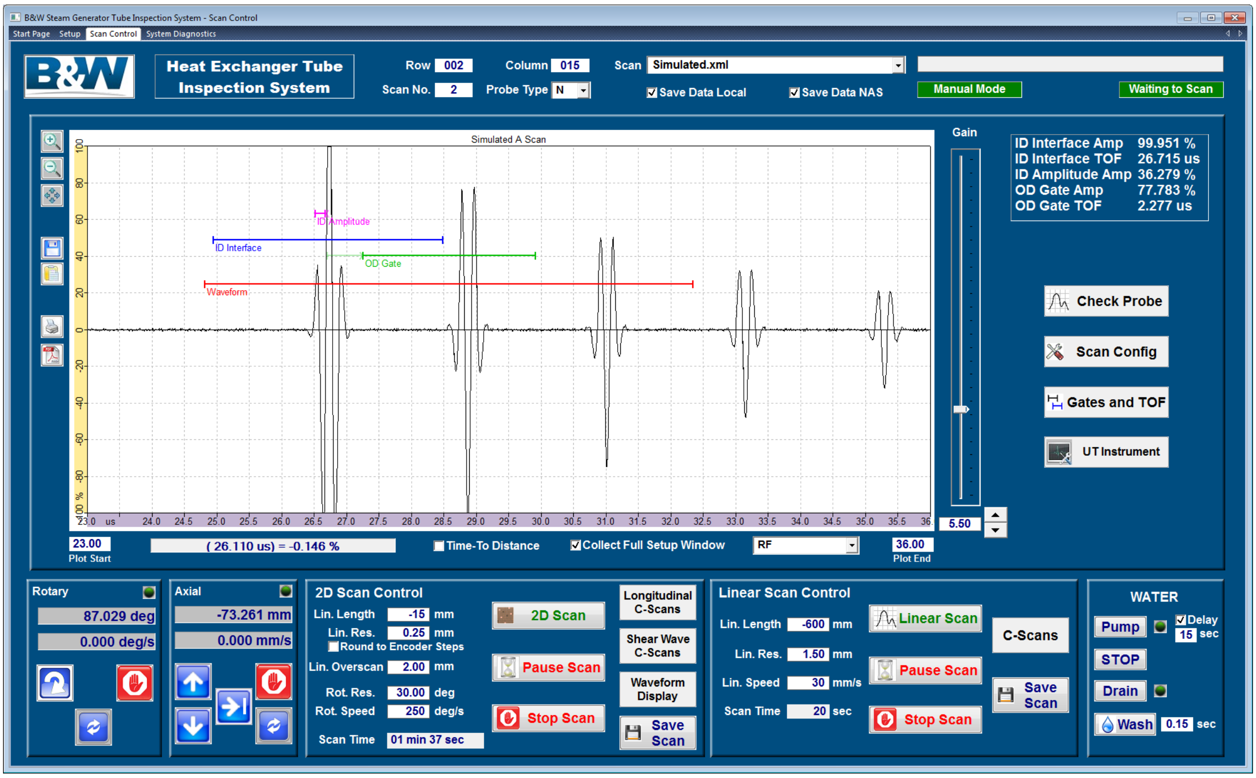

Figure 4: Main Control page of the upgraded Heat Exchanger Tube Inspection System

The main interface page (Fig. 4), has a main panel for viewing the signals and controlling the instrument, with smaller panels below for motion controls, and scan controls.

Additional pages with specific controls for configuration, instrument adjustment, and probe calibration are arranged in pop-up windows so they can be hidden when no longer needed.

2.5.3 Automation of Inspection Configuration

In the previous TRUSTIE system, inspection settings had to be configured on multiple pages in each workspace. There were also seven workspaces and therefore seven workspace files to manage: one for each scan type.

The new system has just one workspace. The operator selects from a dropdown list of predefined scan types, and all of the configuration parameters associated with the chosen scan are automatically loaded. This structure eliminates a tedious manual set up process, while simultaneously reducing the burden of managing multiple workspace configurations.

The operator can define and save any number of new configurations for scan and instrument parameters, so that operational flexibility is not limited by the streamlining of the interface.

Information about the scan such as project, boiler and probe identification is entered in an on-screen form. This information is automatically appended to the scan data file, and propagates into the report header when the file is opened by the analysis workspace. The analyst need not enter any information about the inspection when the data is reviewed and the report is published.

2.5.4 *Coordination of Multiple Displays for RF Data Analysis*

The analyst has a 3D volumetric representation of the tube under inspection, because the entire RF waveform is captured at each sample point in the rotary and axial dimensions of the scan. The standard NDE data plots: A-Scan, B-Scan, and C-Scan are extracted from the volumetric data set. Since the entire RF waveform is available, the analyst can set up new gates on the A-scan (Fig. 5A) to extract any view of the data needed for measurements or to provide better context in their report.

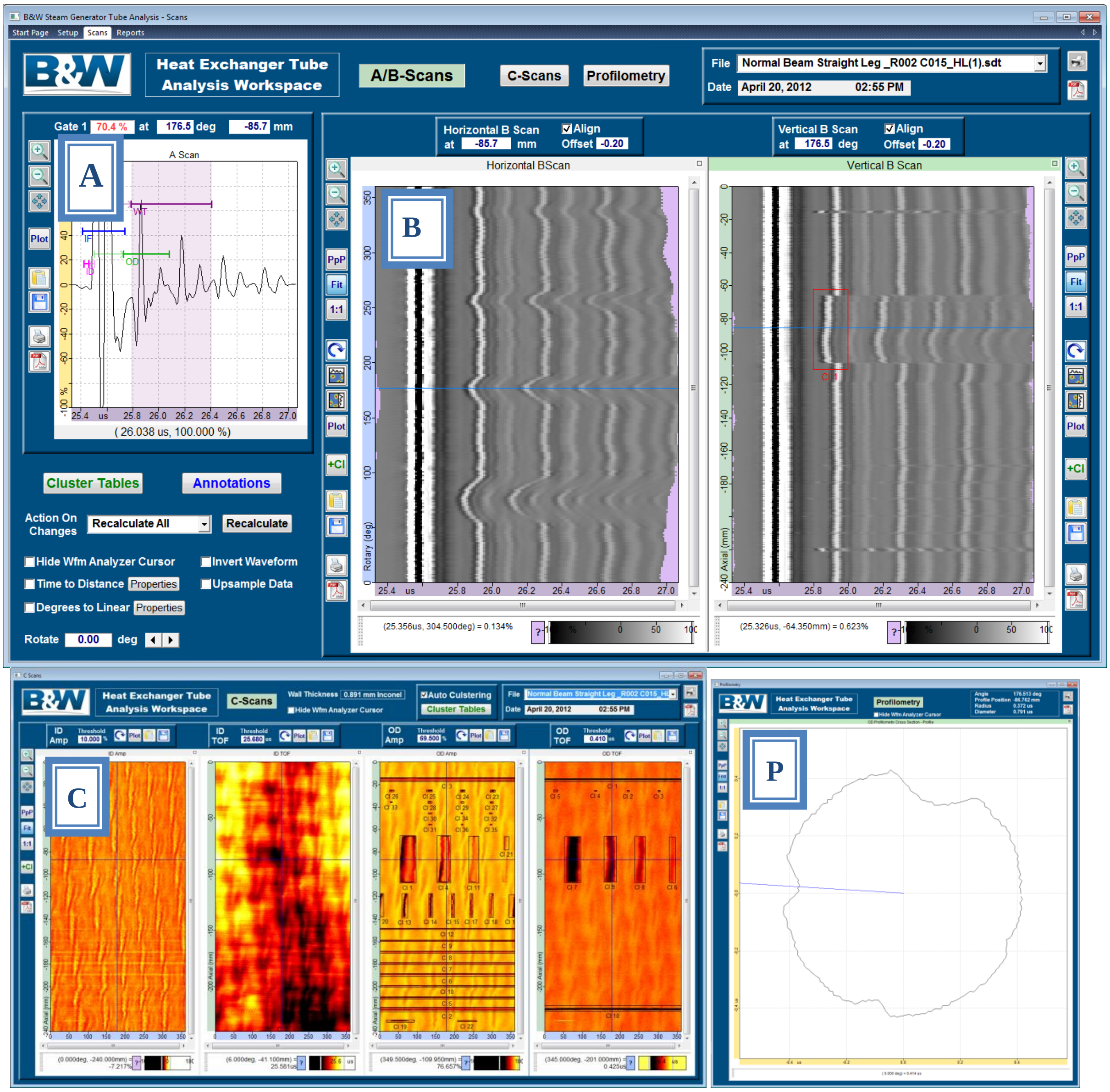

Figure 5: A-Scan: (A), B-Scans: (B), C-Scans: (C), and Profilometry Cross-Section (P) of the new tube analysis workspace.

All of the windows are movable and scalable, and all of the displays are coordinated so that zooming and panning within one display causes the others to follow.

2.5.5 *Automated Defect Recognition and Reporting*

A cluster analysis processor was employed in the new workspace. It is so called because it recognizes clusters of data that meet a set of defined criteria. Fig. 5C and Fig 6 show the cluster annotations as numbered boxes overlaid on the C-Scan image.

The processor acts on any two-dimensional set, highlighting all clusters of data that fall above or below a threshold and within the physical dimensions that are defined by the analyst. Small indications that might be missed in a manual review of a large data set are automatically highlighted and presented to the analyst for review.

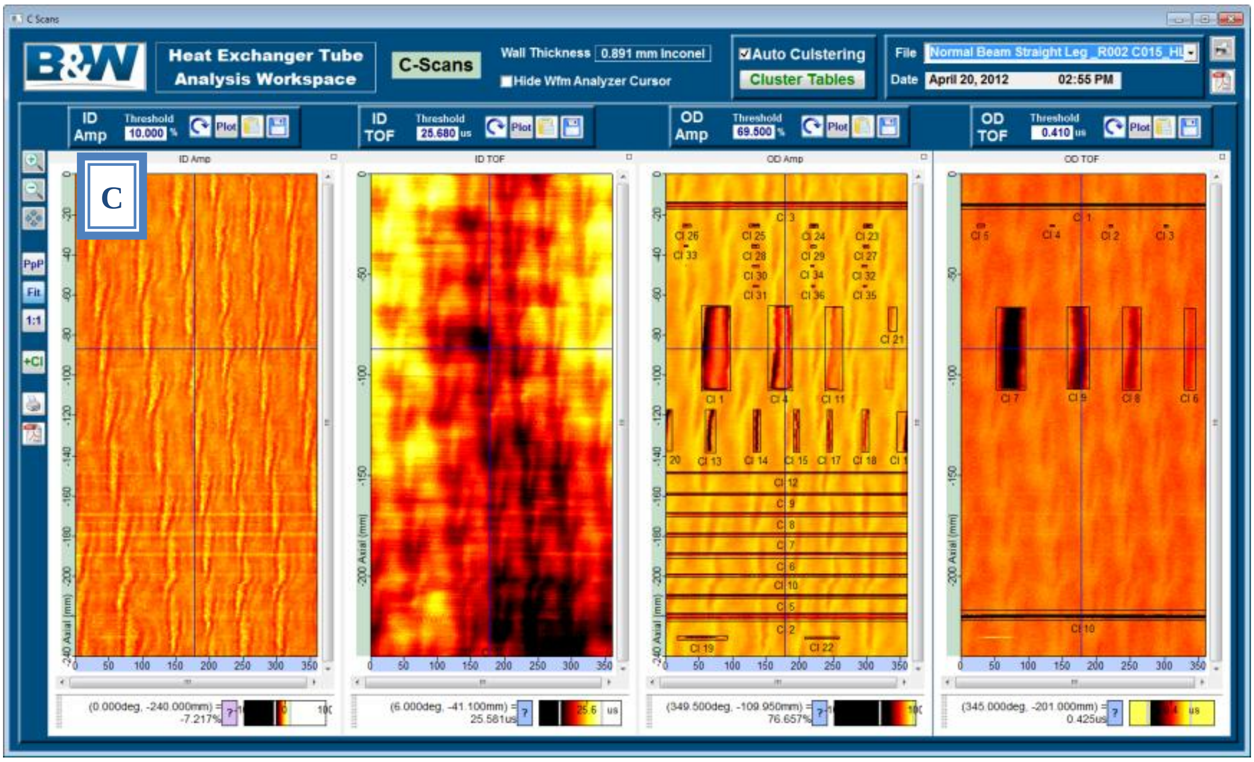

Figure 6: C Scan view with Cluster Analysis on OD amplitude and OD TOF plots

The cluster analysis processor produces a table with dimensions, depths, and peak amplitude for each indication. The table includes columns for analyst comments and decisions. The tables can be exported into Microsoft Excel or Access database files directly from the workspace, further simplifying reporting. This capability was absent from the original software.

Multipage PDF reports can be generated composed of appropriate header information, display plots with annotations, and tables of cluster details. These tools streamline the reporting and reduce the potential for errors because the images and tables do not need to be transcribed or exported and formatted into another document.

2.6 Operational Experience

Following trials at UTEX Scientific and at Babcock & Wilcox, the updated inspection system was deployed for a planned outage at Bruce Nuclear Generating Station A (BNGS-A).

This first deployment was a success. The Babcock & Wilcox inspection services team reported that the set-up time was significantly reduced, creating a benefit in reduced radiation exposure time for personnel in the rubber area and within containment.

The previous configuration often required two parallel runs of the copper umbilical cable: one in the vault, and another in the rubber area for testing and calibration work. The portable equipment and fiber optic link of the new system eliminated much of this work.

The elimination of the 200 m long umbilical cable, allowed the inspection team to operate from a permanent trailer, remote from the actual inspection site. This reduced costs, and eliminated delays that were associated with moving the trailer to within 200 m of each inspection site.

The inspection system operators and analysts reported confidence in the new software and appreciation of the easy to use design.

2.7 Future Opportunities

There remain several opportunities to further improve the system. Among these potential updates are:

- Integration of the TRUSTIE probe and drive unit with the Eddy current inspection robot, which will enable faster movement of the probe and drive shaft between tubes. The tube location would be automatically reported by the robot, and the InspectionWare workspace would record this information directly into the header of the scan data file.
- Improvements in sensitivity to the smallest indications, which are currently difficult to detect. The objective is to become aware of changes in the tubes as early as possible, so that the issue can be managed and damage corrected as early as possible. This objective may require development of specialized probes.

3 Conclusions

A new portable motion control and instrumentation package was developed to extend the service life and improve the inspection capabilities of the TRUSTIE inspection systems employed by Babcock and Wilcox.

New software was developed to simplify the user interface, and to automate inspection and analysis tasks.

The goals of increasing productivity and minimizing potential sources of error were achieved: following internal testing and deployment to a service inspection campaign, Babcock and Wilcox reported that the system meets or exceeds their goals for the upgrade project. Inspection services team members generally report satisfaction with the new system.

Cost savings were realized during the deployment, due to reduced setup times and increased productivity.

Safety benefits were realized due to reduced exposure times for staff within the rubber area and within containment.

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