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Using Data Visualization Tools to Support Degradation Assessment in Nuclear Piping

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ABSTRACT

Nuclear utilities collect a vast amount of in-service inspection data as part of periodic inspection plans and the detailed assessment and monitoring of various degradation mechanisms, such as fretting, corrosion, and creep. In many cases, the focus is primarily on ensuring that the observed minimum or maximum values are within the acceptable regulatory limits, while the rest of the (often costly) surveillance data remains unused and unanalyzed.

The objective of this study is to illustrate how data visualization tools can be used effectively to analyze and consider all of the in-service inspection data, and hence provide valuable support for the degradation assessment in nuclear piping. The 2D and 3D visualization tools discussed in this paper were developed mainly in the context of flow accelerated corrosion (FAC) assessment in feeder piping, where the complex pipe geometries and flow conditions have a significant impact on the ultrasonic (UT) wall thickness measurements. The visualization of eddy current inspection results from the assessment of pitting corrosion of steam generator tubing will also be discussed briefly.

The visualization tools provide a more comprehensive view of the degree and extent of degradation, and hence directly support the planning of future inspection of critical components by identifying key locations and areas for detailed monitoring. The results furthermore increase the confidence and reliability of fitness-for-service (FFS) assessments and life cycle management (LCM) planning decisions with respect to component repair or replacement.

1. INTRODUCTION

The management of nuclear power plant safety requires the assurance of equipment integrity (i.e., reliability) and the avoidance of failure over the lifetime of the plant. In-service inspection is a key tool in this process, by revealing the current state of the equipment with respect to the reliability and performance requirements. Because of its critical role in plant safety, the nature and extent of in-service inspection is specified in various regulatory guides and standards [1-7].

Given the high degree of variability and complexity in plant equipment, the data collected through in-service inspection naturally takes on many different formats and types. The testing and surveillance of safety systems yields extensive failure and unavailability information, which is used to assess the safety of the plant on an ongoing basis. Fitness-for-service (FFS) assessments and life-cycle management (LCM) planning require the prediction of equipment reliability in the future (e.g., over future outage intervals), and hence involve the assessment of the change (i.e., degradation) of performance over time.

In CANDU®[1] systems, the inspection of piping for various degradation mechanisms is a key challenge given the large number of piping, both on the primary and secondary sides. The inspection is typically conducted using non-destructive evaluation (NDE) methods, such as eddy current and ultrasonic testing. However, obtaining the data is often costly, particularly for primary side components, due to accessibility and dose issues.

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[1] CANDU® is a registered trade mark of Atomic Energy of Canada Limited.

The objective of periodic inspection plans is to identify (i.e., screen) any concerns or deviations in performance in the component population, while balancing the cost (and dose) against high confidence in the results. In degradation assessment, the key concern is typically in identifying the worst case flaws or components, and ensuring that they satisfy the specified FFS requirements. In both cases, the focus is mainly to verify that the observed extreme (i.e., minimum or maximum) values are within the acceptable regulatory limits. As a result, the remainder of the (often costly) surveillance data may receive little attention and remain under-utilized or even ignored.

The development of data visualization tools allows the consideration of all in-service inspection data in the analysis and hence supports a more comprehensive degradation assessment of systems, structures and components (SSCs). The objective of this paper is to illustrate with specific examples how these tools can be developed and the many benefits realized from their use.

2. DATA VISUALIZATION

Clearly, the process of data visualization depends on the type of data. Certain data are more amenable to visualization than others. Because the focus of this paper is on the degradation assessment of piping, the discussion will focus on the visualization of data from processes such as fretting, corrosion, and creep.

2.1 Key Problem

The fundamental issue when dealing with any data is formatting. The raw in-service inspection data from eddy current (EC) and ultrasonic testing (UT) consists of electrical signals that must be converted to usable data formats. These data files may then have to be converted further so that they can be visualized in a particular software application or program. Some of the most useful commercial and freely available data analysis and visualization programs are discussed in the following section.

2.2 Visualization Tools

Microsoft Excel is one of the most commonly used platforms for data analysis and visualization. It provides a user-friendly interface with numerous analytical functions and the ability to construct many different types of data plots. It is mainly useful for plotting one-dimensional data, i.e., one variable vs. another (e.g., trending of creep over time, etc.). Various kinds of customized applications can also be developed in Excel using the VBA programming (i.e., macro) environment [8, 9].

The plotting and visualization of two-dimensional data is more challenging. Typically this means the contour plotting of some "field" variable, e.g., pipe wall thickness. It is possible to construct contour plots in Excel, however, it may require some advanced programming (this is discussed further in the case study in the following section).

Tecplot is a comprehensive scientific analysis and visualization package with advanced 2D and 3D analysis and data processing capabilities [10]. It is often used to visualize the results from computational fluid dynamics (CFD) simulations and other advanced models. Tecplot is a commercial product and can be expensive, depending on the use and licensing conditions.

ParaView is an excellent free, open source multi-platform data analysis and visualization application originally created by Kitware Inc. and Los Alamos National Laboratory [11]. It is ideally suited for the 3D visualization and analysis of large datasets, and can also be deployed to multiple users through a web application.

The powerful statistical package R is another free, open source program with extensive data analysis capability and support [12]. While data visualization is quite limited in 3D, the plotting is excellent and highly flexible otherwise.

It is evident that many different software applications, both free and commercial, can be used to visualize data from in-service inspection of nuclear piping. While commercial products may be limited by cost, free and particularly open source products may lack support and quality assurance. However, the main objective of data visualization is not to perform detailed analysis of the degradation (which must be conducted using rigorous engineering computing methods), but to provide a more comprehensive view of the degree and extent of degradation of the effected components.

The following sections discuss the application and development of the above visualization tools to support the degradation assessment of feeder piping and steam generators

3. CASE STUDY: FEEDER WALL LOSS DUE TO FLOW-ACCELERATED CORROSION (FAC)

Flow-accelerated corrosion (FAC) is one of the major forms of degradation affecting the operating life of carbon steel piping and other flow carrying components in power plants [13]. The general and localized loss of wall thickness has been observed near the entrance of outlet feeders in CANDU plants, where welds and changes in pipe geometry result in an area of increased velocity and turbulence [14]. Predicting the timing of component failure and end-of-life (EOL) is critical, however, the analysis is affected by numerous uncertainties, including errors arising from in-service inspection and variability in local and global operating conditions [15].

3.1 Inspection Data

The extent of FAC induced wall loss is measured using non-destructive examination (NDE) methods, such as ultrasonic testing (UT). For smaller piping, such as the 2” and 2.5” outlet feeders in CANDU plants, the wall thickness profile is typically measured using bracelet type tools, consisting of multiple UT sensors mounted in very close proximity on an array [16]. The wall thickness values recorded by the individual UT transducers are recorded in a simple comma-separated “trending” file.

For fitness-for-service (FFS) and pipe integrity assessment, the focus is on locating the minimum wall thickness and determining how it is changing over time (i.e., estimating the FAC wear rate). However, because of the manual nature of the inspection process, probe signal loss and coverage issues, and the loss of wall thickness over time due to FAC, it is very difficult to identify any two common points between inspection outages [15]. Therefore, rather than focusing on a single point, it is imperative to consider the wall thickness profile over a larger area. While this information is already recorded by the probe, the data must be processed further to allow proper visualization of the changing wall thickness profile.

3.2 2D Visualization

Ultrasonic probes are highly dependent on the specimen geometry and surface conditions, resulting in a loss of signal in certain areas. The coverage is also limited by the spacing of the probes on the bracelet. In order to construct a smooth and accurate wall thickness profile from the relatively sparse trending file, values must be interpolated between the measurement points.

Kriging is a robust statistical method used extensively in geostatistics for the modelling of sparse spatial data [17]. As opposed to other interpolation algorithms, such as inverse distance weighting that rely on deterministic attributes, kriging analyzes the spatial correlation structure statistically over the entire domain. Various forms of kriging are readily available in both Tecplot and R, however, we have implemented it in Excel to make it accessible to a wider audience.

Figure 1 shows the contoured wall thickness profile of a 2 inch diameter outlet feeder using a 14-point UT bracelet. The plot represents the Left Cheek region of the first bend immediately downstream from the Grayloc weld. The y-axis in Figure 1 represents the circumferential direction around the diameter of the pipe which contains the 14 regularly spaced (i.e., 6 mm apart) ultrasonic transducers. The x-axis corresponds to the axial direction, with x = 0 mm located near the Grayloc hub. During inspection, the probe is mounted near the Grayloc and advanced axially along the length of the pipe. The black dots represent the probe measurements, spaced approximately 1 mm apart in the axial direction, while the small white circle shows the (point) location of the measured minimum thickness for the scan. As shown in Figure 1, the wall thickness ranges from approximately 3.75 mm to 5.25 mm, with the probe reporting a minimum thickness equal to 3.775 mm.

As shown in Figure 1, the 14-point array probe provides a fairly smooth and continuous profile of the wall thickness for a large area of the pipe. However, the actual measurements are limited to the point locations (black dots), which have been processed further by the kriging algorithm. Our implementation in Excel is done through VBA and a separate kriging library using C++. The program takes the raw data from the trending file, passes it to the kriging library, which then returns the interpolated values over a regular, e.g., 1 x 1 mm, grid. The wall thickness contour plot in Excel is constructed using a “surface” plot, with a separate x-y scatter plot overlay showing the location of the probe measurements.

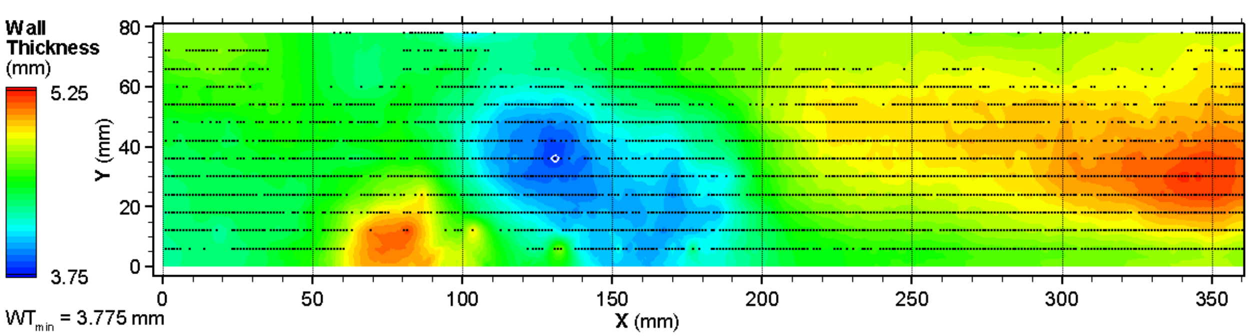

Figure 1. Contoured wall thickness profile of a 2 inch outlet feeder pipe 14-probe Left Cheek scan.

It is evident that Figure 1 provides a very comprehensive snapshot of the wall thickness profile for the pipe at a given time. Rather than a single (i.e., minimum) point value, all of the probe data is now included in the assessment, which helps to verify and support the detailed FAC assessment, especially when plotting data from multiple outages.

3.3 3D Visualization

One problem that still remains in the assessment is that the non-uniform wall thickness profile evident in Figure 1 is due to both fabrication (i.e., bending) and FAC. Feeder pipes have very complex bend geometries which directly impact the underlying wall thickness profile. It may therefore also be beneficial to plot the inspection results in 3D. Both Tecplot and ParaView can be used to make 3D plots, however, our discussion will focus on ParaView since it is free, and readily available to all users.

In order to plot the feeder pipe in three-dimensions, we need detailed information regarding the feeder geometry. This information should be readily available from ISO drawings, including the lengths, angles, and radii of all the relevant bends. The inspection data and the contoured wall thickness profile must then be superimposed on the pipe surface. This requires basic geometric computation, which, although relatively simple mathematically, may be challenging programmatically. In the end, the processed data must be written in proper format to be imported into ParaView. We prefer to use the Visualization Toolkit (VTK) legacy format, which uses a relatively simple ASCII text file structure similar to Tecplot input files, requiring x,y,z co-ordinates with the associated wall thickness values (if appropriate), and the connectivity information between each point (for surfaces). Refer to [18] for further information regarding the data format and structure.

Figure 2 shows sample ParaView plots for the 14-probe wall thickness profiles at feeder bends and 6-probe scans at the feeder Grayloc weld. The plots can be readily rotated to any angle or zoomed in to a specific area for more detailed examination. The results from multiple outages can also be linked and plotted at the same time to visualize how the wall thickness profile is changing over time as a result of FAC.

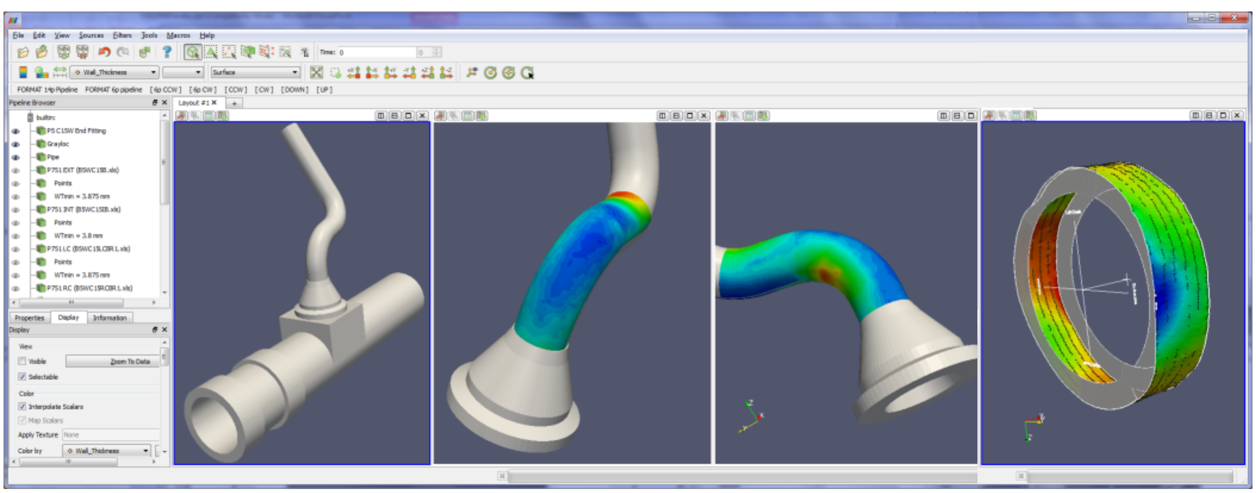

Figure 2. 3D visualization of 14-probe wall thickness scans at feeder bends and 6-probe scans at the feeder Grayloc weld using ParaView.

It is evident that 3D visualization provides the most comprehensive picture of the degradation and a much better feel not only of the FAC process, but also of the extent and scope of inspection. The results can therefore help plan and prioritize future inspection and maintenance work by identifying key areas and locations for detailed monitoring. The results also increase confidence and reliability of FFS and other regulatory assessments, and support LCM planning decisions with respect to component repair and replacement.

4. CASE STUDY: PITTING CORROSION IN STEAM GENERATOR TUBING

Pitting corrosion is a serious form of degradation affecting steam generator tubing of some CANDU reactors. A comprehensive assessment of pitting corrosion at the Pickering B nuclear station was presented in our earlier work [19], with probabilistic modelling results discussed in [20].

Pickering B reactors have twelve steam generators (SGs) per unit, each consisting of 2573, 12.7 mm (0.5 inch) outside diameter tubes manufactured using Monel 400 tube material. Although the steam generators at Pickering B are undergoing a variety of degradation modes, the primary cause of tube degradation is pitting corrosion.

Steam generator tube inspection is conducted using various kinds of eddy current (ET) probes, including the basic bobbin probe and the more versatile X-probe [21]. Each probe is faced with challenges in detection and sizing due to the probe design limitations as well as environmental and operational factors. In addition to flaw detection, the large sludge pile present at the top of tubesheet may also be visible in the eddy current probe signal, hence giving an estimate of the sludge pile height.

As shown in [19], the eddy current inspection results can also be visualized in 3D to get a more comprehensive view of the degree and extent of degradation. Figure 3 shows a sample plot of the result for SG-10 in one of the Pickering B reactors plotted in Tecplot. The plot was constructed by computing the x,y,z co-ordinates for each flaw, with the tubes plotted using quadrilateral and brick elements [10].

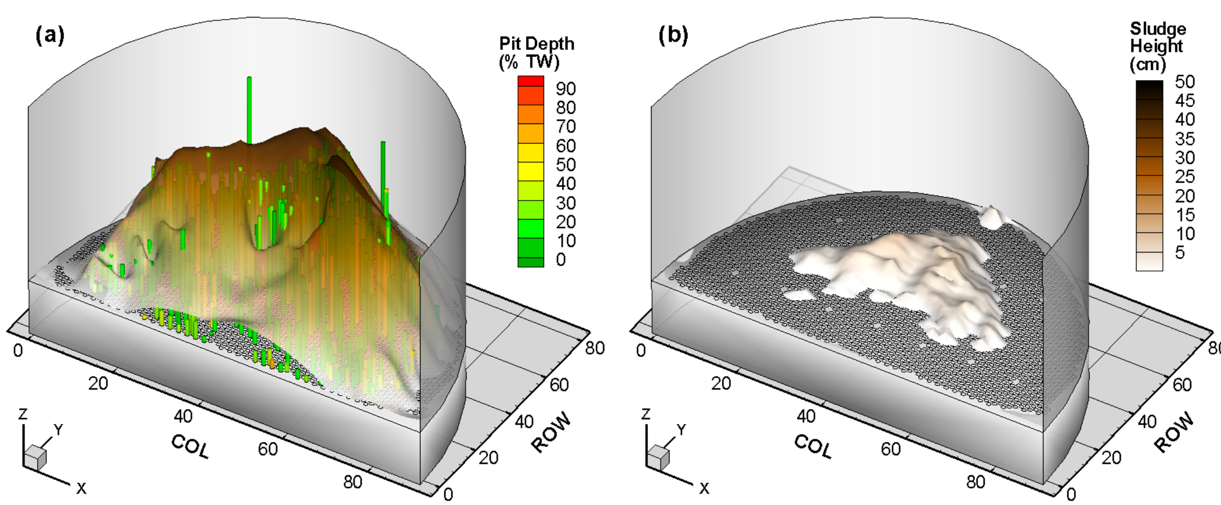

Figure 3. Interpolated sludge profiles in a Pickering B steam generator (a) before water lancing and chemical cleaning (WL/CC) showing the location of pitting corrosion and (b) after the WL/CC campaign.

Figure 3a shows how the location of corrosion pits is highly correlated with the sludge pile height. The coloured bars indicate the location of the pits, with the associated colour representing the pit depth. The sludge pile height is shown in brown colour, with the surface interpolated using the method of kriging in Tecplot. Figure 3b shows how the size of the sludge pile has been reduced significantly following the boiler water lancing and chemical cleaning campaigns. It is evident that in addition to supporting degradation assessment, the data visualization results can also be used to assess the impact and effectiveness of maintenance actions such as water lancing and chemical cleaning.

5. SUMMARY AND CONCLUSIONS

The development of data visualization tools provides added value to nuclear utilities by allowing the consideration of all of the (often costly) in-service inspection data in degradation analysis and regulatory assessments. While detailed assessment is also possible, the primary purpose of data visualization is to provide a more comprehensive view of the degree and extent of degradation of systems, structures, and components (SSCs).

As shown by the case studies in this paper, the key benefits of data visualization tools include the following:

- Effectively utilize all in-service inspection data in the assessment
- Provide a more comprehensive view of the degree and extent of degradation
- Help plan and prioritize future inspection and maintenance work by identifying key areas and locations for detailed monitoring
- Verify and guide on-going outage work
- Increase confidence and reliability of fitness-for-service (FFS) and other regulatory assessments
- Support life-cycle management (LCM) planning decisions with respect to component repair and replacement.

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