Pipeline Research Council International (PRCI)
Pipeline Program Research Exchange Meeting
Atlanta, GA, 9-11 February, 2010

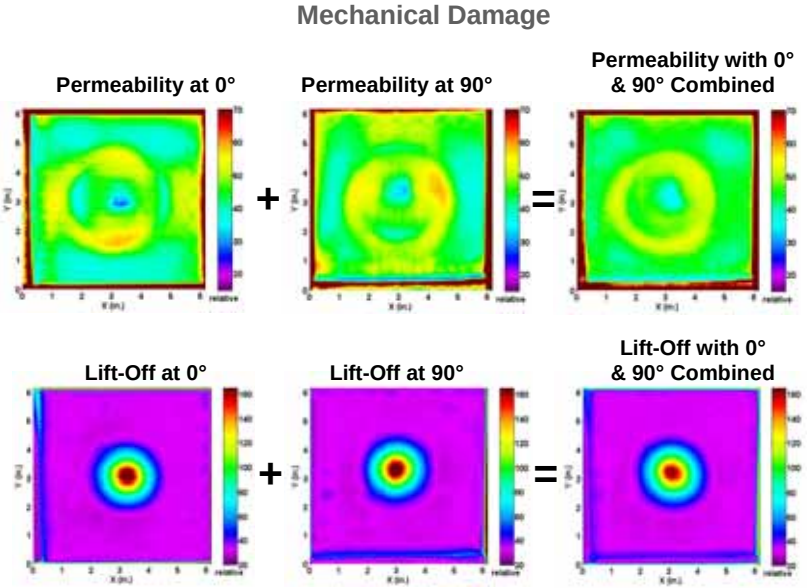
Pending PRCI Project

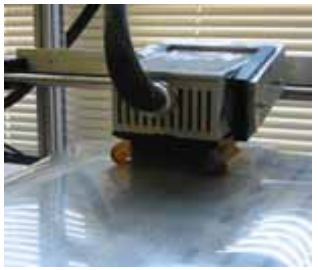
Pipeline NDT from Inside and Out, with MWM-Array Technology

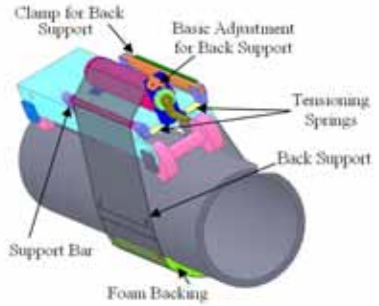
10 February 2010

Presenter: Neil Goldfine, Ph.D

JENTEK Sensors, Inc.
110-1 Clematis Avenue
Waltham, MA 02453-7013; USA
Phone: 781-642-9666
Email: jentek@shore.net







Acknowledgements

Solutions developed with funding from:

DOT:

SBIR (Stress Corrosion Cracking):
"High Resolution Electromagnetic Imaging and Decision Support for Pipeline Life Management"

BAA 304 title:
"MWM-Array Detection & Characterization of Damage through Coatings and Insulation"

BAA 306 title:
"Adaptation of MWM-Array and MFL Technology for Enhanced Detection/Characterization of Damage from Inside Pipelines"

SBIR (Mechanical Damage):
"Digital Imaging of Pipeline Mechanical Damage and Residual Stress"

Chevron:

Project title: "Development of Enhanced Inspection Tool through Protective Barriers"

RTD (Subcontract to RTD, under DOT BAA):

"Development and Demonstration of an Integrated Tool for Mapping, Sizing and Evaluation of SCC for Remaining Strength Prediction"

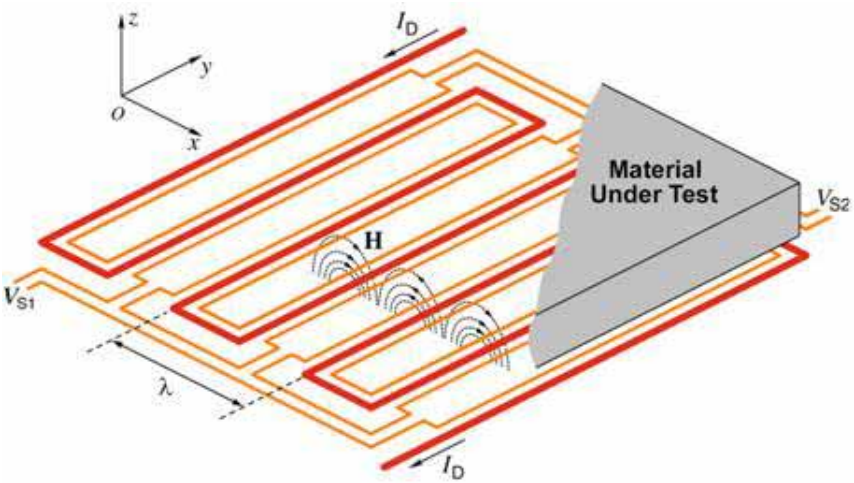
Other Sources: Air Force, Navy, Army, NASA, DOE, DARPA, FAA

Outline

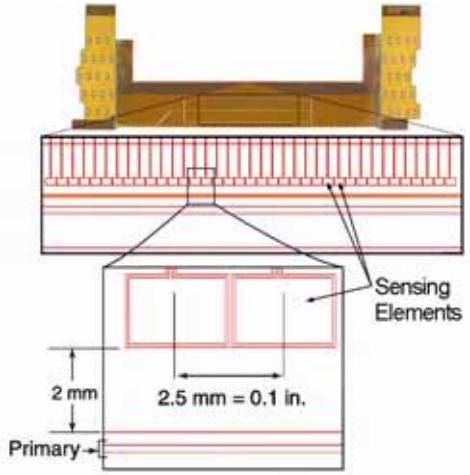
- **Introduction**
- **– MWM Technology**
- Problem Definition
- Inspection Application Results
  - Mechanical Damage
  - Stress Corrosion Cracking (SCC)
  - Near-Surface Corrosion Imaging
  - Stress Mapping / Weld Inspection
- Summary and Next Steps

MWM® and MWM®-Array Eddy Current Sensors

Paradigm Shift: Sensors are Designed to Match Models

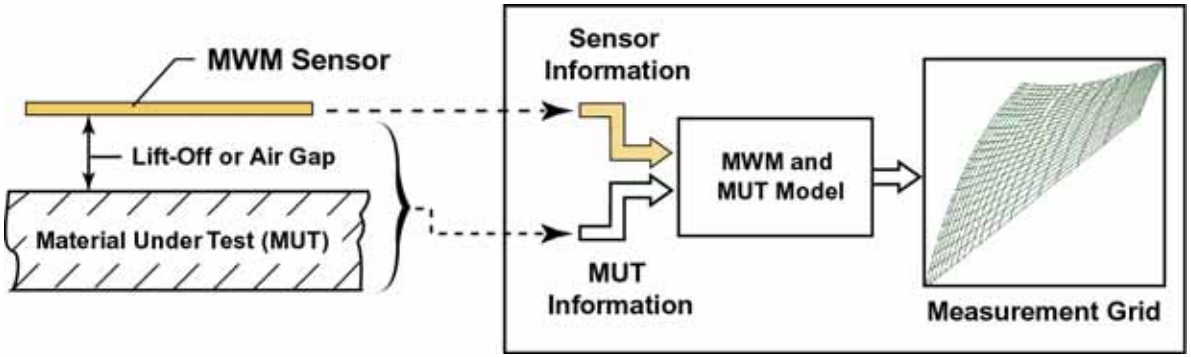


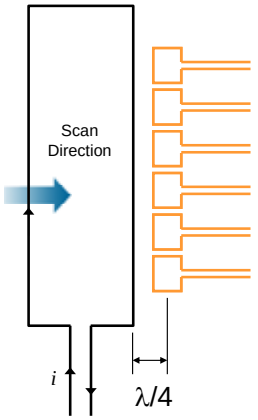
FA24 MWM-Array



VWA001 MWM-Array

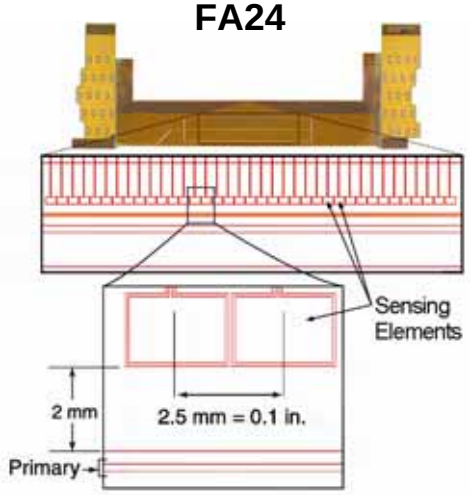
JENTEK Grid Methods



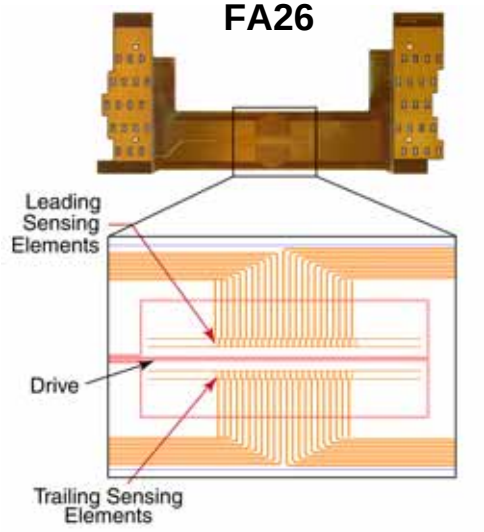


MWM-Arrays used in Pipeline Programs

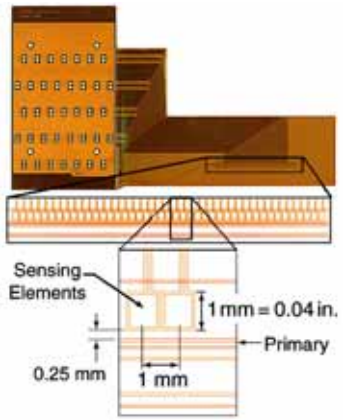
FA24



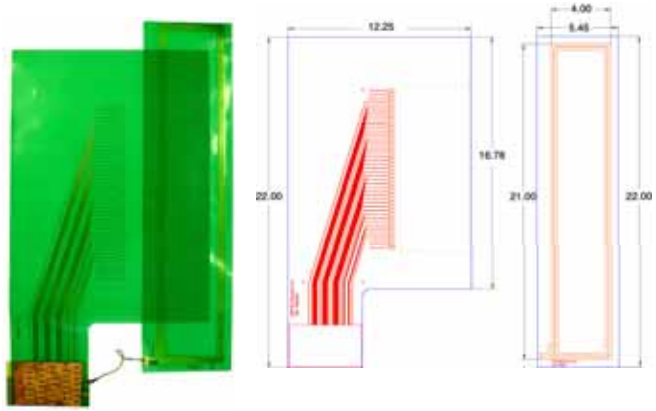
FA26



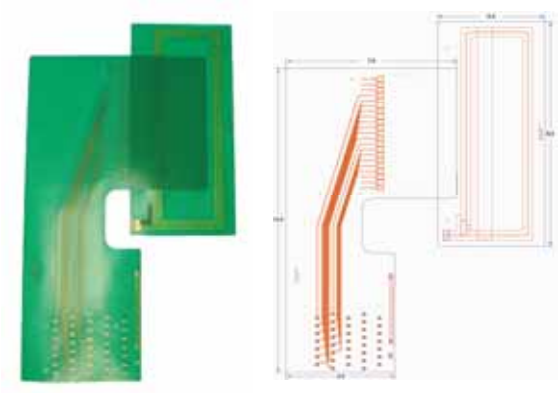
FA28



VWA001



VWA003

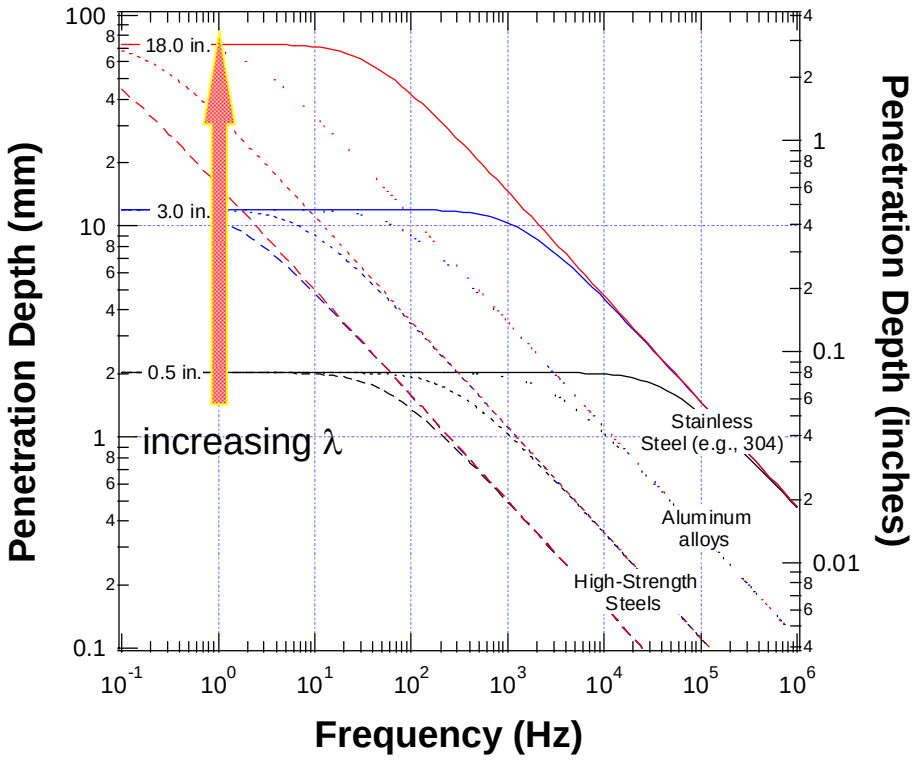


NEW MR-MWM-Arrays under development for very low frequencies

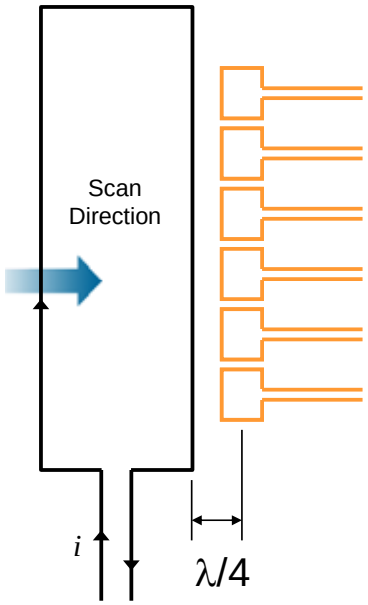
Sensors are not shown to scale.

Sensor Selection

- Decay rate determined by skin depth at high freq. and sensor dimensions at low freq.
- Large dimensions needed for thick coatings
- Low frequencies needed to penetrate through steel pipe wall



Skin depth: $\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$

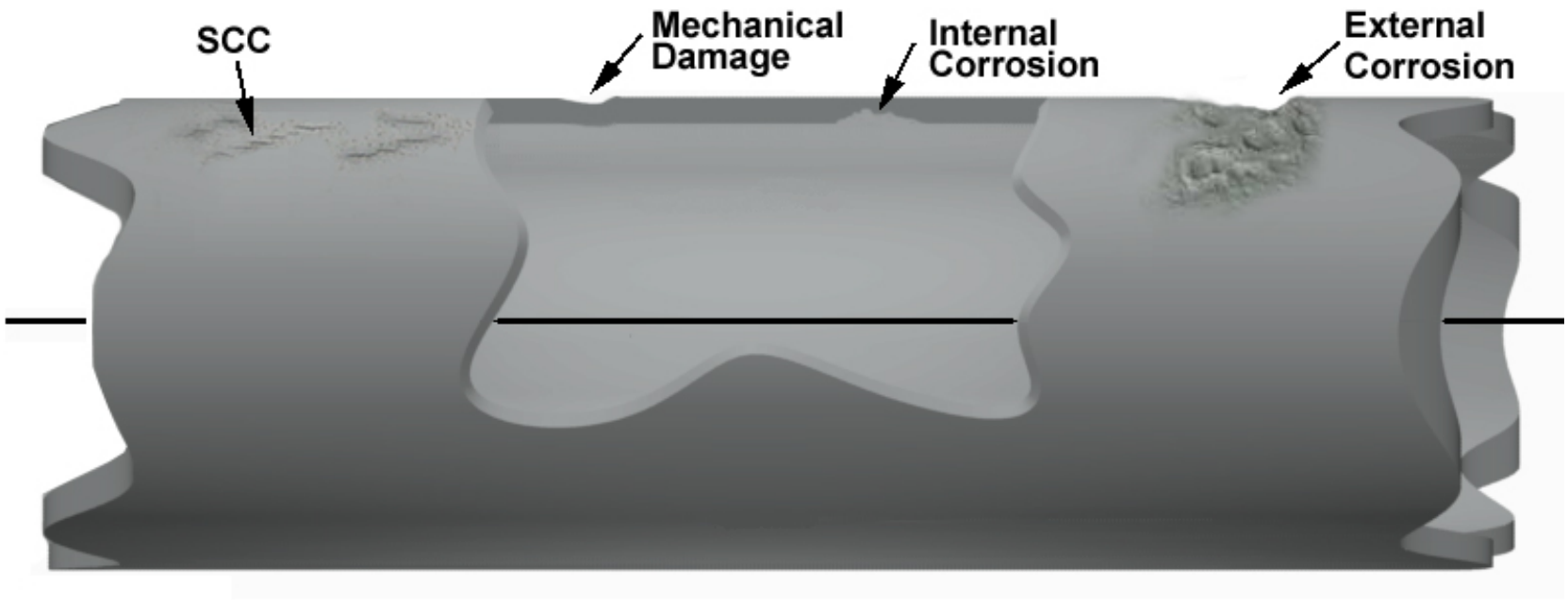


Outline

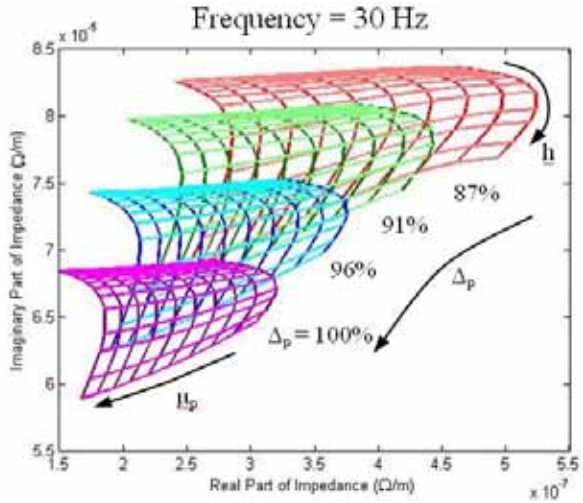
- Introduction
  - MWM Technology
- **Problem Definition**
- Inspection Application Results
  - Mechanical Damage
  - Stress Corrosion Cracking (SCC)
  - Near-Surface Corrosion Imaging
  - Stress Mapping / Weld Inspection
- Summary and Next Steps

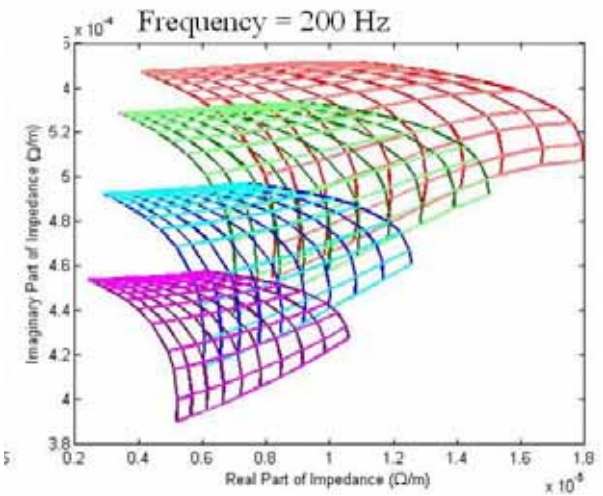
Damage Conditions

- Mechanical Damage, SCC, External Corrosion, Internal Corrosion
- External damage often under coatings (0.01 to 4 inches thick)

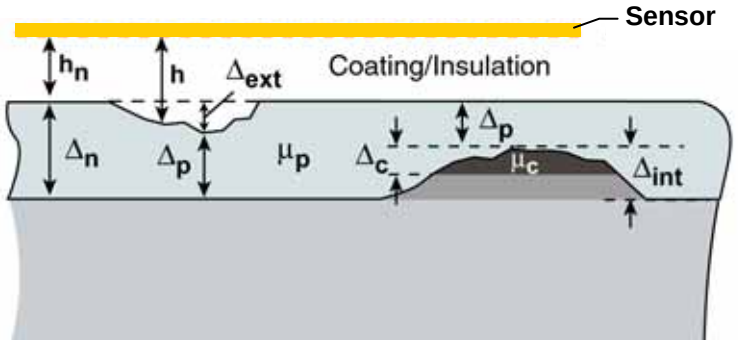


HyperLattices are Precomputed Sensor Response Databases

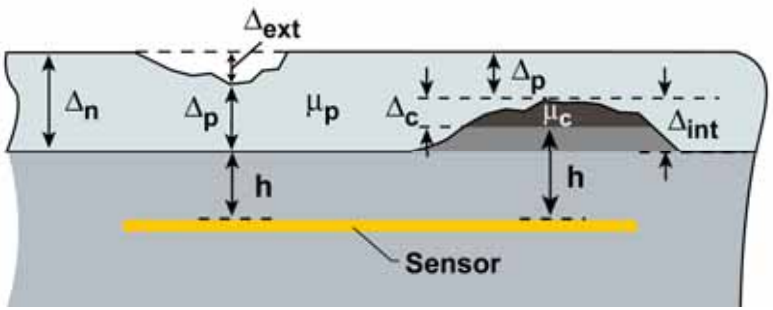




External Inspection



In-Line Inspection



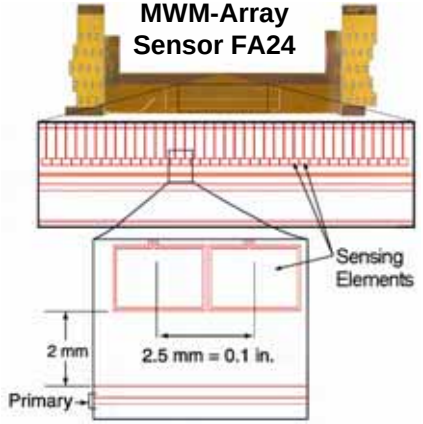
Outline

- Introduction
  - MWM Technology
- Problem Definition
- **Inspection Application Results**
  - **Mechanical Damage**
  - Stress Corrosion Cracking (SCC)
  - Near-Surface Corrosion Imaging
  - Stress Mapping / Weld Inspection
- Summary and Next Steps

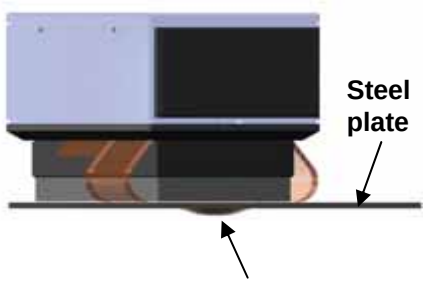
Mechanical Damage Inspection Demonstration

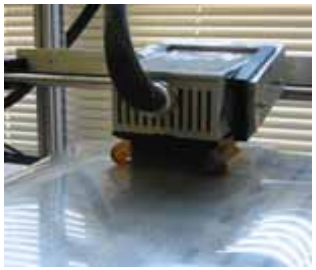
Mechanical Damage Conditions

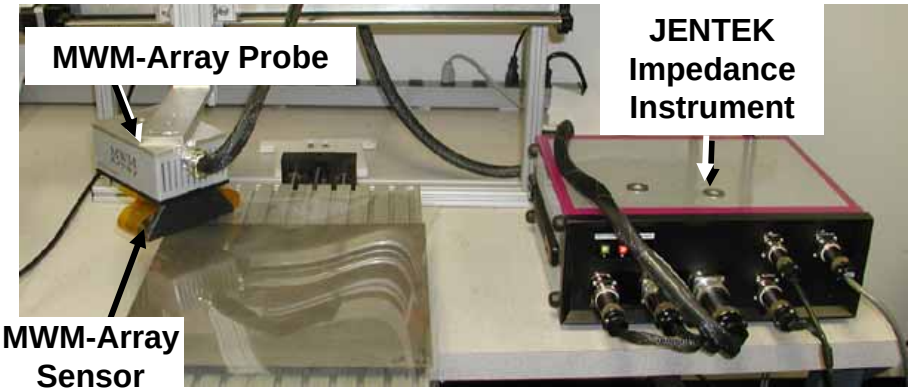
JENTEK Dented Steel Plate

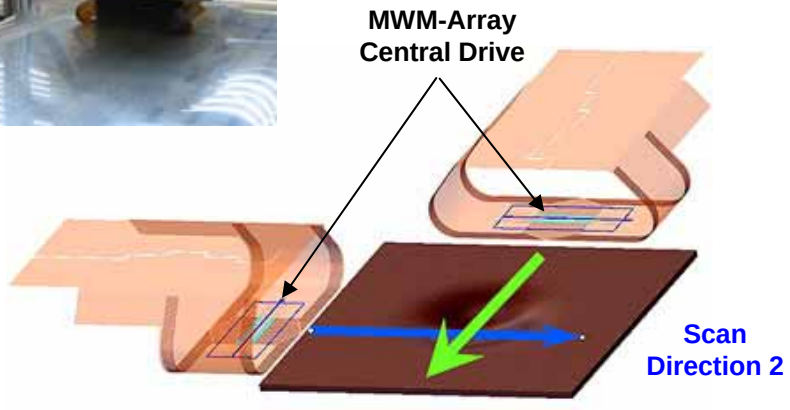


Illustration, Side View
MWM-Array Probe and
MWM-Array Sensor

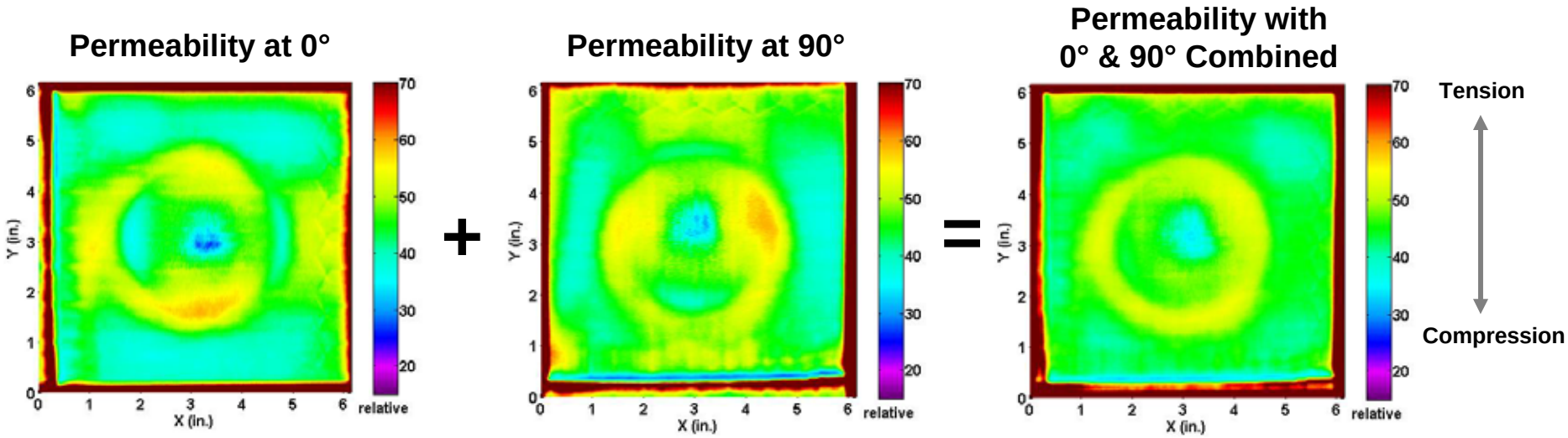








Mechanical Damage Imaging

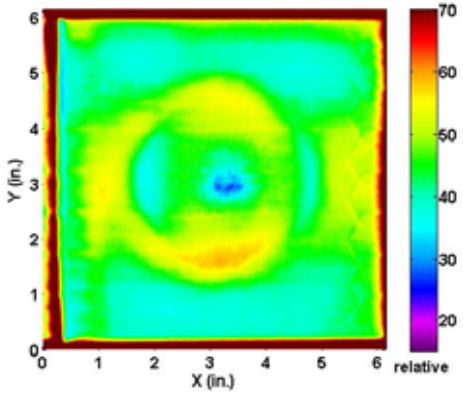


Residual Stress and Microstructural Changes

Mechanical Damage Imaging

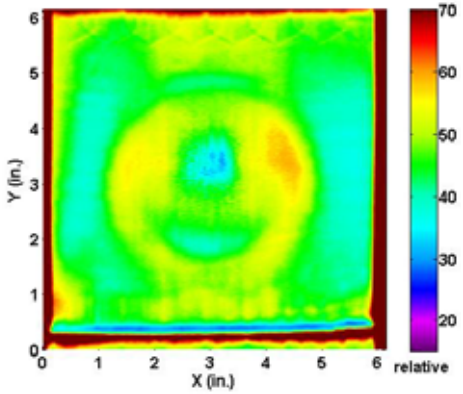
Stress

Permeability at 0°



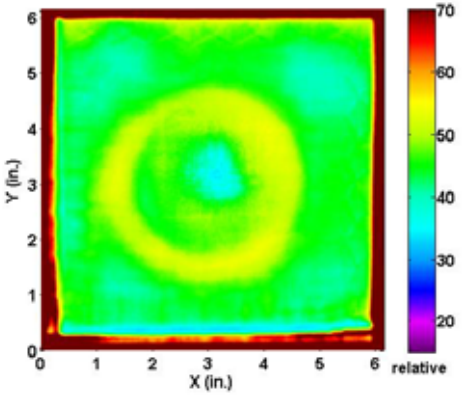
+

Permeability at 90°



=

Permeability with 0° & 90° Combined

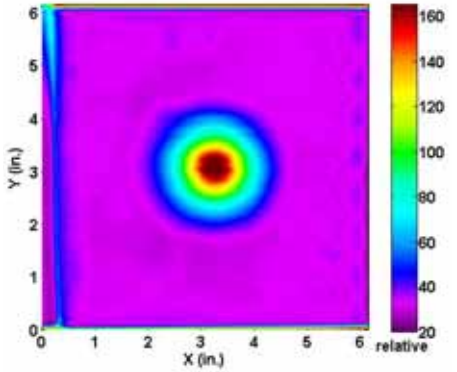


Tension

Compression

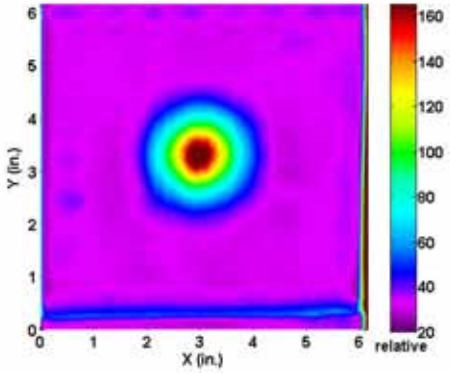
Topology

Lift-Off at 0°



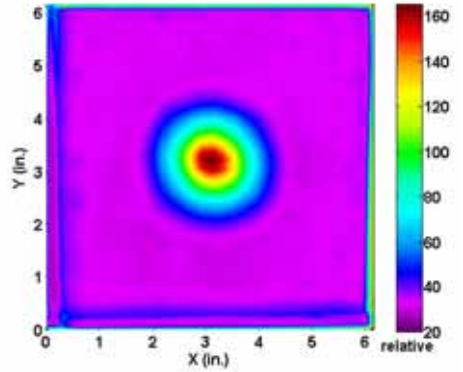
+

Lift-Off at 90°



=

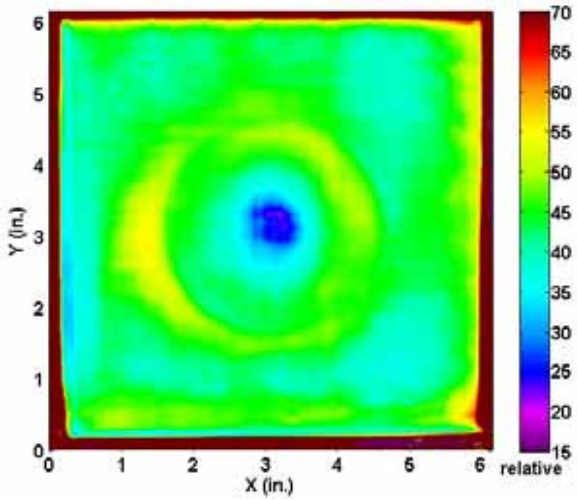
Lift-Off with 0° & 90° Combined



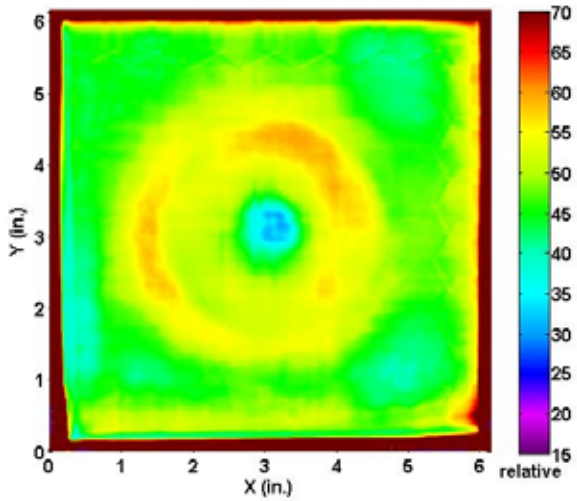
Topology Independent of Orientation

Effective Permeability Images for Symmetric Mechanical Damage in a Plate

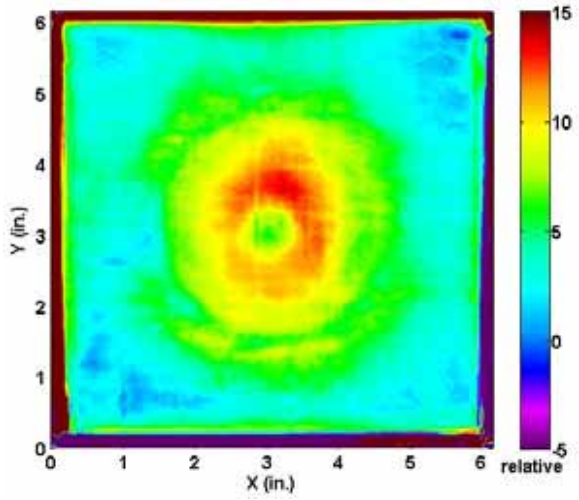
Before Anneal



After Anneal



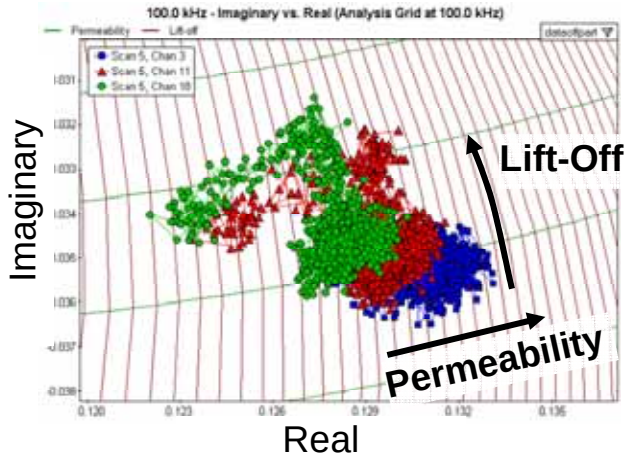
Difference



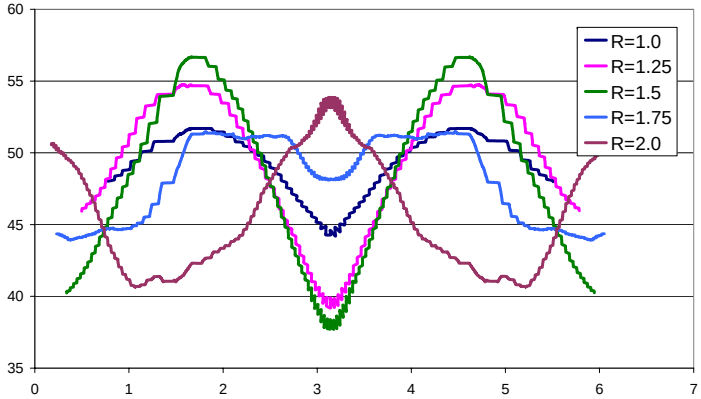
- Steel plate
- Annealed (stress relieved) at 550°C; four hours; air cool
- Permeability measurements are sensitive to the stress distribution around the mechanical damage site

Independent Imaging of Surface Topology and Magnetic Permeability at the Same Time

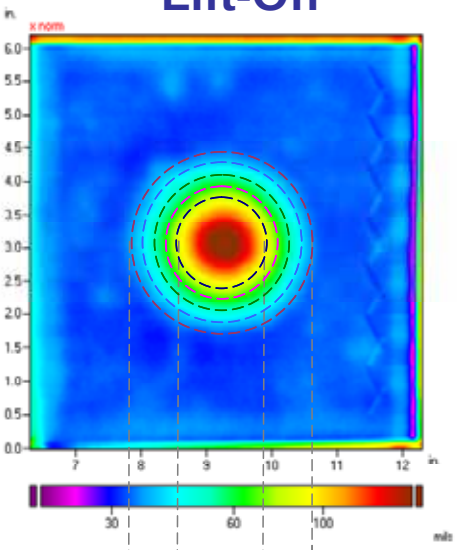
Grid

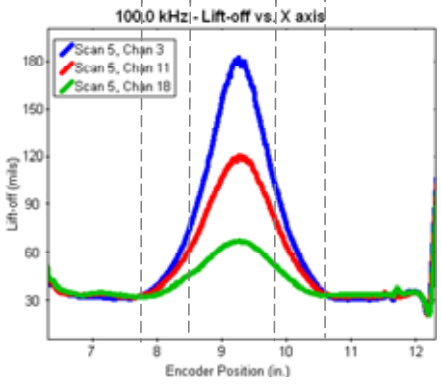


Permeability Variation at Constant Distances From the Center of a Dent: 0 Degree Scan Through 30mil Shim

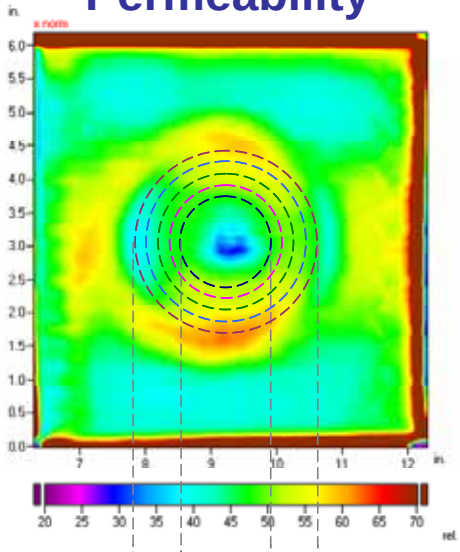


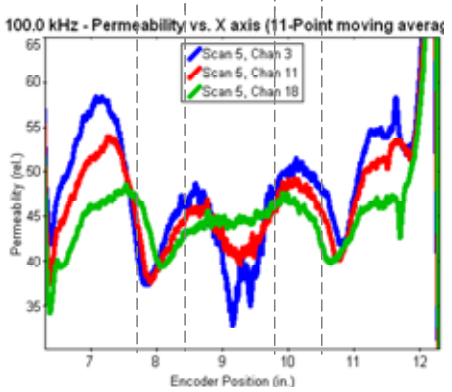
Lift-Off





Permeability*

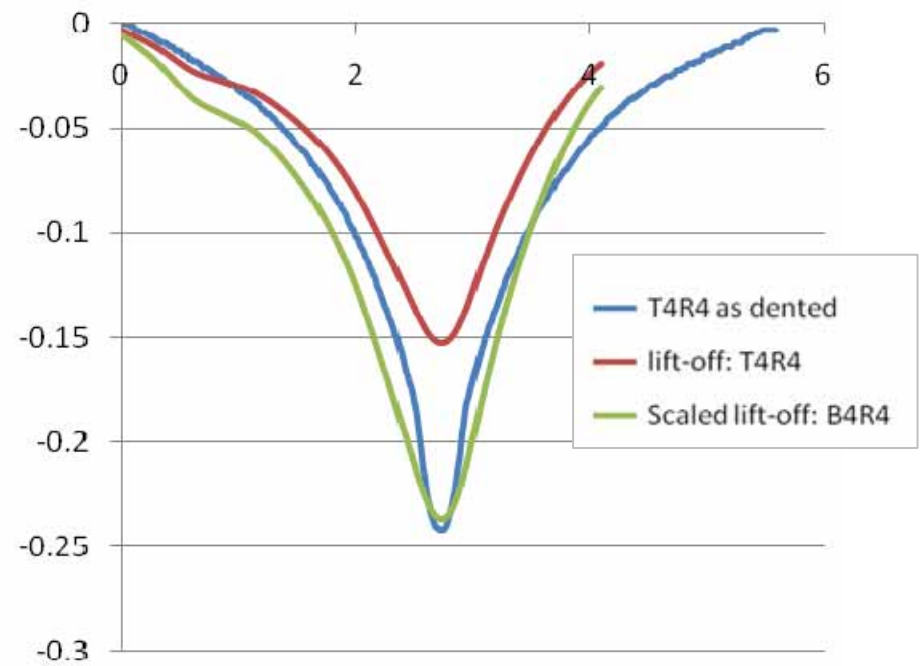




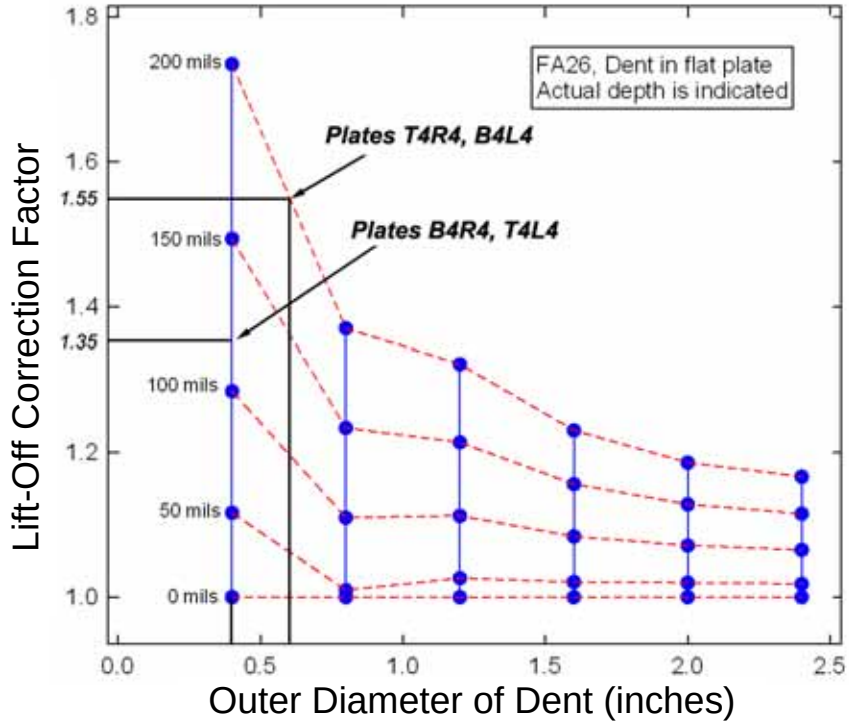
***0° scan data only**

JENTEK Sensors Proprietary

Comparison Between MWM-Array Lift-off and Dial Indicator Measurements

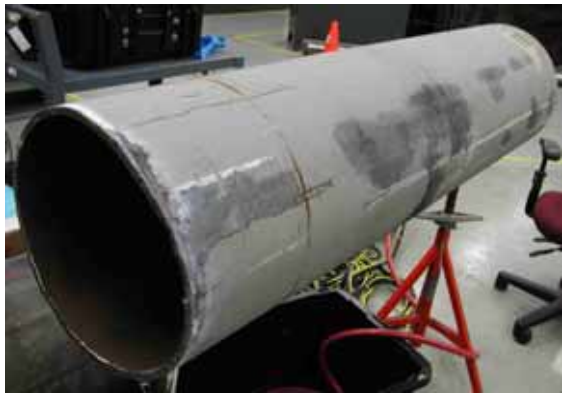


FEM Generated Grid

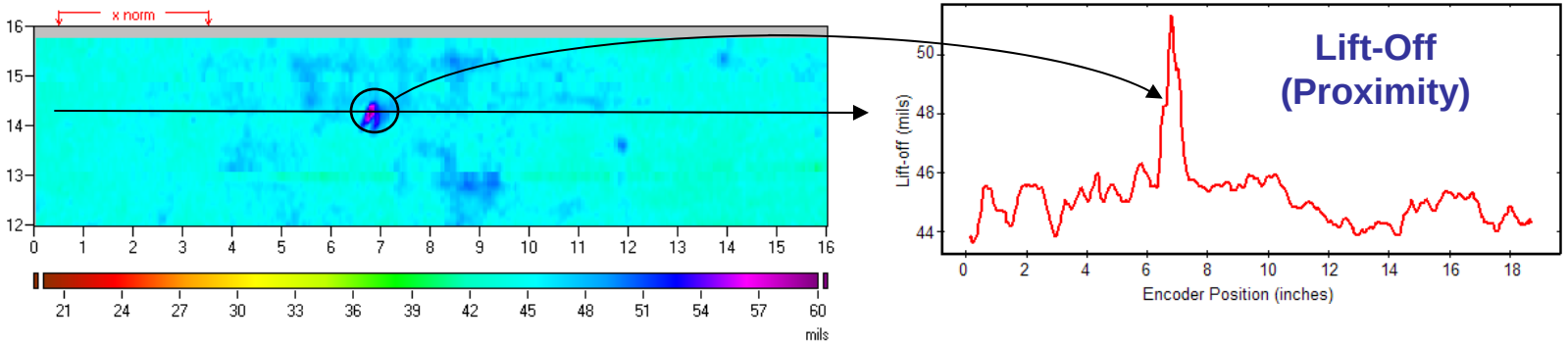


- **Lift-off correction factor to compensate for geometric effects on the lift-off estimates**

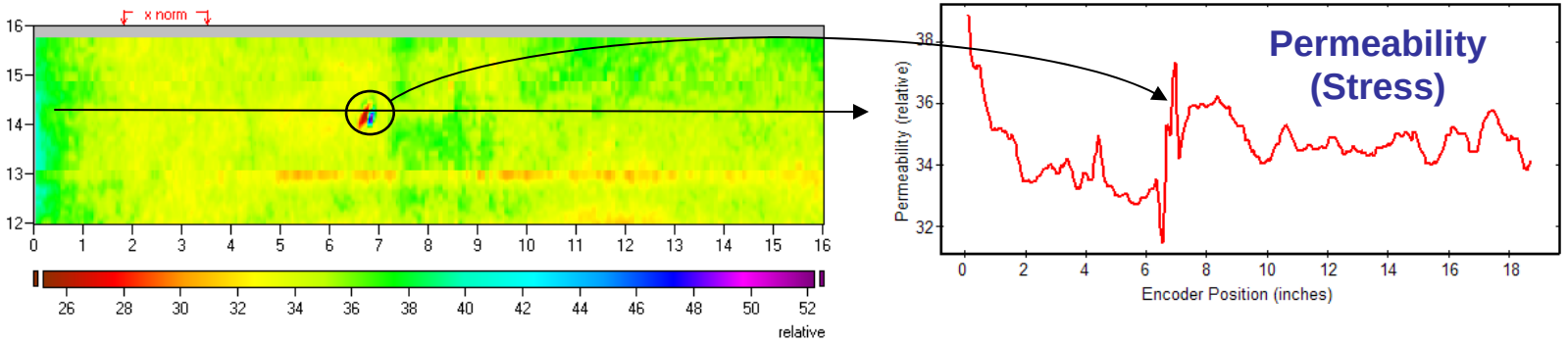
FA24: 16-in. Diameter Pipe



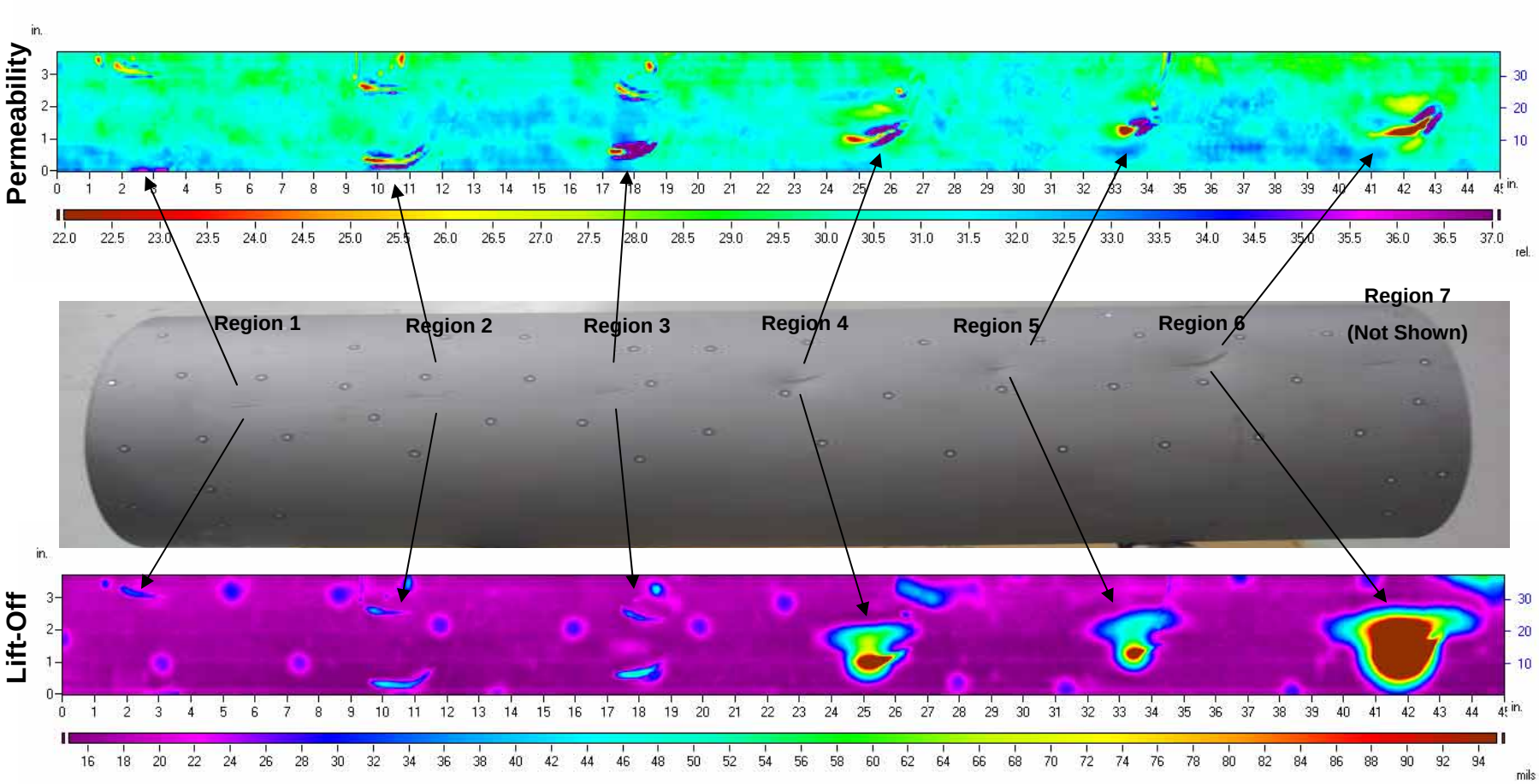
Lift-off



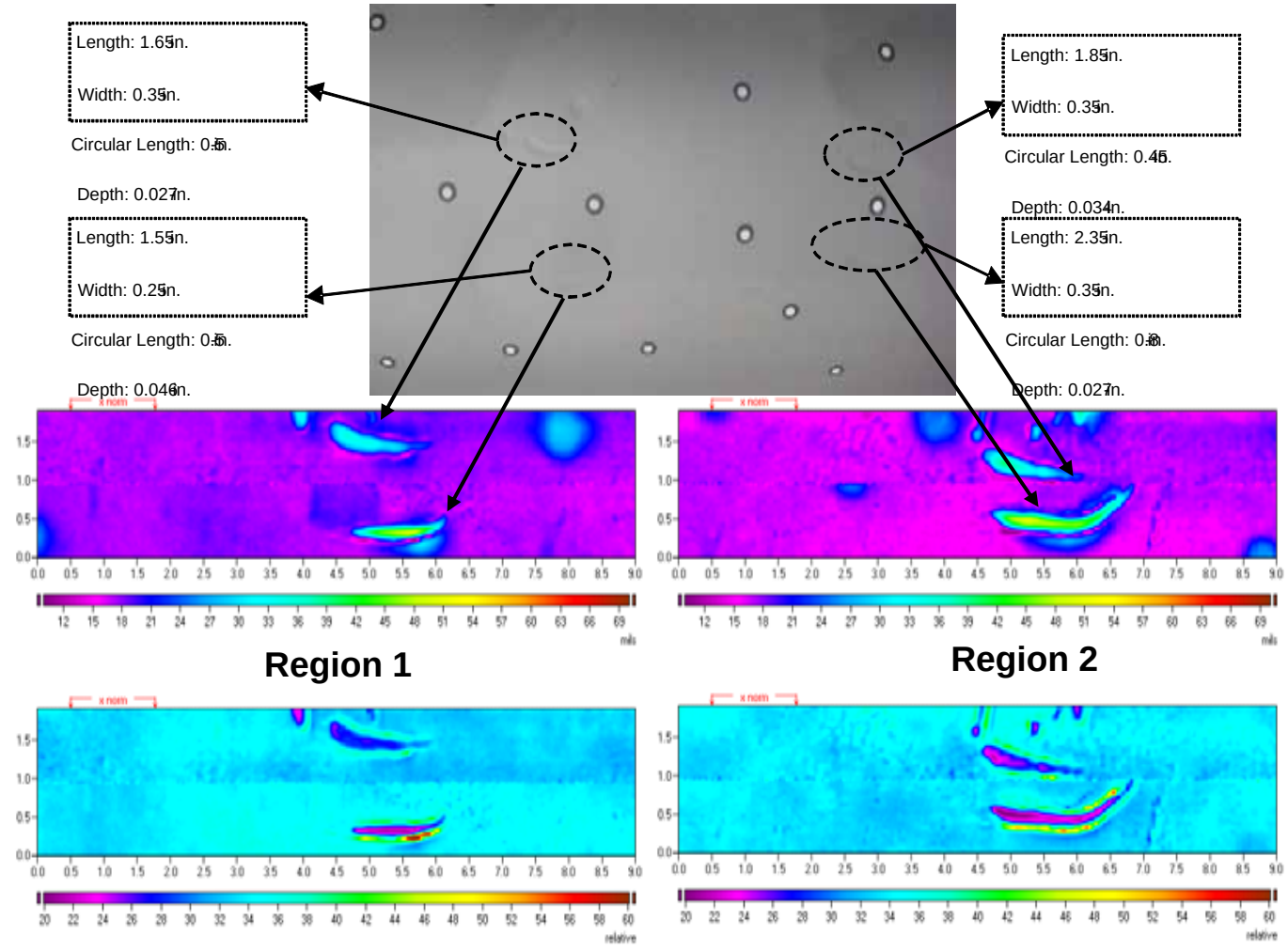
Permeability



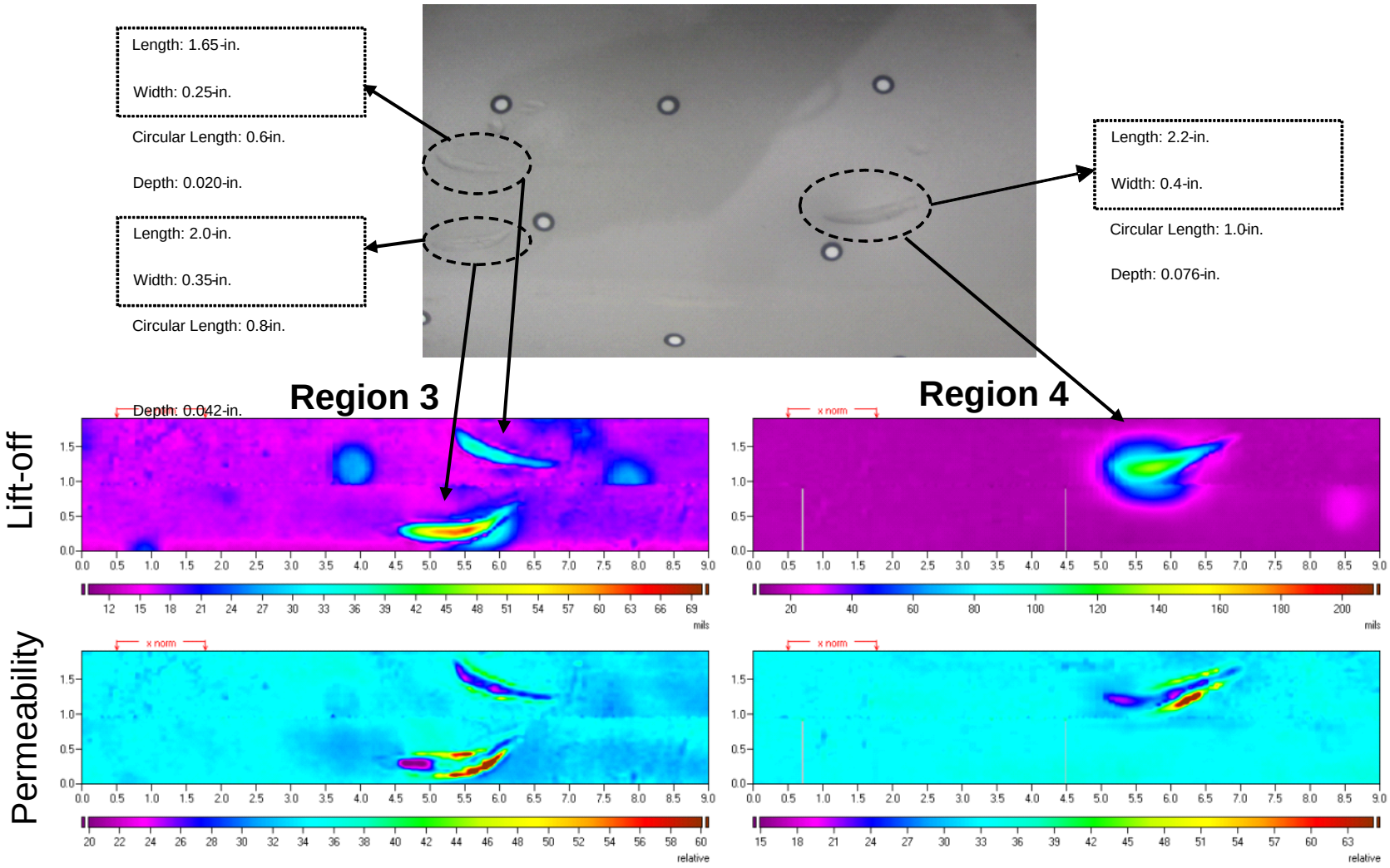
MWM-Array FA24 Scans; 16-in. Diameter Pipe



MWM-Array FA26 Scans; 16-in. Diameter Pipe

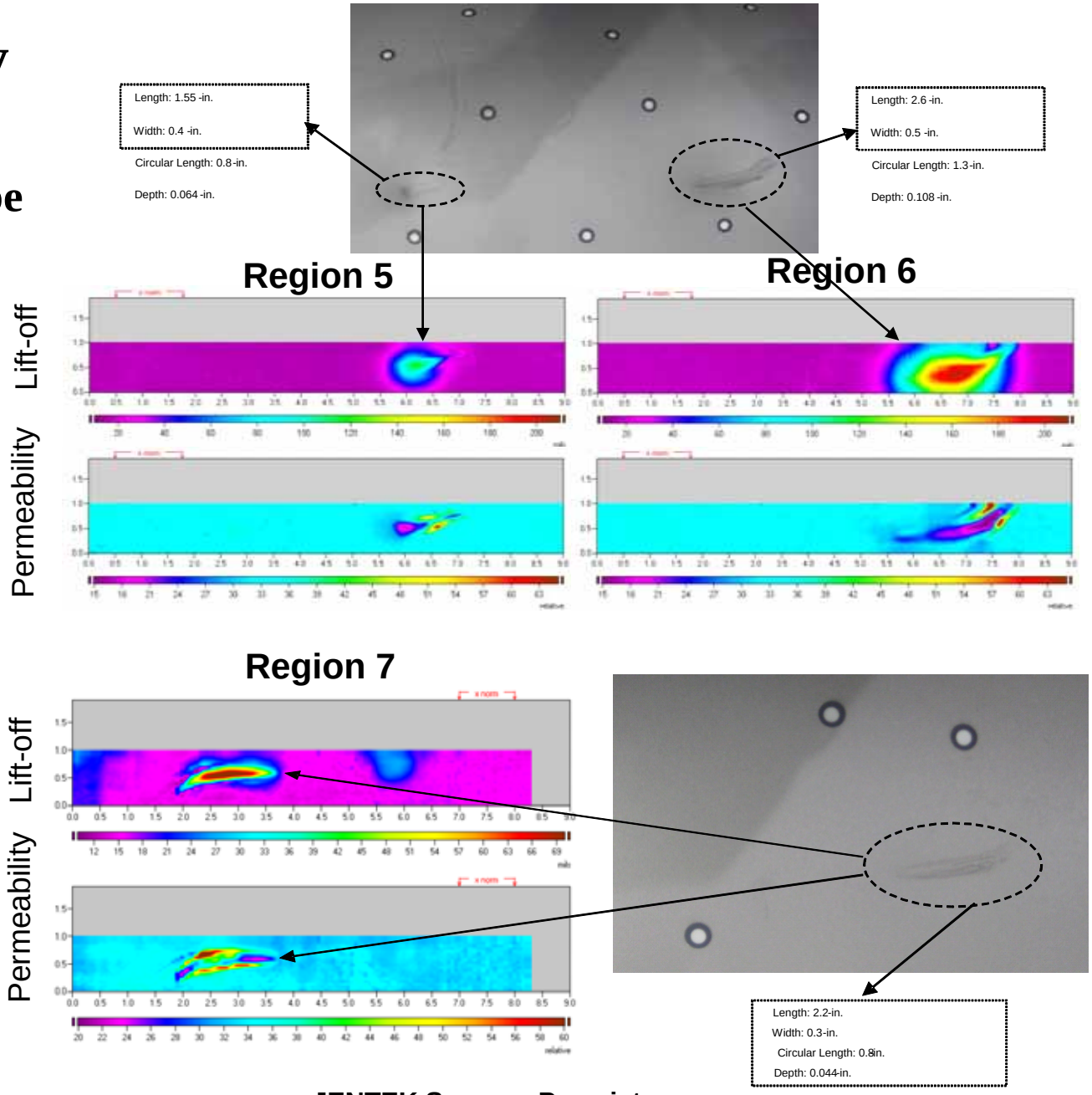


MWM-Array FA26 Scans; 16-in. Diameter Pipe



MWM-Array FA26 Scans

16-in. Diameter Pipe



Outline

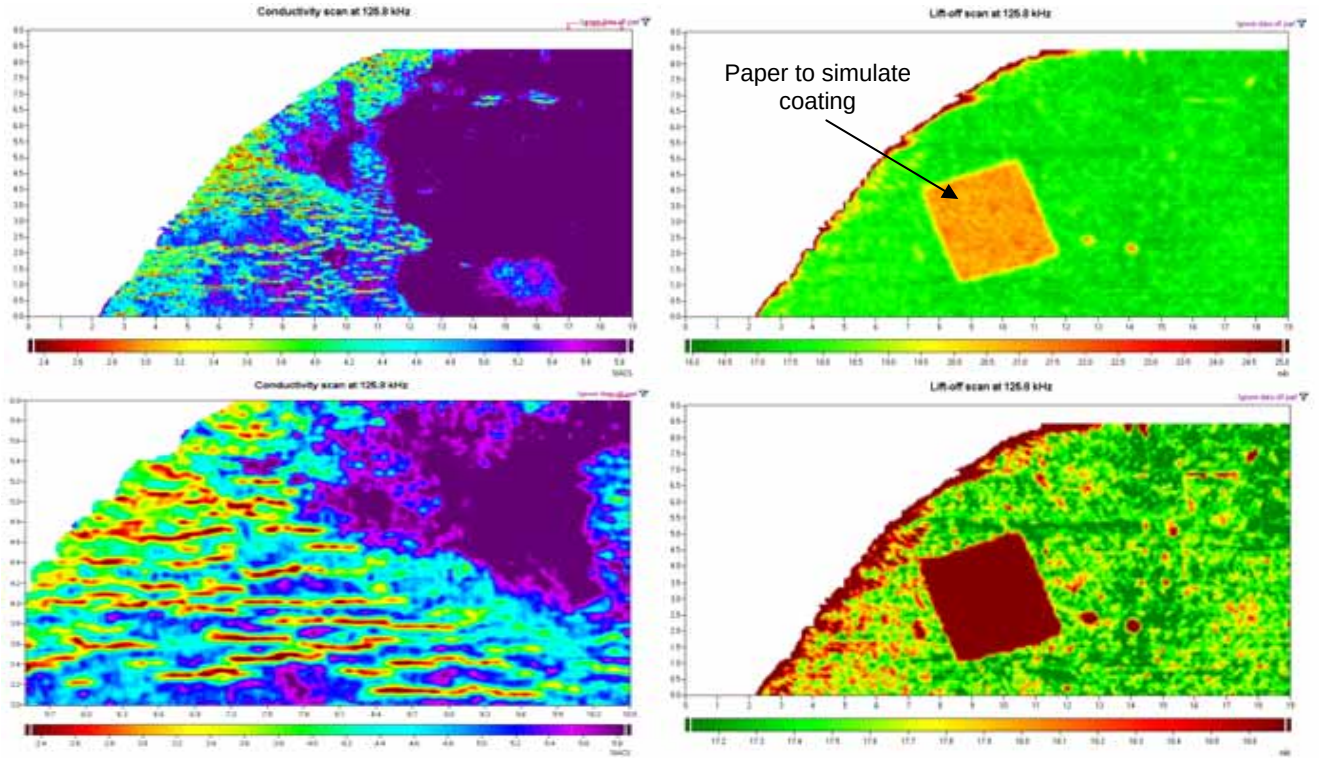
- Introduction
  - MWM Technology
- Problem Definition
- **Inspection Application Results**
  - Mechanical Damage
  - **Stress Corrosion Cracking (SCC)**
  - Near-Surface Corrosion Imaging
  - Stress Mapping / Weld Inspection
- Summary and Next Steps

MWM-Array Scans of Stress Corrosion Cracking

Pipeline Sample Provided by Applus/RTD

Conductivity Images

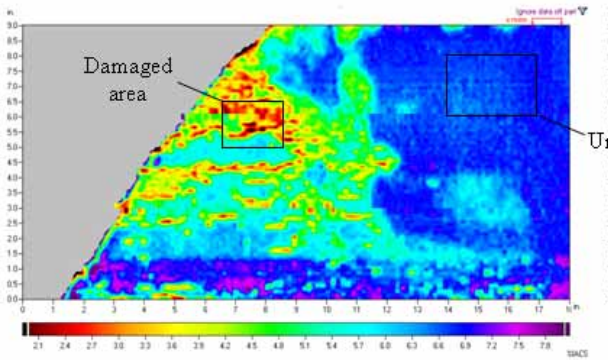
Lift-Off Images



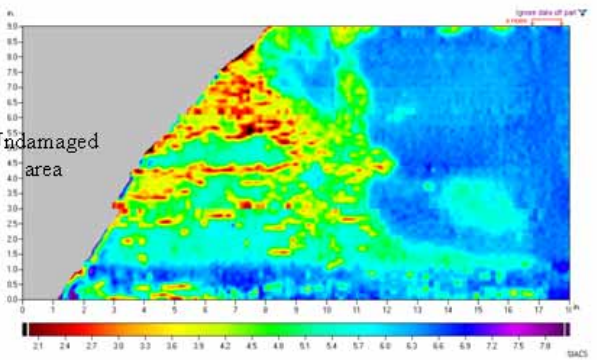
FA24 MWM-Array Sensor Data

Coating Thickness

0.010 in.



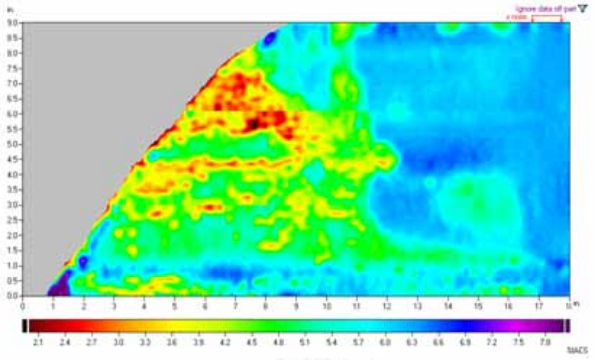
0.010-inch



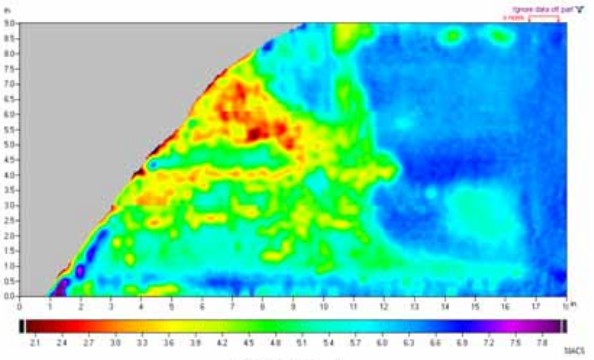
0.020-inch

0.020 in.

0.080 in.



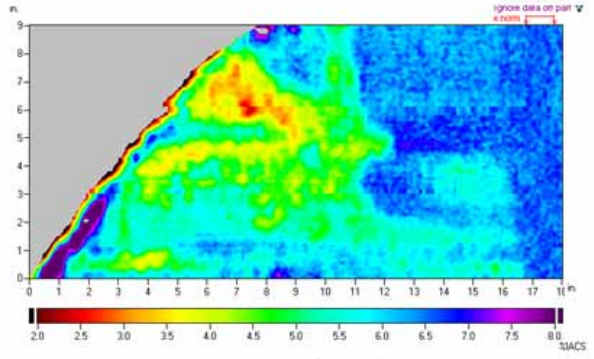
0.080-inch



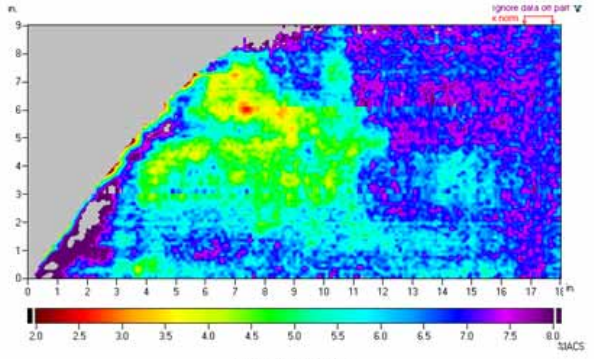
0.135-inch

0.135 in.

0.260 in.



0.260-inch



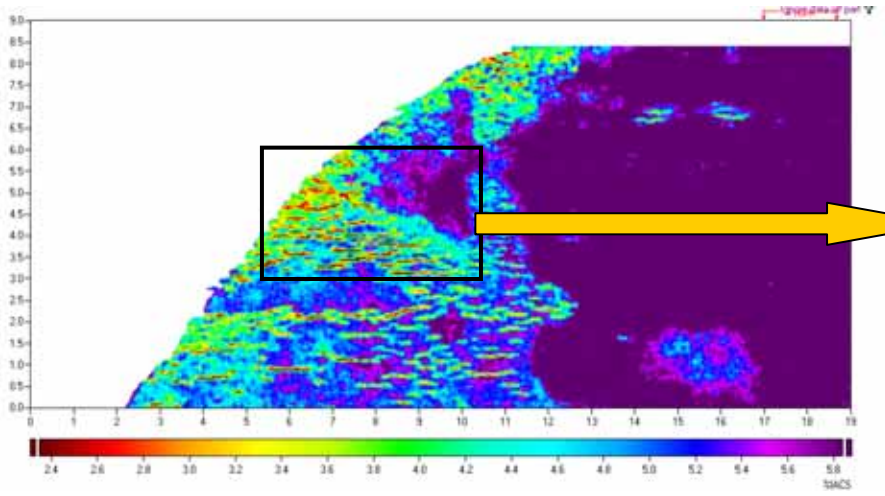
0.330-inch

0.330 in.

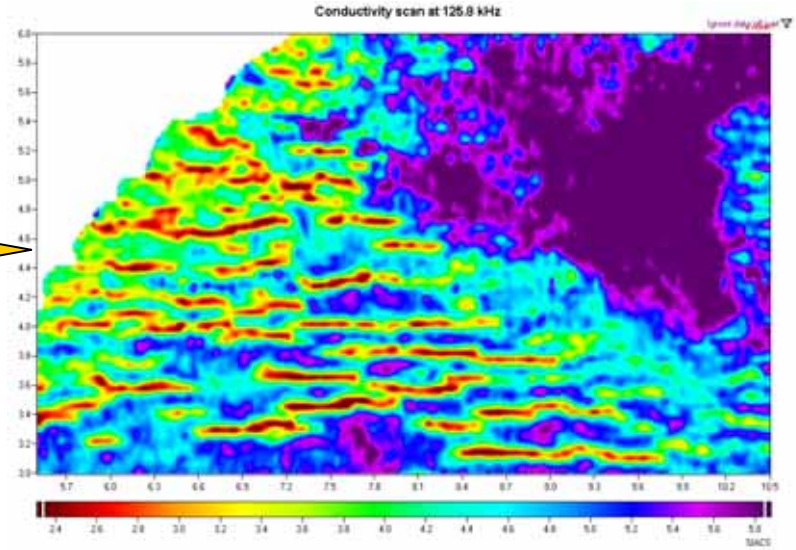
JENTEK Sensors Proprietary

Imaging of Stress Corrosion Cracking

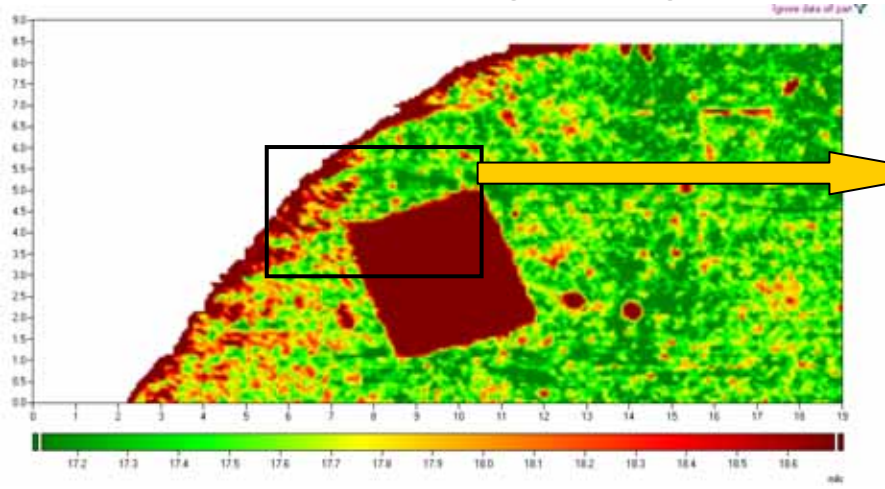
Conductivity Scan



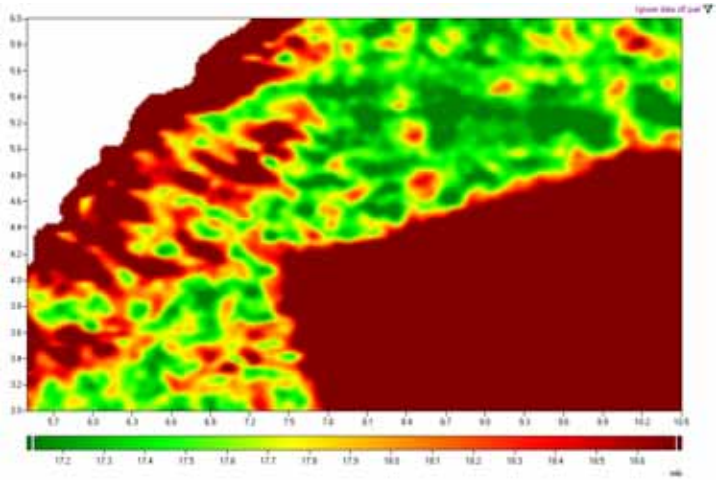
Close-Up of Conductivity Scan



Lift-Off Scan - Through Coating



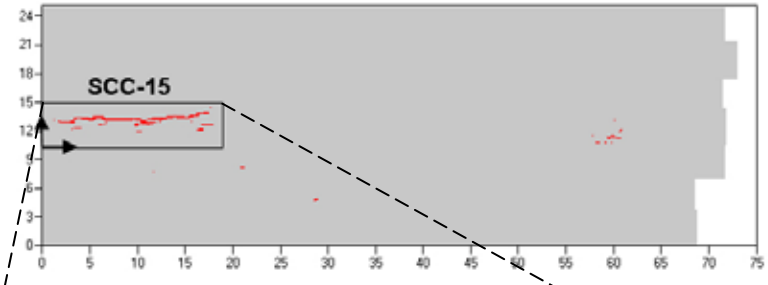
Close-Up of Lift-Off Scan



JENTEK Sensors Proprietary

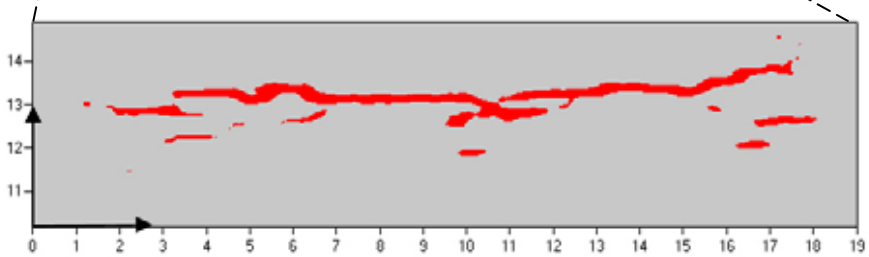
Imaging of SCC in Pipeline Sample

Scans of Pup Section with Identified SCC

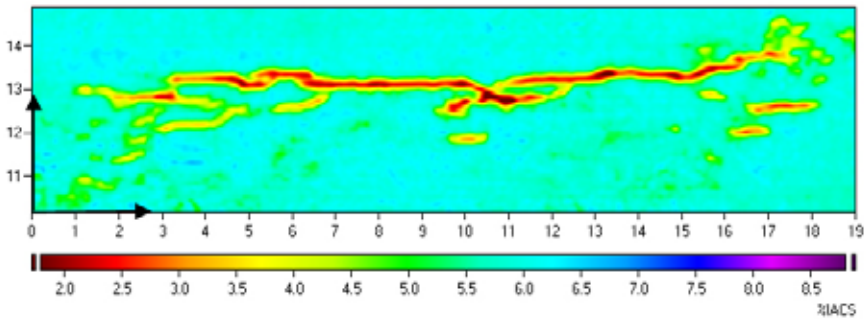


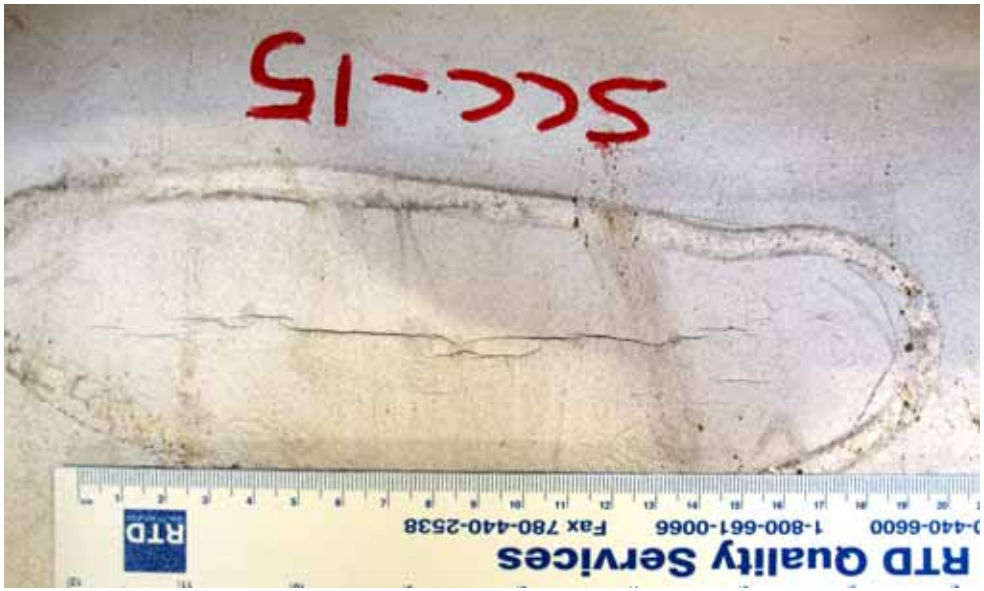
(RTD p/n NPS34 #1)

MWM-Array Threshold Image



MWM-Array Spectrum Color Image

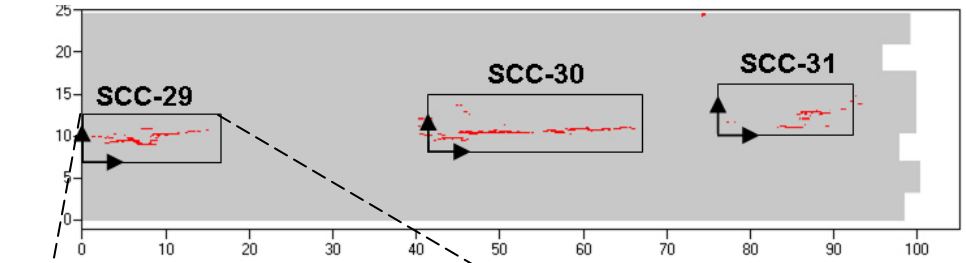




JENTEK Sensors Proprietary

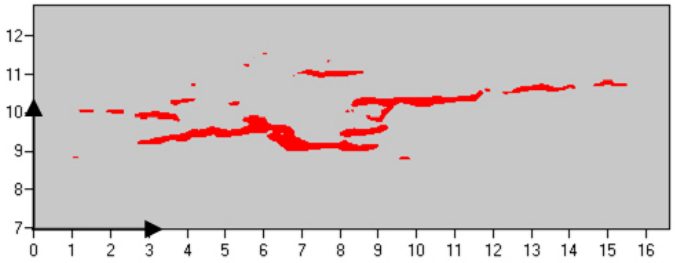
MMW-Array Scans of Second Pup Section

Scans of Pup Section

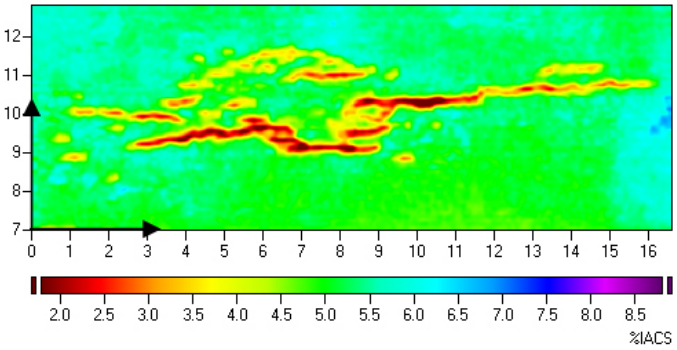


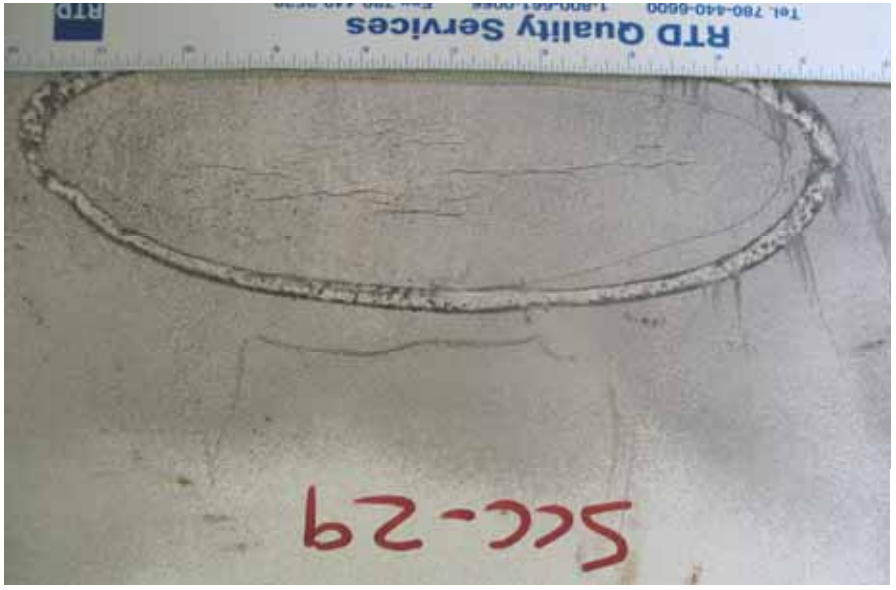
(RTD p/n NPS34 #2)

Threshold Image



Spectrum Color Image

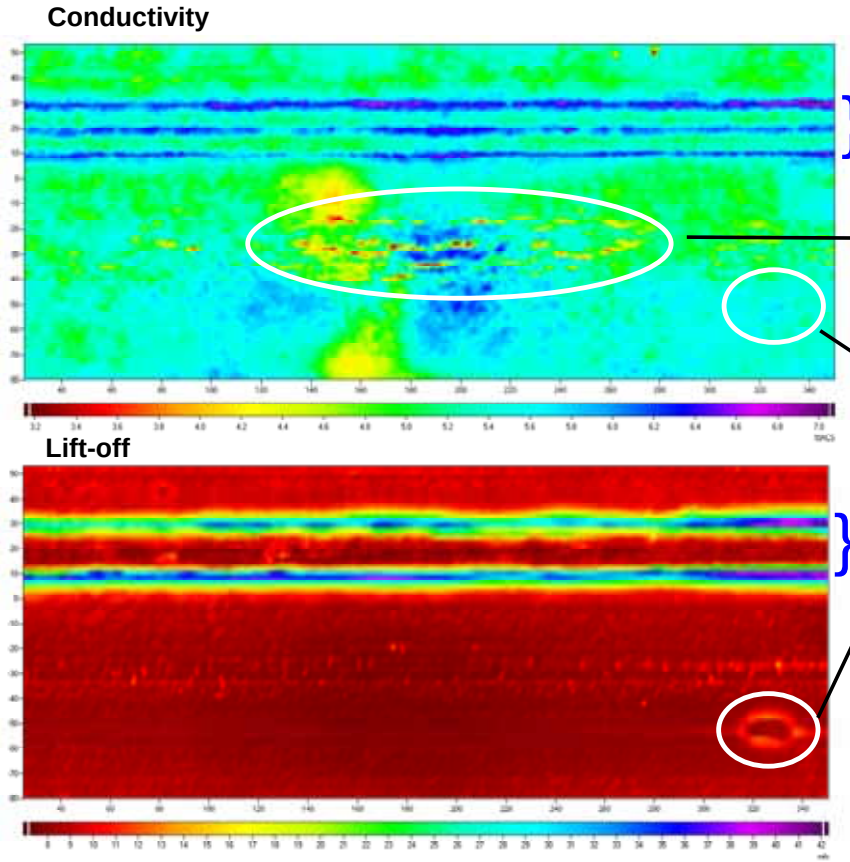




JENTEK Sensors Proprietary

Stress Corrosion Cracking Damage

Applus/RTD DOT program

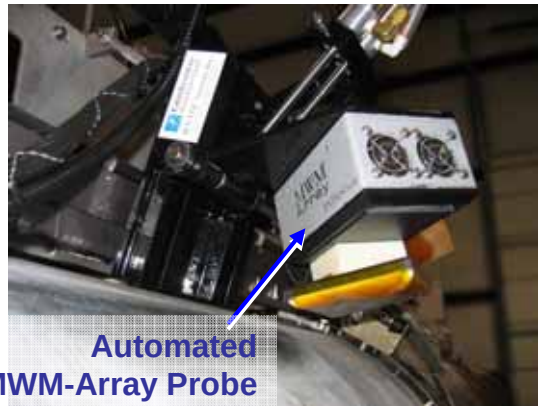


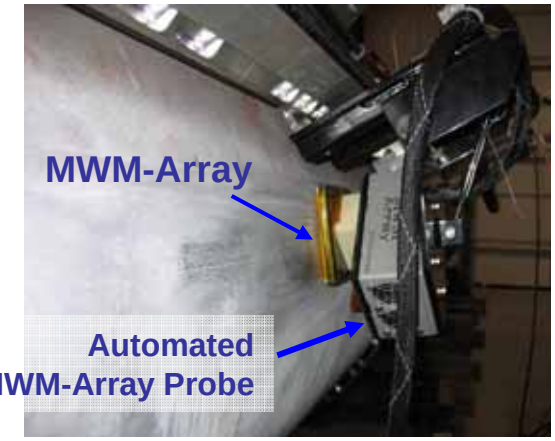
Welded axial seam

Region of SCC

Raised bump in surface material

Minimal artifacts introduced in conductivity image





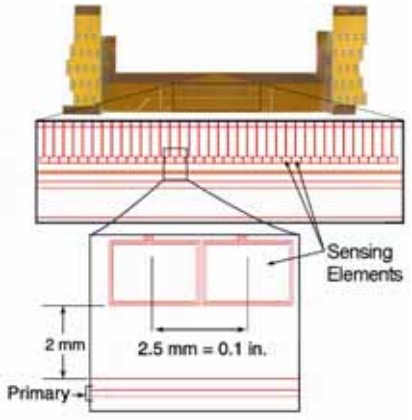
Outline

- Introduction
  - MWM Technology
- Problem Definition
- **Inspection Application Results**
  - Mechanical Damage
  - Stress Corrosion Cracking (SCC)
  - **Near-Surface Corrosion Imaging**
  - Stress Mapping / Weld Inspection
- Summary and Next Steps

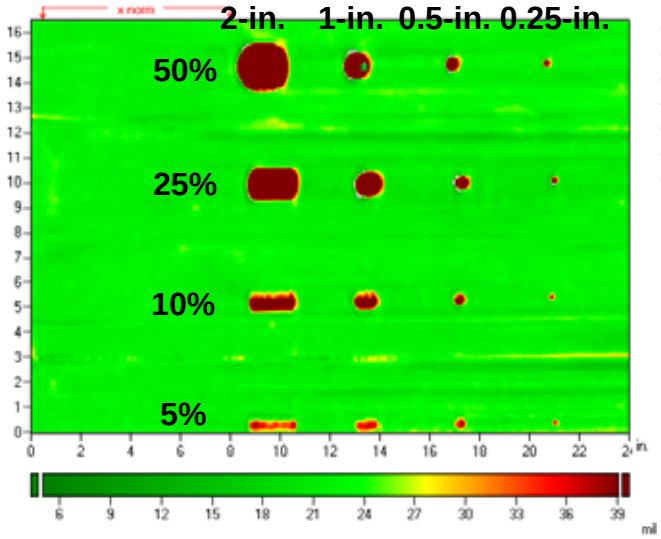
FA24: Near-Surface Material Loss

- 6.625-in. outside diameter and 0.28-in. wall thickness
- Through a thin (0.020-in.) coating
- Relatively small element size provides high spatial resolution

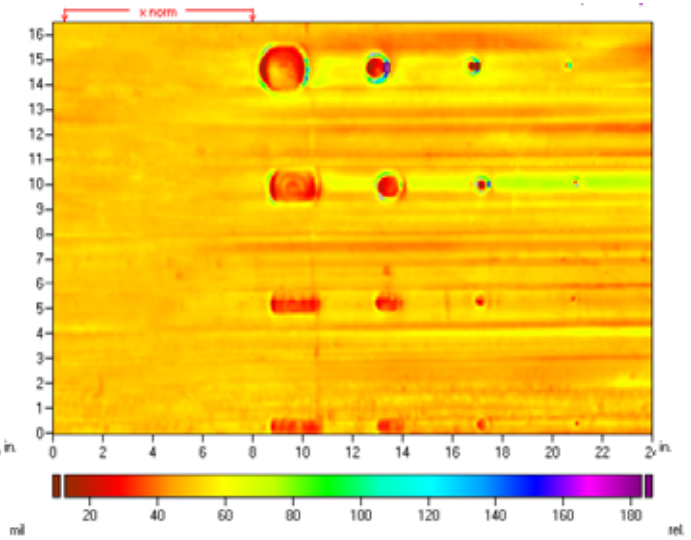
MWM-Array FA24

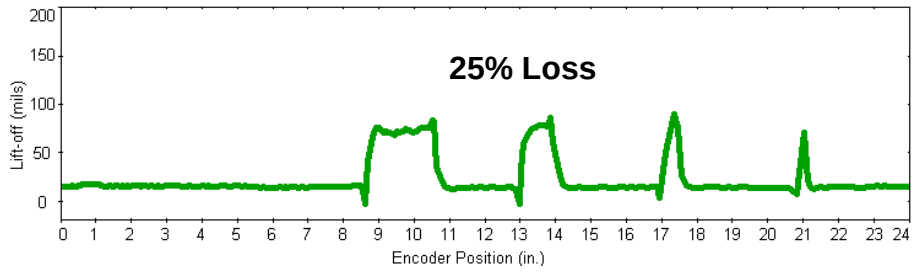


Lift-off



Relative Permeability

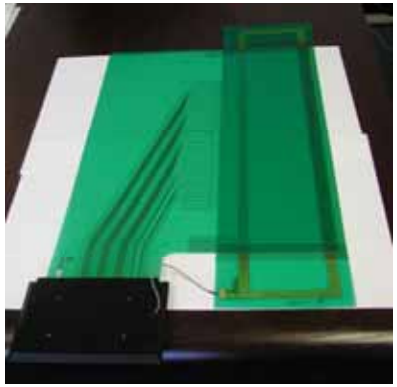


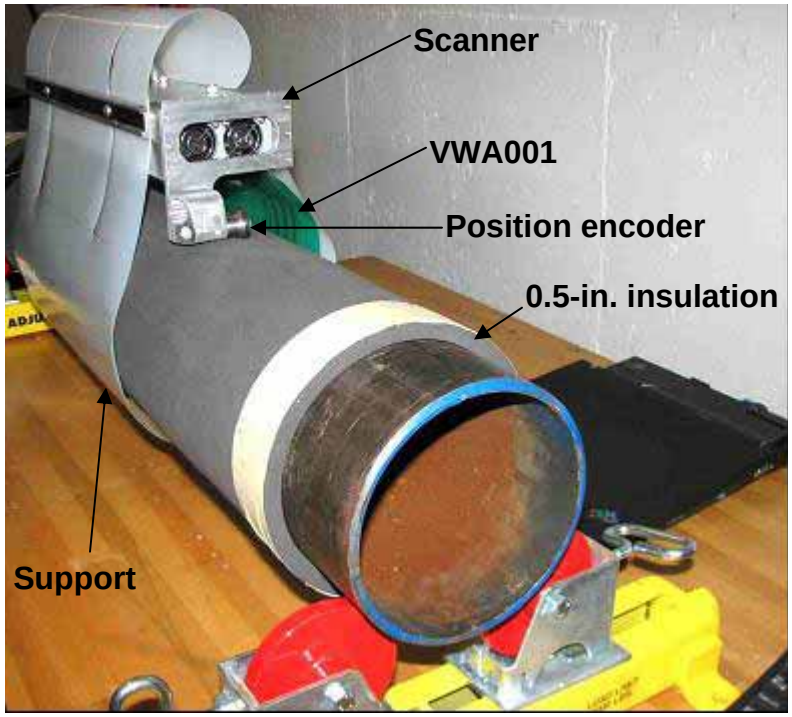


JENTEK Sensors Proprietary

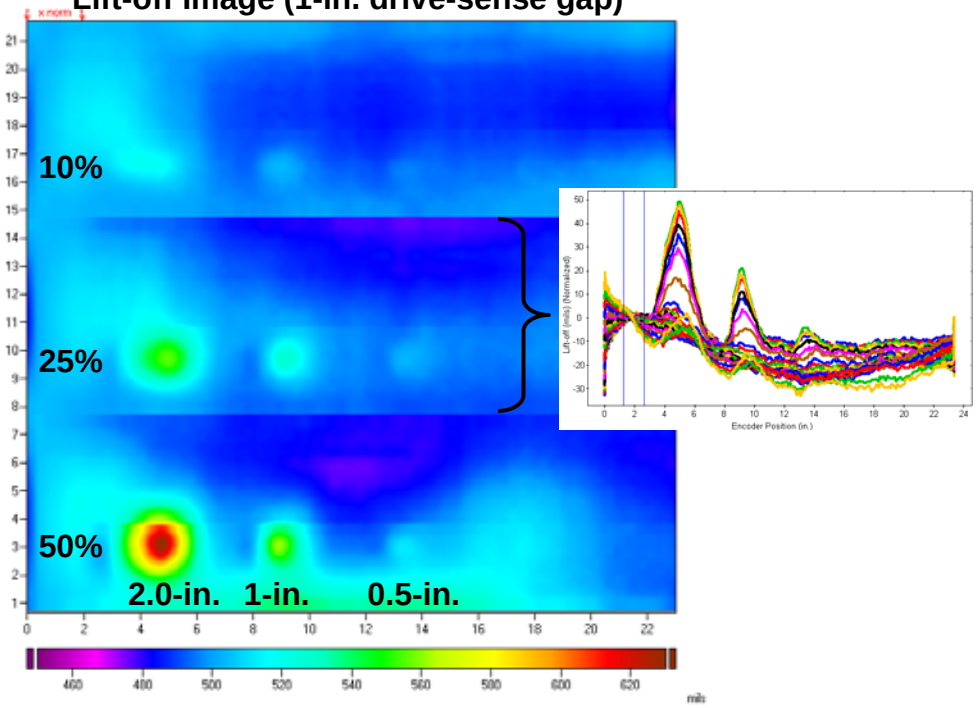
VWA001: Near-Surface Material Loss

- Variable wavelength MWM-Array
- Adjustable drive-sense gap





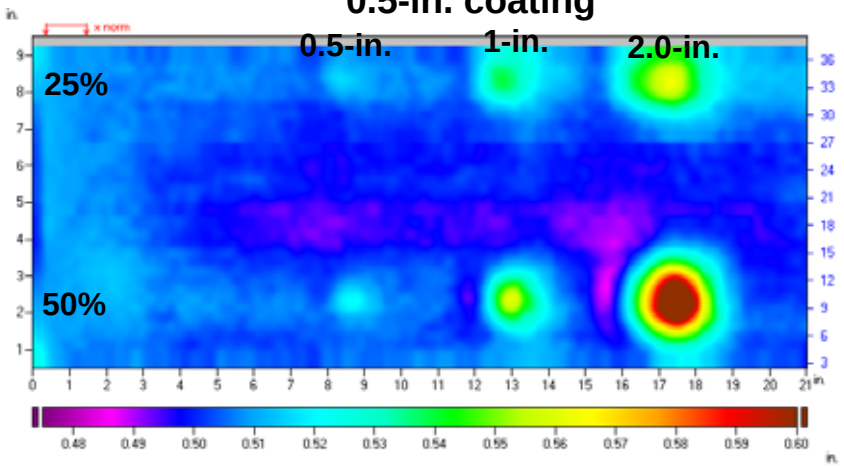
Lift-off Image (1-in. drive-sense gap)

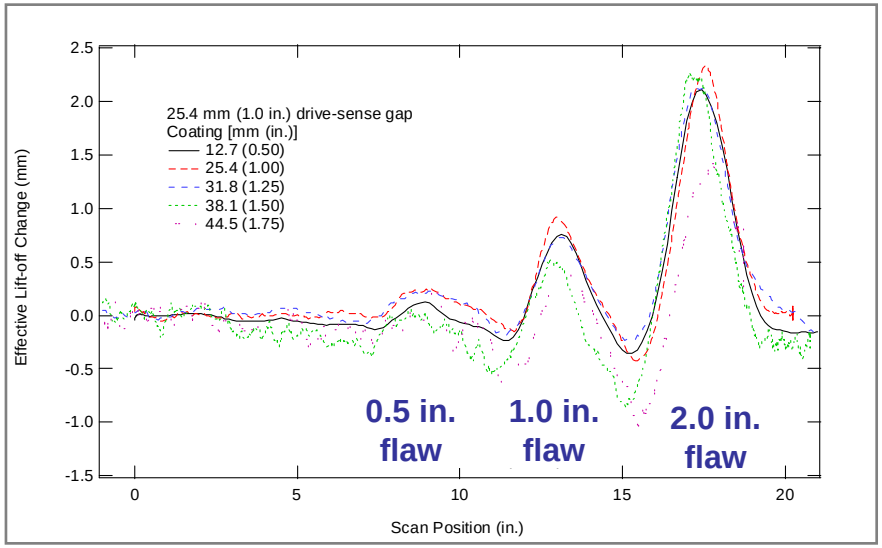


VWA001: Near-Surface Material Loss (2)

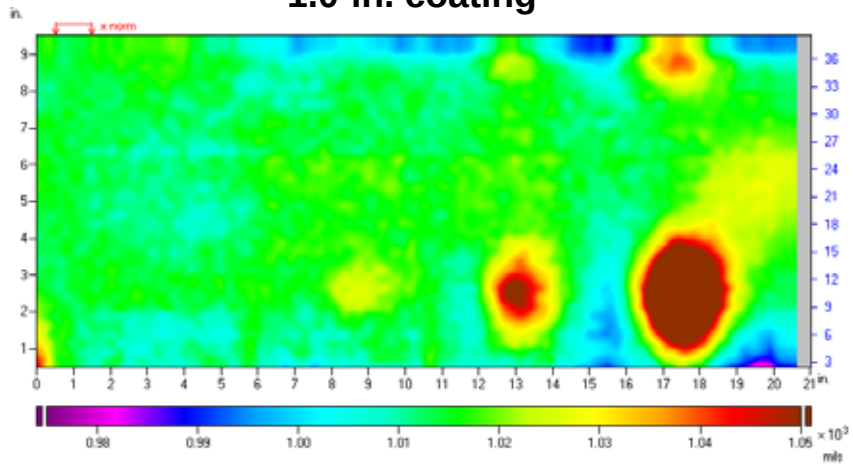
- 1-in. drive-sense gap
- Single-pass lift-off images
  - 0.5 to 1.5-in. coating thicknesses

0.5-in. coating

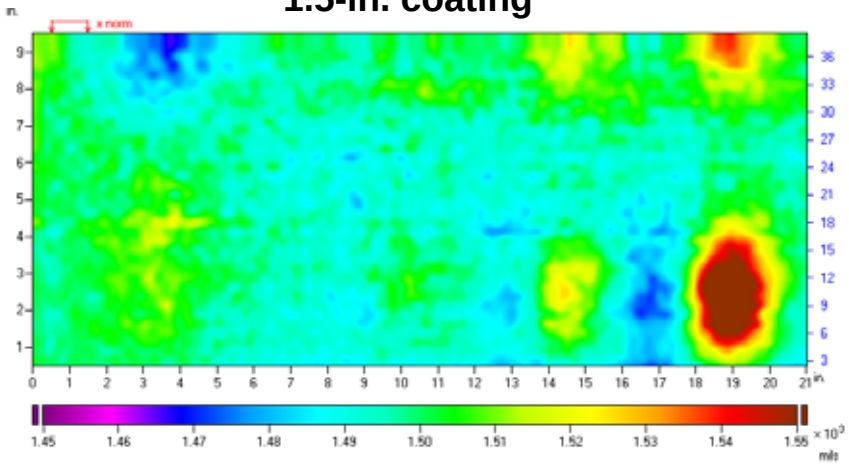




1.0-in. coating



1.5-in. coating



JENTEK Sensors Proprietary

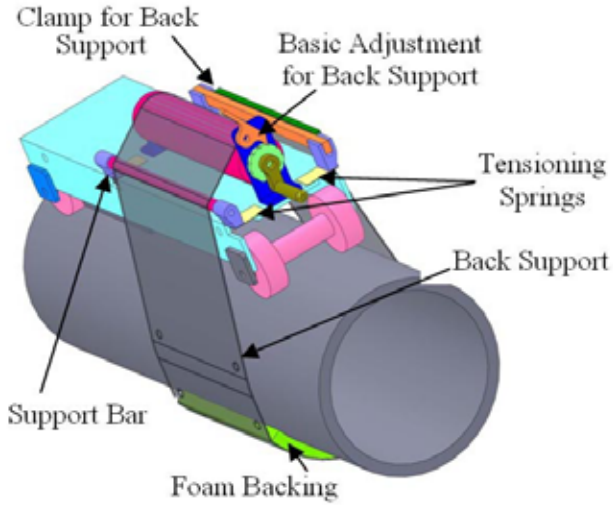
Prototype External Scanner

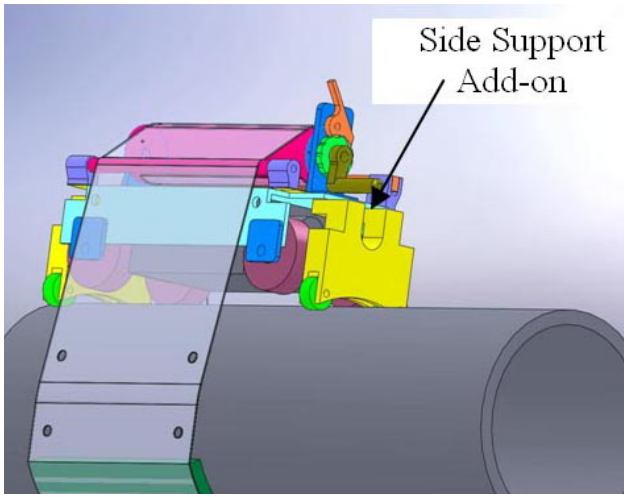
- Prototype wrap-around scanner with VWA001 and in-place to inspect pipe section
- 40-ft long, ~6-in. diameter PRCI riser samples with several engineered flaws
  - 0.5-in. Splashtron insulation
  - Tape wrap followed by cure
  - Scan in one direction – otherwise sensor catches

1st Generation Scanner

PRCI Riser Samples

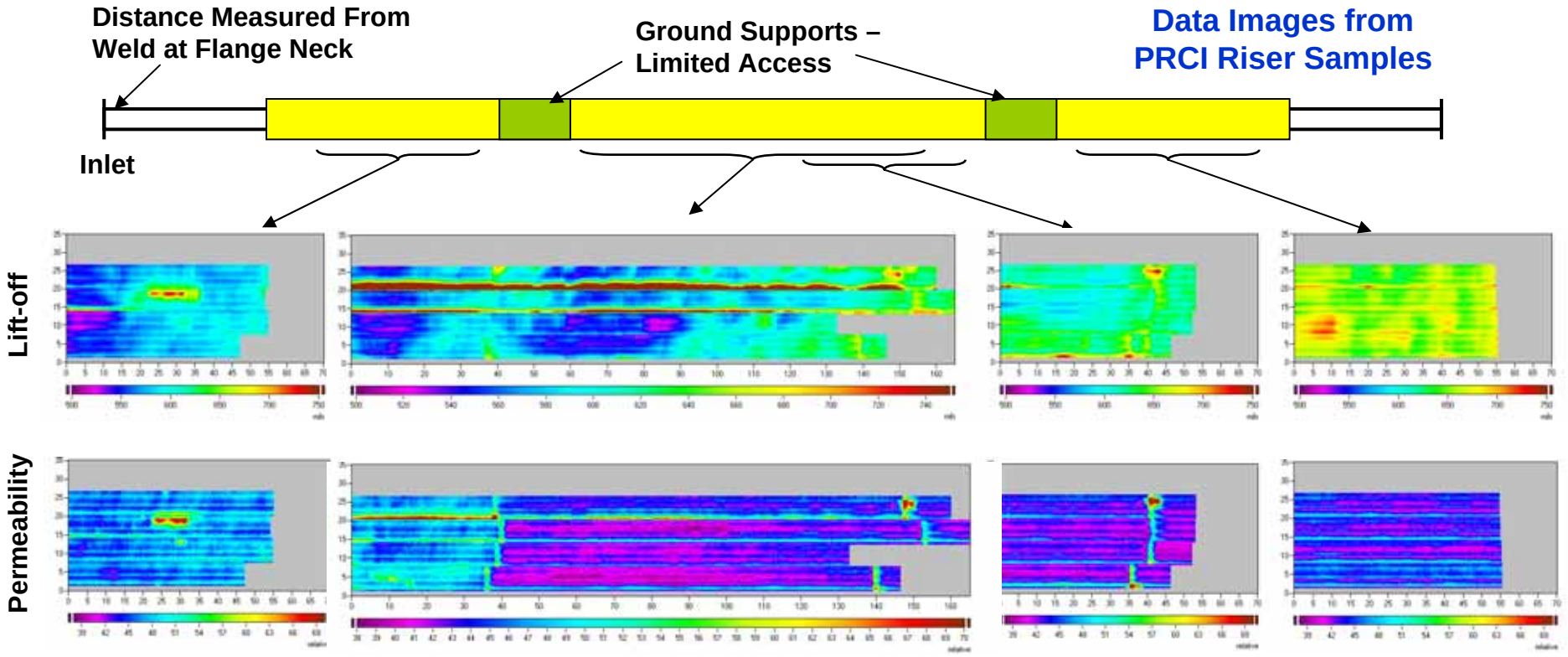
2nd Prototype Scanner



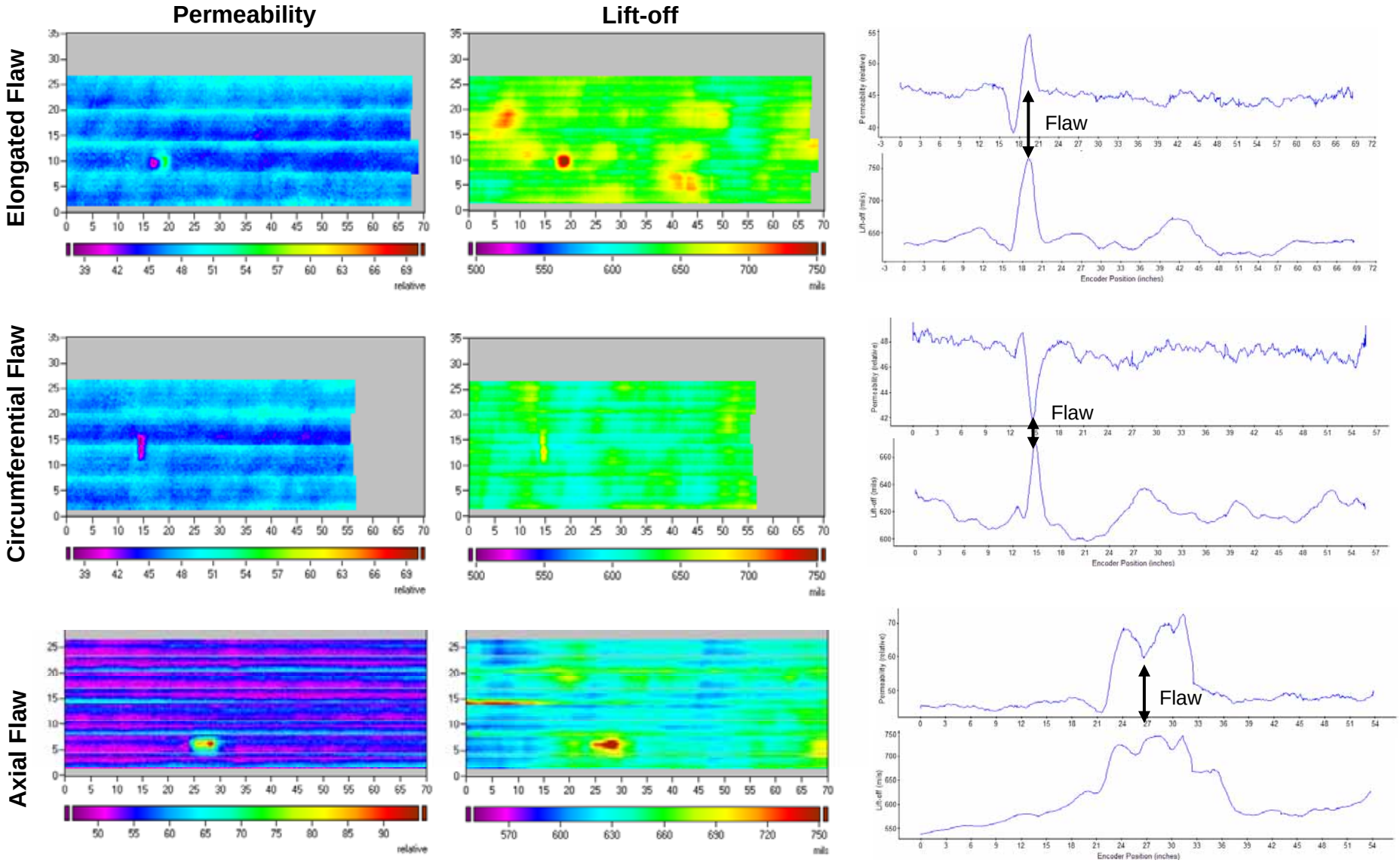


Results from Prototype External Scanner

- Features apparent in both property images
- Significant coating variations can be present
  - ~0.1 in. thickness variation here, up to 0.25-in. for other pipe sections
  - Modified scanner to reduce weight, improve axial position measurements, and accommodate coating thickness variations

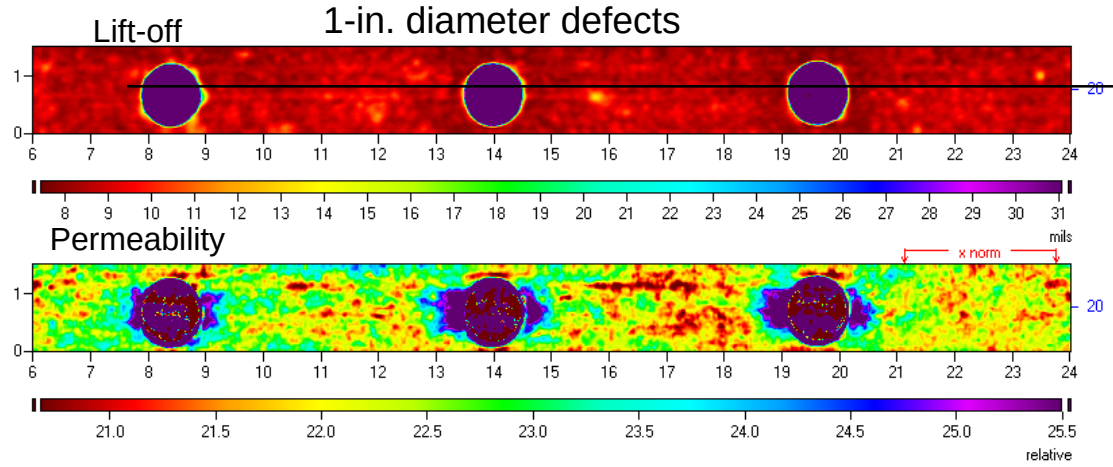


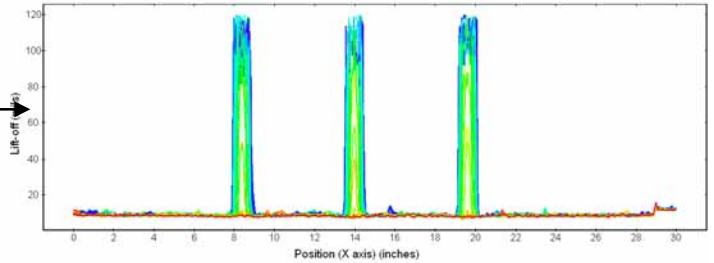
Results from Prototype External Scanner

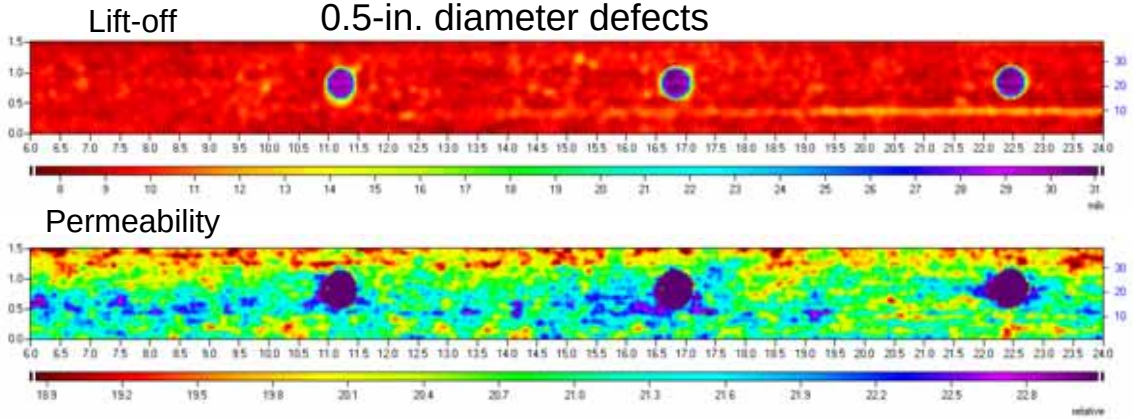


FA28 Internal Scan Results

- Demonstrated high frequency capability through scans in 6-in. dia. pipe section.
- Local machined areas of material loss imaged with small sensor array
  - 0.1, 0.2, 0.3-in. deep loss regions in 0.4-in. steel wall
  - Larger array needed for inspection through thick coatings and material loss estimates.





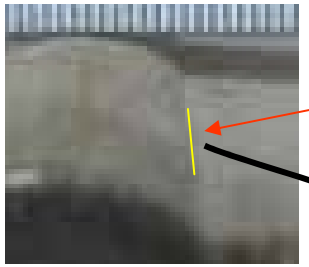


Outline

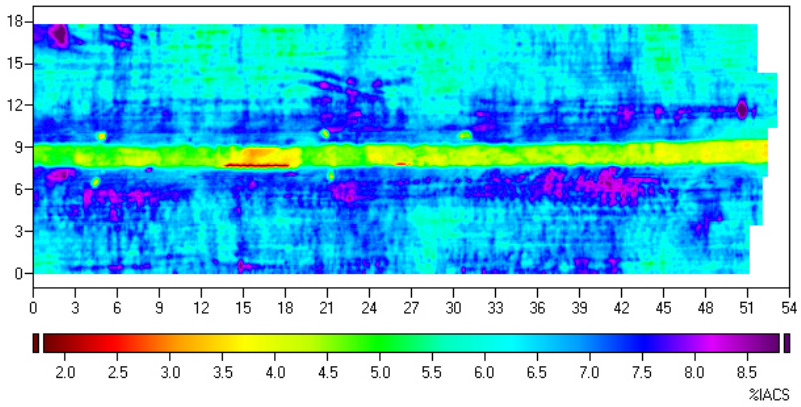
- Introduction
  - MWM Technology
- Problem Definition
- **Inspection Application Results**
  - Mechanical Damage
  - Stress Corrosion Cracking (SCC)
  - Near-Surface Corrosion Imaging
  - **Stress Mapping / Weld Inspection**
- Summary and Next Steps

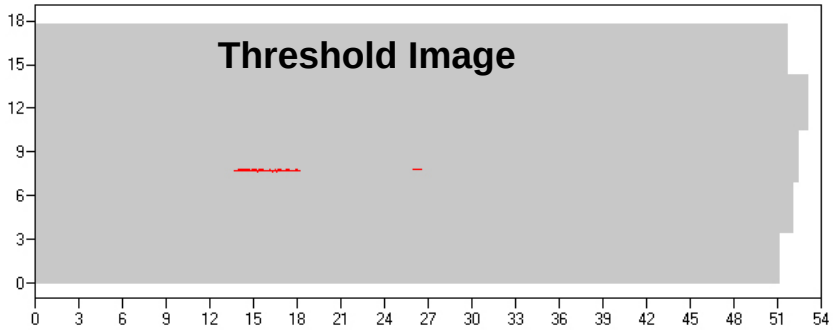
Weld Mapping in Pipeline Sample

- **Scans of DSAW Toe Cracks (EDM-Notches)**



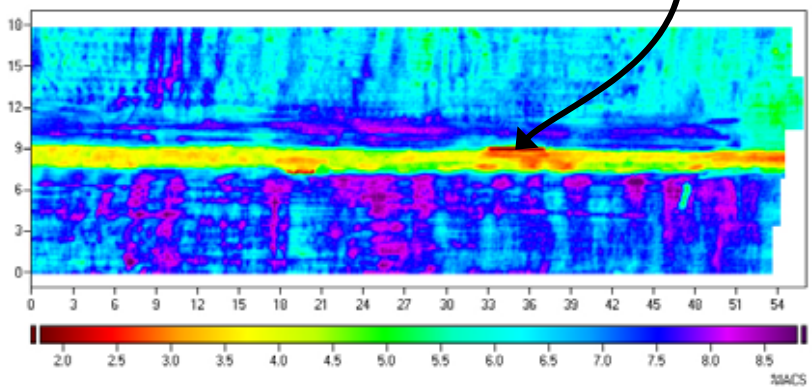
Spectrum Color Image

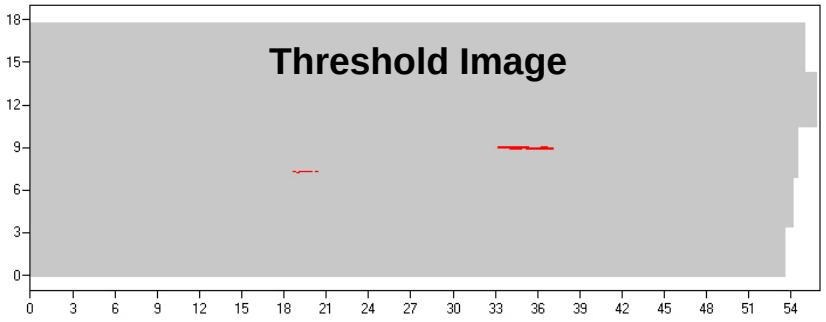




Sonaspection Specimen 2558-003-2, two EDM notches

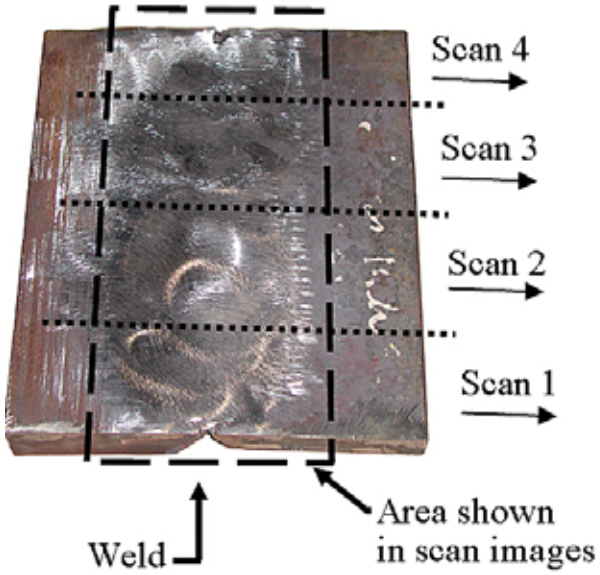
Spectrum Color Image



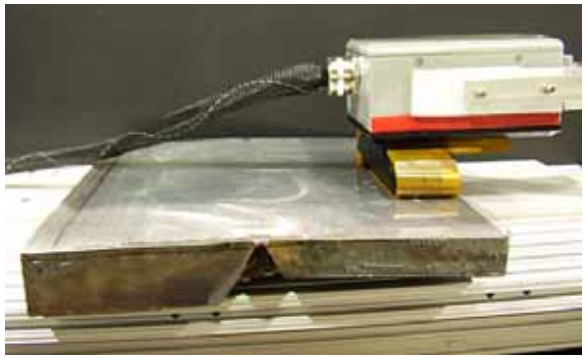


Sonaspection Specimen #2558-003-3, two EDM notches

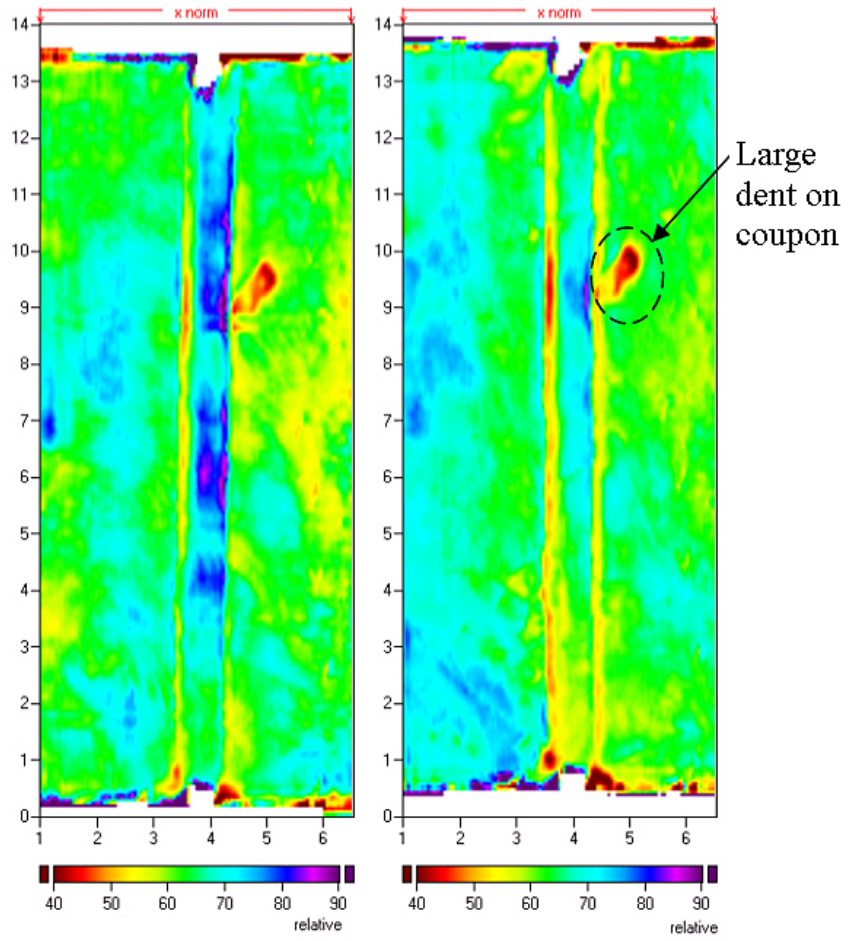
Residual Stress Imaging



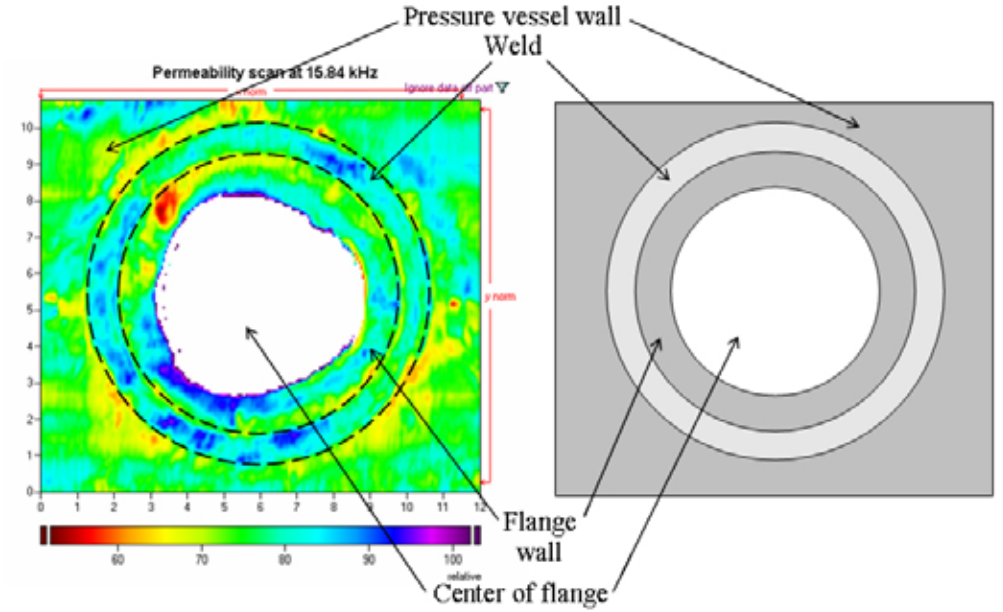
Permeability/stress scanning across the weld

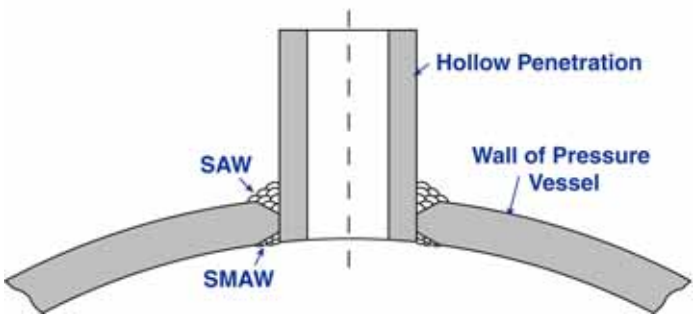


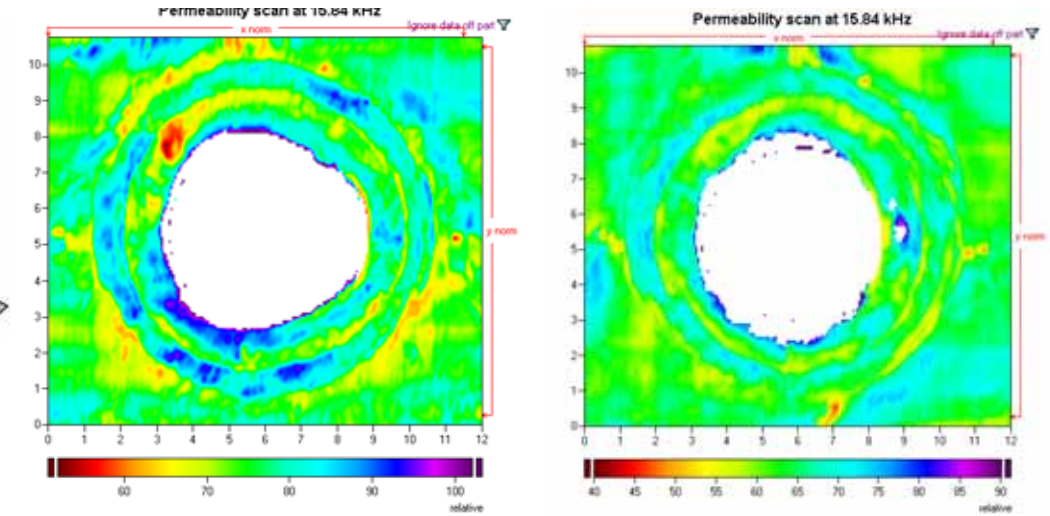
Effect of Thermal Stress Relief on Weld in Witness Coupon, Pressure Vessel Steel



MWM Scan Images of Pressure Vessel Shell Weld



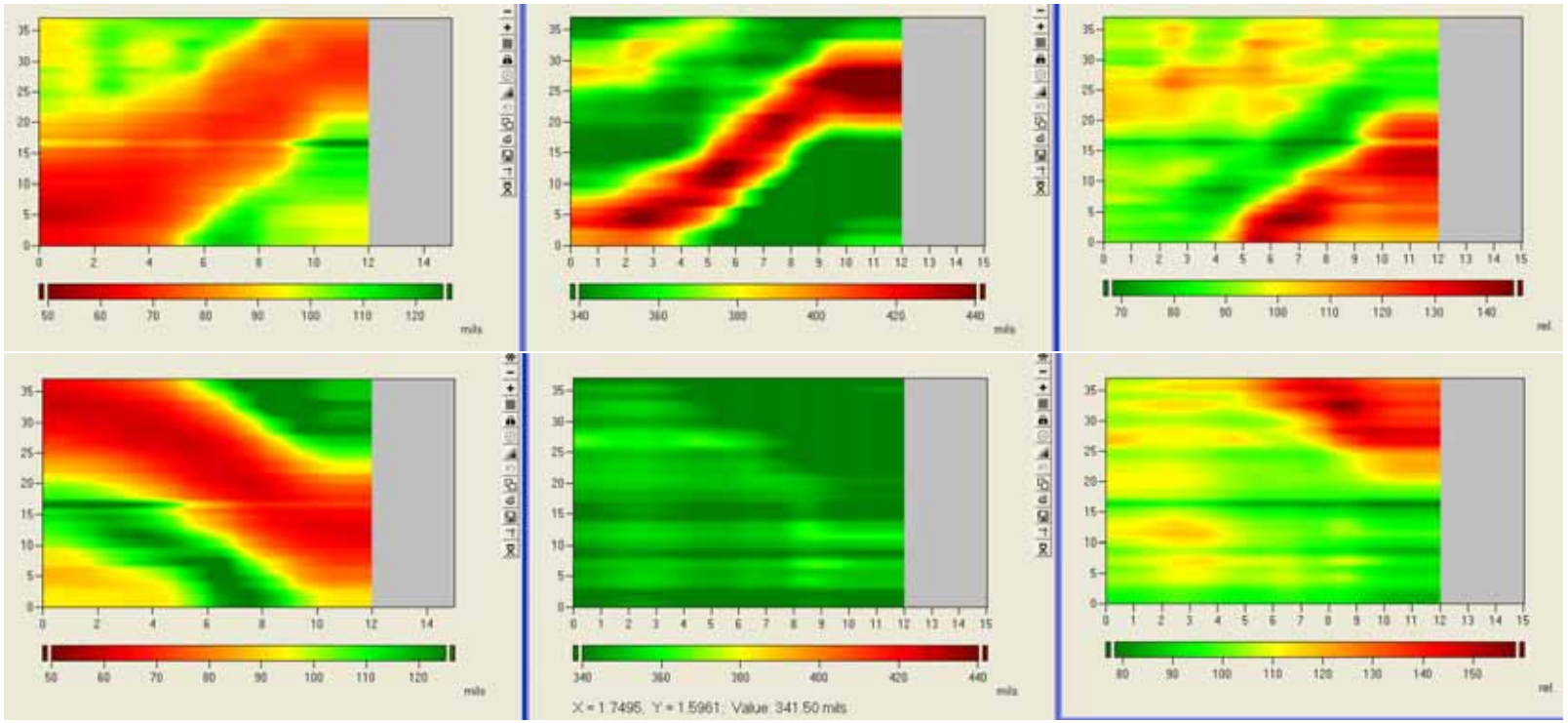




JENTEK Sensors Proprietary

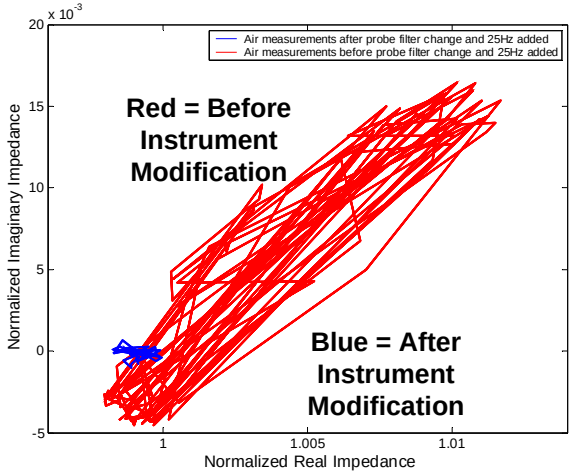
Low Frequency Capability Status

- Developing instrumentation to permit through-wall inspection
- Demonstrated prototype capability for thin walls (<0.25-in. thick)
  - Near-surface material loss (lift-off), plate thickness, permeability
- Manual scanning with rigid (flat) array at this time
  - Investigating other sense elements and flexible designs



MR-MWM-Array Wall Thickness Measurement

Raw impedance response; measurement in air; single channel of the MR-MWM-Array (31 Hz)



Thickness-Lift-off Grid

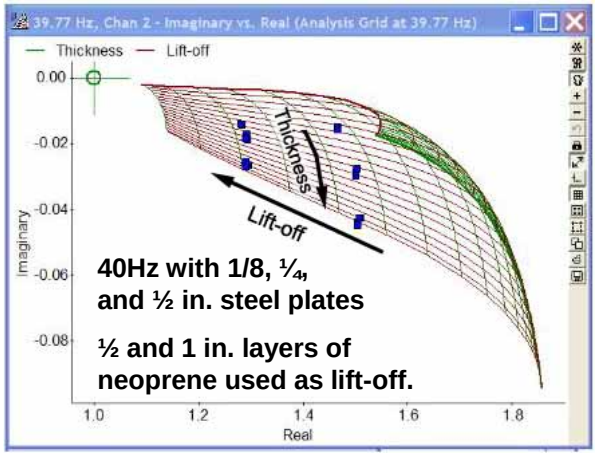
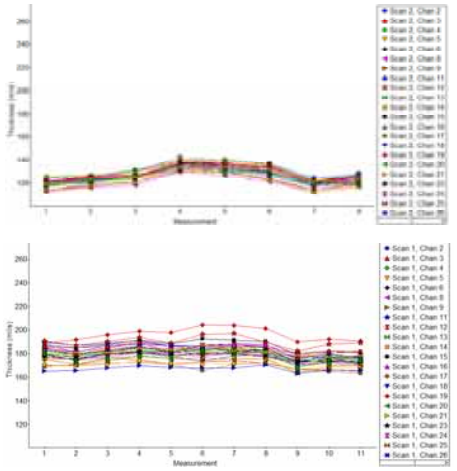
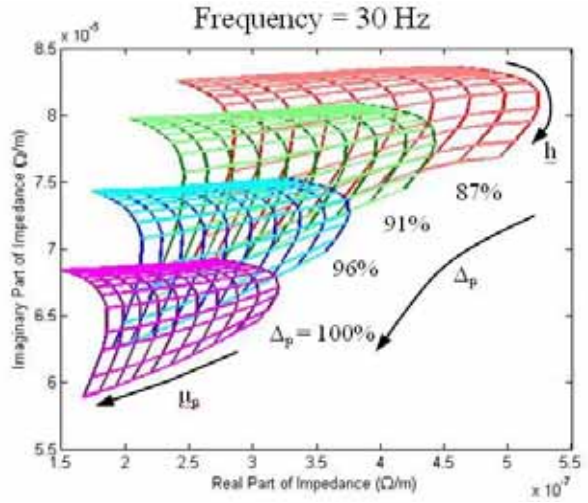
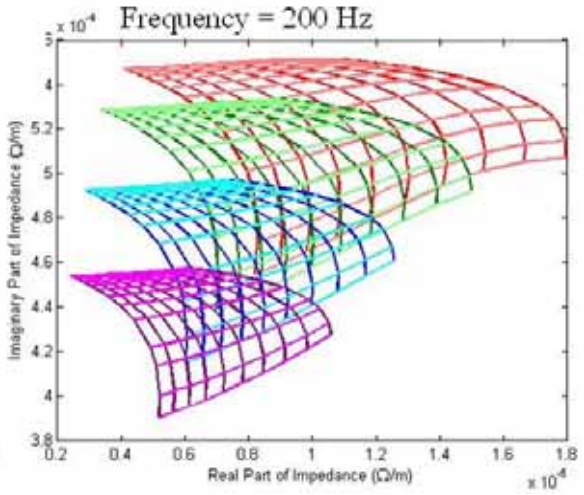


Plate Thickness Estimate for Varying Plate Thickness & Conductivity



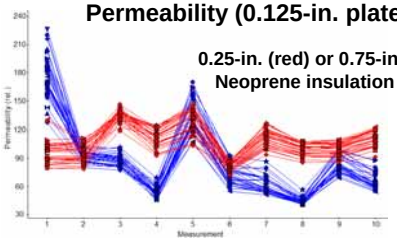
Lattices showing lift-off, permeability and thickness





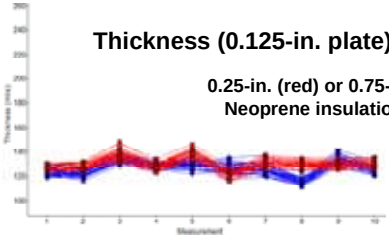
Permeability (0.125-in. plate)

0.25-in. (red) or 0.75-in. (blue) Neoprene insulation layer



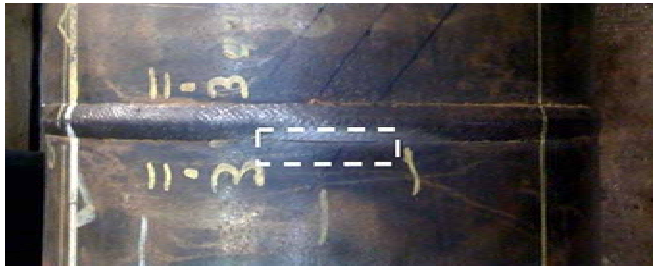
Thickness (0.125-in. plate)

0.25-in. (red) or 0.75-in. (blue) Neoprene insulation layer

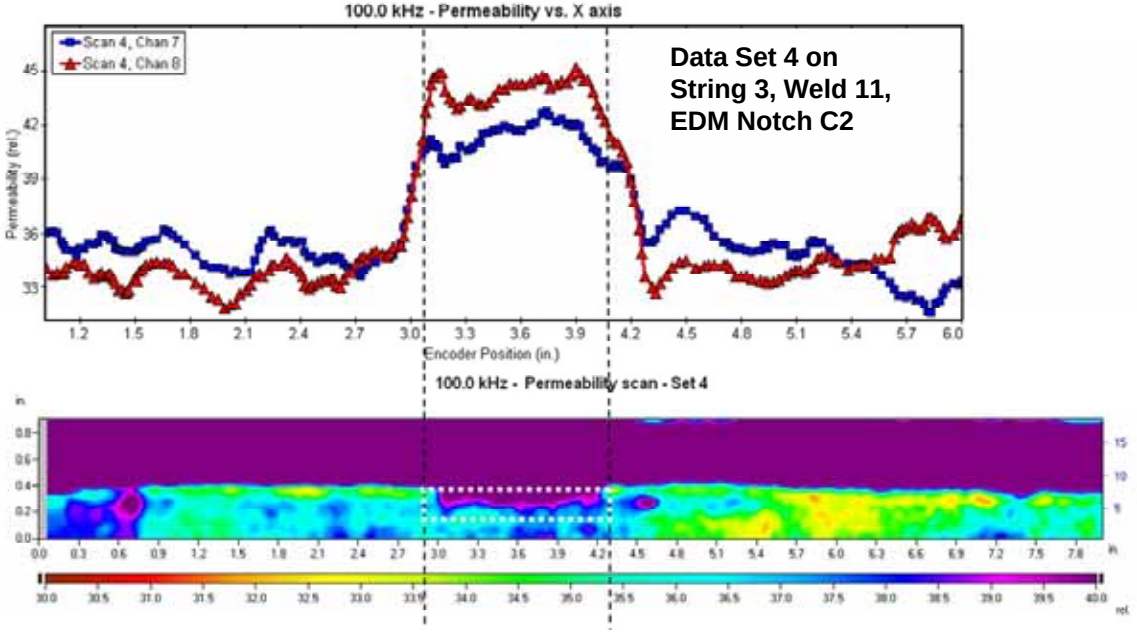


JENTEK Sensors Proprietary

Weld Fatigue Imaging (MWM-Array FA24)
(PRCI/Chevron Funded Task)



EDM notch C2 on Weld 11 of String 3



JENTEK Pipeline Inspection Capabilities

External Inspection through coatings and insulation

Application	Coating Thickness				
	Very Thin	**Thin**	**Moderate**	**Thick**	**Weather Jacket**
	<0.030 in.	0.030 to 0.25 in.	0.25 to 1.5 in.	1.5 to 4.0 in.	~0.040 in. Al or stainless steel
Ext. Mechanical Damage	Presence detectable; depth estimate depends on sensor array.		Presence detectable		
Ext. Corrosion	Presence detectable; depth and extent estimation possible.		Presence detectable; depth and extent estimation possible	Presence detectable (<3-in.)	Detection through < 0.5-in. ins.; low freq. capability required
Ext. SCC	Presence detectable; depth estimate depends on sensor array and freq.				
Internal Corrosion	Presence through thin plates (<0.125-in. steel) detectable; thickness through 0.25-in. plates measured; low freq. capability required				
Fatigue Cracks	Detection and assessing with mounted/scan approaches				
Stress					

Notes:
- **ILI application requires system adaptation to a specific platform; capabilities of "internal corrosion" and "ext. corrosion" above switched.**
- **Minimum resolvable discrete flaw size varies with coating thickness/standoff**
- **Unlabeled areas have not yet been tested**

1. **Capability demonstrated; prototype system available (TRL: 7-9)**
2. **Capability demonstrated; system refinement needed (TRL: 5-6)**
3. **Feasibility demonstrated; system refinement needed (TRL: 3-4)**
4. **Feasibility demonstrated; substantial system improvements needed (TRL: 1-3)**

JENTEK Sensors Proprietary

Summary and Next Steps

- **DOT 304 and 306 Projects Ongoing**

  304 title: "MWM-Array Detection & Characterization of Damage through Coatings and Insulation"

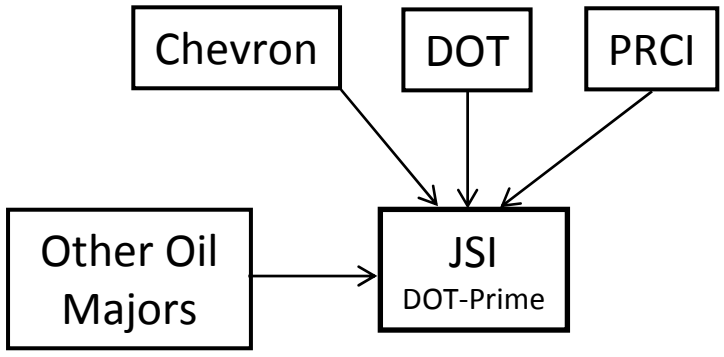
  306 title: "Adaptation of MWM-Array and MFL Technology for Enhanced Detection/Characterization of Damage from Inside Pipelines"

- **Proposed Follow On:**

  DOT BAA Topic 1b: "MWM-Array Characterization of Mechanical Damage and Corrosion

  DOT BAA Topic 3: "MWM-Array Detection and Characterization of Cracks in Pipeline Welds"

Topic 1b Teaming Partners



Topic 3 Teaming Partners