Developments in Electromagnetic Inspection Methods II

**Electromagnetic NDE for Selective Leaching**

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**ABSTRACT**

Within currently approved License Renewal applications, many plants have committed to one-time-inspection of components potentially susceptible to selective leaching or de-alloying of alloy constituents. Thus, plants are required to identify susceptible components, inspect them with suitable NDE techniques, and report findings. Some of the above and below ground components are made of gray cast iron materials and the current inspection requirements include visual and hardness testing. To improve better detection and flaw characterization capabilities, EPRI has initiated a multi-year project to address detection and quantification of graphitic corrosion of gray cast iron components.

This paper presents current state-of-the-art electromagnetic NDE tool that employs a range of sensors from the multiple array remote-field eddy current sensors to a single through-transmission eddy current sensor on piping and non-piping components made of gray cast iron. Single to multiple channel volumetric sensor data will be displayed and evaluated using a combination of strip charts, Lissajous plots, and phase- and/or amplitude-based color plots.

**Keywords:** Eddy current, remote-field, selective leaching, gray cast iron.

**INTRODUCTION**

Electric Power Research Institute’s (EPRI’s) project for nondestructive evaluation (NDE) of selective leaching began in 2008 with the first year effort focused on detection and characterization of graphitic corrosion in gray cast iron components.

This paper details the Ferroscope technology for NDE of selective leaching on cast iron components and the subsequent demonstration results obtained at R.E. Ginna Nuclear Power Plant [1]. The on-site demonstration involved the applications of remote-field and near-field eddy current sensors respectively to coated and concrete lined retired fire protection line and the jacket water/lube oil cooler heat exchanger channel heads, all of which were made of gray cast iron.

**FEROSCOPE INSPECTION**

The Ginna on-site demonstration was conducted using the 16-channel PC-operated Ferroscope instrument from Russell NDE Systems along with 16-channel E-Pit sensors and 1-channel through-transmission probe. Figure 1-1 shows the Ferroscope system and the E-Pit sensors used to test from the OD side of the retired 6-inch diameter cast iron fire protection line that was coated on the OD side and concrete lined on the ID side.

If it was possible to access the buried fire protection line, it would have involved the use of I-Pit sensors. Unfortunately, since the fire protection lines were being cut and re-routed, it was not possible to perform any ID scans. Figure 1-2 shows some of the typical I-Pit sensors that would have been used from the ID side to inspect smaller-diameter piping made of cast iron or steel.
Figure 1.1 - Ferroscope Inspection System with 16-channel E-Pit Sensors Applied to a Retired Fire Protection Line made of Gray Cast Iron

Figure 1.2 - I-Pit Array Sensors for Inspecting Smaller Diameter Piping of 2-6 Inches

Another sensor that was fabricated specifically for the jacket water/lube oil cooler channel head inspection is shown as Figure 1-3. This was a single-channel through-transmission probe that allowed placement of the transmitter either on the OD side or the ID side for detecting corrosion or wall thickness reductions.
FERROSCOPE DATA ANALYSIS

It should be noted that E-Pit array sensors operated both in the remote-field and near-field effects to detect and characterize volumetric and surface flaws. The 12-channel differentially-connected remote-field eddy current sensors were located approximately 10 inches away from the transmitter coil, thus allowing equal sensitivity to both OD- and ID-initiating flaws. The four channel pancake eddy current coils, located about half-way from the transmitter sensor, operated more in the near field region with greater sensitivity to OD-initiating flaws. The flaw depth analysis depended on the phase angle separation between the air and nominal wall readings, while the overall increase in the degradation volume directly correlated with the increased signal amplitude.

The single channel through-transmission low frequency eddy current probe was operated more in the near field region, and the subsequent analysis was done by noting the relative change in the phase angle readings between the transmitter and the receiver coils in air and in nominal wall piping. Optimally, this relative change in the phase angle should be closer to 100 degrees with the judicious selection of the operating frequency. So, without having a calibration standard, it is possible to correlate this change in the phase angle to percent wall losses. This approach was used to conduct the single channel through-transmission inspection of the jacket water/lube oil cooler channel heads.

16-CHANNEL E-PIT ARRAY SENSOR APPLICATION

This testing and evaluation focused on the retired 6-inch diameter fire protection line that was approximately 20 inches long. Since the overall array probe was approximately 16 inches long, another 16 inches long new pipe section was butted against each other to allow inspection of the longer retired piece shown on the left in Figure 3-1.
Because of the transmitter to receiver separation distances of around 5 inches and 10 inches, respectively, for the four pancake array coils and 12 differentially-connected receiver coils, those distances represented receiver-specific dead zones or not-inspected areas from the pipe end. Because of the dead zones, the retired pipe section was tested from both ends. The estimated cast iron pipe wall thickness was around 0.370 inch thick with another 0.130 inch thick concrete lining placed on the ID side.

Multiple scans of the retired pipe section yielded no recordable indications from the 30+ year-old piping. To demonstrate that this system can detect localized flaws, a request was made and granted to drill several simulated pits made of drilled holes that were approximately 50% and 77% deep from the OD surface. They were placed far enough away from one pipe end to allow detection by both receiver types.

Figure 3-2 shows the air calibration performed by balancing on the pipe surface and then lifting the sensor assembly away from the pipe three times to record lift-off conditions. The operating frequencies selected for this evaluation included 47Hz for pancake arrays coils and 94Hz for differential receiver coils. The phase rotations applied to both frequency channels resulted in the lift-off signals to be horizontal with the signals extending to the left of the balance points.
In general, the flaw depth analysis was conducted at higher frequency of 94Hz due to a larger phase angle spread with 47Hz data providing more of flaw confirmation. Figures 3-3 (a) & (b) show the 77% flat-bottom hole signals at both 47Hz and 94Hz.

Similarly, Figures 3-4 (a) and (b) show the 50% flat-bottom hole signals at both 47Hz and 94Hz.
Based on the current phase angle setup of rotating the lift-off on the horizontal axis, the 94Hz differential receiver coil outputs showed clockwise rotations of phase angles for decreasing OD flaw depths (for example, 119º for 77% wall loss versus 143º for 50% wall loss). For 27% difference in the OD wall loss, this represented 25º phase shift, which was closer to ideal phase shift of 1º for 1% wall loss.

For pancake coils, the OD flaws at 47Hz rotated counter-clockwise in the ID plane with decreasing flaw depths (for example, 23º for 77% wall loss versus 22º for 50% wall loss). At this lower frequency, the 27% difference in the wall loss resulted in only 1º difference. As such, this 47Hz channel was suited more for flaw detection than flaw sizing. Since this set of pancake array coils was offset by approximately five inches from the location of 12 differential coils, it was necessary to scan past the pipe edge to allow flaw detection by pancake array coils as shown by the 4-channel strip charts and the associated Lissajous plot.
SINGLE-CHANNEL THROUGH-TRANSMISSION SENSOR APPLICATION

This application was performed after opening the east ends of the cast iron channel heads that were attached to jacket water and lube oil coolers. In Figure 4-1, they are located on the left-hand side of the two stacked coolers. Figure 4-2 shows one of the channel head openings with approximate clock positions noted for referencing individual scan numbers.

Figure 4.1 - Jacket Water and Lube Oil Coolers Showing East and West Ends of Cast Iron Channel Heads

Figure 4.2 - East End Channel Head of Jacket Water Cooler Showing Clock Positions to Indicate Scan Locations

The channel head wall thickness was estimated to be around 0.750 inch. No specific thickness confirmation, however, was available due to difficulty of obtaining reliable ultrasonic thickness
readings caused by the porous nature of cast iron materials. Because of the increased thickness, the two operating frequencies employed were reduced to 30Hz and 60Hz.

At each clock location, the through-transmission probe was inserted to the face of the tube sheet and data was recorded during the manual retraction. At each location, three data runs were made and recorded. Figure 4-3 shows the actual channel head scanning and recording of data. Each scan data represented up to seven inches of axial distance.

Since there were no representative channel head pieces available for calibration standard, it was necessary to rely and record air readings first based on the selected transmitter-to-receiver coil spacing. Next, nominal phase angle readings were obtained and averaged from the lube oil cooler channel head thickness readings. The following phase angle readings were obtained at 60Hz:

- Through-transmission probe in the air was +146.4º.
- The average nominal channel head thickness reading was +72.9º.
- This represented a 73.5º difference for 100% wall thickness or roughly 1.36% wall loss for 1º of change.

Based on the above approach, all of the recorded data were reviewed and representative phase shifts were recorded for each clock run position as shown in Figure 4-4. The following analysis statistics were obtained for each cooler.
Lube Oil Cooler:
- 32 phase angle differences were calculated from each strip chart data run.
- The average phase angle shift over 32 readings was 9.3°.
- This represented 12.6% reduction in wall thickness (9.3° x 1.36%/°).

Jacket Water Cooler:
- 30 phase angle differences were calculated from each strip chart data run.
- The averaged phase shift over 30 readings was 6.9°.
- This represented 9.4% reduction in wall thickness (6.9° x 1.36%/°).

Even though wall reductions of 12.6% and 9.4% were calculated, they were deemed not statistically significant in light of 15% measurement errors that are normally associated with such remote-field/near-field measurements. These numbers also fell within the manufacturing tolerance of the fabricated wall and were not associated with service-induced wall losses.

a) 60Hz Signal Outputs Showing 72.7° Phase Shift at Near the Tube Sheet

b) 60Hz Signal Outputs Showing 82.3° Phase Shift at Near the Head Opening
SUMMARY

The following observations were made during the on-site demonstration:

- Successful application of the E-Pit array sensors were made from the OD side of the retired fire protection line.
- Localized simulated pits were reliably detected and characterized by both near-field pancake array coils and differentially connected remote-field array sensors.
- Both the jacket water and lube oil cooler channel heads on the east sides were successfully tested using a single channel through-transmission eddy current probe.
- No structurally significant wall losses were noted; noted wall loss reductions were found to be within the NDE measurement errors and manufacturing tolerances.
- Despite the absence of calibration standards, it was possible to perform quantitative assessment by relying on air and nominal wall phase angle measurements.
- Even though the I-Pit sensor or ID probe was not used, the demonstrated Ferroscope technology is equally capable to inspect buried piping made of cast iron or steel from the ID side.

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REFERENCE