

# Near field array for inspection of ferritic/ferromagnetic stainless steel (NFA FS)

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# NFA FS - Introduction

Eddy current (ET) inspection of ferritic and/or ferromagnetic stainless steels such as 400 series stainless steel (SS), SEA-CURE™ and Monel has always been challenging. The typical inspection method used for these materials has been full saturation ET where powerful and carefully arranged magnet assemblies magnetically saturate the tube wall allowing the eddy current to flow as though the material were non-ferromagnetic. In addition to mechanical challenges associated with magnet probes, full saturation ET is effectively blind below ferromagnetic support structures.

# NFA FS – Introduction (cont'd)

A new eddy current technique has been developed that does not require the use of magnets. Near field array for ferritic/ferromagnetic stainless steel (NFA FS) is an ET array solution for thorough inspection of thin-walled ferritic/mildly-ferromagnetic tubing capable of detecting and characterizing inside diameter (ID) and outside diameter (OD) defects both in the freespan and below ferromagnetic structures. The NFA FS contains no magnets and uses near field ET (a combination of field and low-frequency eddy current). This paper will review the operating principles of the probe and present laboratory and field experiences from the last two years.

# NFA FS – Background

In 2014 Eddyfi released the Near Field Array (NFA) probe for the detection and characterization of ID pitting in Fin-Fan carbon steel tubing. Later that year Eddyfi was approached by Duke Power to inquire whether it would be possible to adapt the NFA technology to aid their efforts to inspect SEA-CURE™ and 439 stainless steel tubing.

Inspection of mildly ferromagnetic stainless steel is hampered by unwanted signals created by relative permeability variations in the tube wall<sup>1</sup>. The method typically used to inspect this material is full saturation eddy current where powerful magnets are specially arranged to magnetically saturate the tube wall rendering it effectively equivalent to a non-magnetic material.

# NFA FS – Background (cont'd)

As the probe passes below ferromagnetic support plates or baffles, the magnetic field is drawn away from the tube wall creating a region within which; a) the tubing is no longer magnetically saturated and b), there is a support transition signal that is often an order of magnitude larger than the reference calibration tube flaw signals.

# Operating principles

Inspection of thin-walled non-ferromagnetic tubing is usually performed with at least one of the inspection frequencies being set to  $F_{90}$ .  $F_{90}$  is the frequency where the measured phase angle from *shallow* ID defect signal is separated from a *shallow* OD defect signal by approximately  $90^\circ$ .

$F_{90}$  is derived from the skin depth and phase lag equations<sup>1</sup>:

$$\delta = 50 (\rho / f \mu_r)^{1/2}, \quad \beta = x / \delta \quad \text{where,}$$

$\delta$  = standard depth of penetration (mm),  $\rho$  = electrical resistivity of the test material ( $\mu\Omega$  cm) and  $\mu_r$  = the relative permeability of the test material and,  $\beta$  = the standard phase lag (radians) at a depth of  $x$  mm.

# Operating principles (cont'd)

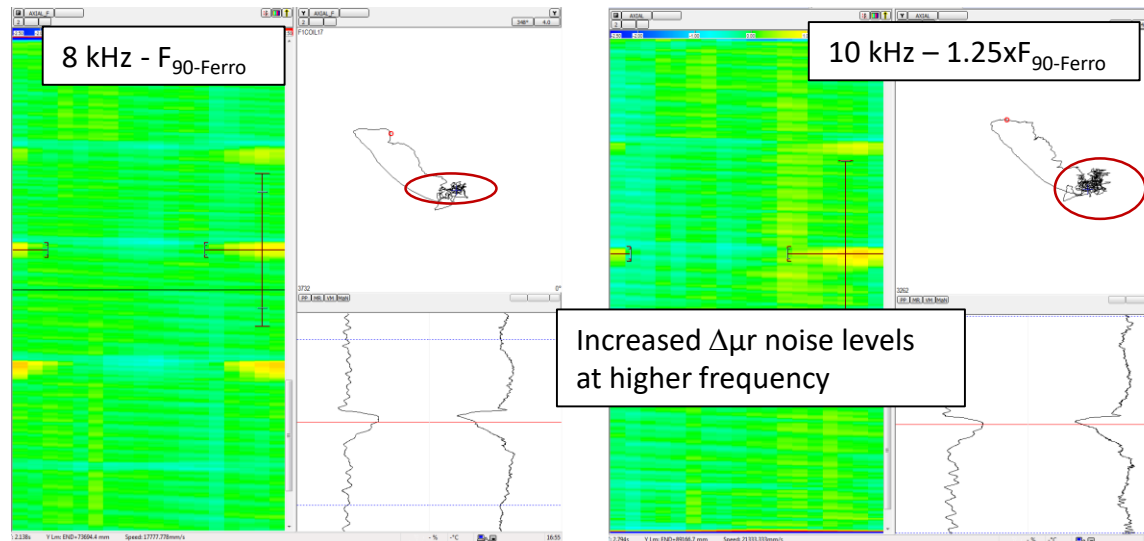
$F_{90}$  can therefore be shown to be  $F_{90} = 3\rho/t^2$  where  $t$  is the thickness of a thin-walled tube and  $\mu_r=1$  is assumed for non-ferromagnetic materials. That being said, the objective of the NFA-FS probe is to inspect materials that are ferromagnetic.

Therefore, putting  $\mu_r$  back into the equation yields:

$$F_{90\text{-Ferro}} = 3\rho/\mu_r t^2$$

# Operating principles (cont'd)

The operating principle of the NFA FS probe is that, at frequencies substantially higher than  $F_{90\text{-Ferro}}$ , noise, related to local variations of relative permeability ( $\Delta\mu_r$ ), is very large. As the frequency approaches  $F_{90\text{-Ferro}}$ ,  $\Delta\mu_r$  noise drops to manageable levels producing signal responses that permit ID/OD discrimination at reasonable signal-to-noise ratios.



Comparison of NFA FS data collected at  $F_{90\text{-Ferro}}$  and at 125% of  $F_{90\text{-Ferro}}$



# Operating principles (cont'd)

This method, however, is not perfect and sometimes the noise reduction is not sufficient at  $F_{90\text{-Ferro}}$  necessitating a further reduction of the inspection frequency. At this lower frequency detection of ID and OD flaws is retained but ID/OD discrimination is lost.

Thus far viable techniques with acceptable signal-to-ratios have been found for SEA-CURE™, Monel™, 439 SS and Duplex SS up to 1.1 mm (0.043") wall thickness. It is recommended that any new combination of material type or wall thickness be laboratory tested prior to field implementation.

# Probe design process

- Numerous prototypes were designed and produced testing different coil layouts, firing sequences, spacing, and frequency response ranges.
- The probe body was designed to share as many components as possible with the popular DefHi™ probe (rugged nylon push tube, replaceable centering devices, titanium outer casing).

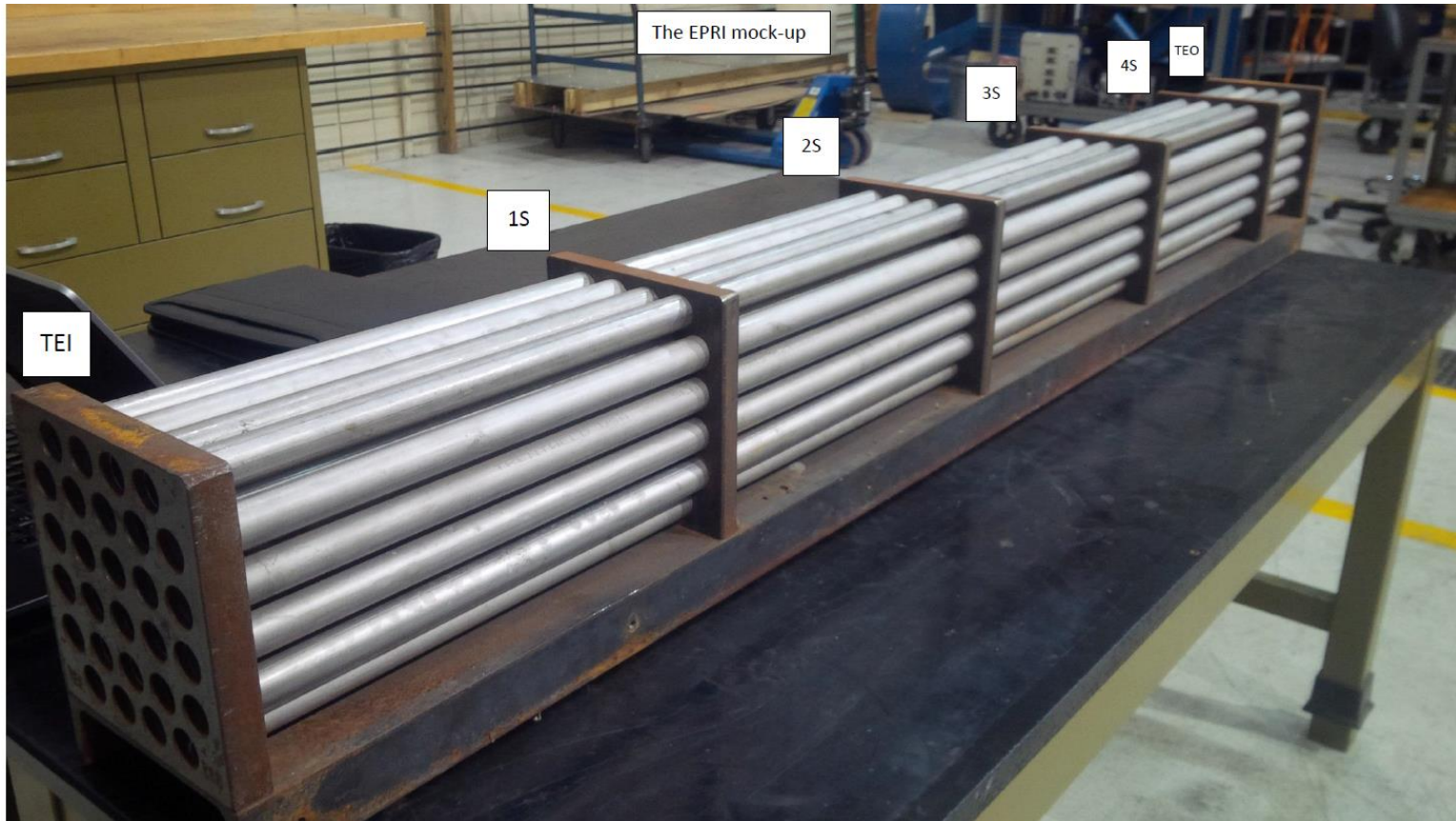


- Results from the laboratory and field experiences prompted design and configuration changes that were continuously incorporated into the design.

# Laboratory results

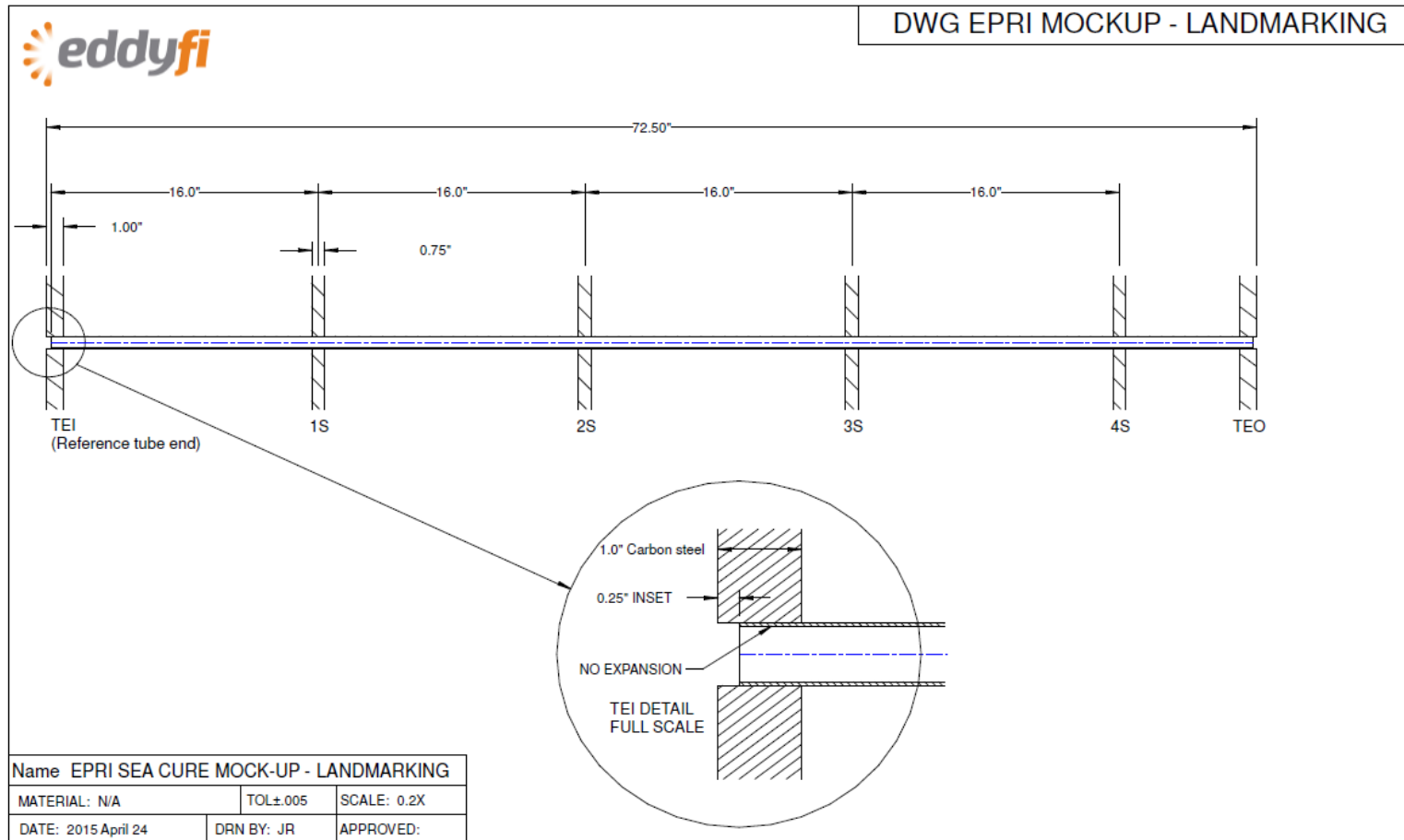
- Laboratory data were collected on the SEA-CURE™ mock-up at the Electric Power Research Institute (EPRI) in Charlotte, North Carolina, 2015 April 08.
- The probe used for the examination was a repurposed 23 mm (0.905") OD NFA probe originally developed for the inspection of carbon steel pipes for ID flaws.
- The EPRI mock-up contained 21, 25.4 mm OD x 0.71 mm WT (1" x 0.028") SEA-CURE™ tubes, 13 of which were unflawed.

# Laboratory results (cont'd)



*Photo of the Sea Cure™ mock-up at the EPRI NDE Centre, Charlotte N.C.*

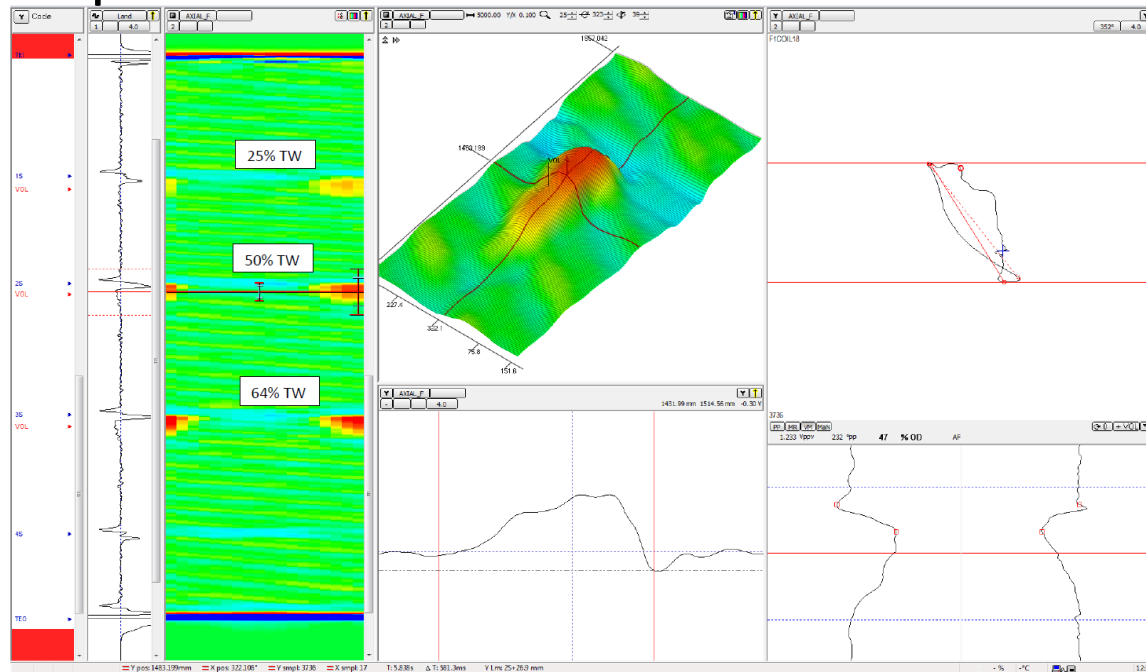
# Laboratory results (cont'd)



Schematic of the Sea Cure™ mock-up at the EPRI NDE Centre, Charlotte N.C.

# Laboratory results (cont'd)

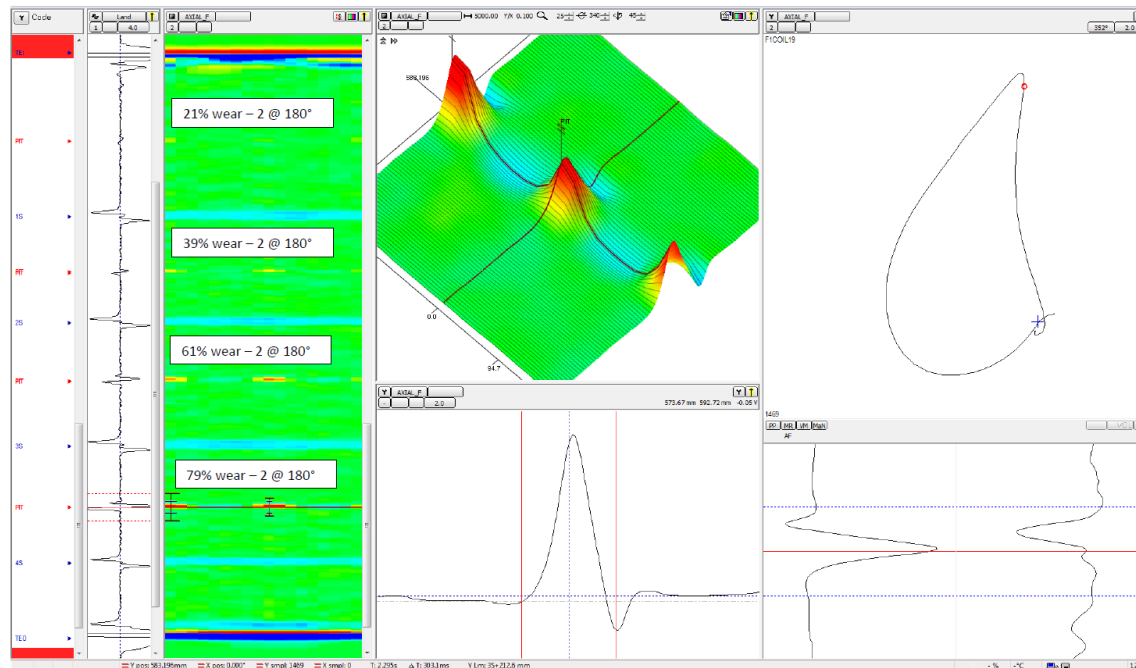
- The NFA probe was able to detect and characterize large area volumetric flaws such as simulated support-plate wear and erosion both below support structures and in the free-span



*Tapered wear scar indications below carbon steel supports in the Sea Cure™ mock-up at the EPRI NDE Centre, Charlotte N.C.*

# Laboratory results (cont'd)

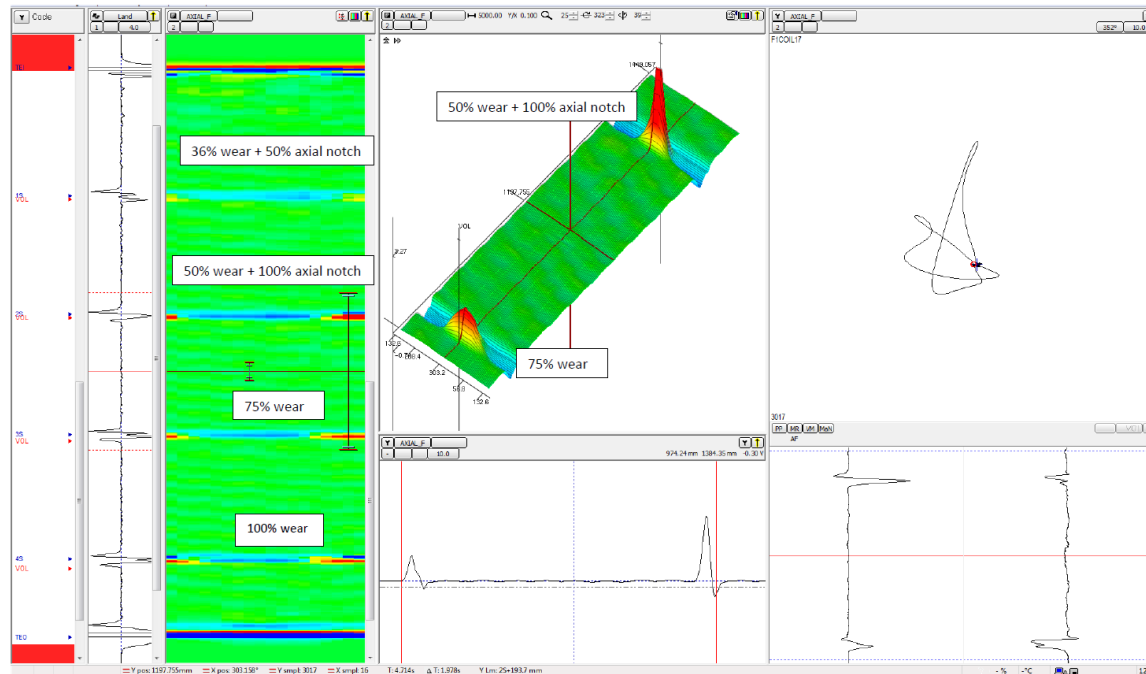
- The NFA probe was able to detect and characterize large area volumetric flaws such as simulated support-plate wear and erosion both below support structures and in the free-span



2-sided free-span wear indications in the Sea Cure™ mock-up at the EPRI NDE Centre, Charlotte N.C.

# Laboratory results (cont'd)

- The NFA probe was also able to detect and characterize axially and circumferentially oriented EDM notches simulating cracking in the tube

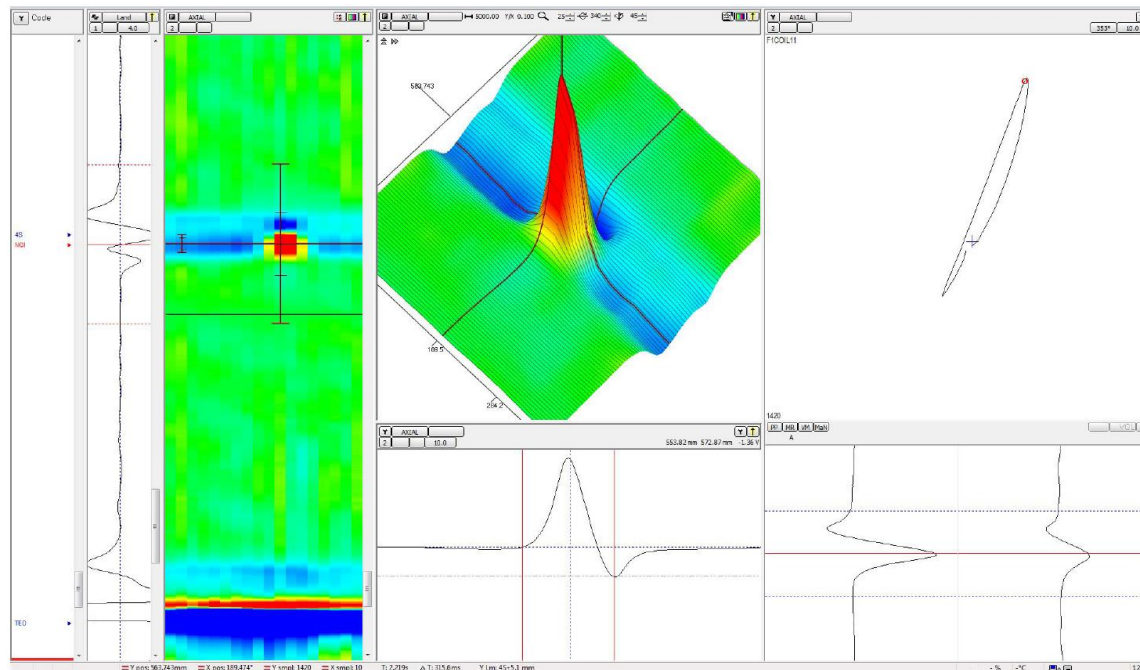


*Wear scar and EDM notch indications in the Sea Cure™ mock-up at the EPRI NDE Centre, Charlotte N.C.*



## Laboratory results (cont'd)

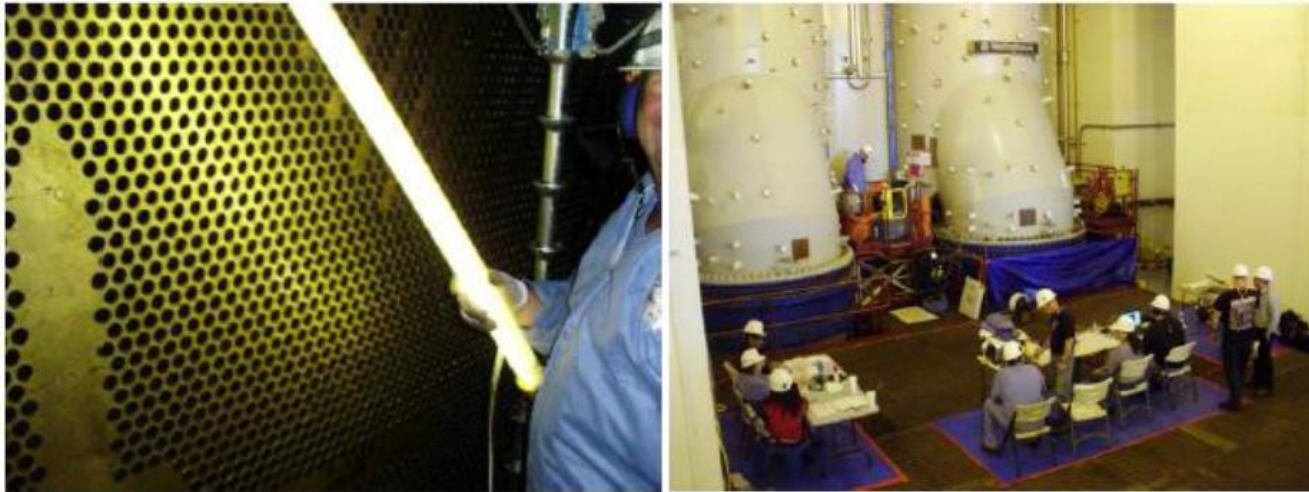
- The NFA probe was also able to detect and characterize axially and circumferentially oriented EDM notches simulating cracking in the tube



Axially oriented 100% TW EDM notch below a carbon steel support in the Sea Cure™ mock-up at the EPRI NDE Centre, Charlotte N.C.

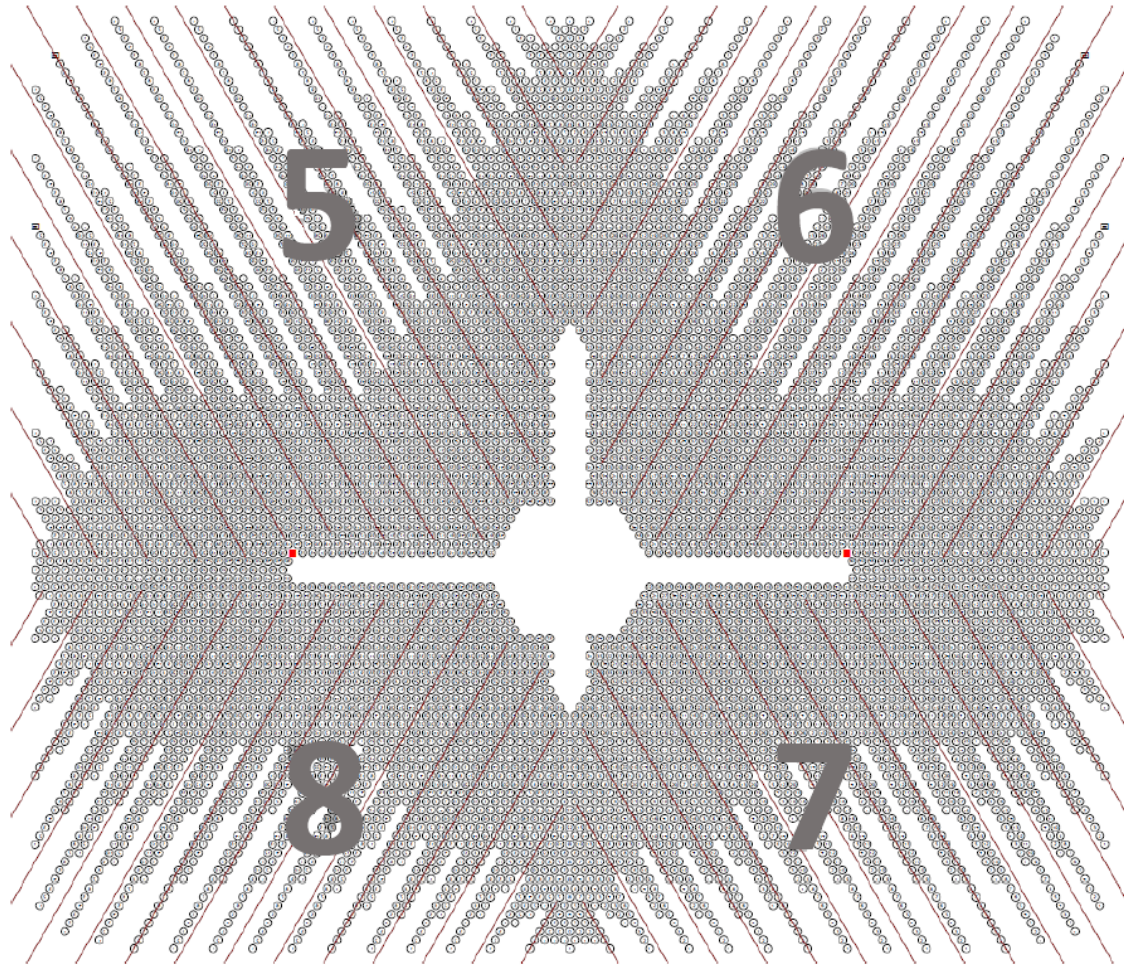
# HNP - Field trial

- Shearon Harris Nuclear Plant (HNP) North Carolina (PWR – Westinghouse) main condensers - 25.4 mm OD x 0.71 mm WT (1" x 0.028") SEA-CURE™
- 200 tubes selected for inspection<sup>2</sup>
- HNP previously experienced a tube leak in this system due to cracking at a support plate. This crack was undetected by magnetic saturation bobbin probes.



Photos of the main condenser tube sheet face and inspection staging area

# HNP - Field trial (cont'd)

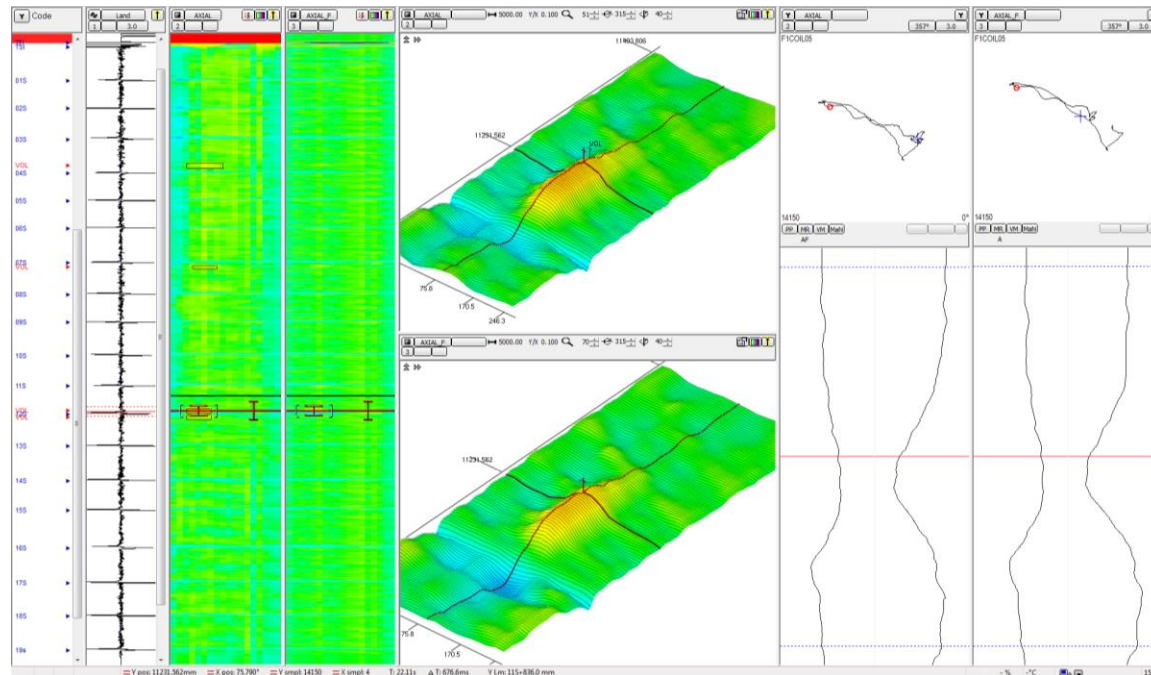


Tube sheet map showing four of the sixteen quadrants that made up the two main steam condensers



# HNP - Field trial (cont'd)

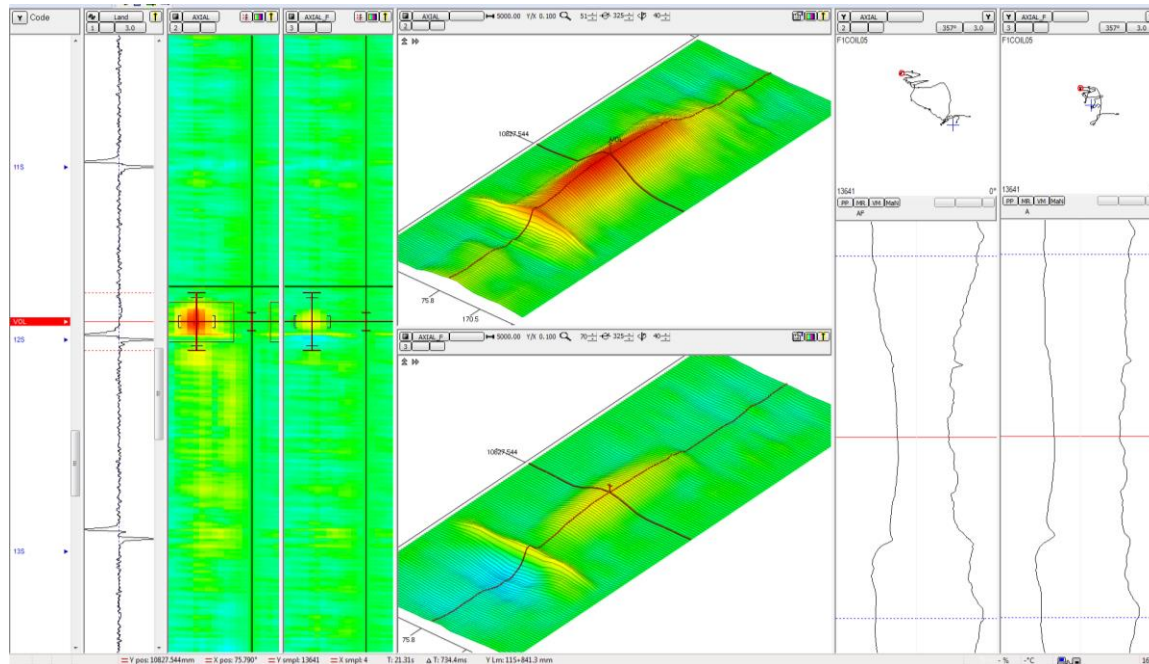
- Results from the field trial were very encouraging with multiple indications detected and no previously reported flaws missed.



Multiple volumetric indications in a main steam condenser tube including a shallow region of volumetric wall loss adjacent to a support structure (possible erosion)

# HNP - Field trial (cont'd)

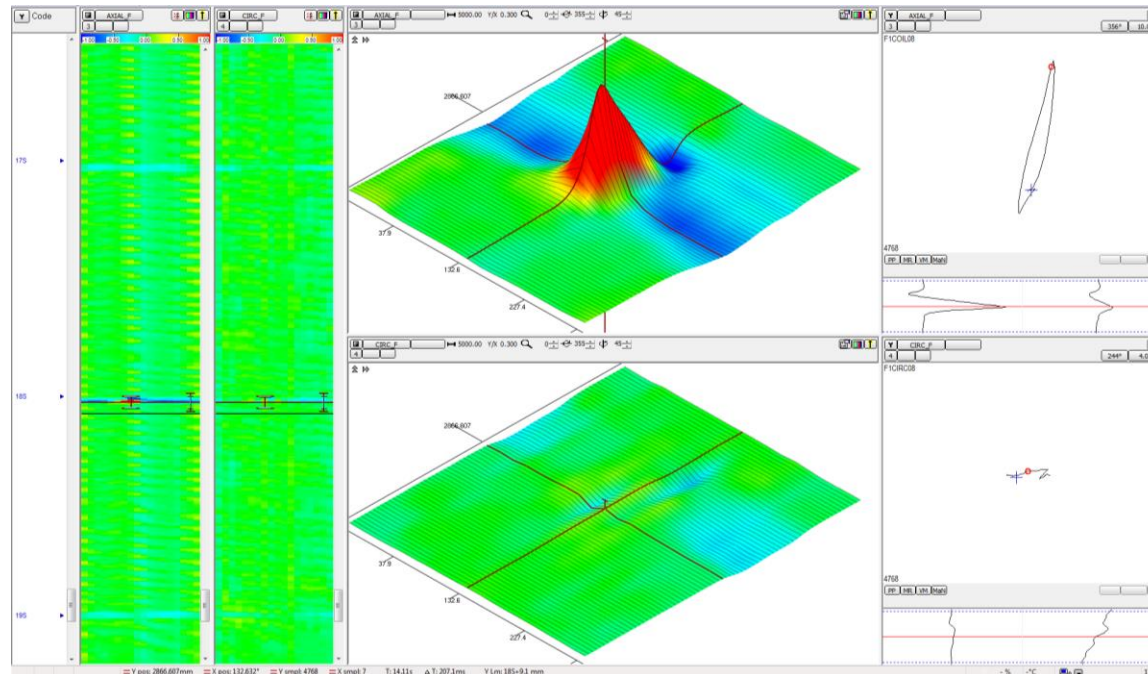
- Results from the field trial were very encouraging with multiple indications detected and no previously reported flaws missed.



*A “Top Hat” indication in a main steam condenser tube*

# HNP - Field trial (cont'd)

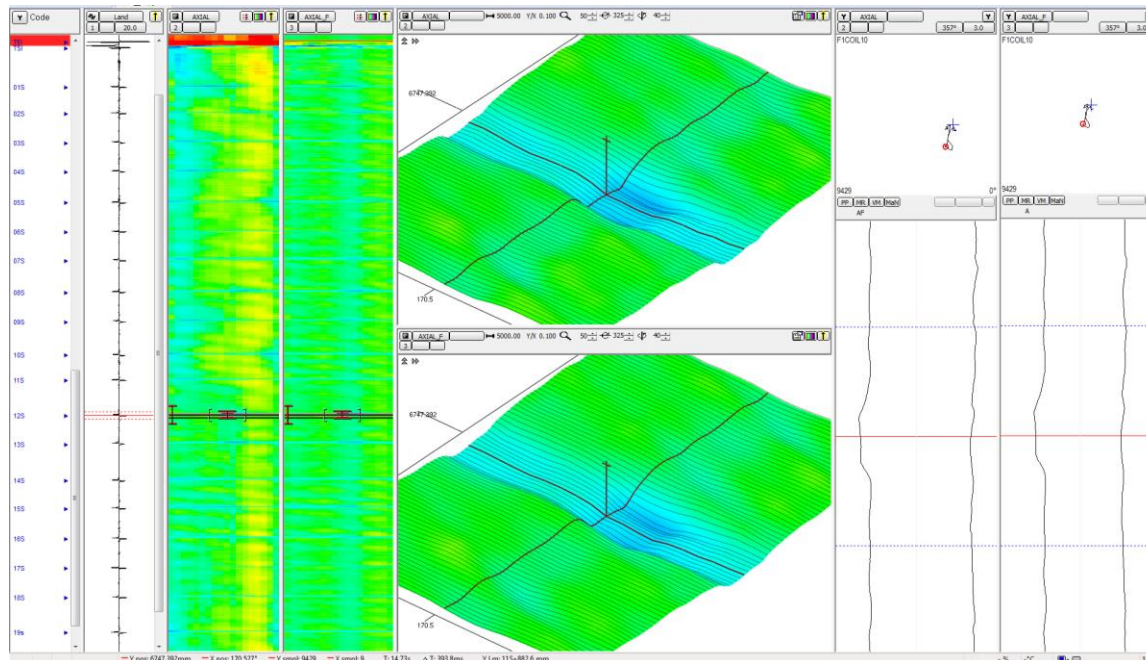
- In addition to scanning in-service tubes a number of previously plugged tubes were unplugged so that they could be scanned with the new technique.



A likely-through-wall axially-oriented indication later confirmed by destructive examination to be a 100%TW crack below a support plate. This crack had previously been undetectable using existing magnetic-saturation-probe techniques even though it was known that the tube was leaking.

# HNP - Field trial (cont'd)

- An inspection-of-record was successfully completed Fall 2016 using the new integral probe drive



A tube with no detectable degradation

# RNP – Inspection of Record

- Robinson Nuclear Plant South Carolina (PWR – Westinghouse Model) main condensers – 2017 March

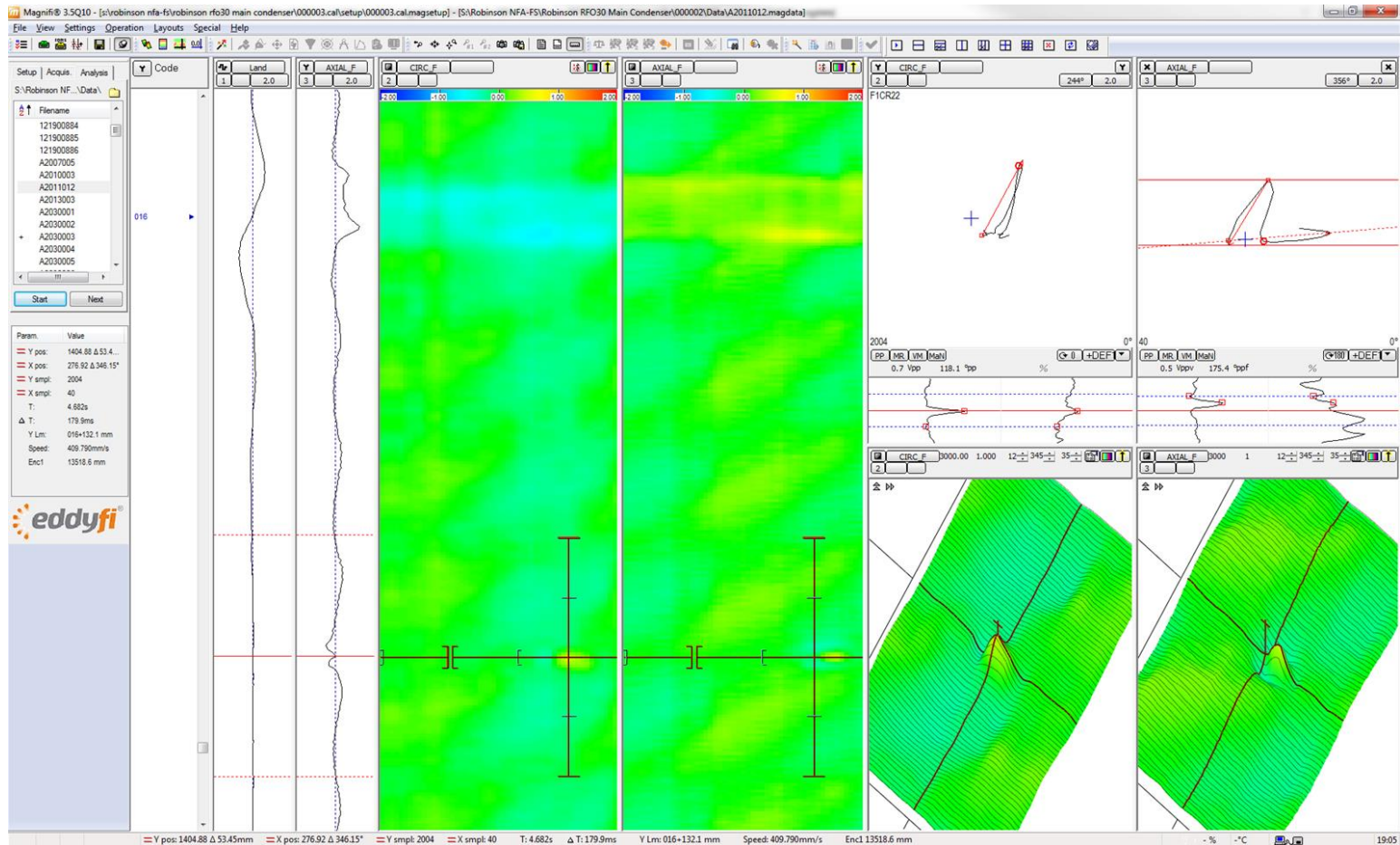




# RNP – Inspection of Record (cont'd)

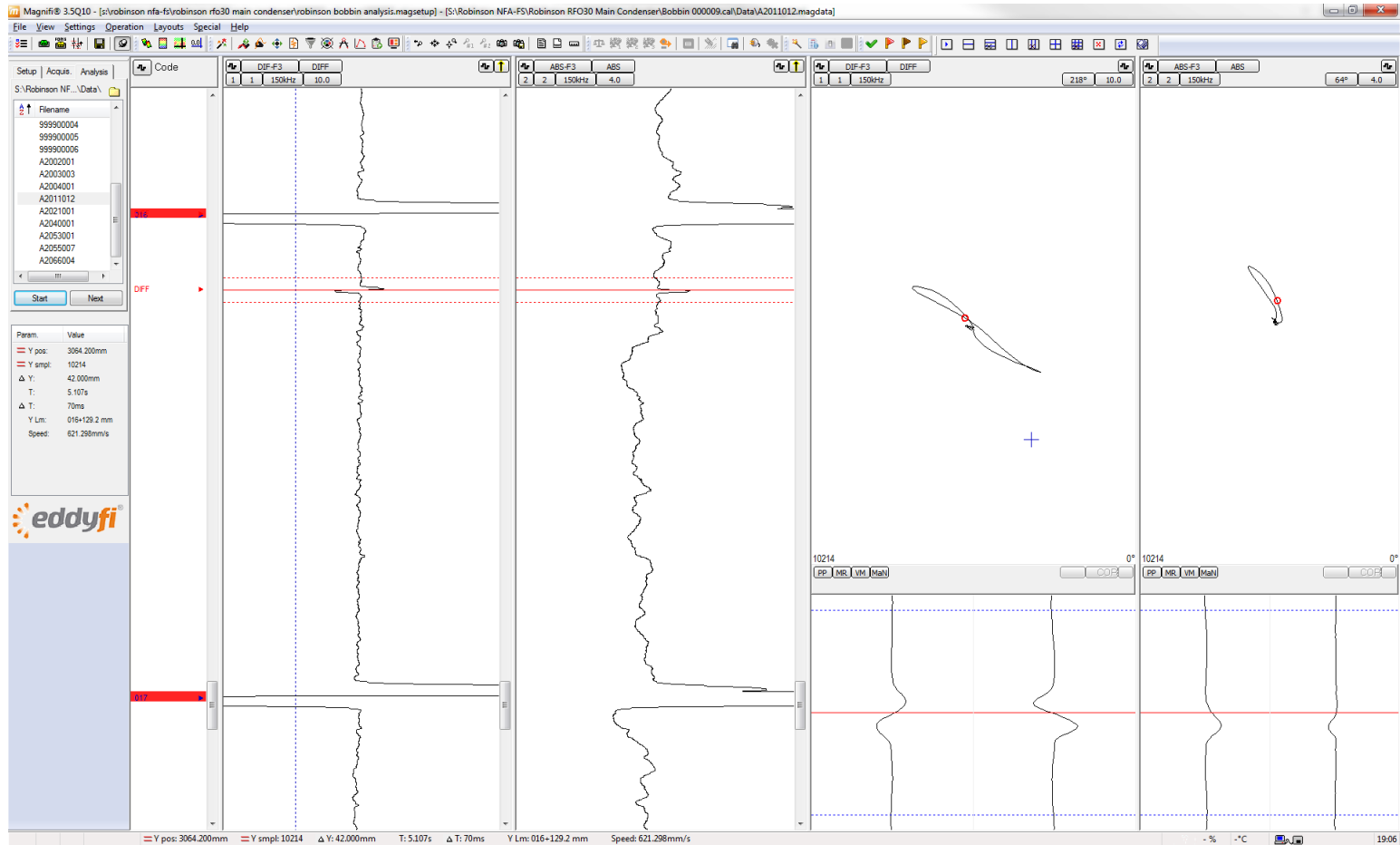
- 439 SS – 19.05 mm OD x 0.71 mm WT ( $\frac{3}{4}$ " OD x 0.028" WT)
- Inspection of record
- Tubing featured some minor pitting, axial cracking (both possibly related to welded seam tubing) and low level erosion.
- Data were collected with the most *mature* version of the NFA FS and all detected indications were rescanned with a full saturation bobbin probe for comparison.

# RNP – Inspection of Record (cont'd)



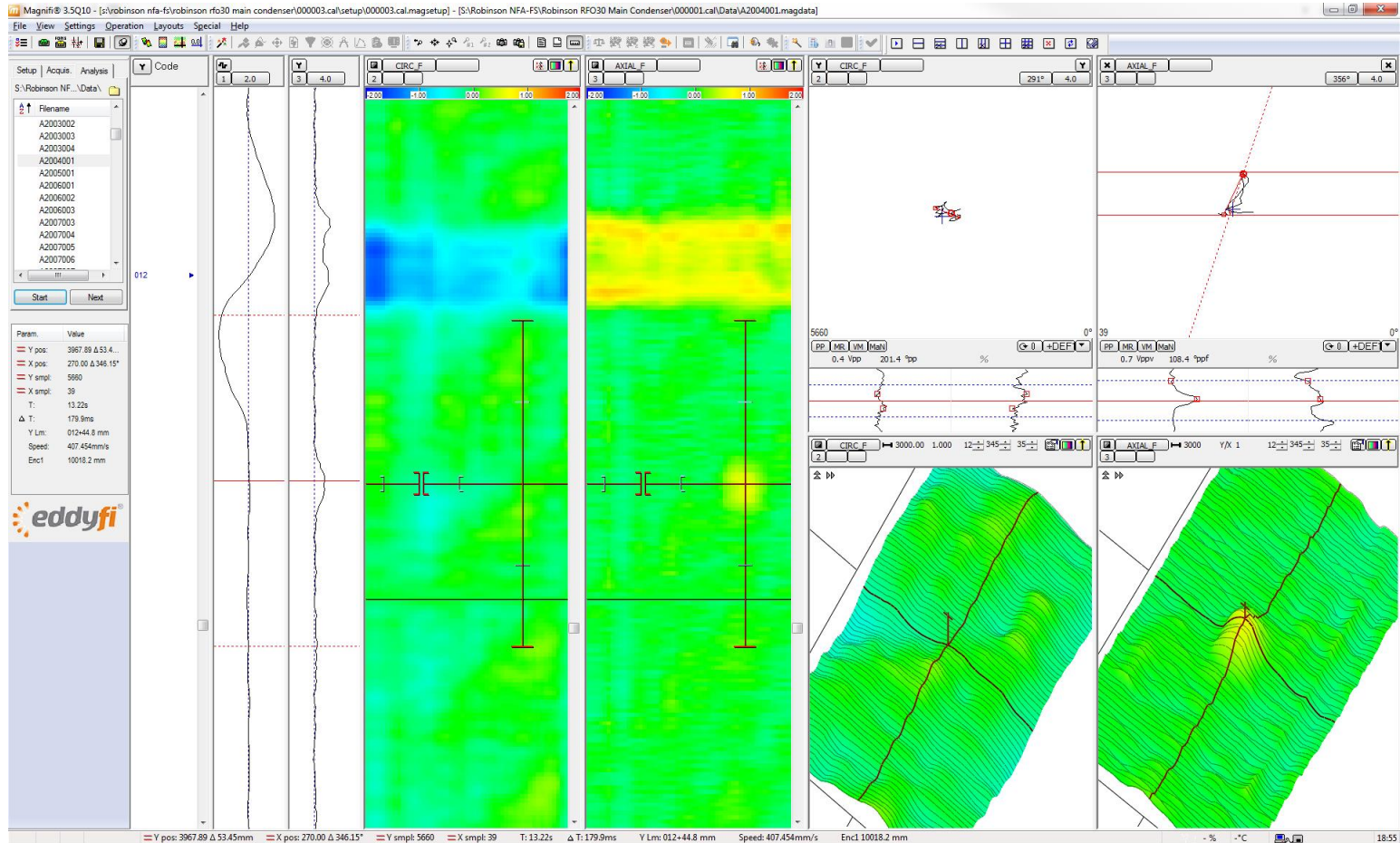
NFA FS scan of a freespan single volumetric indication

# RNP – Inspection of Record (cont'd)



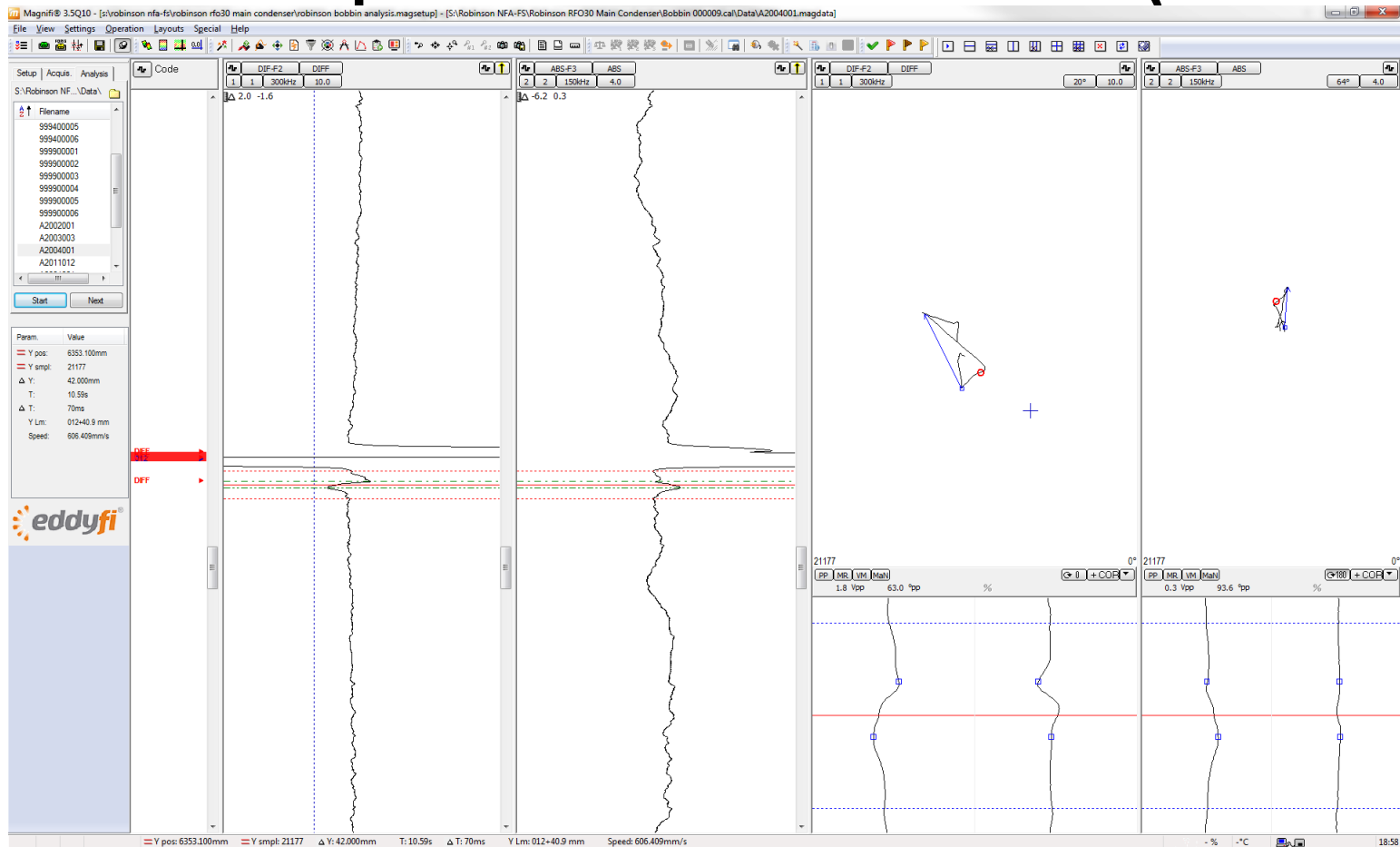
The previous single volumetric indication as found with the saturation bobbin probe

# RNP – Inspection of Record (cont'd)



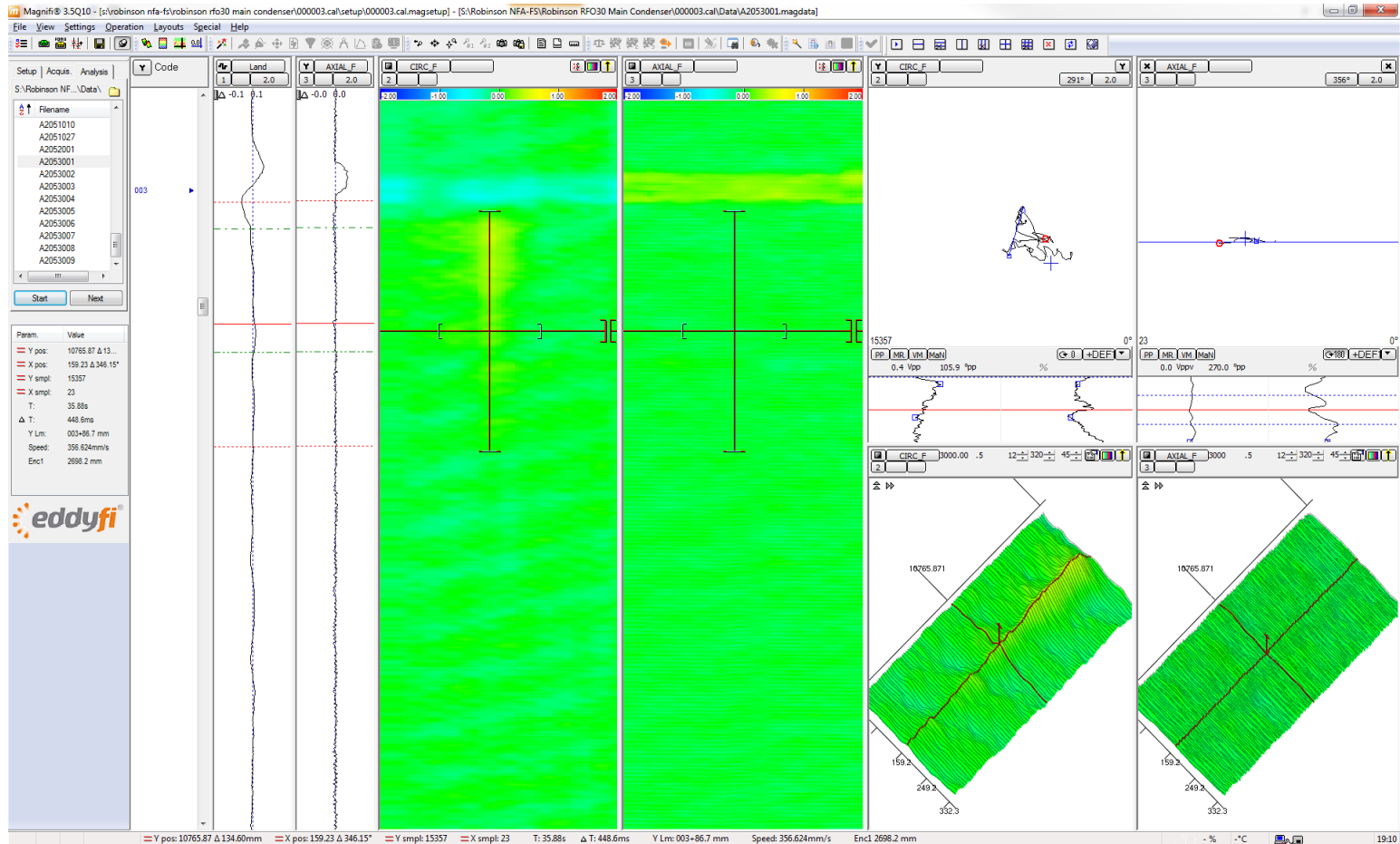
NFA FS scan of a freespan single axially oriented indication

# RNP – Inspection of Record (cont'd)



The previous indication as found with the saturation bobbin probe

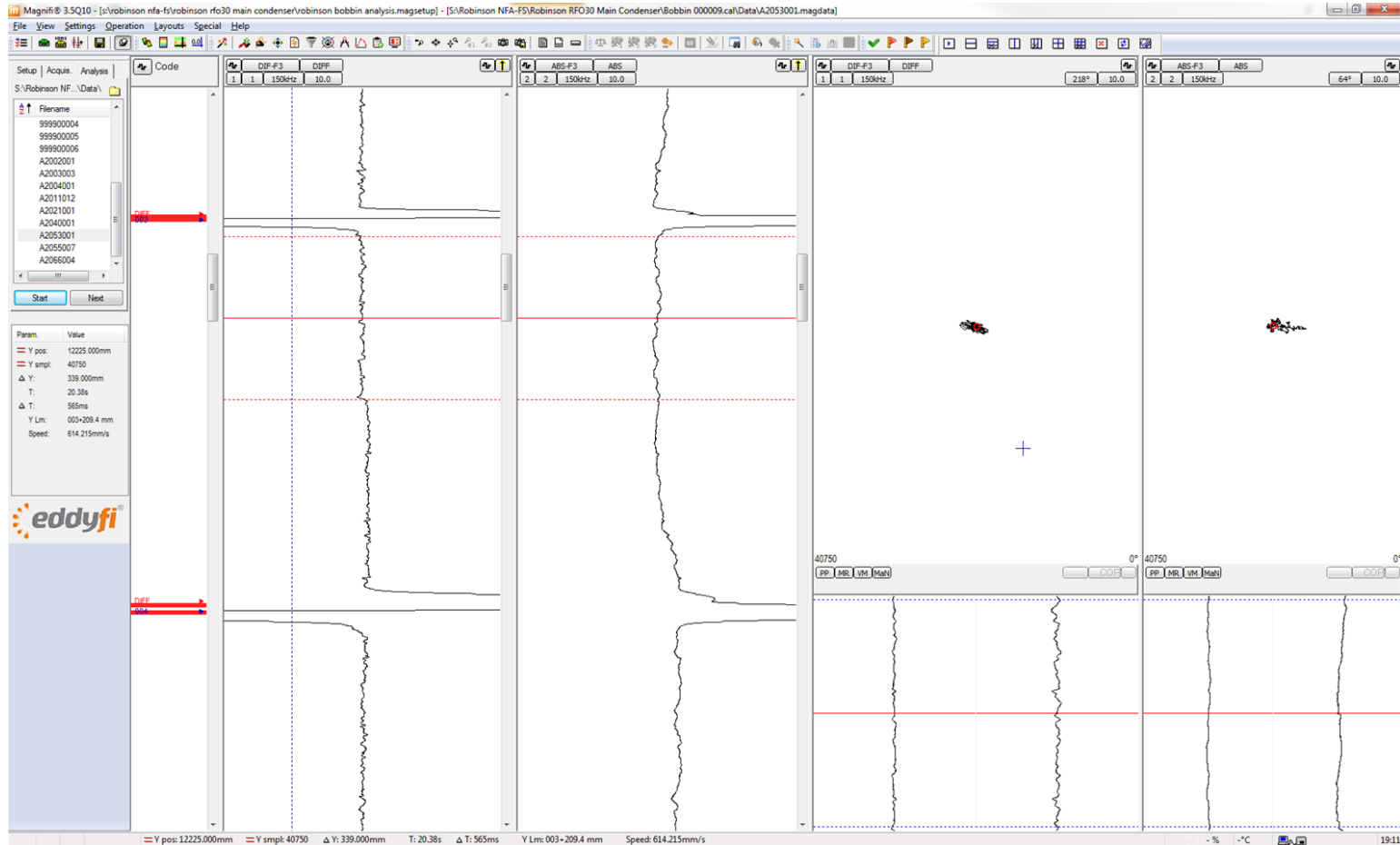
# RNP – Inspection of Record (cont'd)



NFA FS scan of a shallow, gradually tapered volumetric indication (likely erosion)



# RNP – Inspection of Record (cont'd)



The saturation bobbin probe was unable to detect this indication

# Summary and Conclusions

- The NFA FS probe was designed and developed to meet the specific challenges associated with the inspection of mildly ferromagnetic thin walled tubing such as SEA-CURE™, Monel™, 439 SS, Duplex SS and 3Re60.
- A method for selecting an appropriate inspection frequency has been suggested and laboratory and mock-up testing has, thus far, validated this method.
- Multiple field trials and now two inspections of record have been successfully completed with no negative transients (missed indications, mismatches with previous data)
- All *new tubing* should be lab tested prior to field deployment.



# Acknowledgements

- Ty Mau at Duke Power
- Nathan Driessen and Nathan Muthu at EPRI
- “The Crews” from Curtis-Wright (Anatec) and The Merrick Group

# References

1. Cecco V., Van Drunen G., Sharp F.L., Eddy Current Manual Volume 1 – AECL-7523 Rev. 1, 1981 Nov.
2. Electric Power Research Institute (EPRI), NDE Program Highlights newsletter, 2015 April