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Conclusions: One of the main difficulties in development of insulation breakdown condition monitoring techniques is the ability to control the gradual deterioration on-line in a test rig. Although detection and diagnosis of failure (ie in this case complete turn-to-turn shorting) after the event may be useful in some circumstances this alone will not prevent unplanned plant downtime. The importance of the test facilities described cannot be stressed enough as it is the detection and diagnosis of the very onset of failure that is of importance to end users of the technology being developed.

Detecting the occurrence of insulation breakdown is the main goal of this research, however in order for these technological developments to be transferred to industry it must be ensured the monitoring may be carried out on-line and be cost effective. In addition the equipment should be retrofitable (preferably non-intrusive), require no prior knowledge of insulation problems and detect winding problems at an early stage to allow for remedial action.

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AUTOMATED MONITORING OF DEFECTS IN HEAT EXCHANGER AND STEAM GENERATOR TUBING BY EDDY CURRENT TEST DATA ANALYSIS

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Abstract: Steam generators and heat exchangers used in power plants are periodically inspected using eddy current testing (ECT) to detect and identify various forms of degradation in their tubing and to quantify defect size (such as in tube cracking, mechanical wear, pitting, etc.). The University of Tennessee has developed computerized algorithms for automated analysis of ECT data in collaboration with the Electric Power Research Institute (EPRI). A commercial platform is being used for ECT data preprocessing. The automated diagnostics system has the following key features: (1) ECT data acquisition from on-line measurements or from archived data files. (2) Visualization (review) of the ECT data. (3) Calibration of the ECT data to conform with ASME Section XI standards. (4) Specification of landmarks such as hot leg, cold leg, anti-vibration bars, etc. (5) Development and implementation of defect detection and sizing algorithms using applied artificial intelligence methods. The new diagnostics system has successfully performed classification and sizing of defects in operating steam generators, including intergranular attack, stress corrosion cracking, pitting, and wear due to interaction between anti-vibration bars and tubing.

Key Words: Anti-vibration bar; Automated diagnostics; Eddy current testing; Fuzzy logic; Pitting; Stress corrosion cracking; Tube defects; Wavelet transform.

1. Introduction:

Large power generating plants have heat exchangers and steam generators that contain thousands of tubes. Steam generators (SGs) in nuclear power plants are either of the once-through or of the U-tube type with a large number of Inconel tubing. Over a period of time, during their operation, the tubing are subjected to high pressure, temperature, flow, and water chemistry conditions that cause stress corrosion cracking, intergranular attack, pitting, anti-vibration bar damage, mechanical fretting caused by tube-support plate interaction, and other defects. Repair and replacement of this equipment is costly, and entails long periods of downtime. In order to detect possible tubing problems, power plants undertake periodic examination of SGs using eddy current testing (ECT). The design of probes and test technology is highly advanced in nuclear plant applications, with robot-manipulated systems for positioning ECT probes and to automate the test procedure.

Multiple teams of experts generally evaluate the ECT measurements, and decision is made about the integrity of tubes, taking into consideration safety and economic issues.

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The knowledge base of tube defects and their propagation rates are used to forecast the operational life of tubing. Repairs and tube plugging schedules may be specified based on this information. The manual processing of a large amount of data and the need for quick decision-making is very demanding, and causes fatigue among personnel, with possible errors in data processing. For this reason, on-line data processing and automated decision-making are being developed in order to enhance the reliability of ECT as a predictive maintenance technology.

The University of Tennessee has developed computerized algorithms for automated analysis in collaboration with the Electric Power Research Institute (EPRI) [1]. In order to simplify the development of the overall analysis program and to maintain industry standards and conventions, commercial software is being used for ECT data preprocessing. The automated diagnostics system has the following features:

- ECT data acquisition from on-line measurements or from archived files.
- Visualization (review) of the ECT data.
- Calibration of the ECT data.
- Specification of landmarks, such as hot leg and cold leg, anti-vibration bars, etc.
- Interfacing the commercial platform with customized algorithms developed by The University of Tennessee for tubing defect detection and isolation, and defect sizing.
- Recording the results into a database.

The automated diagnostics system developed by The University of Tennessee consists of two primary modules: (1) A module for noise removal (both low and high frequency components) from the ECT data using wavelet transforms. (2) A module for defect isolation and sizing that uses a fuzzy logic inference technique. This module consists of a rule base similar to the experience outlined in the EPRI Performance Demonstration Database. A schematic of the ECT data analysis system is shown in Figure 1. This new method was applied to both laboratory and operational plant data provided by EPRI. Successful defect isolation and sizing was performed using ECT data from operating steam generators, containing defects caused by intergranular attack, stress corrosion cracking, pitting, and anti-vibration bar and steam generator tubing interactions.

A description of the method, features of the automated diagnostics system, and the results of applications to operating plant steam generator tubing monitoring are presented.

2. Eddy Current Testing:

The eddy current method of nondestructive examination (NDE) is based on the principle of electromagnetic induction between an inspection coil and a test object, such as a steam generator tube. When an alternating current passes through a coil placed adjacent to an electrically conductive material, the resulting magnetic field induces circular or eddy current in the test specimen. The eddy current, in turn, generates an EMF that opposes the primary coil field, and effectively changes its electrical impedance [2]. The change in impedance of the ECT probe primary coil is a measure of the change in the property of the test specimen, such as a defect in the tube.
The changes in the eddy current probe impedance are caused by the following conditions:

- Changes in test object dimensions
- Changes in the distance between the test coil and the test object (probe wobble)
- Changes in the test object conductivity
- Defects in the test object.

Each of the above affects the eddy current flow, which in turn affects the eddy current magnetic field. As the test coil is moved across an area with tube wall degradation, a momentary change will occur in the coil reactance. By monitoring the impedance of the test coil, the characteristics of the tubing under inspection may be determined [3].

The bobbin probe is used frequently for steam generator tubing inspection. A bobbin probe may be configured to measure either absolute or differential changes in the tube surface. The absolute bobbin probe has a single, circumferentially wound coil that is excited by an AC source. As the environment around the absolute bobbin coil changes with respect to a nominal configuration, the impedance measured by the probe changes, and is recorded continuously. The differential bobbin probe has a pair of circumferentially wound coils connected in a differential form, and is excited by a high-frequency AC. The coils are wound in opposite directions, so that when the environment around each coil is not the same, a net impedance change will result. This characteristic is useful in locating the defect on the tube, and corresponds to the point where a *null* would occur in the impedance plane (or equivalently in the resistance and reactance plots). The bobbin coils are not highly sensitive in detecting defects that occur gradually in the axial direction. The eddy current test using a bobbin probe has a relatively fast inspection speed, and is usually used for detecting volumetric damage mechanisms such as thinning, pitting, wear and stress corrosion cracking. More effective measurements may be performed using rotating pancake probes. These tend to be slow, and often are used for verifying the results derived from bobbin probes.

3. Multi-frequency Analysis:

In a typical eddy current inspection, multiple data channels are used. Each channel has a unique combination of mode and frequency. Data are acquired at both absolute and differential modes and at different AC excitation frequencies. A typical coil frequency set may be 800, 400, 200, and 100 kHz. As the frequency increases the depth of penetration of eddy currents decreases. The standard depth of penetration is calculated as

$$d\,(inches\ ) = 1980\,\sqrt{\frac{r}{\mu f}} \qquad (1)$$

Where r = resistivity in Ohm-centimeter
μ = magnetic permeability (use 1 for nonmagnetic materials)
f = frequency in Hz.

At least three frequency values are used in practice. A low frequency channel signal is dominated by outer diameter (OD) artifacts and a high frequency channel signal is dominated by inner diameter (ID) artifacts. Often mixing of signals at different frequencies is performed in order to exclude OD artifacts, such as tube support plates.

4. Steps in Automated Tube Diagnostics Using ECT Data:

The automated system for defect isolation and sizing in steam generator tubing consists of the following important steps:

- Data acquisition and formatting using a commercial platform. Archived data files (generally in the EddyNet™ format) are converted to the desired format.
- Calibration of the ECT data for both magnitude and phase angle compatibility. Calibration data are established using ASME Section XI standard tubing with different depths of through-wall notches. The calibration tube has notches drilled to 100%, 80%, 60%, 40%, and 20% through the tube wall (TW). Figure 2 shows the data taken from a standard calibration tube. Figure 2a is a plot of the resistance (real part of impedance) as a function of data point index. Figure 2b is a similar plot of the reactance (imaginary part of impedance). Figure 2c shows the impedance plane plots for different % TW notches. These Lissajous figures indicate distinct changes in the phase angle as a function of defect size.
- Data preprocessing to filter both high frequency (de-noising) and low frequency components in the signal. These may be introduced due to instrument noise, probe wobble, and other sources. In this work a wavelet transform based technique has been implemented to perform sub-band filtering [4].
- Specification of landmarks such as hot leg, cold leg, anti-vibration bars, tube support plates, etc. This data review enables the user in the proper choice of expert knowledge and rule-base.
- Analysis of pre-processed ECT data for defect classification and sizing. This is performed in the intelligent-based module of the system.
- Recording the decision into a database.

5. Results of Application to Operating Plant Data:

The general approach for the automated steam generator ECT data analysis system was demonstrated using the EPRI database containing fifteen defective steam generator tubing in pressurized water reactor nuclear power plants. The defect types included *outer diameter stress corrosion cracking (ODSCC), intergranular attack (IGA), pitting (PIT),* and *anti-vibration bar (AVB) wear.* The data were acquired from plants designed by different reactor vendors. SCC consists of single or multiple major cracks with minor to moderate amounts of branching, and is a result of chemical corrosion and stress (at changes in tube geometry). IGA is characterized by a relatively uniform attack of grain boundaries over a surface of tubing, and may be either volumetric or two-dimensional. Pitting is a volumetric degradation, with acidic pitting being the most prevalent (due to the introduction of chlorides, sulfur anions, and copper oxides into the steam generator from the balance-of-plant components.

The commercial software system *MultiView™ 4.1 D16* by *R/D Tech* was used as the standard platform for acquiring ECT data, calibration, and visualization. Signal de-noising was performed using the data file created by MultiView. This wavelet-based routine was developed under Microsoft Visual C++ 6.0 compiler. The multi-resolution

aspect of the discrete wavelet transform was utilized in removing low-level (high frequency) noise components in the recorded ECT data. The technique requires additional information for setting the noise threshold. The signal is successively divided into sub-band frequency levels, generally referred to as approximations (low frequency) and details (high frequency). The higher frequency components are eliminated in the de-noised signal and are easily recognized as possible tube wall degradation compared to the raw ECT signal [4].

The wavelet transform may also be used for filtering low-frequency components. Absolute bobbin coil channels are susceptible to drifts in the null value. A proper null value is important in the determination of phase angles. By using the wavelet transform to remove the lowest frequency characteristics from the signal, the null drifts are eliminated from the signal with very little distortion of the defect signal. Figures 3 and 4 show typical eddy current signals before and after sub-band elimination of the low-frequency components in the real and imaginary part of the impedance data. These pre-processing results in virtually zero-drift in the signal. Distortion does occur at the ends of the data sample, but this is typically outside the range of the actual tube data.

The fuzzy logic inference (FLI) uses a rule base similar to the experience outlined in the EPRI *Performance Demonstration Database (PDD).* The FLI module provides defect identification and an estimate of the defect size. Both the defect classification and sizing were performed using the phase angle information. Phase angle is the signature most sensitive to tube degradation. With proper calibration and frequency mixing in MultiView, the improved tube diagnostics system called *EDDYAI* has been able to detect 100% of the tube defects in the benchmark database [5]. This was possible with the development of an improved rule base and membership functions for the fuzzy logic inference that included the information provided in the PDD.

6. Concluding Remarks:

The University of Tennessee has developed several algorithms for steam generator tubing defect classification and sizing. The diagnostics system is interfaced with a commercial software platform that performs data conversion, calibration, and frequency mixing. The false alarm rates in defect classification were minimized by a combination of signal pre-processing and improved rule base used in the fuzzy logic inference engine. Future work in this area will include the use of both impedance plane magnitude and phase, and a combination of wavelet transform and pattern classification for defect isolation in steam generator and heat exchanger tubing.

Acknowledgments:

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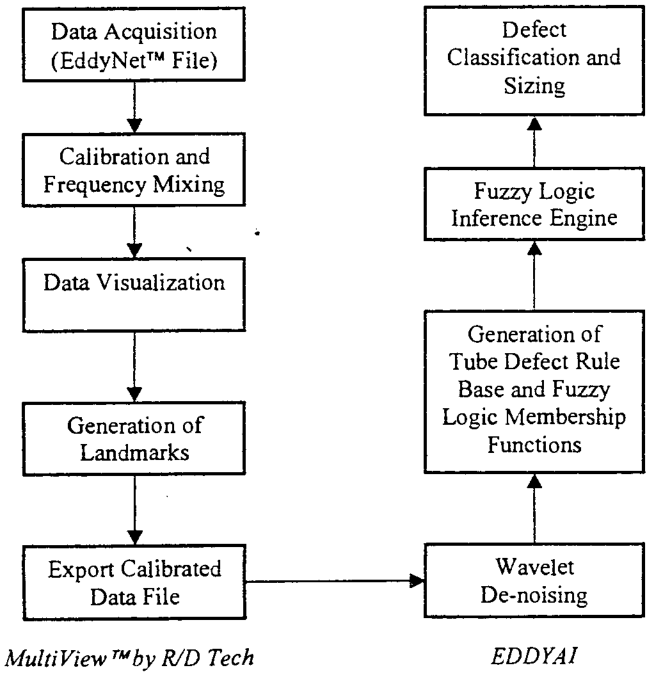

Figure 1. Schematic of the automated eddy current test data analysis system.

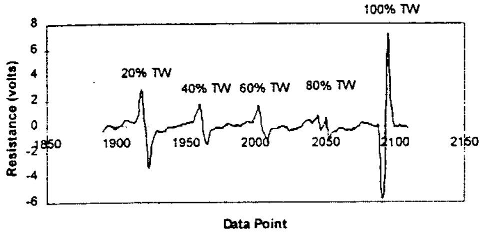

Figure 2a. Resistance component of ECT data for the ASME Standard calibration tube.

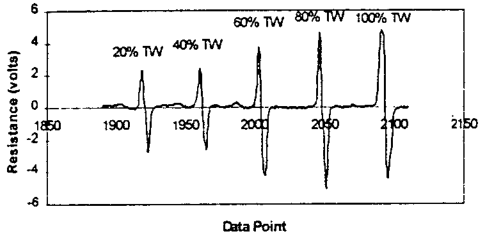

Figure 2b. Reactance component of ECT data for the ASME standard calibration tube.

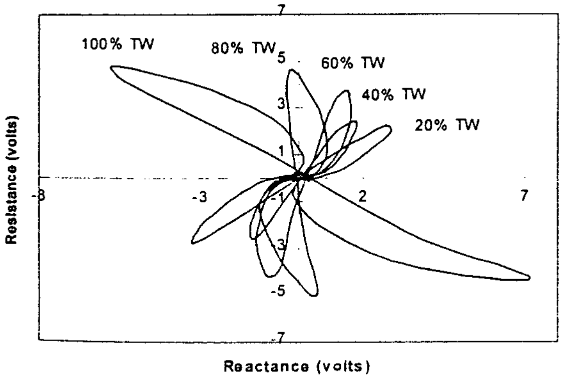

Figure 2c. Impedance plane plot of the ECT data for the above case showing 20% to 100% through wall (TW) notches.

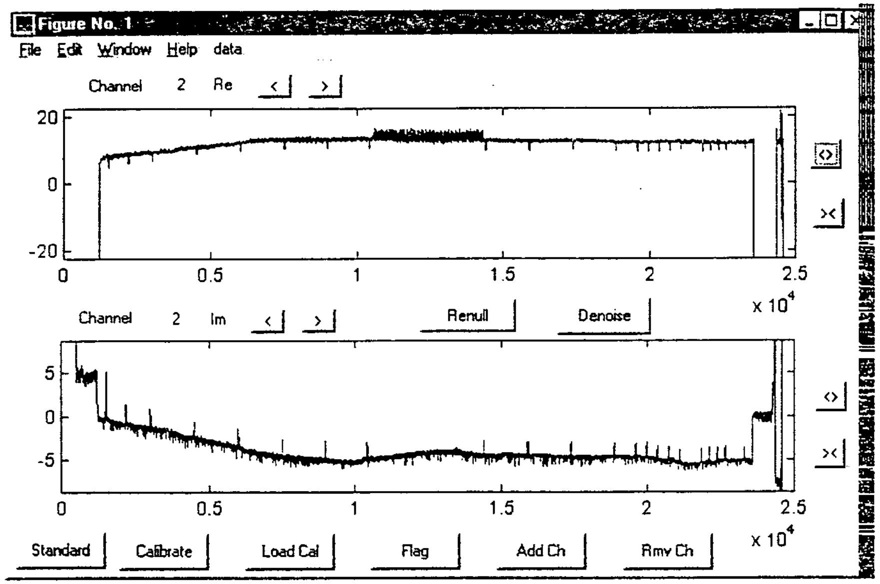

Figure 3. A typical eddy current test signal showing the real and imaginary parts of the impedance with low-frequency components.

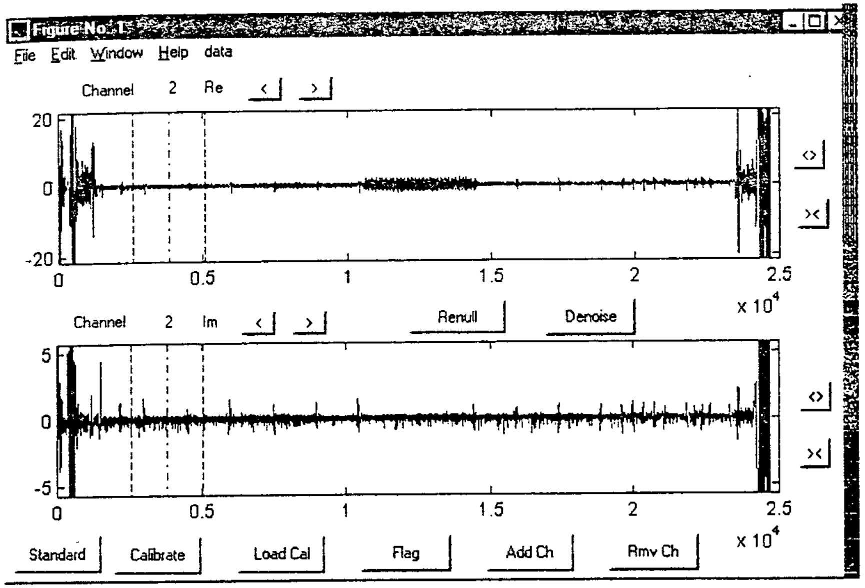

Figure 4. Real and imaginary parts of the ECT impedance signal (shown in Figure 3), after removal of the low frequency drift, using the wavelet transform. Signal distortion is seen in the ends, but does not interfere with the signal of interest.

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