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Field Demonstrations of MR-MWM-Array Solutions for Detection, Imaging and Sizing of Corrosion under Fireproofing (CUF) with Wire Mesh

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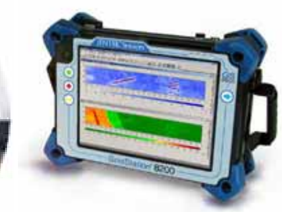


ارامكو السعودية
Saudi Aramco

JENTEK® Sensors, Inc.

مجموعة الرشيد
Al-Rushaid Group

Problem Description

Internal and External Corrosion Imaging through Fireproofing

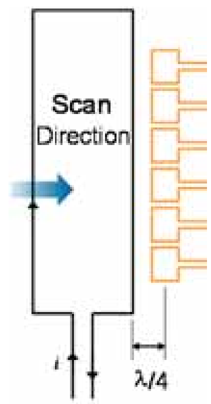
- **Requirements:**
  - Inspect large areas through fireproofing with and without wire mesh
  - Correct for variations in fireproofing thickness
  - Correct for variations in steel properties
  - Provide an image of the wall loss
  - Differentiate between external and internal corrosion
- **Applications include vessel skirts, LPG legs, structures**
- **Related applications include:**
  - Inspection through insulation with weather jacket for vessels and piping
  - In-line inspection for corrosion and longitudinal stress

Technology Summary / Overview

1. Sensors: MR-MWM®-Arrays

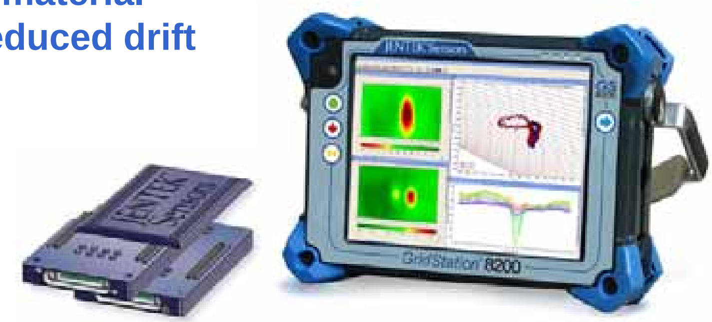
- **Paradigm shift** in sensor design (first priority is predictable response based on physics-based modeling)





2. Next Generation 8200α GridStation® Electronics

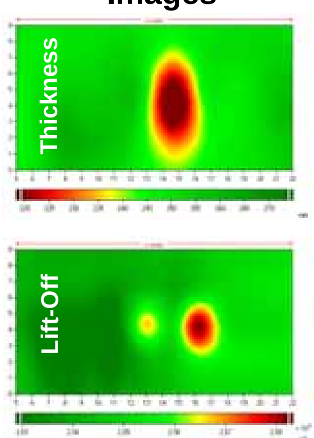
- **10x signal-to-noise improvement**
- **Very low frequencies (deep penetration)**
- **Crack detection through up to 0.5 inches of material**
- **Reduced drift**



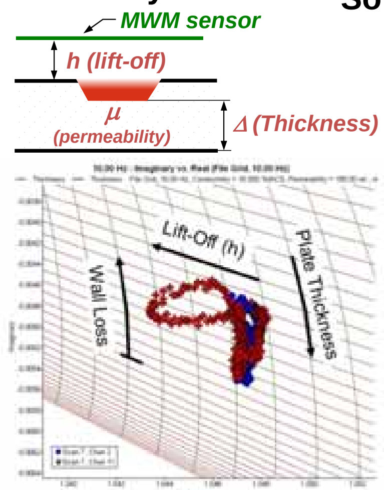
3. GridStation® Software using Hyperlattices™

- **Rapid, autonomous data analysis**
  Performs multivariate inverse method (MIM) using precomputed databases
  - Defect Images
  - Performance Diagnostics
  - Noise Suppression

Images

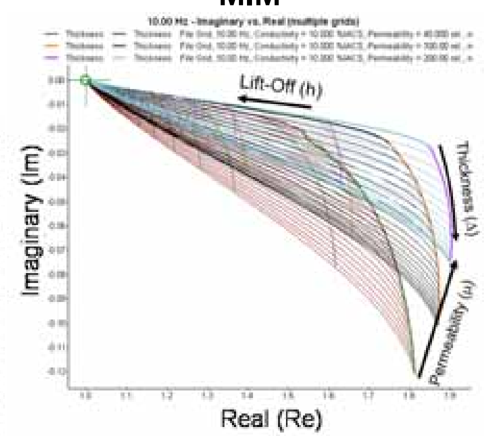


Analysis



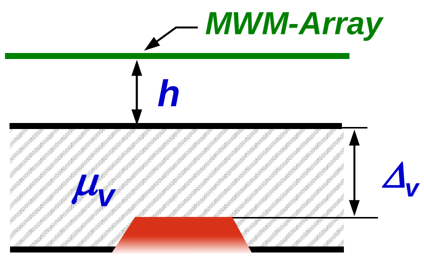
Solve Multiple Unknown Problems

MIM



Consider Three Corrosion Imaging Problems

3-unknowns (CUF)



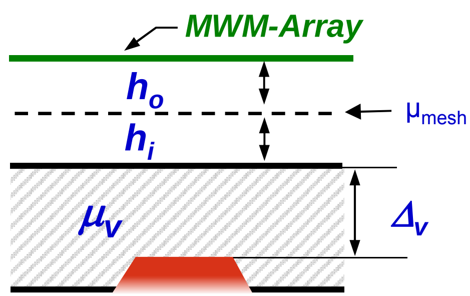
h, Δ_v, μ_v

h = insulation thickness + external metal loss

Δ_V = remaining vessel wall thickness

μ_V = vessel magnetic permeability

4-unknowns (CUF)



h, Δ_v, μ_v , μ_{mesh}

h_o = distance between sensor & wire mesh = air gap + concrete thickness outside wire mesh

h_i = distance between wire mesh and external surface of vessel = concrete thickness inside wire mesh + external metal loss

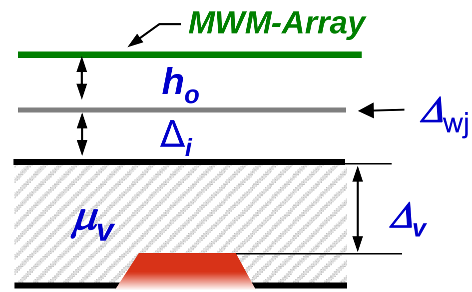
Δ_V, = remaining vessel wall thickness

μ_V = vessel magnetic permeability

μ_{mesh} = effective magnetic permeability of the wire mesh for an assumed constant mesh thickness

***NOTE:** To simplify from 5 unknowns to 4 unknowns, h_i is assumed to be constant*

5-unknowns (CUI)



h, Δ_{wj}, Δ_i , Δ_v, μ_v

h_o = distance between sensor & external surface of weather jacket

Δ_{wj}, = weather jacket thickness

Δ_i = insulation thickness + external metal loss

Δ_v = remaining vessel wall thickness

μ_v= vessel magnetic permeability

Demonstrations at Two Saudi Aramco Facilities

- Site teams included:
  Saudi Aramco, Al-Rushaid and JENTEK personnel
- Prototype scanner functioned well, but was too heavy. Modifications will be made to improve ease of use.
- Scanning of large areas was accomplished in multiple vertical passes, with automatic scanning in the vertical direction, and manual shifting of the scanner around the vessel.

How many Frequencies are Needed to Solve for 3-Unknowns?

2-unknowns (CUF)

1 Frequency

h and Δ_v

Linear equations example

$h + \Delta_v = 3$ in.

$\Delta_v = 1$ in.

Solve: $h = 2$ in.

Nonlinear equations example:

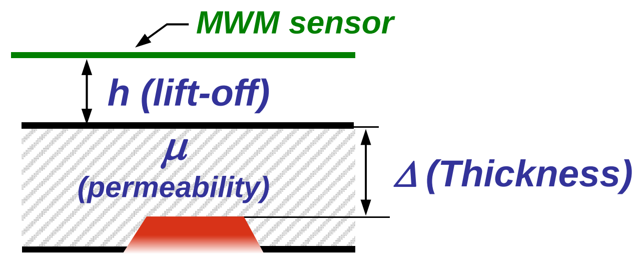
Function 1 (h and Δ_v) = S1=Re(V/I)

Function 2 (h and Δ_v) = S2=Im(V/I)

Must solve using an alternative method.

3-unknowns (CUF)

2 Frequencies



Function 1 (h, Δ_v, μ_v) = S1=Re(V/I) at f1

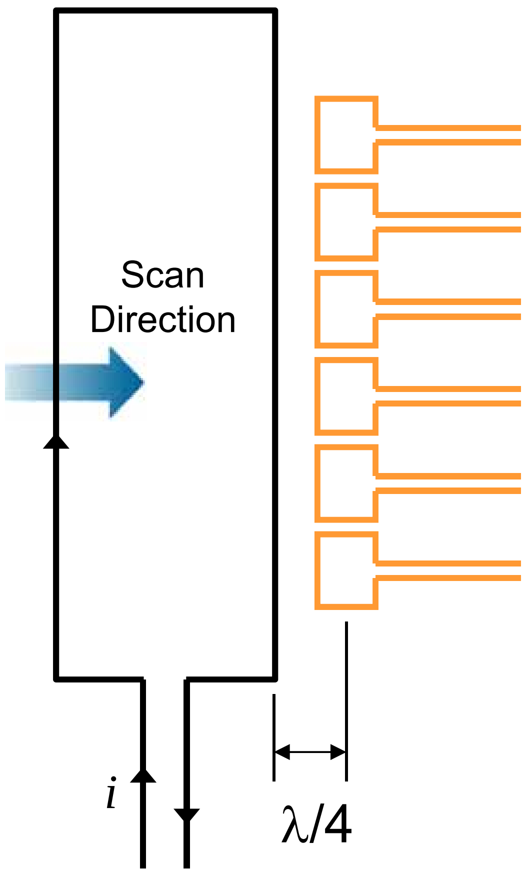
Function 2 (h, Δ_v, μ_v) = S2=Im(V/I) at f1

Function 3 (h, Δ_v, μ_v) = S3 need 2nd freq.

<u>For Low Frequency Eddy Current Sensing</u>

Each frequency provides two equations. Thus, to solve a three unknown problem, two frequencies are needed. To solve a two unknown problem, only one frequency is needed. For 5 unknowns, three frequencies are needed.

A Quick Introduction to MWM-Array Eddy Current Sensing



1. A current is applied to a single large drive conductor
2. This time varying current is applied at a frequency, such as 5Hz (5 cycles/second)
3. This time varying current produces a magnetic field
4. The electronics measures a voltage at each sensing element at the same time for up to three frequencies at the same time
5. For each frequency a magnitude (V/I) is measured and a phase which is the time delay of the voltage relative to the current is measured
6. The Real part of the impedance is the Magnitude x cos(phase); the Imaginary part of the impedance is the Magnitude x sin(phase)

Flat Plate Demonstration of 3-Unknown Method

For External and Internal Corrosion

Sensor

- 18-channel sensor
- Motorized scanning vehicle
- External and internal wall loss imaging

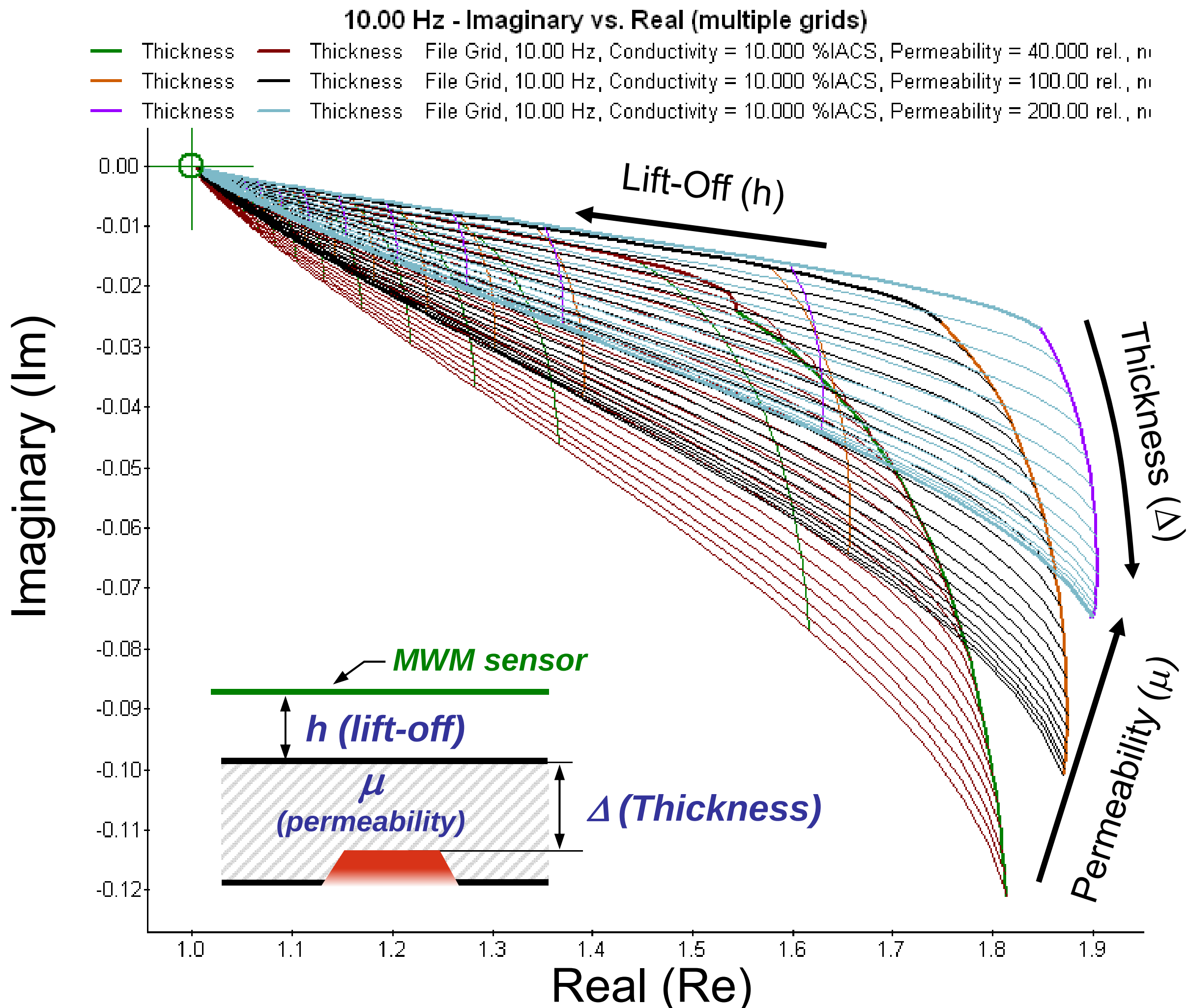
Flat Plate
Dimensions: 4 ft. x 4 ft.
Thickness: 0.25 in.

Flaw
Diameter: 2.25 in.
Depth: 0.150 in.

MR-MWM-Array
(Curved or Flat surfaces)

3-Unknown Lattices

- GridStation Lattices for MR-MWM-Array **wall loss imaging**
- Used for **external and internal** wall loss imaging



$|Z|$ = Magnitude

θ = Phase

$$|Z| = \sqrt{Re^2 + Im^2}$$

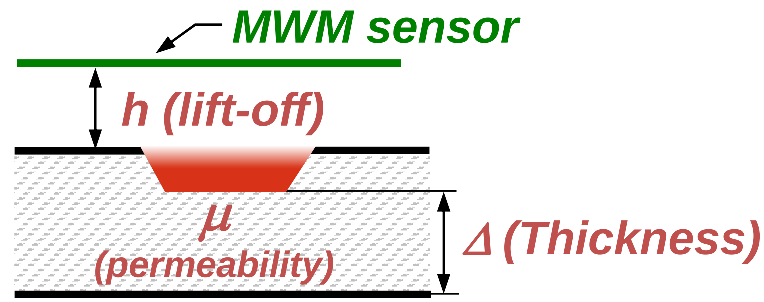
$$\theta = \arctan(Im/Re)$$

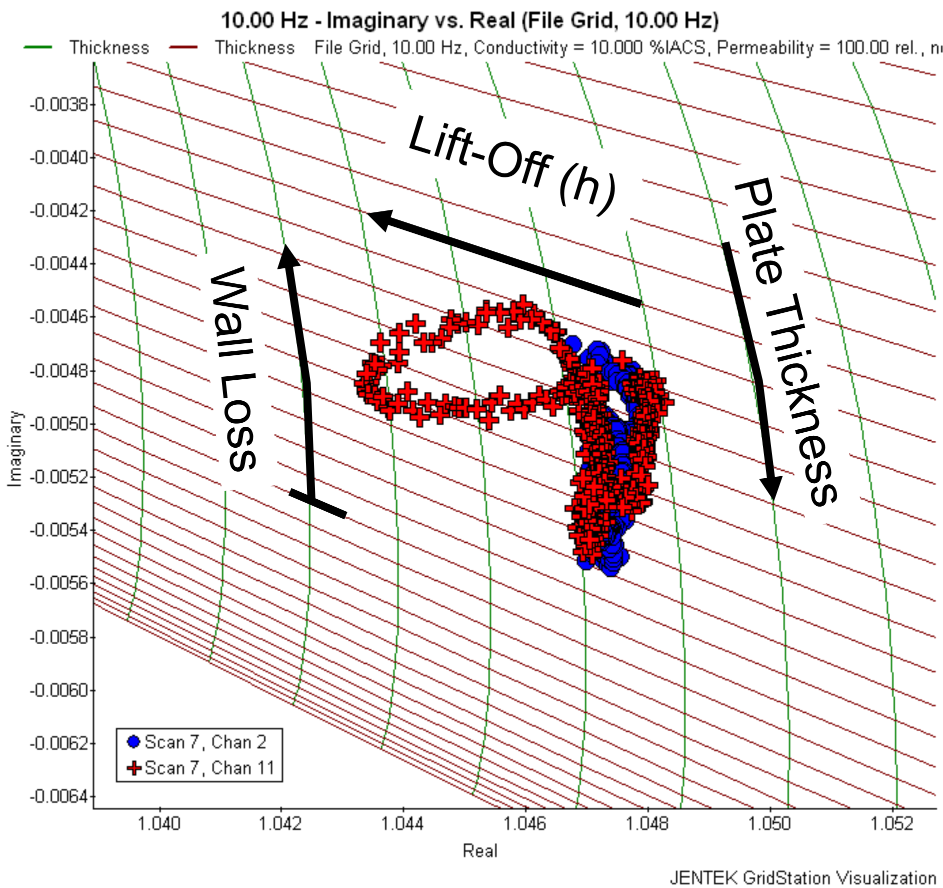
$$Re = |Z|\sin(\theta)$$

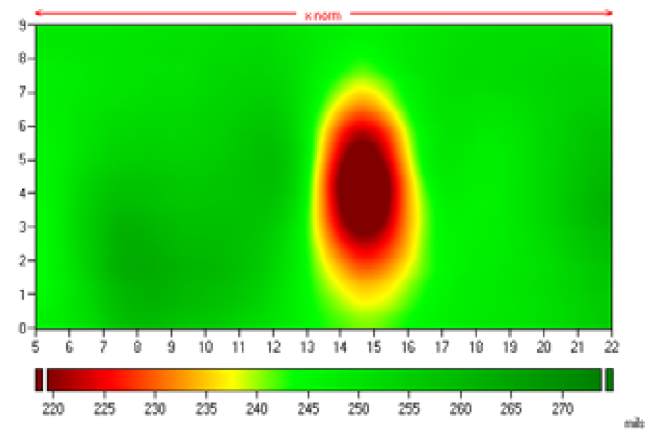
$$Im = |Z|\cos(\theta)$$

Independent Plate Thickness and Lift-off Imaging

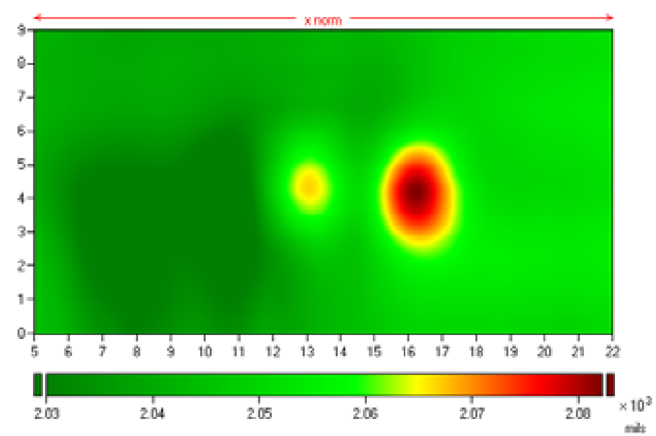
- Channel over defect shows defect signature as thickness reduction and lift-off increase







Thickness

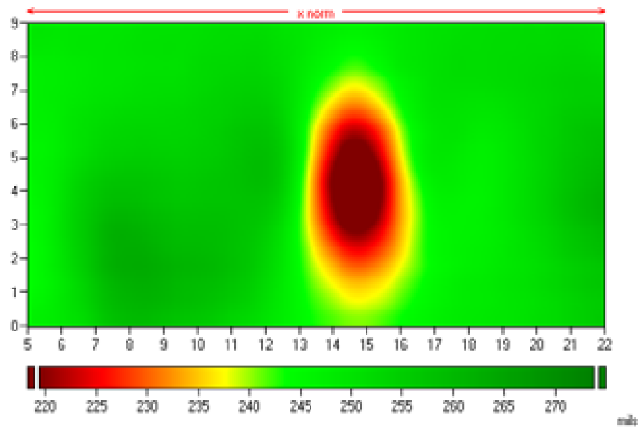


Lift-Off

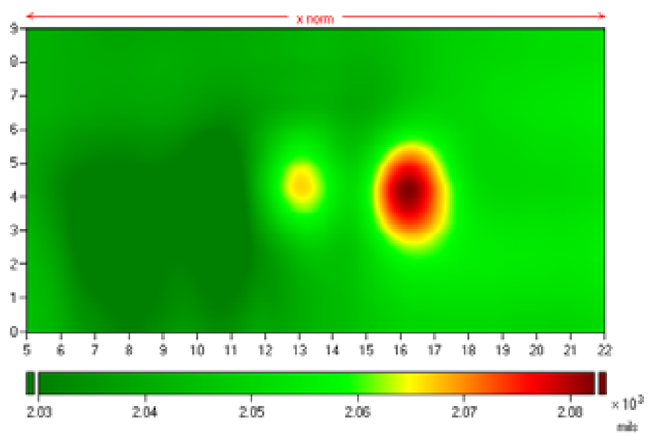
Discrimination Between External and Internal Wall Loss

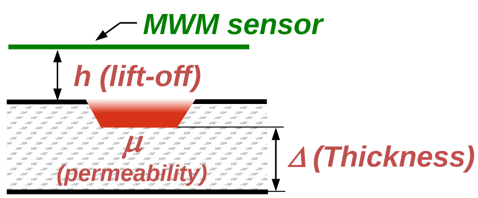
External Wall Loss

Thickness



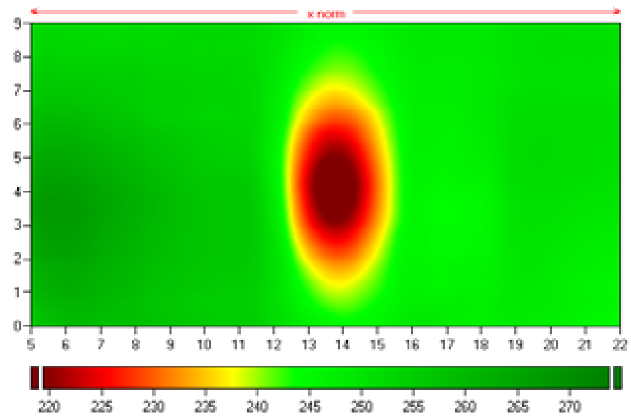
Lift-Off



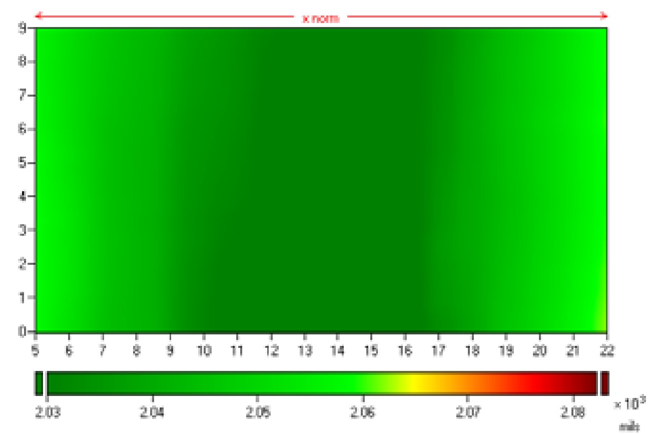


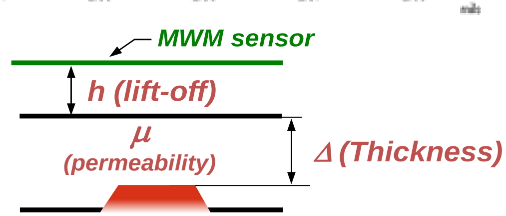
Internal Wall Loss

Thickness



Lift-Off

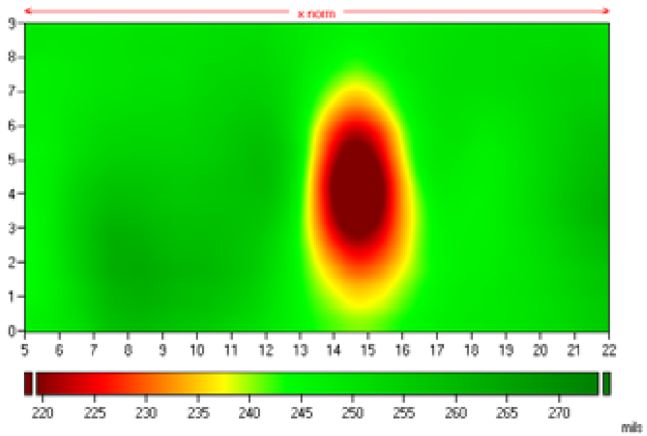




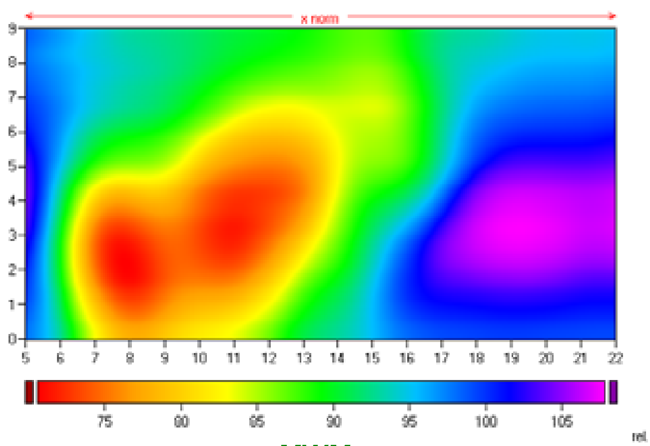
Independent Wall Thickness and Permeability (Longitudinal Stress) Imaging

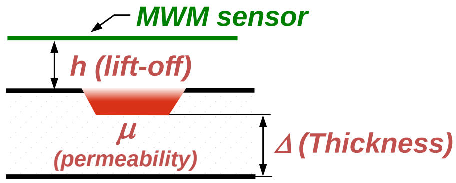
External Wall Loss

Thickness

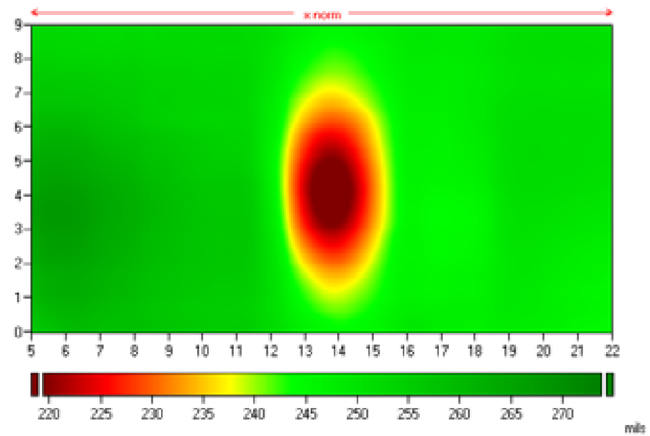


Permeability

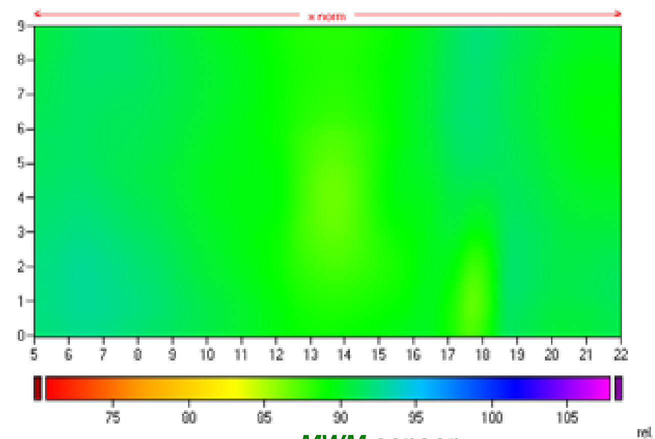




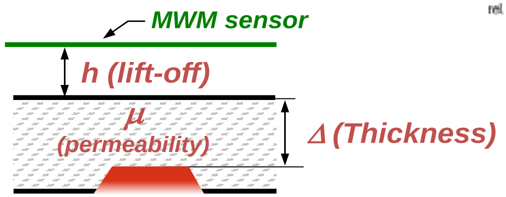
Internal Wall Loss



Thickness



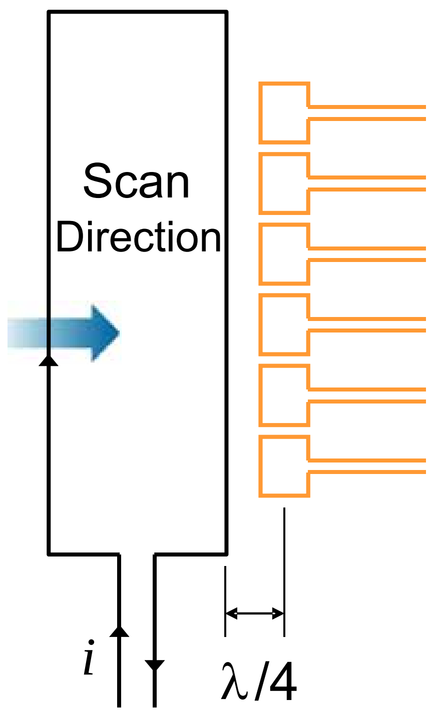
Magnetic Permeability



- Need to add correction for sensor construct effects
- Longitudinal permeability is related to stress

MWM-Array Sensor Selection

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

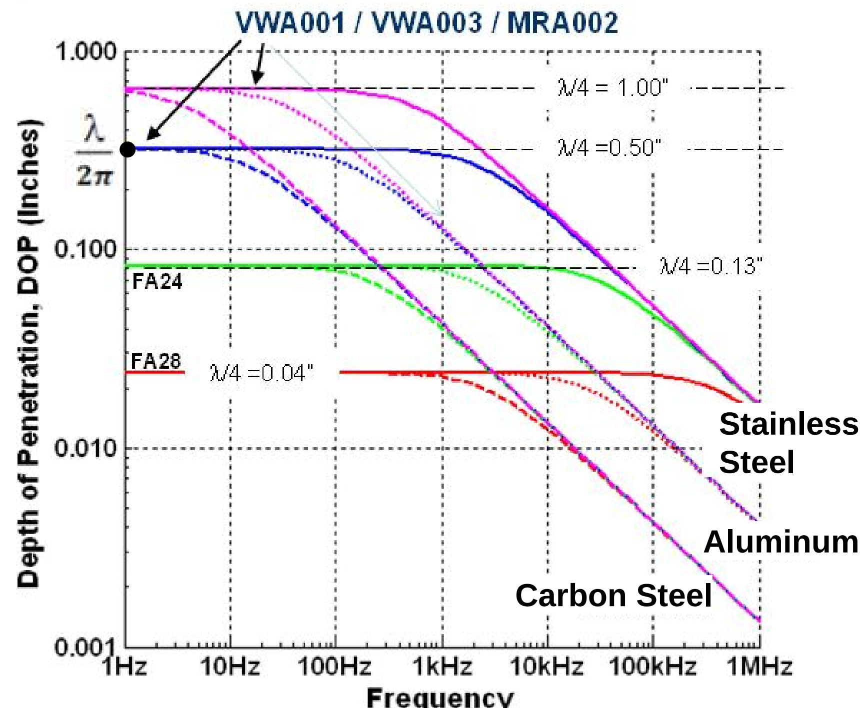


Depth of Penetration = $1/\mathrm{Re}(\Gamma_n)$

Low Frequency Limit = $\frac{\lambda}{2\pi}$

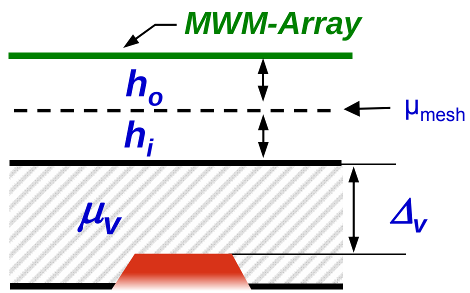
$$\Gamma_n = \sqrt{(2\pi n/\lambda)^2 + j2/\delta^2}$$

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

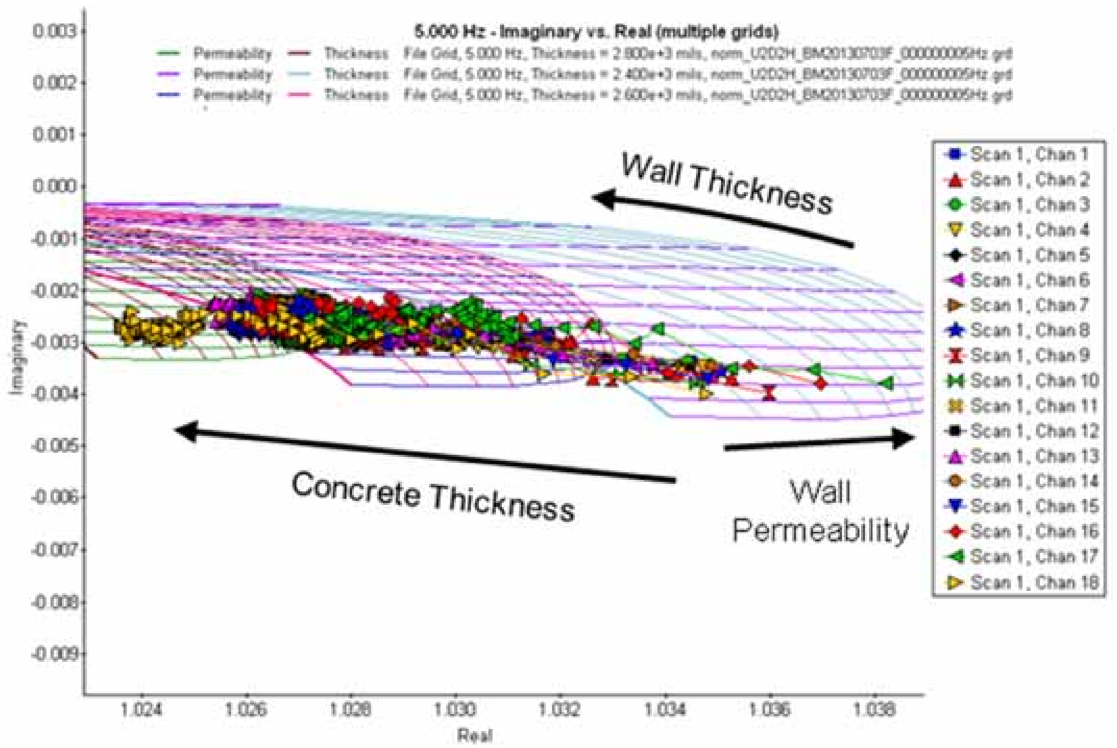


1 inch = 25.4 mm

Corrosion Under Fireproofing (CUF) with Wire Mesh

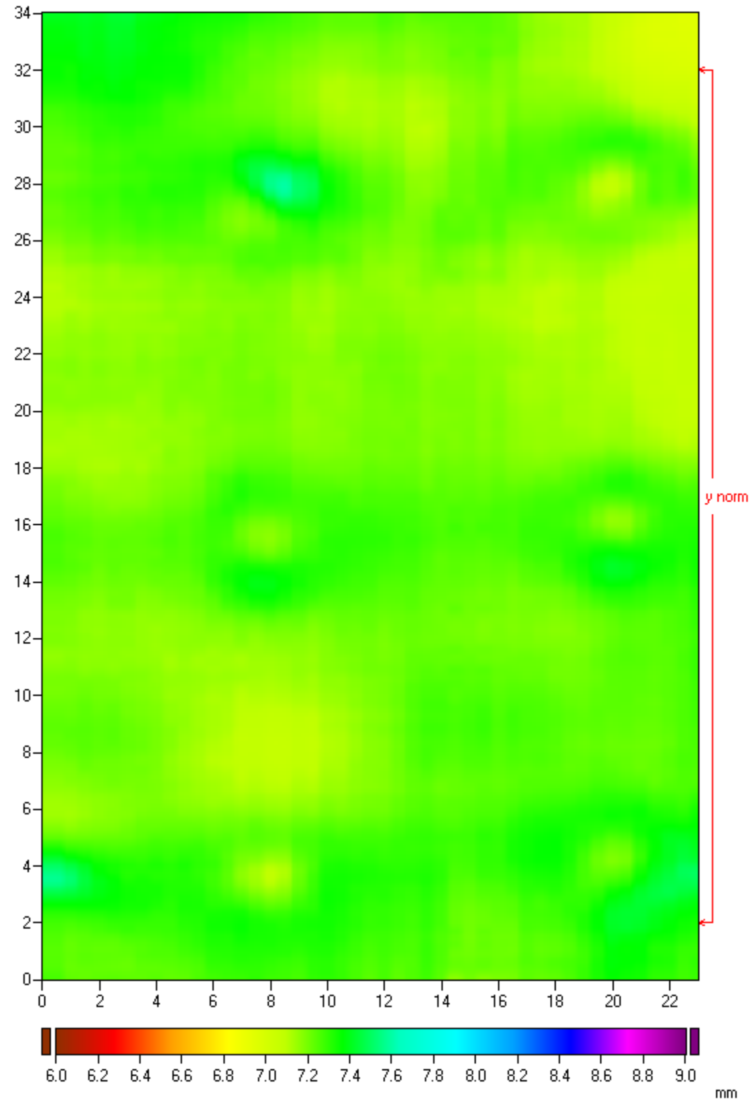


h, Δ_v, μ_v , μ_{mesh}

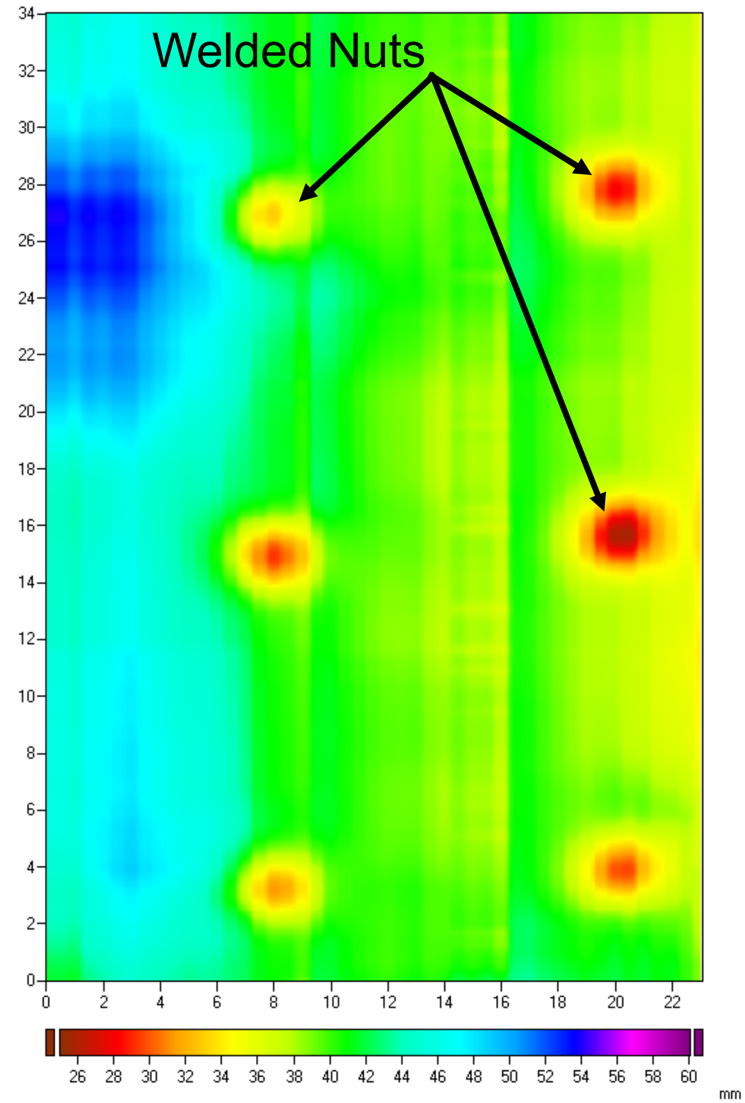


Wall Thickness and Concrete Thickness

Wall Thickness

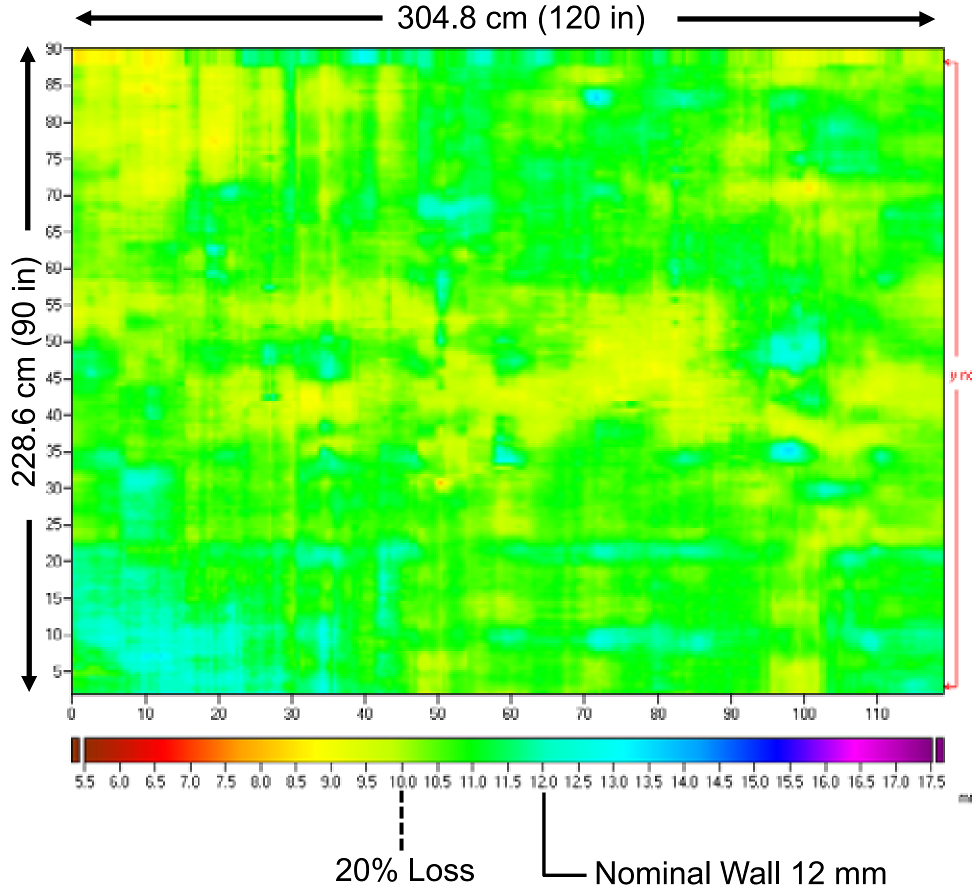


Concrete Thickness

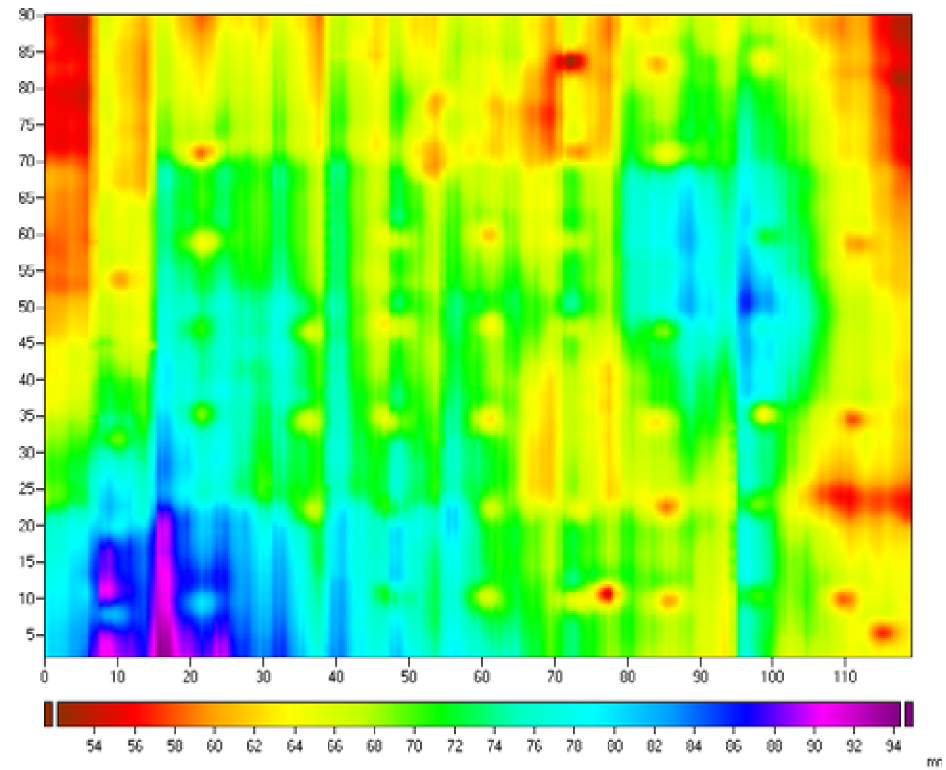


Wall Thickness and Concrete Thickness

Wall Thickness

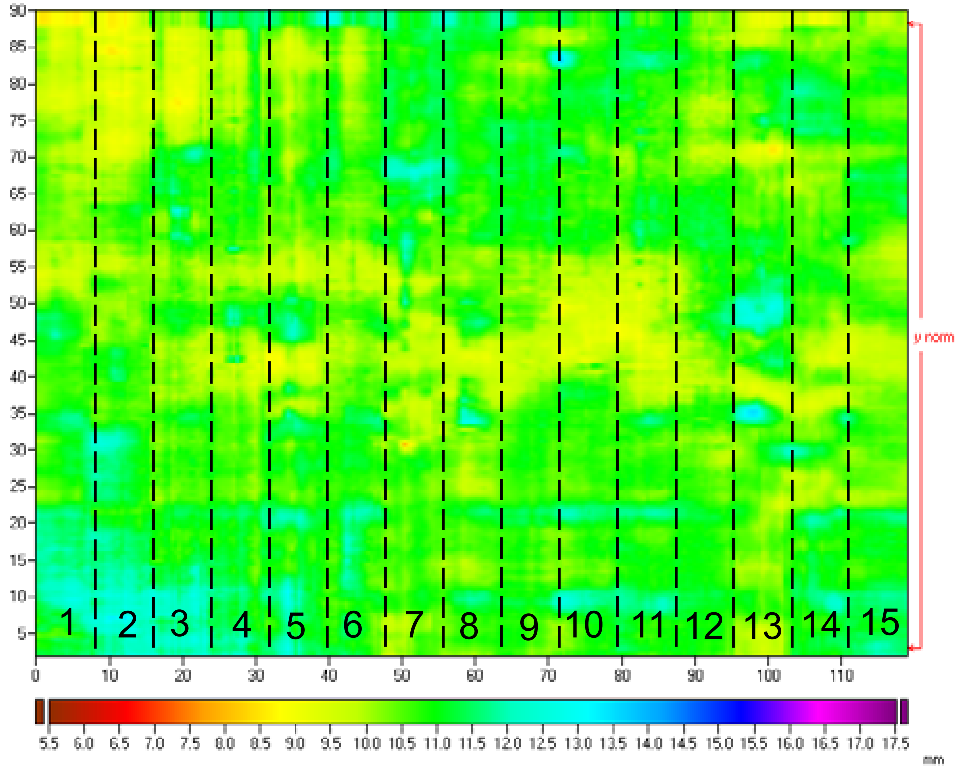


Concrete Thickness



Note that typical steel plate varies by ±10-15% without corrosion

Building Thickness Image from Multiple Scans



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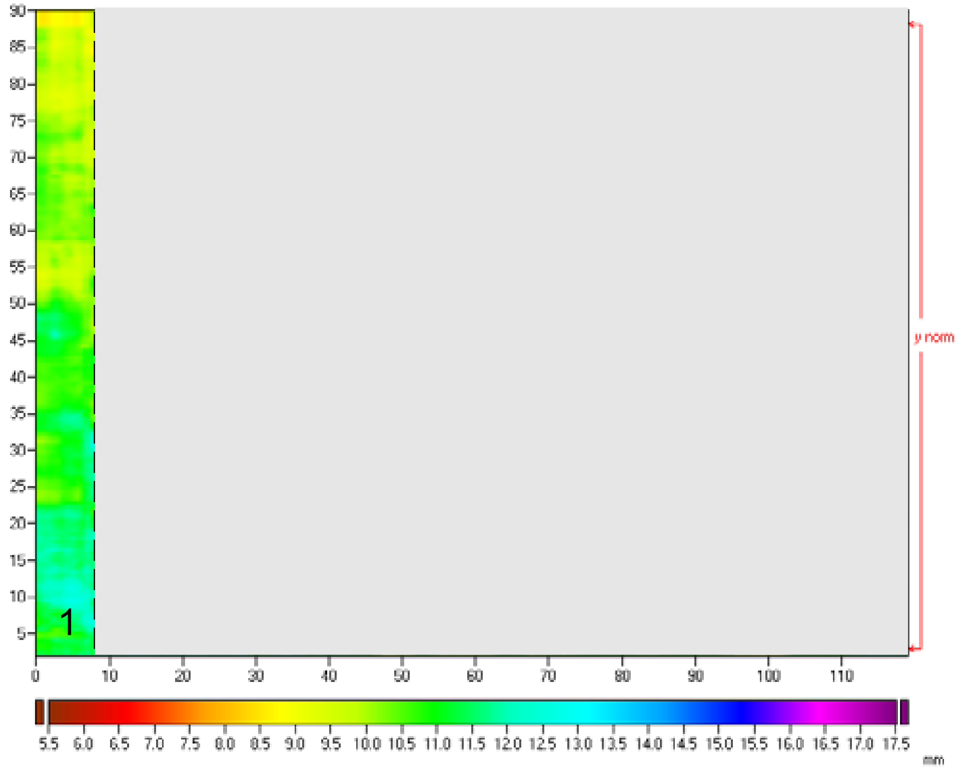

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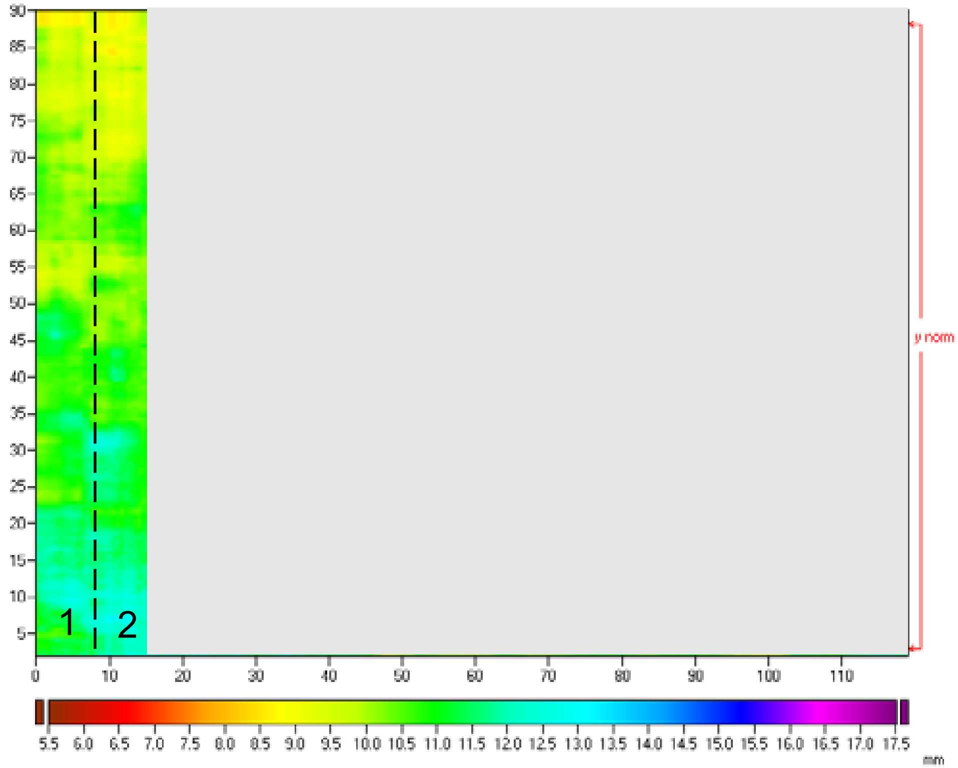

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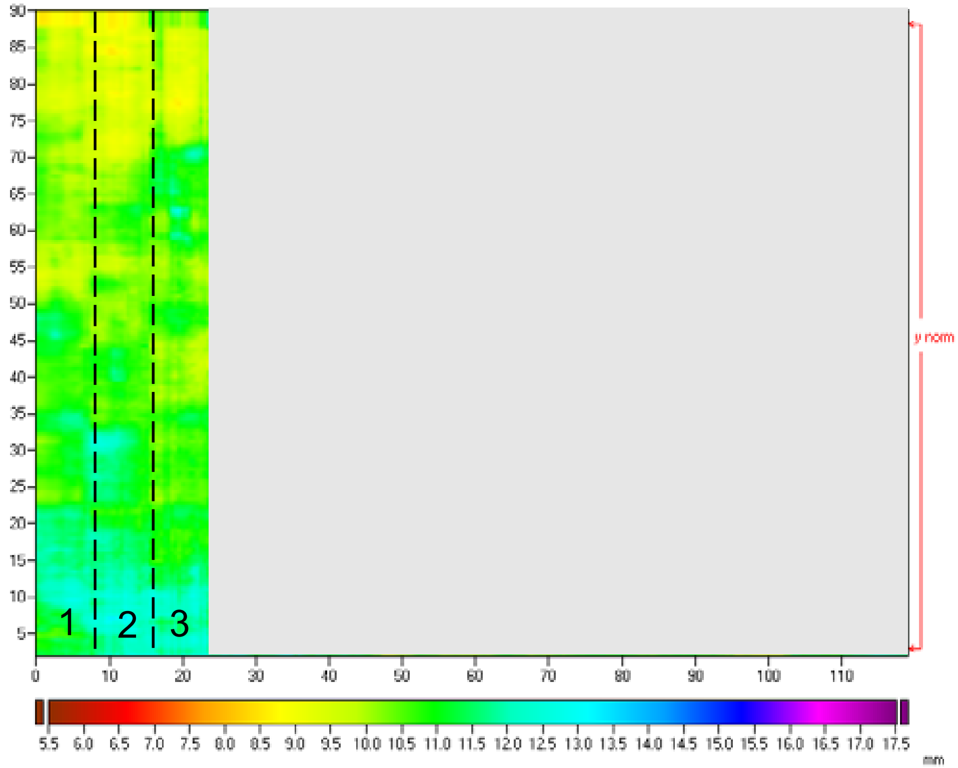

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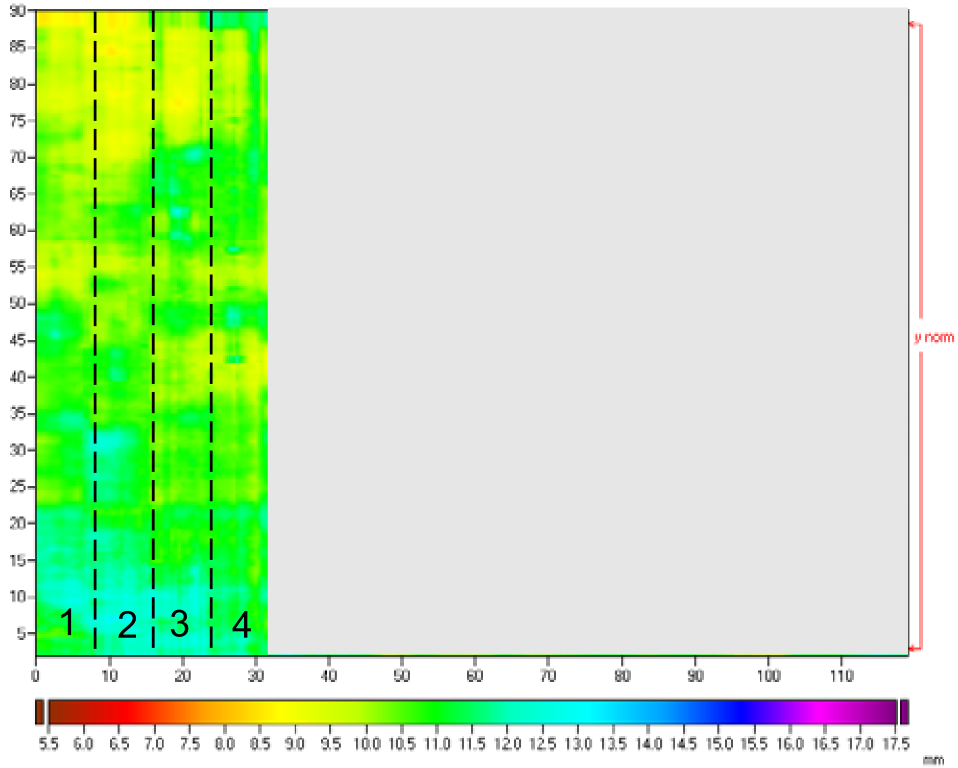

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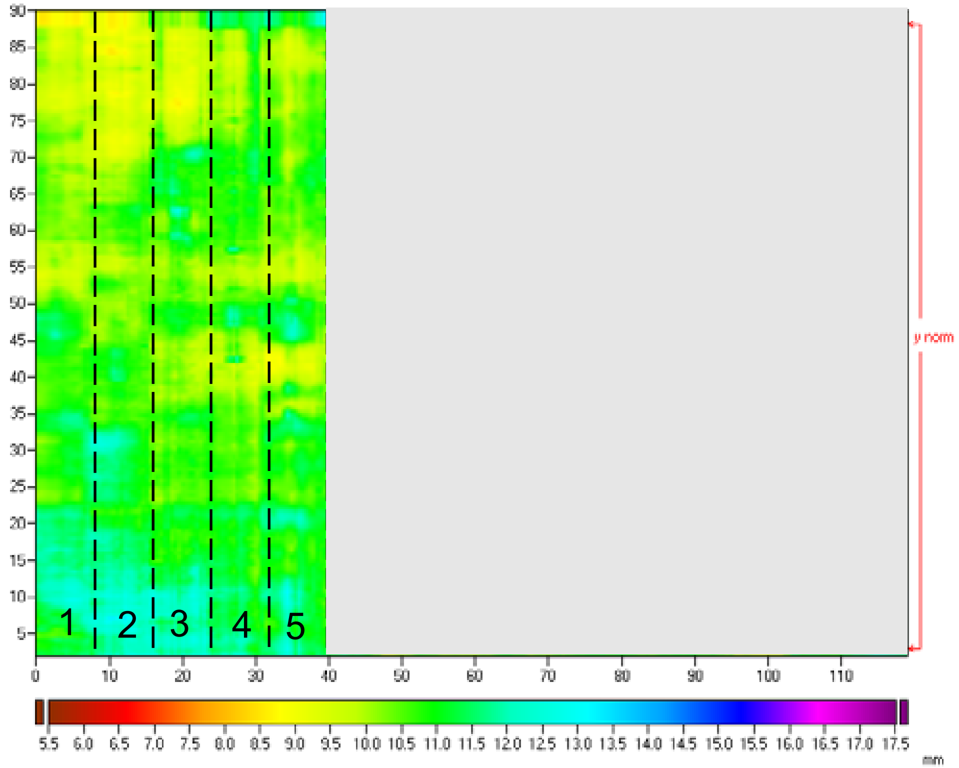

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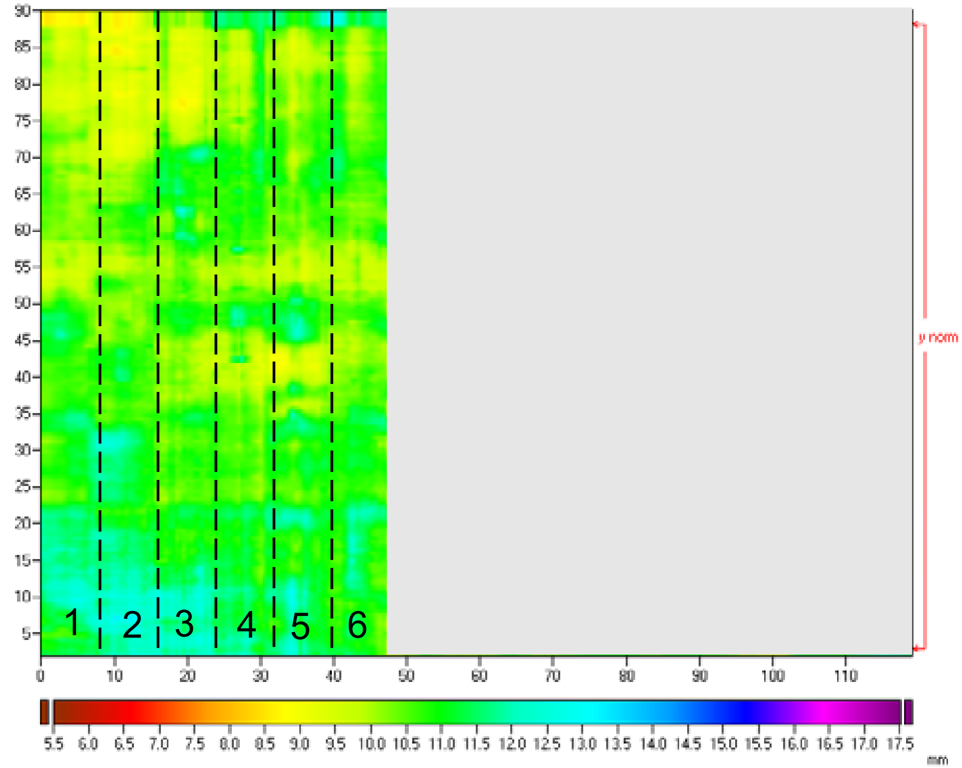

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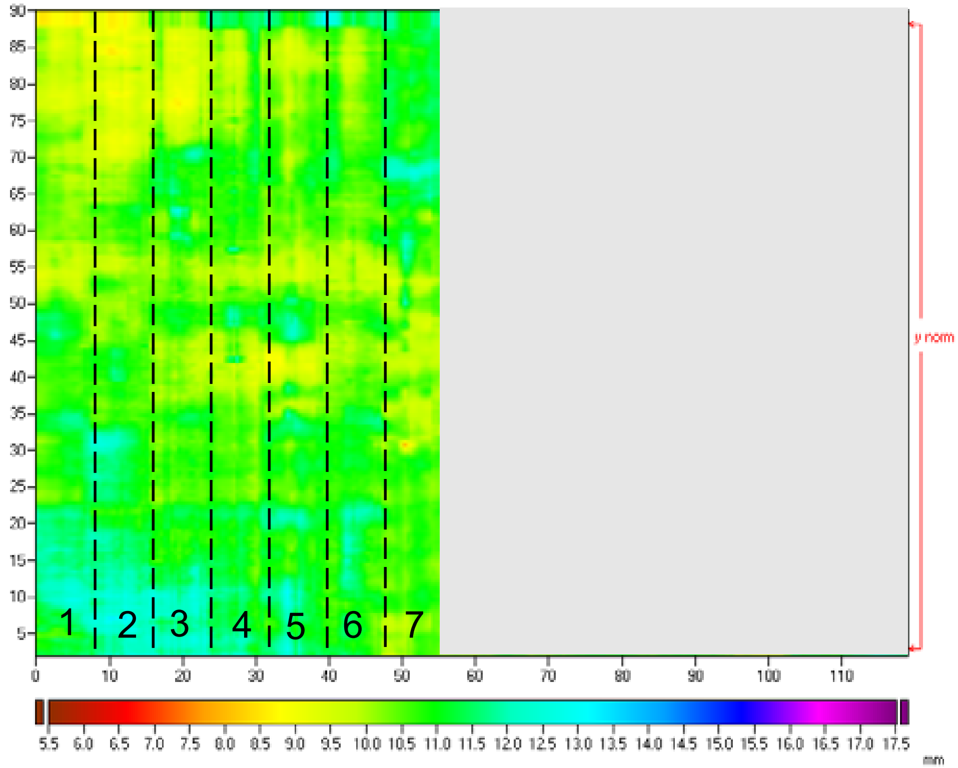

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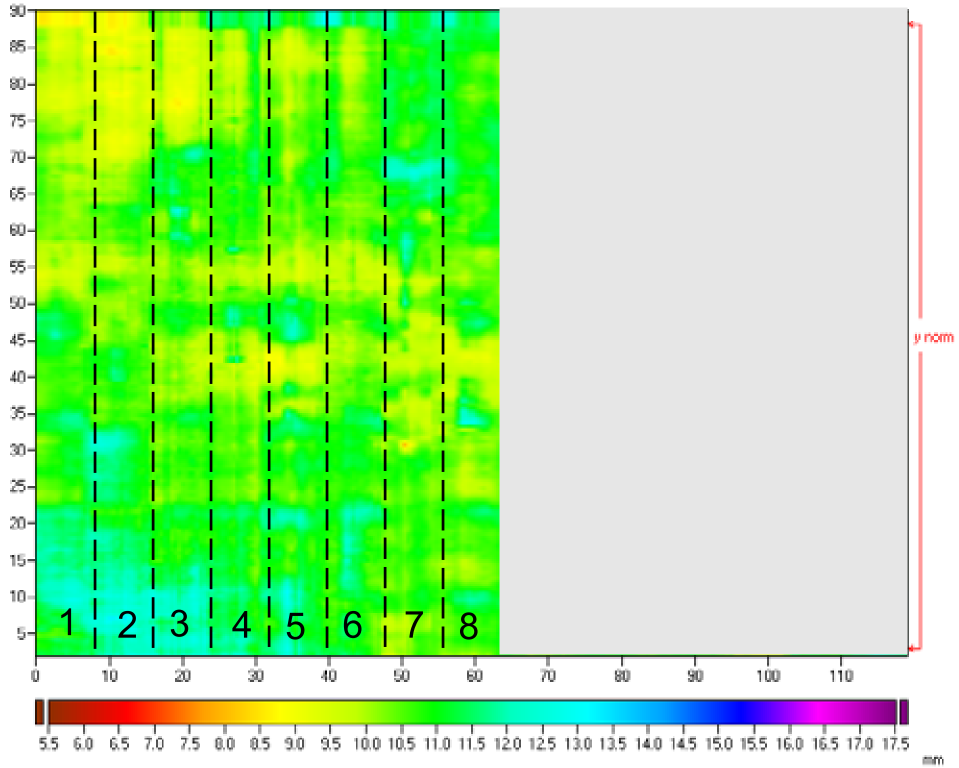

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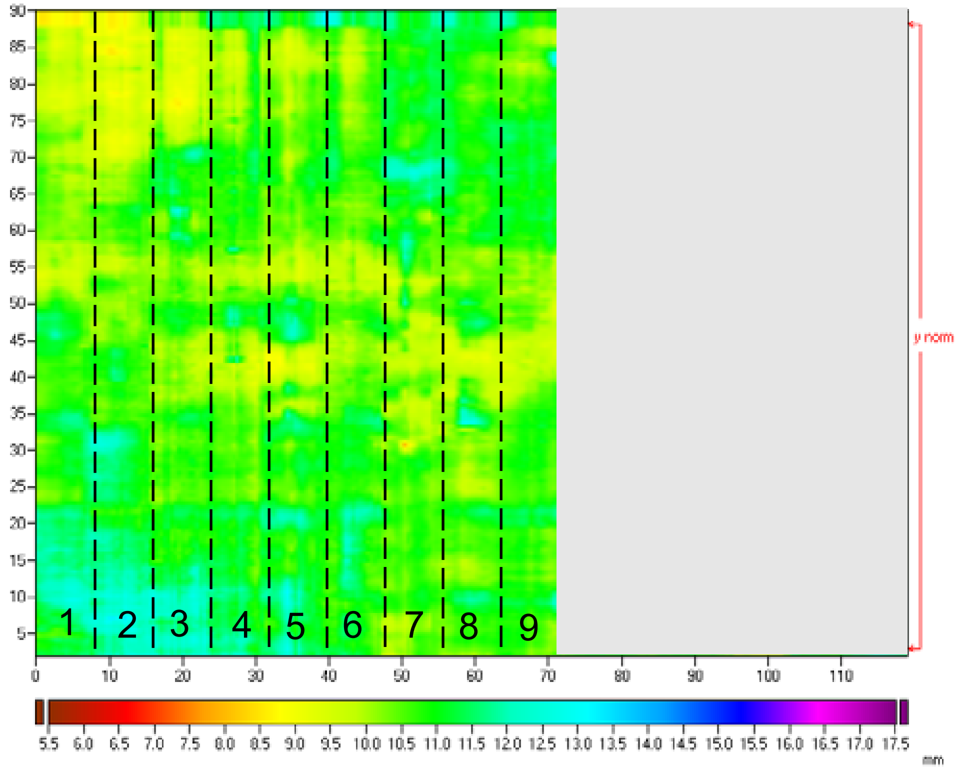

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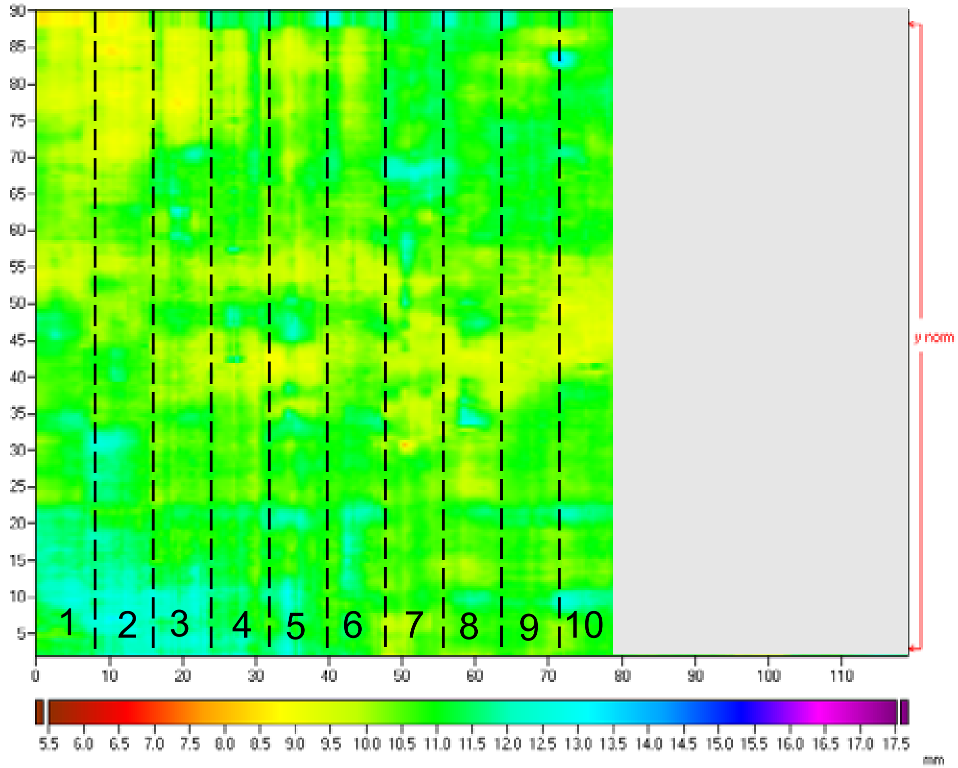

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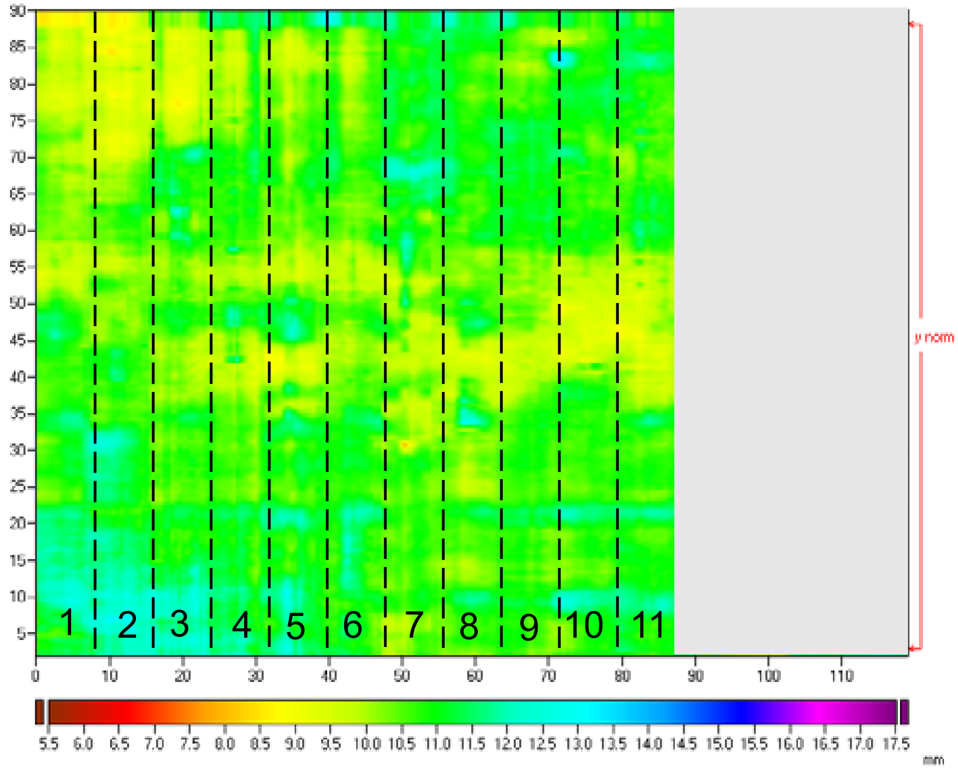

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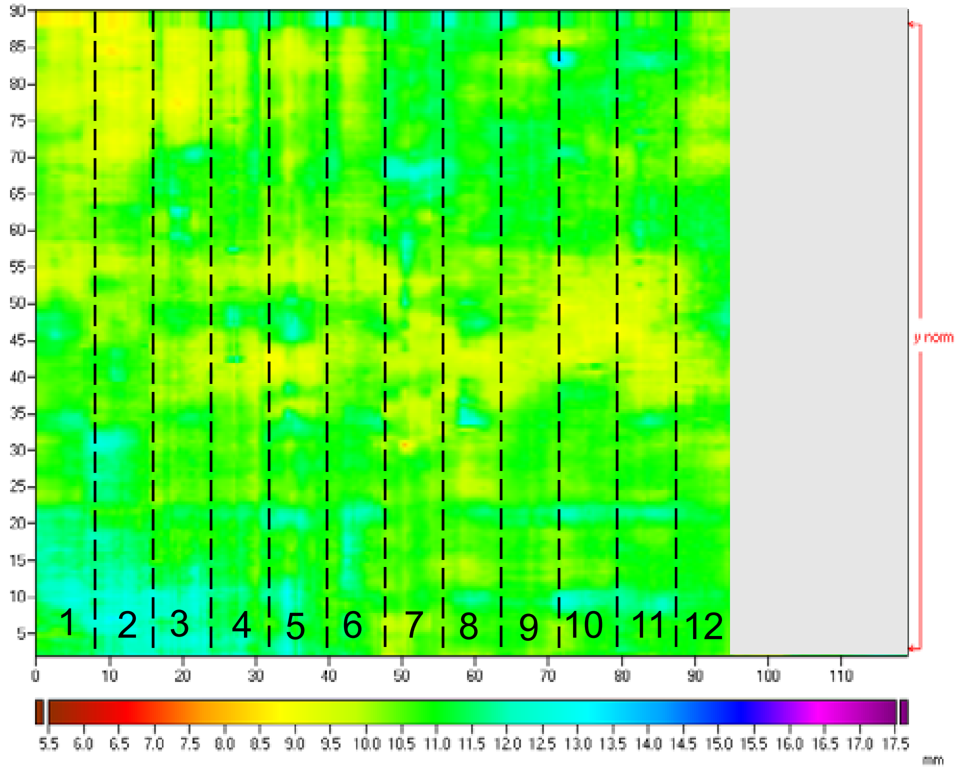

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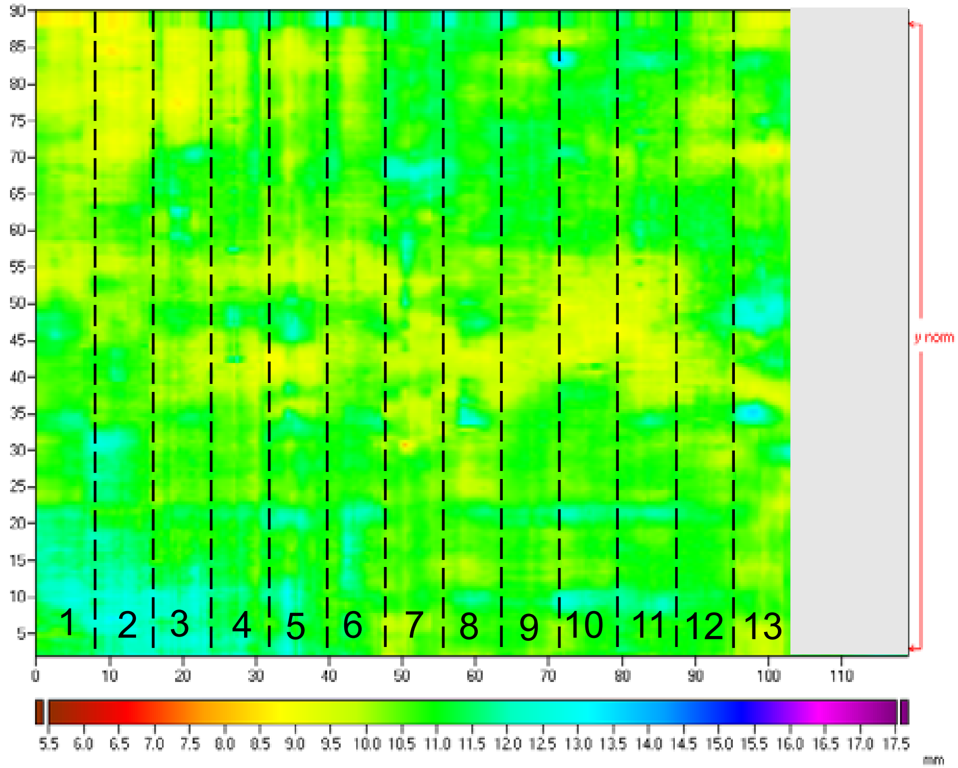

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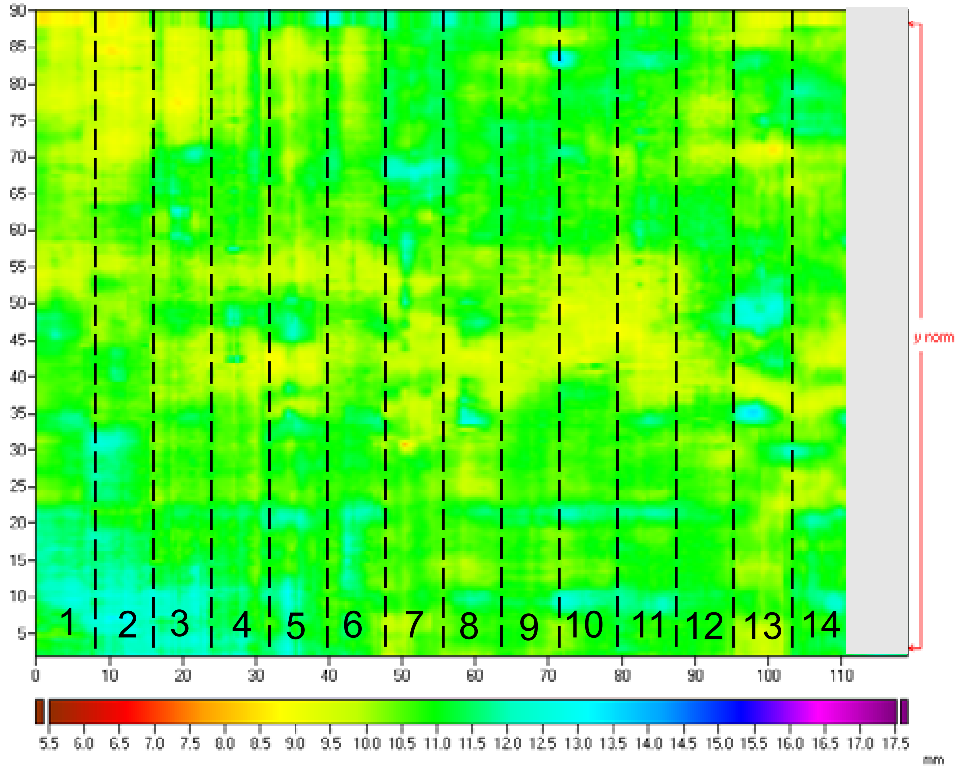

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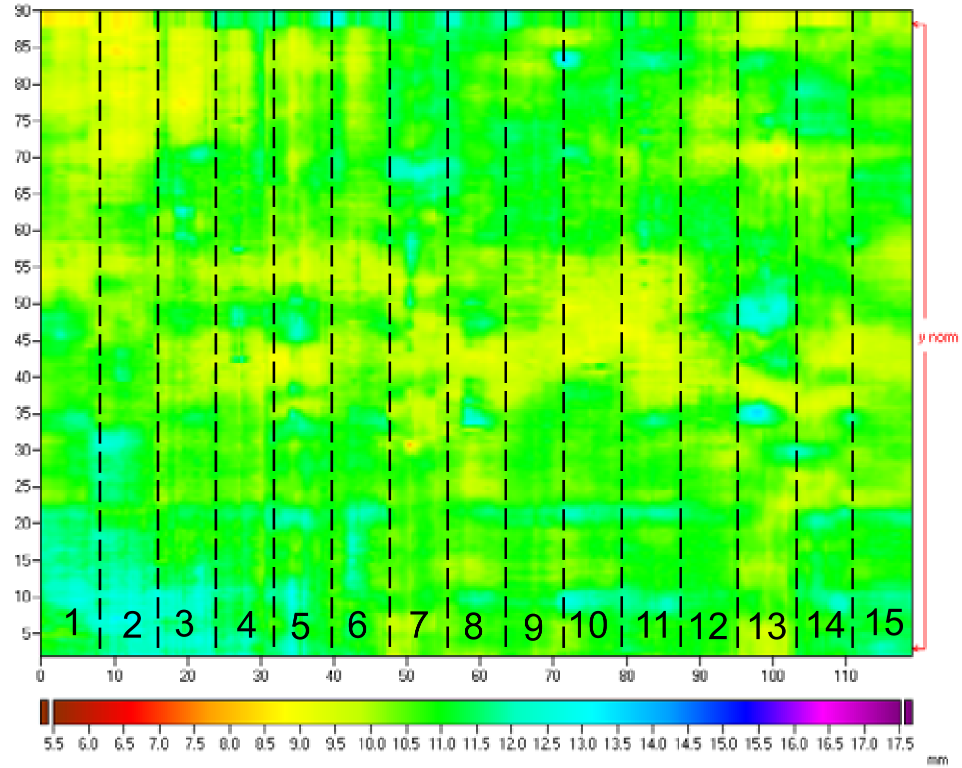
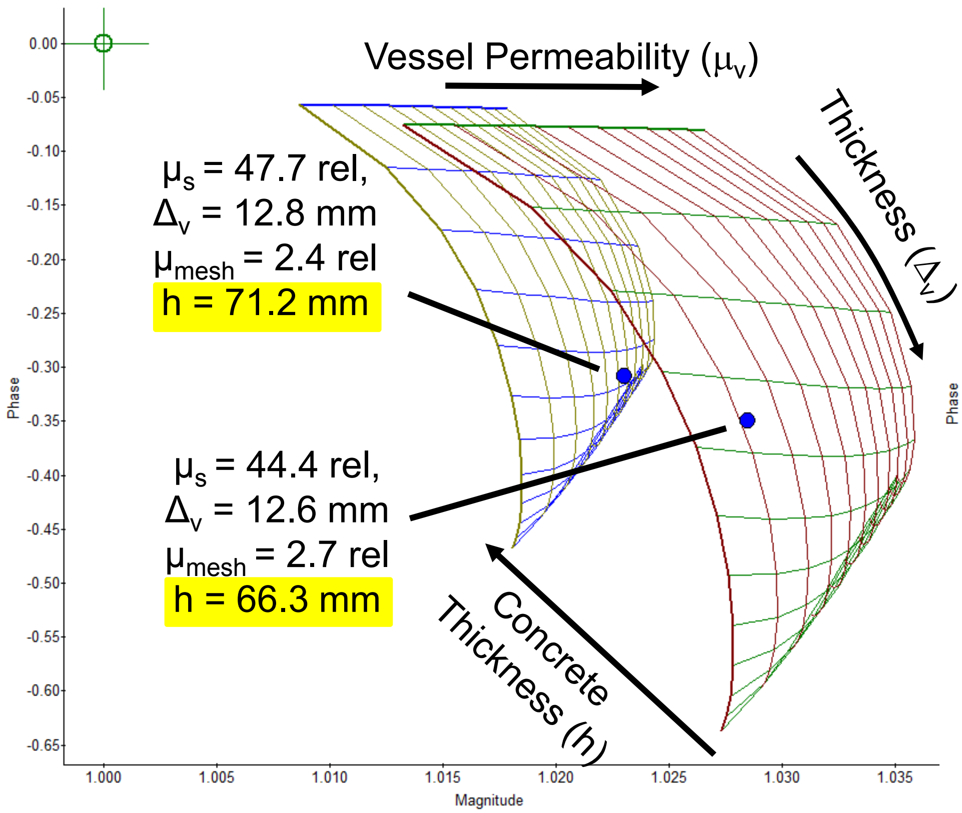
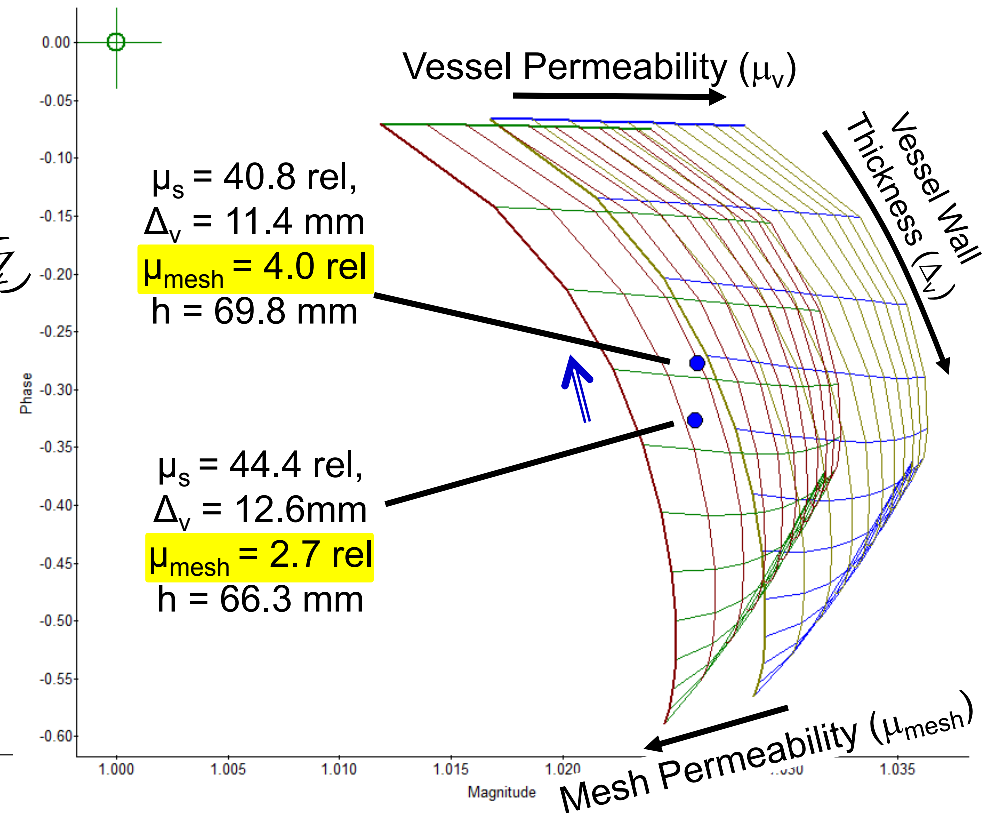


Sensitivity to Mesh Permeability and Concrete Thickness

Concrete Thickness Effect



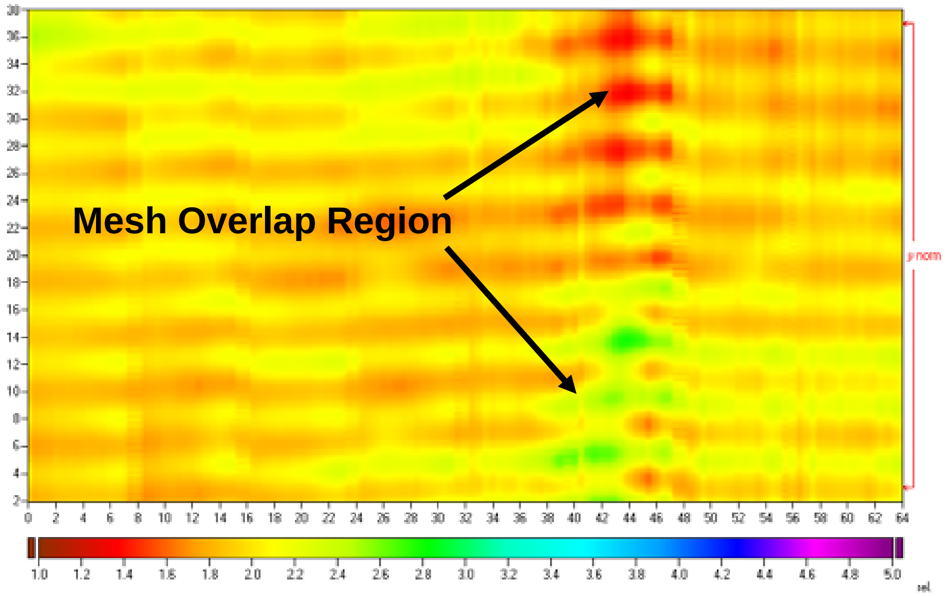
Wire Mesh "Effective" Permeability Effect



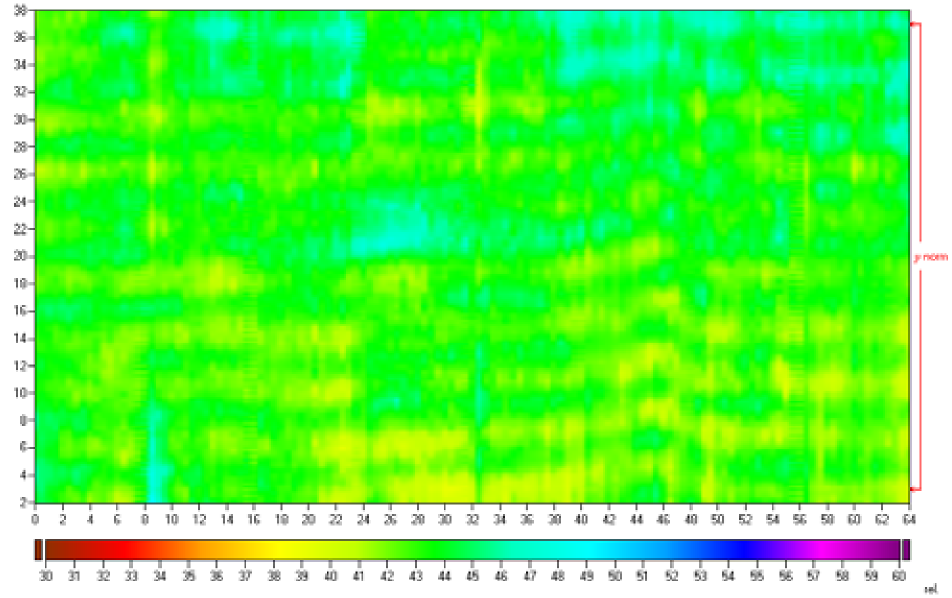
Note: This mesh effect is in the vessel wall thickness direction

Removing Mesh Contribution

Mesh Permeability



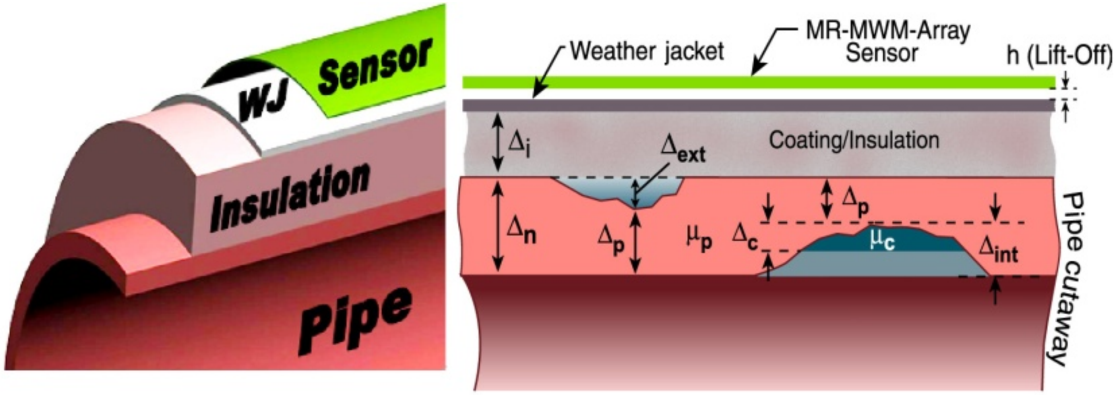
Wall Permeability



Mesh Models Still Under Development

MWM-Array Imaging of External and Internal Corrosion through Insulation with Weather Jacket

Problem Definition



Δ_p = Remaining pipe wall thickness

μ_p = Pipe wall magnetic permeability

Δ_{ext} = External wall loss

Δ_{int} = Internal wall loss

Δ_n = Nominal pipe wall thickness

h = Lift-off

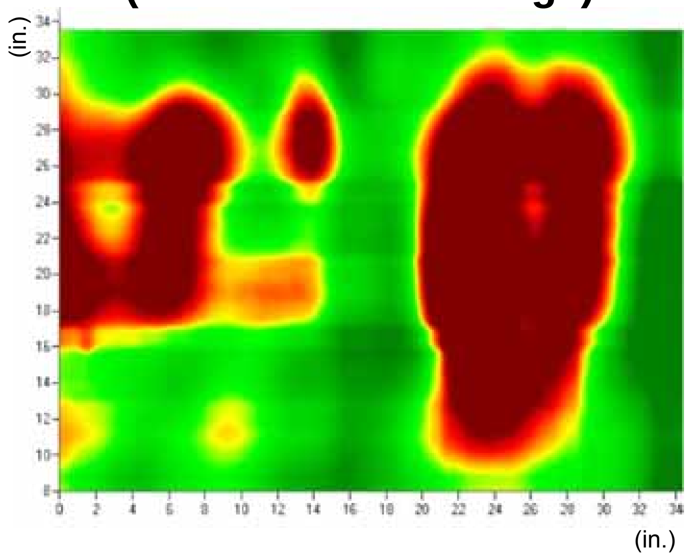
μ_c = Permeability of internal corrosion product layer

Δ_c = Thickness of internal corrosion product layer

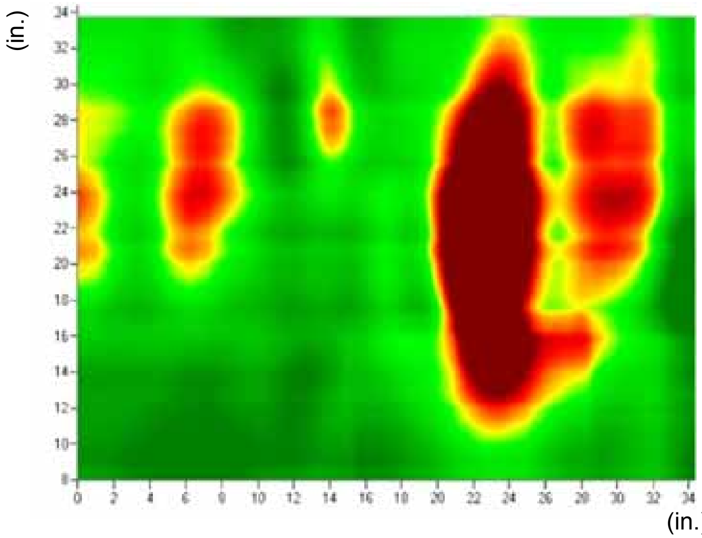
Δ_i = Coating/insulation thickness

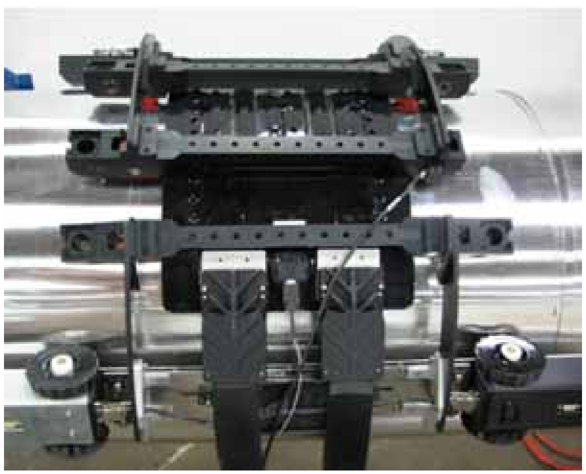
MWM-Array Inspection for CUI

Pre-Alpha System Performance (Wall Thickness Image)



Improved Resolution with Alpha System (Wall Thickness Image)





Summary

- **Demonstrated capability to:**
  - Correct for wire mesh
  - Image vessel skirt wall thickness
  - Scan large areas
- **Future work**
  - Improve scanner
  - Improve sensor effective footprint
  - Improve mesh model
  - Additional field trials in approvals