ASNT 2020
THE ANNUAL CONFERENCE

WHERE THE NDT WORLD COMES TOGETHER.

November 9-12, 2020 | #ASNTAnnual2020

Easy to Use Eddy Current Arrays with Physics Model-Based Data Analysis

Dr. Neil Goldfine

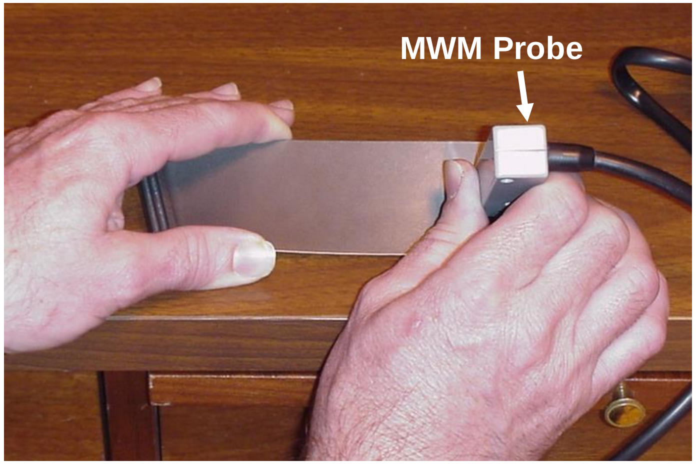
Jenteksensors.com

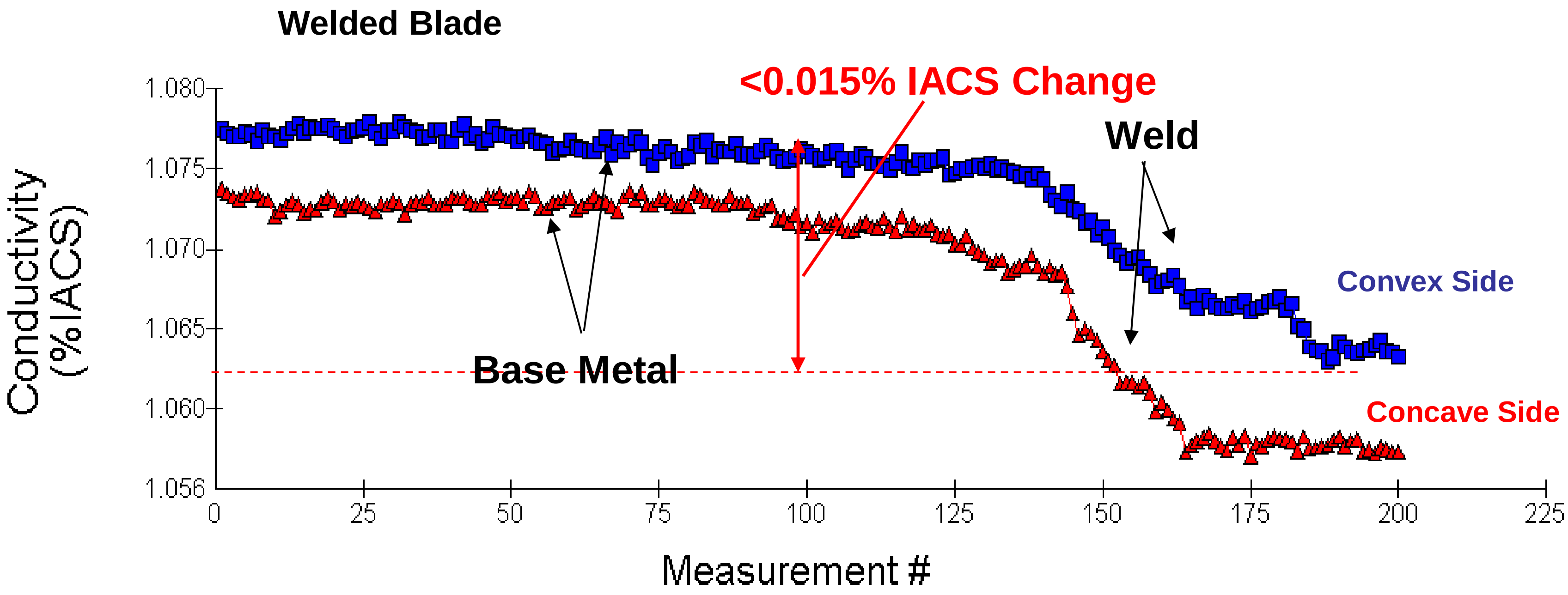
3 Decades of Research and Transitions

- **Example Successful Transitions of Research In-Use Today**
  - **S.1** Engine blade weld repair identification (2002 thru 2020+)
  - **S.2** Propeller cold work quality assessment (2002 thru 2020+)
  - **S.3** Friction Stir Weld (FSW) qualification (intermittent 2005-2020+)
  - **S.4** Engine component NDT (2005-2020+)
  - **S.5** Coating characterization (intermittent 2007-2020+)
  - **S.6** Space Shuttle Leading Edge at KSC (2007-2010)
- **Example Engineering-Science Innovations & Ongoing R&D**
  - **I.1** Model-based Multivariate Inverse Methods Using HyperLattices
  - **I.2** Segmented Filed ET-Arrays (SF-ET-Arrays)
  - **I.3** MWM-Array and Parallel architecture impedance instruments
  - **I.4** Fatigue, Stress and Corrosion monitoring
  - **I.5** Accessible ET-Array systems, software and training
  - **I.6** Aircraft NDT for cracks and corrosion
  - **I.7** Additive manufacturing and weld inspection

S.1: US Navy Turbine Blade Weld Inspection (<2002)

- System was upgraded for the application
- Effective, rapid procedure
- Blades with weld repairs readily identified
- 10,000 blades inspected, no false positives (i.e., all detections confirmed)





S.1: US Navy Turbine Blade Weld Inspection (2020)

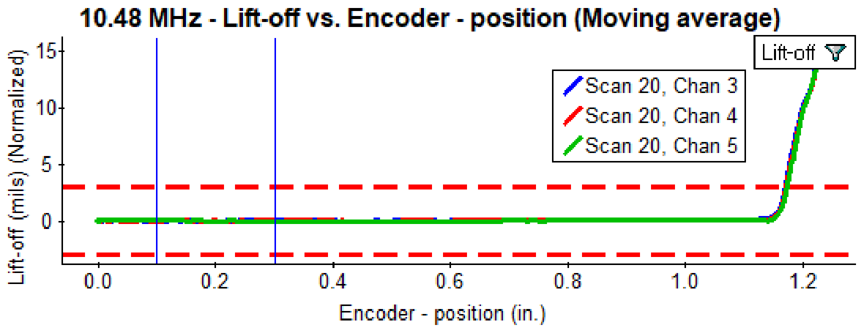
Upgraded in 2020

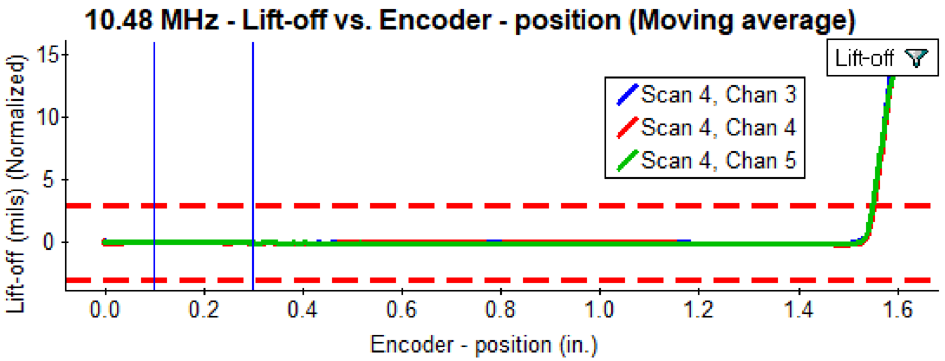
- jET 7-Channel Handheld
- FA274 MWM-Array
- Simple scanning fixture
- New Software “Tabs” for POI (Probability of Inspection) verification

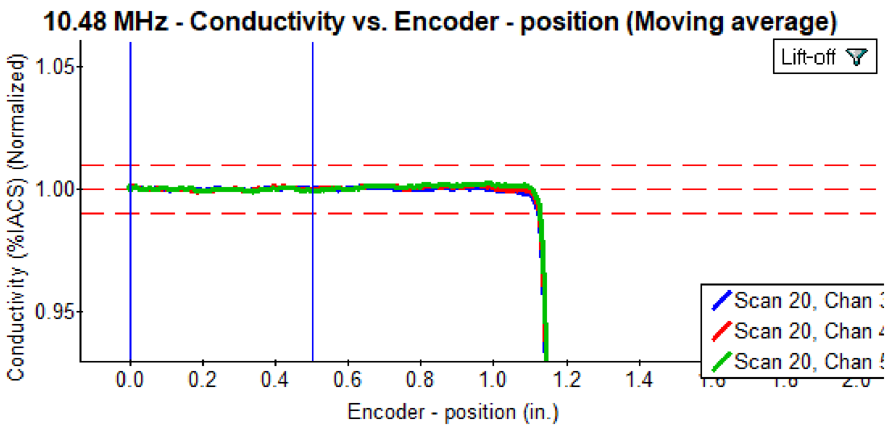
S.1: US Navy Turbine Blade Weld Inspection (2020)

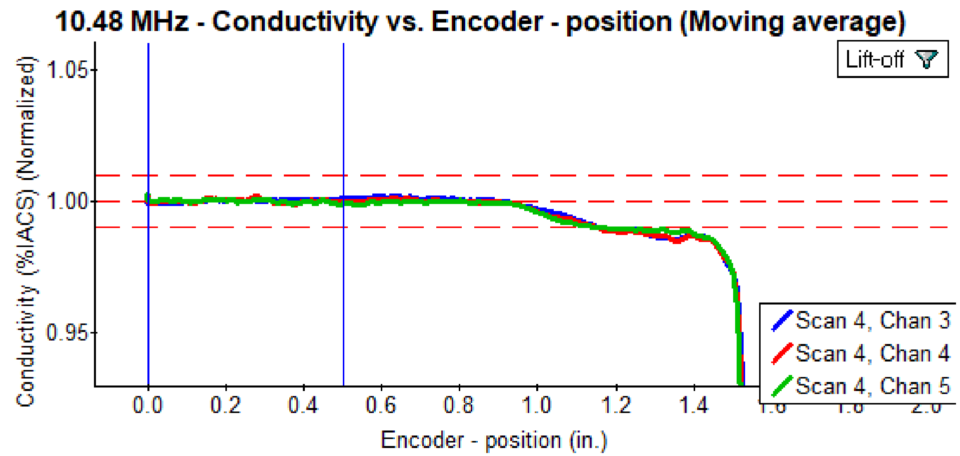
Good Blade

Bad Blade





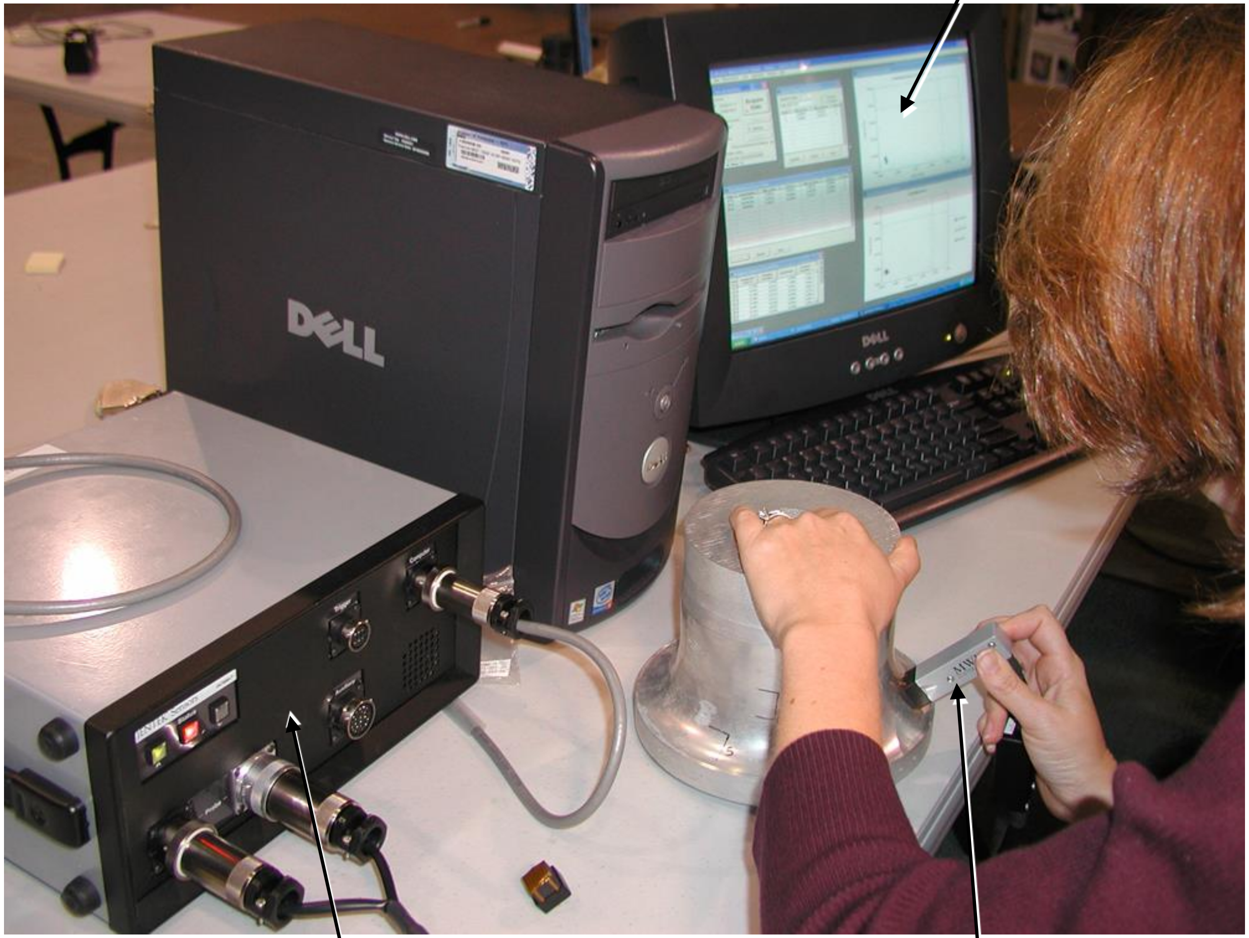




S.2: USAF Prop. Cold Work (<2003, 2018 jET upgrade)

C-130 Blade
Shanks

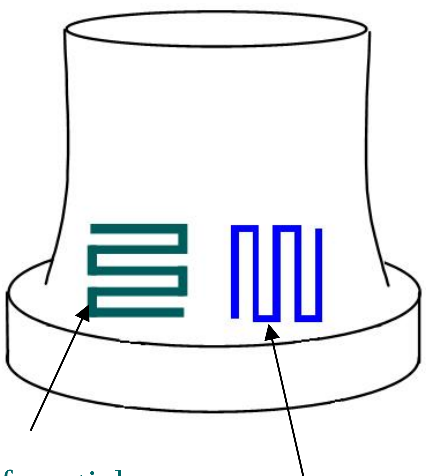
GridStation
Software



7-Channel
Instrument

MWM Probe

S.2: USAF Prop. Cold Work (<2003, 2018 jET upgrade)



Circumferential

Axial

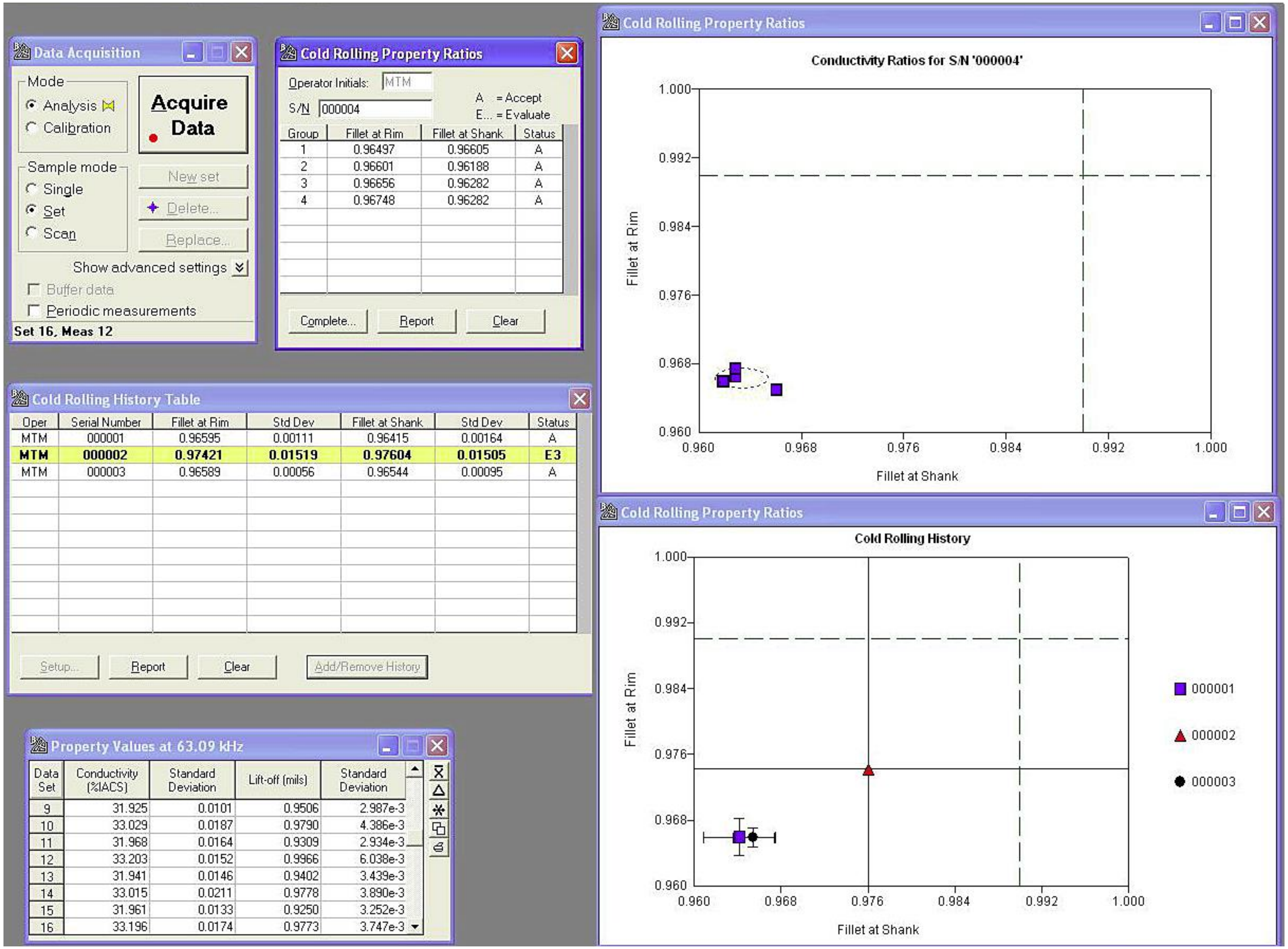
Position 1

Position 2

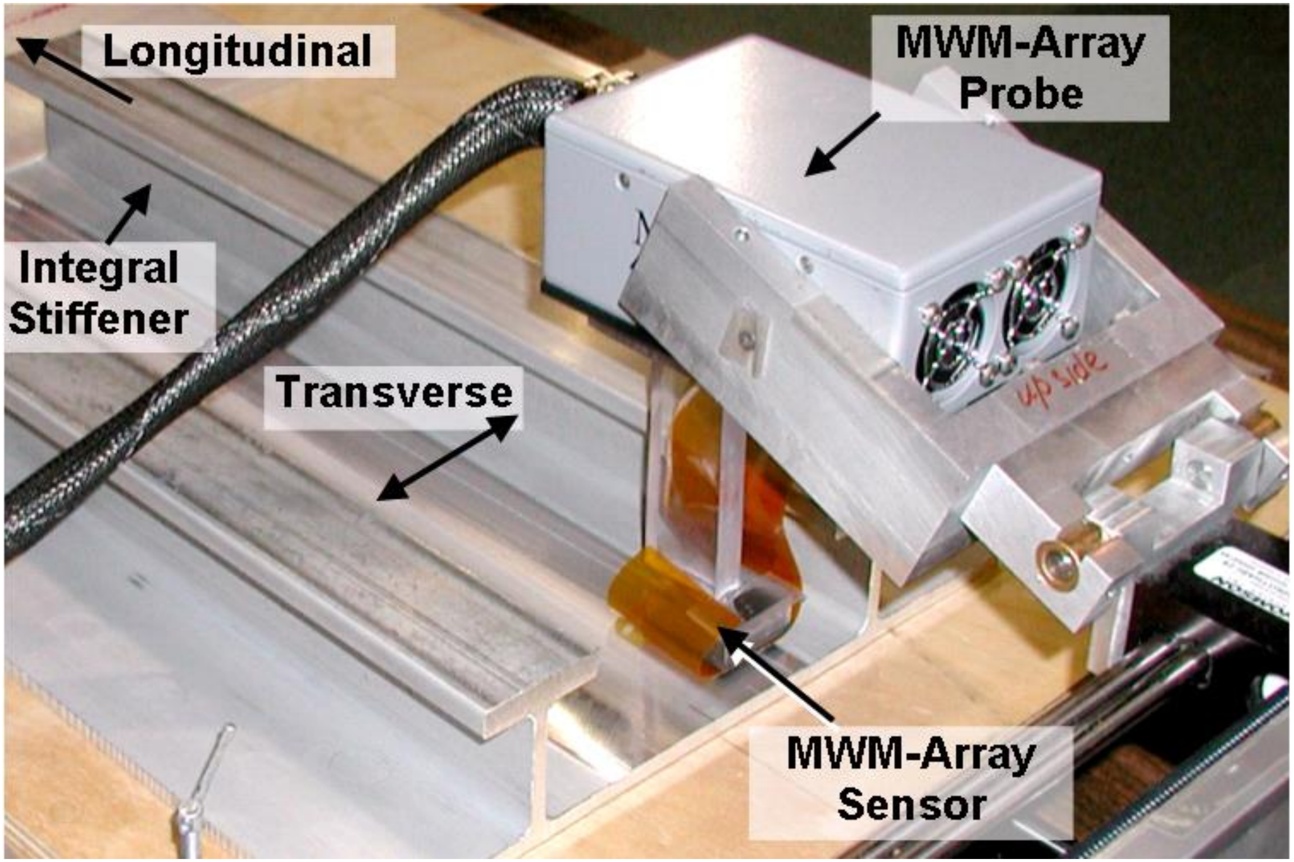
Position 3

Position 4

S.2: Typical JENTEK GridStation® Interface for Cold Work Quality Control

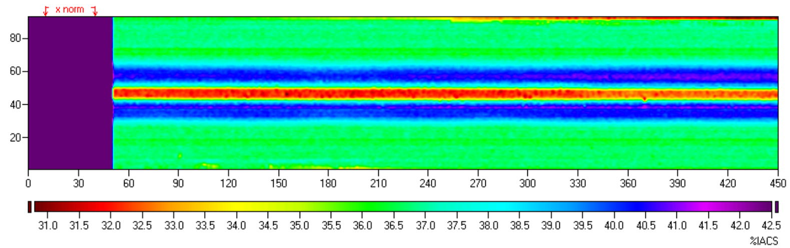


S.3: Scanning Set-up for JENTEK, ALCOA FSW Study (2005 – continued in 2020 transitions)

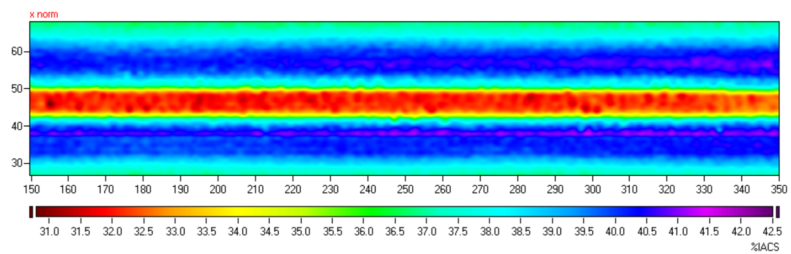


S.3: MWM-Array Longitudinal Scans

Good, Full Penetration

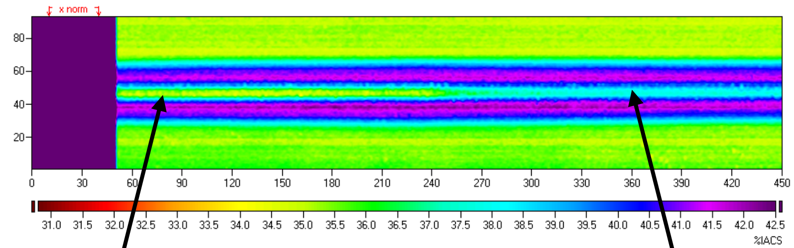


Full Scan



Close-up View

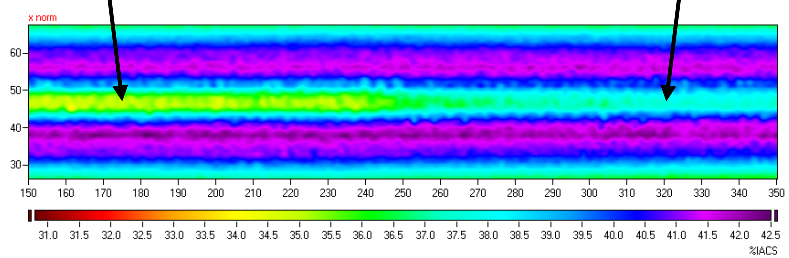
Kissing Bond and Lack of Penetration



Full Scan

Kissing bond

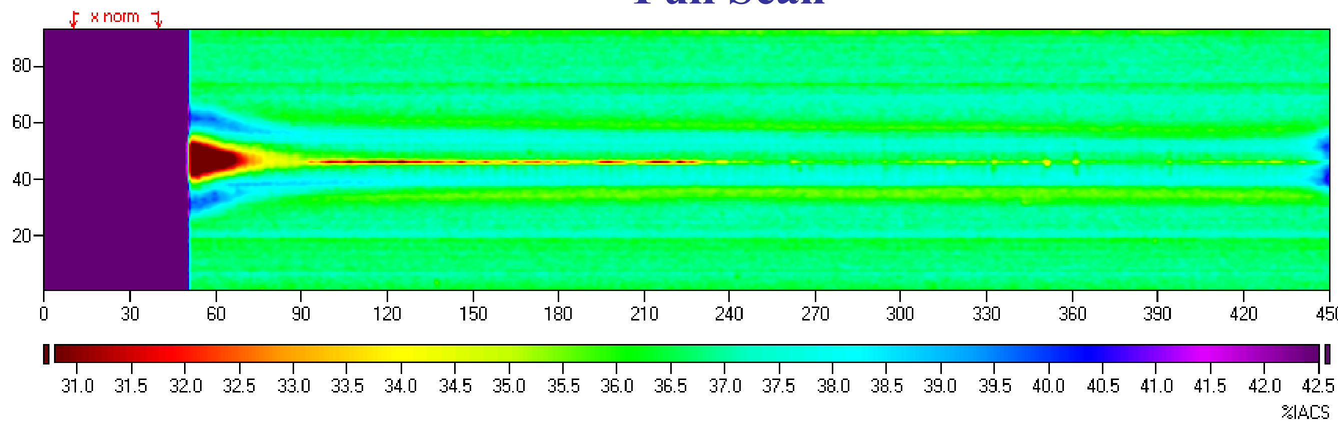
Lack of penetration



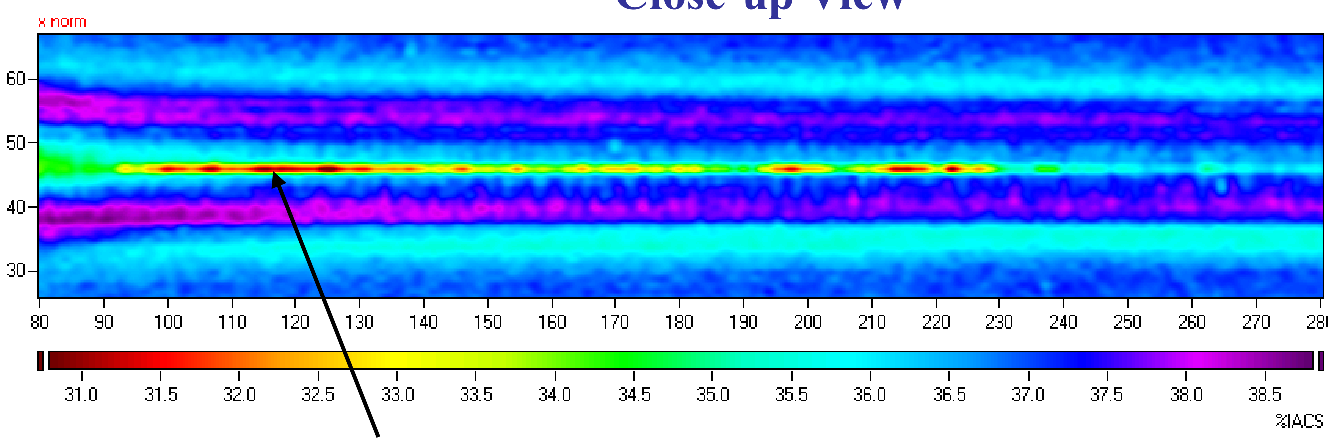
Close-up View

S.3: MWM-Array Longitudinal Scan

Full Scan



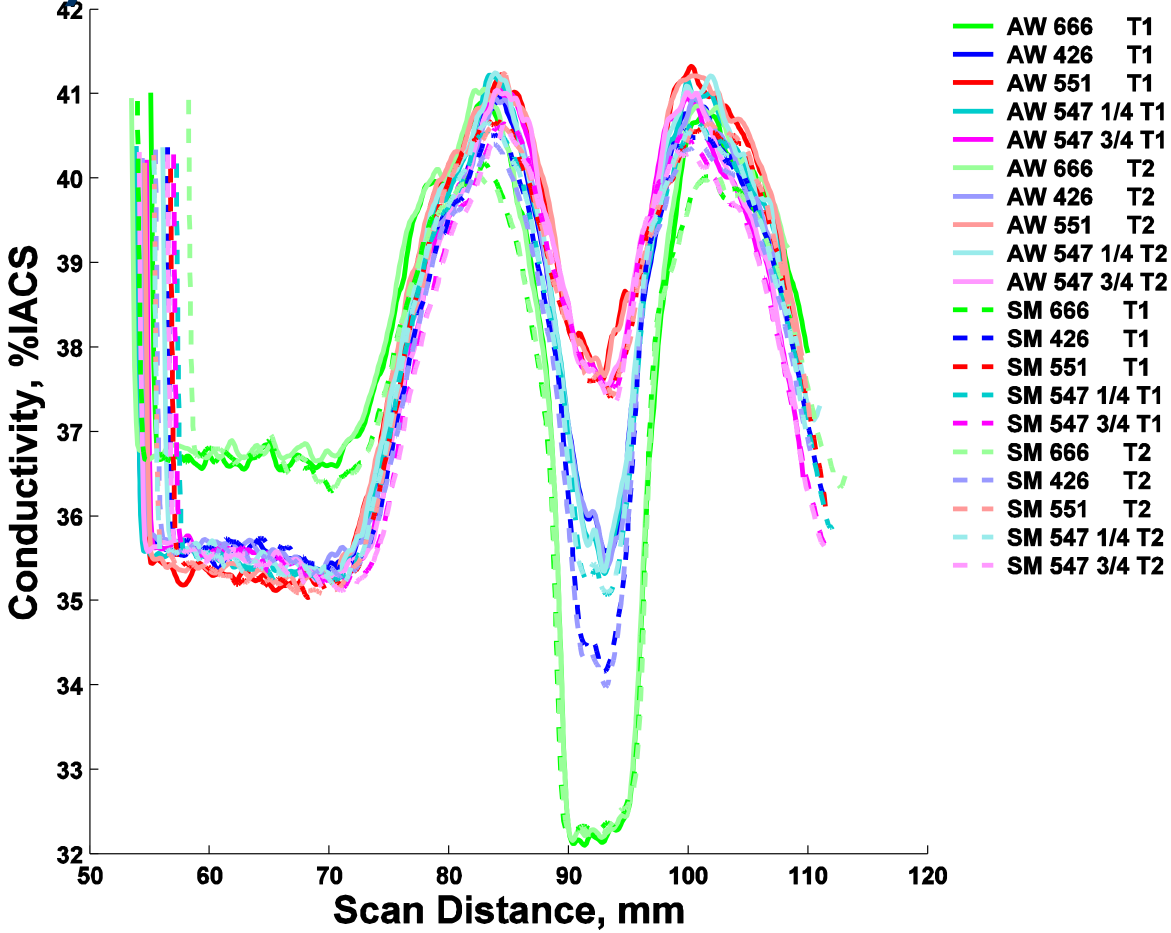
Close-up View



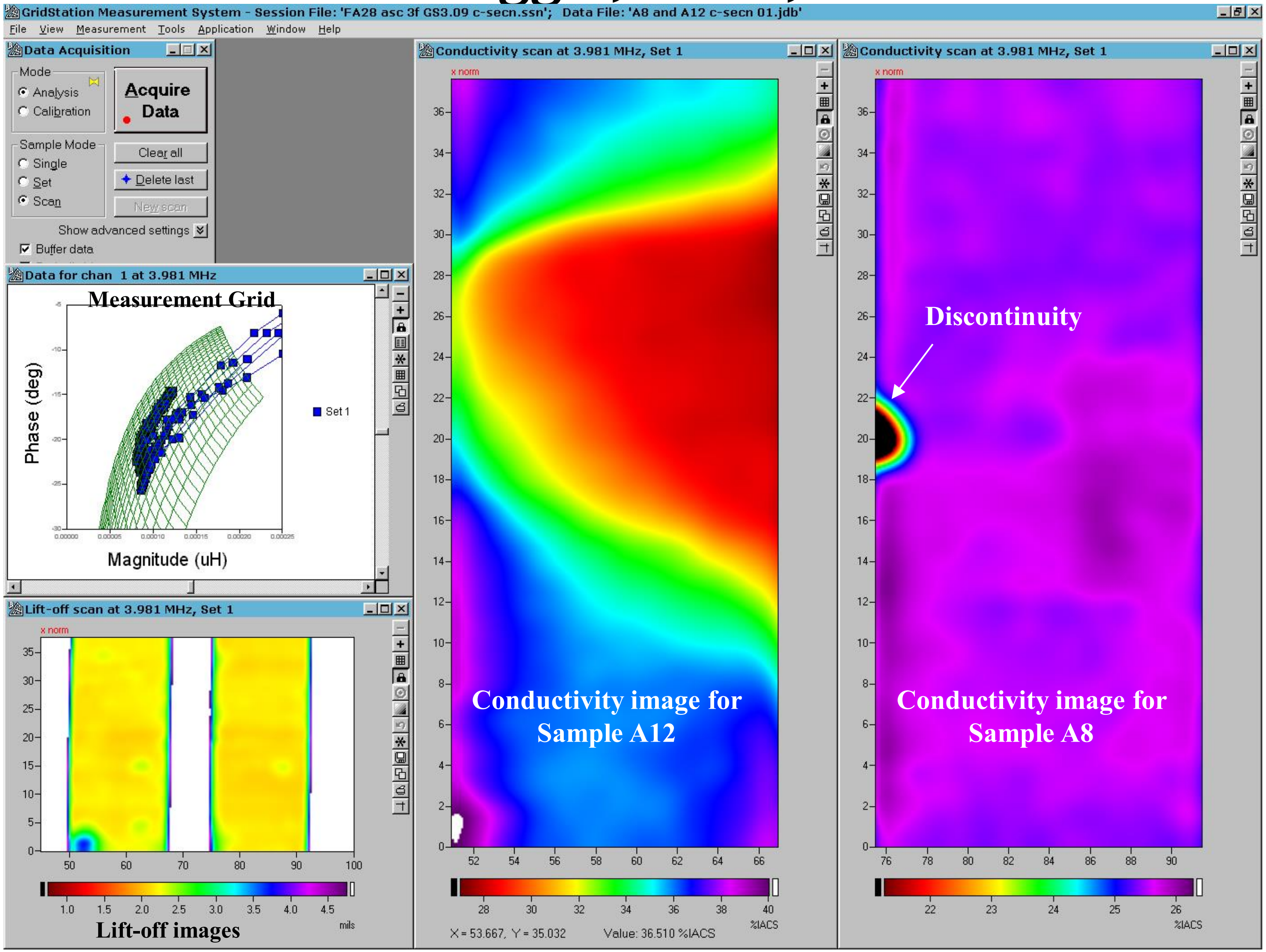
Intermittent Planar Discontinuities

S.3: Conductivity Scans across FSW

Plots of conductivity acquired during transverse scans of panels in the as-welded (solid lines) and skim-machined (dashed lines) surface conditions



S.3: Images of conductivity for two FSW panels cross-sections show nugget, TMZ, HAZ and base metal



S.4 Knife Seal Inspection (2005 still in use)

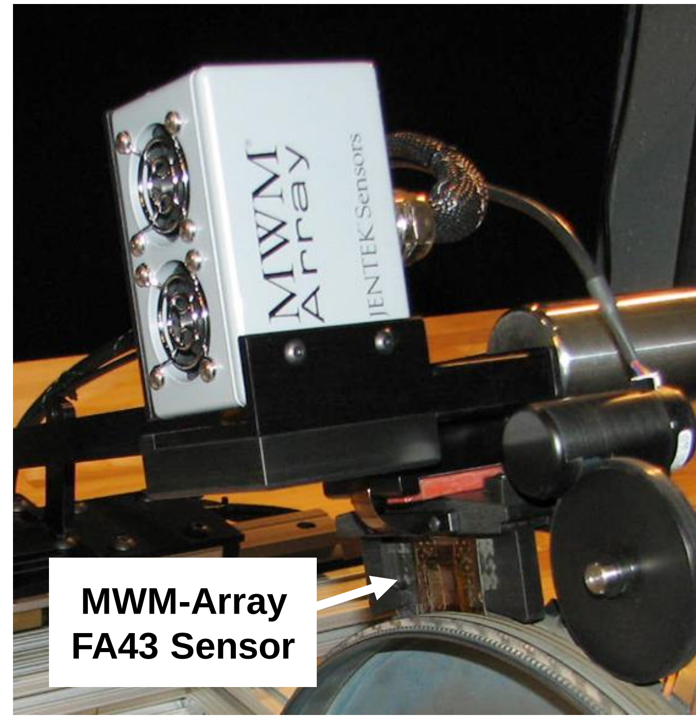
- "Technical aspects of the method are FAA approved" (See Service Bulletin)
- Engine OEM implemented this inspection
- Multiple systems in use world-wide since 2011
- AE family engine knife seal Inspection on several stages for cracks
- Thousands of engine stages inspected per year
- Inspection performed with blades in place (minimal disassembly saves substantial dollars)

AE SERIES PROPULSION SYSTEM
Service Bulletin Index

Rolls-Royce

LIST OF AE 3007A SERIES SERVICE BULLETINS

SB No.	Rev No.	Title	Compliance Category	Date	Models Affected	Module or ATA Locator
AE 3007A-72-386		See AE 3007A-A-72-386				
AE 3007A-72-388	1	Engine - 6th- thru 13th-Stage Compressor Wheel Knife Edge Seals - Jentek Eddy Current Inspection	8	09-May-11	7A, 7A1/1, 7A1/3, 7A1, 7A1E, 7A1P, 7A2, 7A3	72-37-00

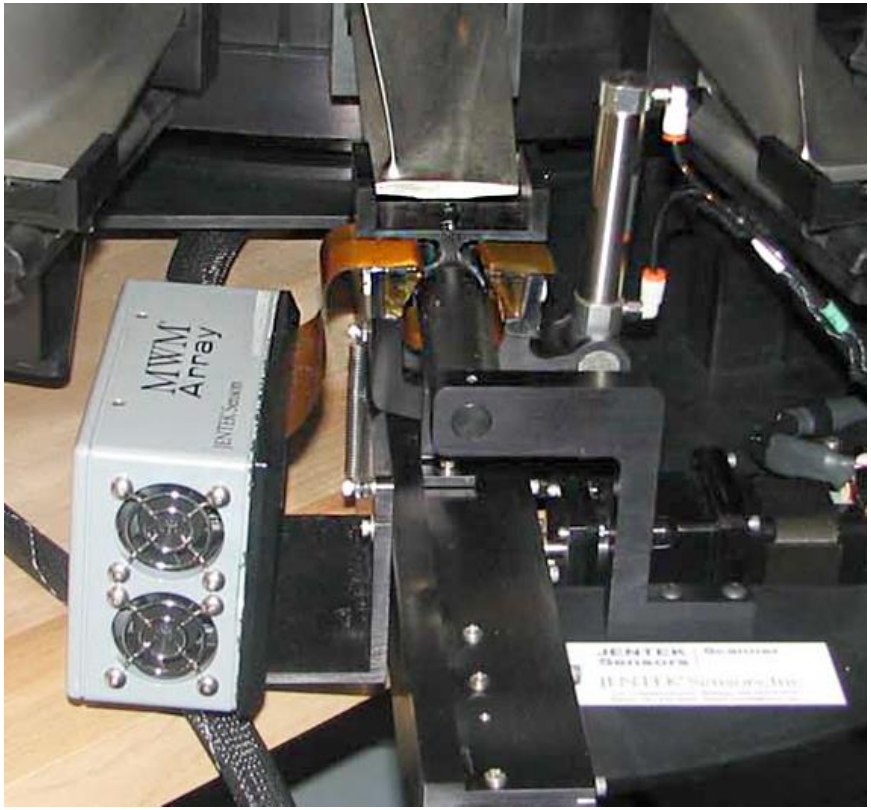


MWM-Array FA43 Sensor adapted for knife seal inspection

Reference: https://aeromanager.rolls-royce.com/control/publicsite/publicnoticeboard/categorylist?userAction=performDisplayDocument&selectedLevel=2&selectedLevelID=65

Distribution Statement A -- Approved for public release; distribution is unlimited, as submitted under NAVAIR Public Release Authorization Tracking number 2015-217.

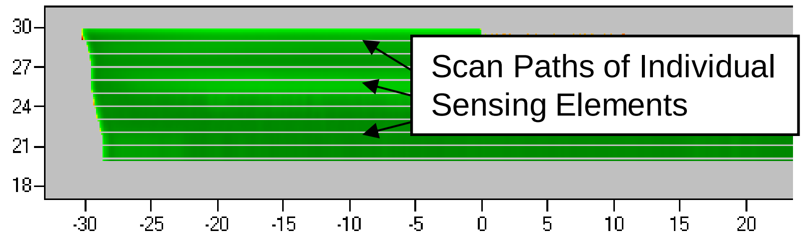
S.4 US Navy Blade Dovetail Inspection 2010, still in-use

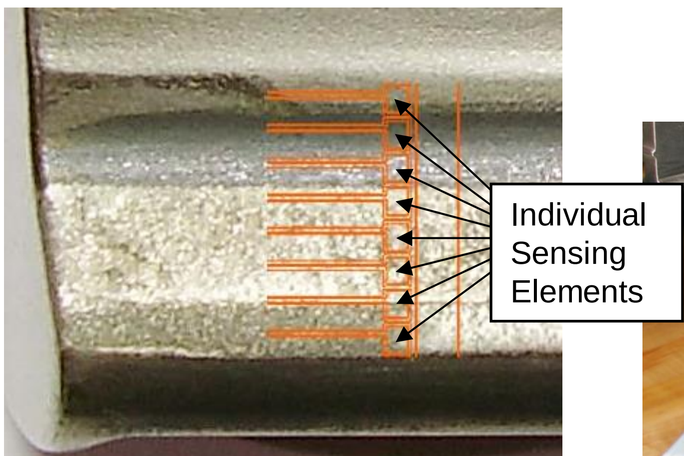


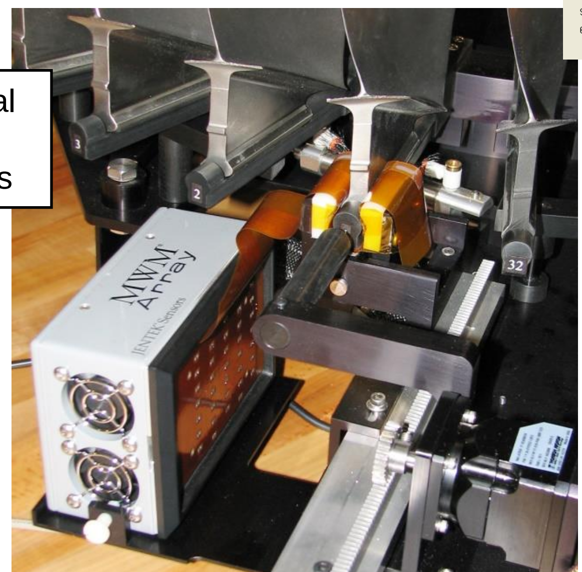
- Engine Blade Dovetail
- Provide crack depth measurement to enable CBM /repair of blade dovetail for life extension
- Technical approach: multiple frequency MWM-Array detection, location and depth sizing for cracks in regions with fretting damage
- Validation method – Detection performance validation included POD study
- Status: Solution validated and system delivered

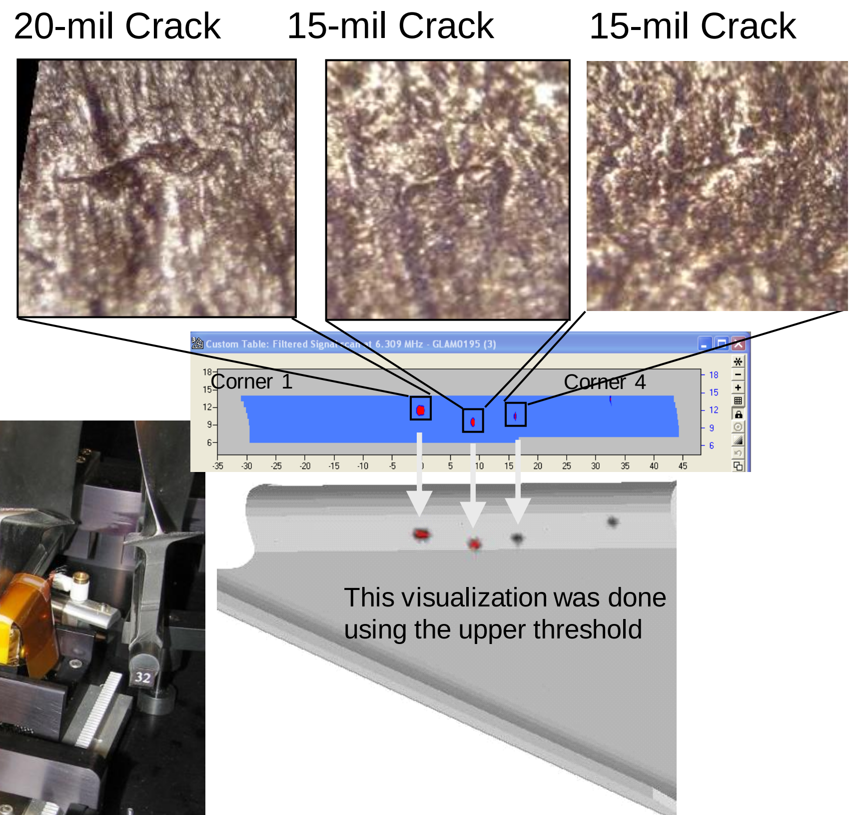
S.4 US Navy Blade Dovetail Inspection 2010, still in-use

Sensor Coverage for Blade Dovetail Scans



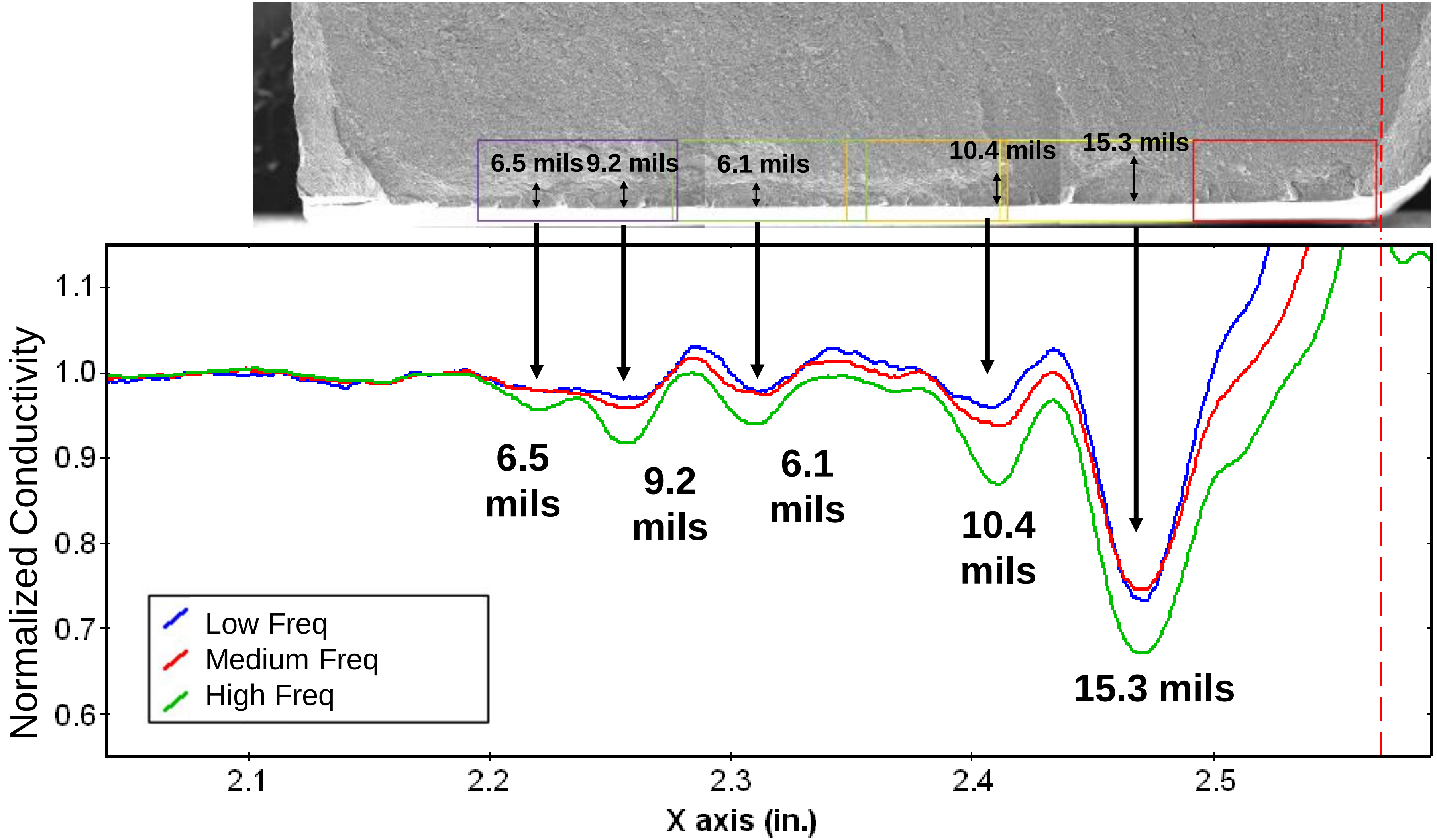






S.4 US Navy Blade Dovetail Inspection 2010, still in-use

Blade #13



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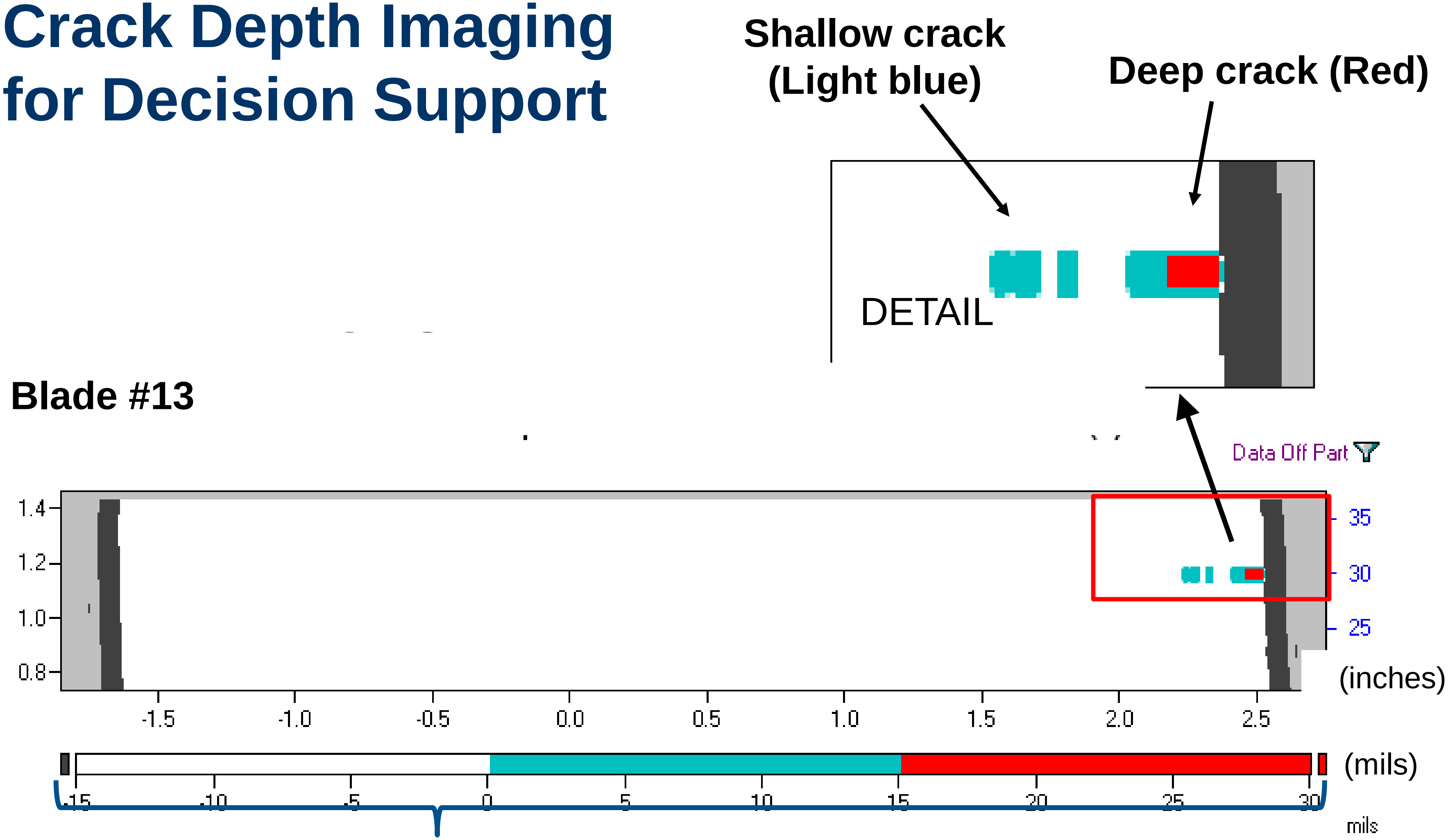
S.4 US Navy Blade Dovetail Inspection 2010, still in-use

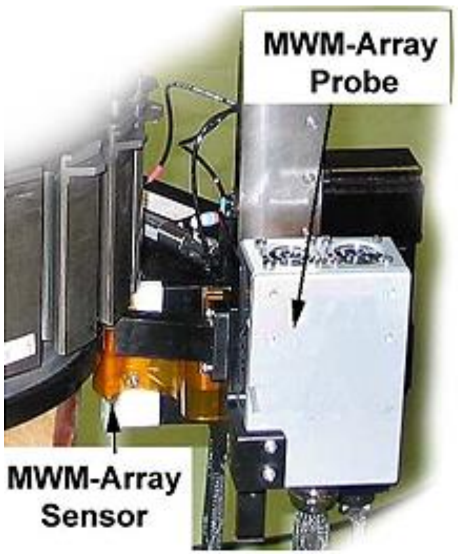
Crack Depth Imaging for Decision Support



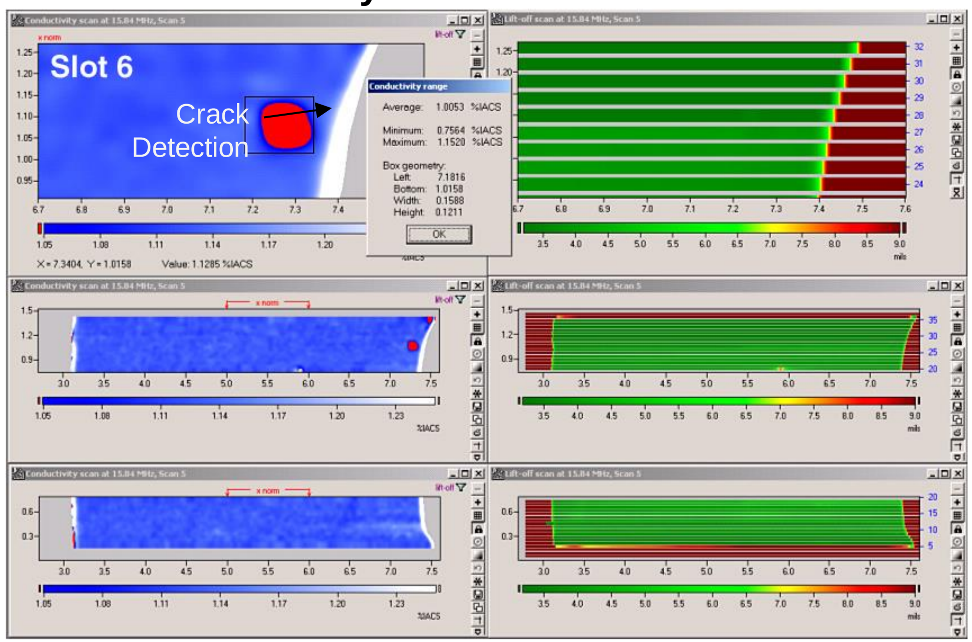
Entire image encompasses one complete side of dovetail

S.4 US Navy Disk Slot Inspection 2005, still in-use

- In use at NAVAIR Depot since April 2005, **for a decade**
- Nine disks with **verified cracks detected**, several of these large and small cracks **not detected by conventional ET and LPI**
- No false indications (numerous slots inspected)



Conductivity **Lift-Off**



Winner, FAA-Air Transport Association 2007 "Better Way" Award for "MWM and MWM-Array Engine Component Inspection Technology"

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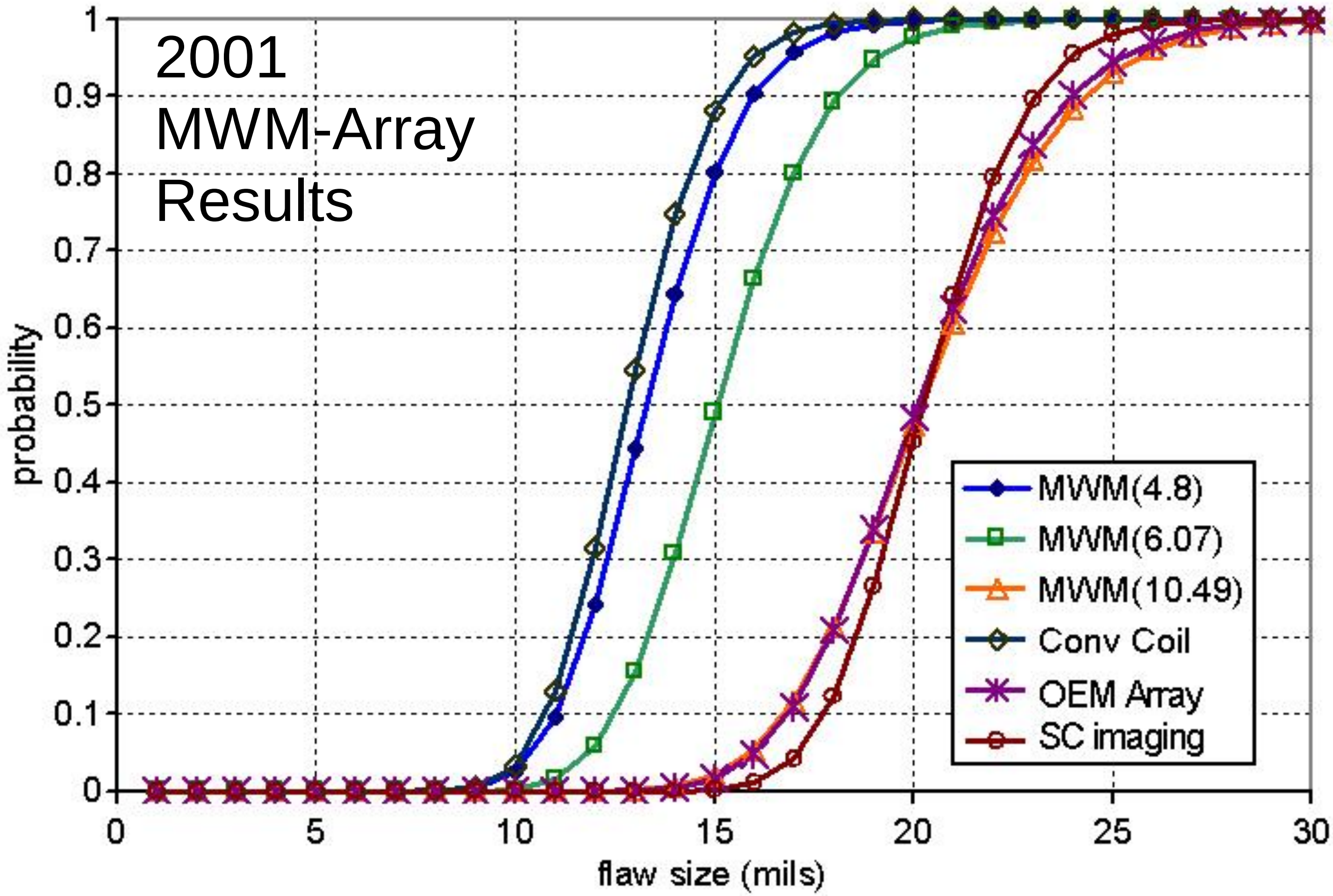
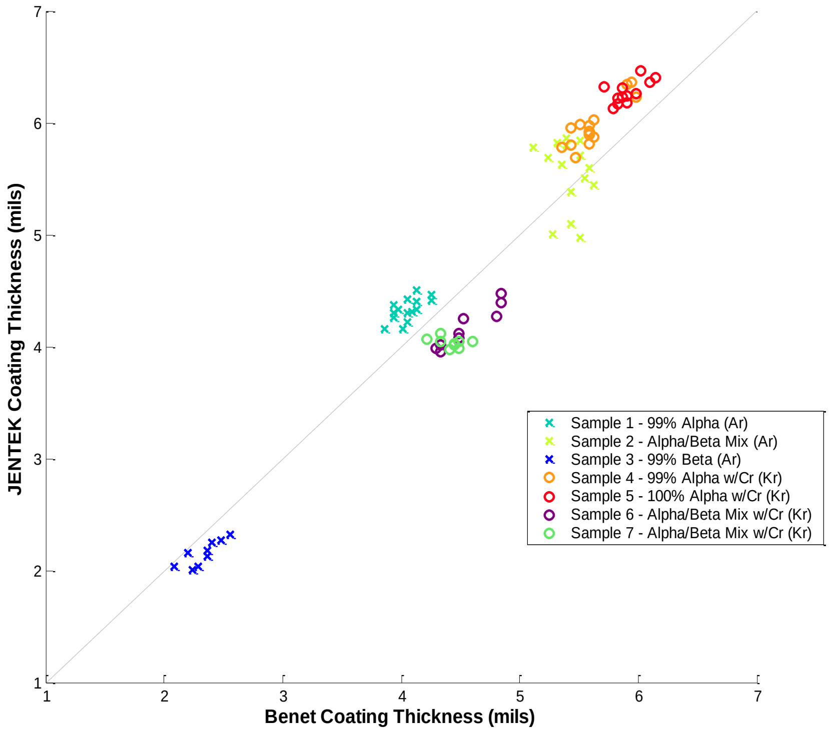
S.4: 1st Funded POD Study (FAA)

ENSIP-Type Flat Specimens (numerous other POD studies funded)

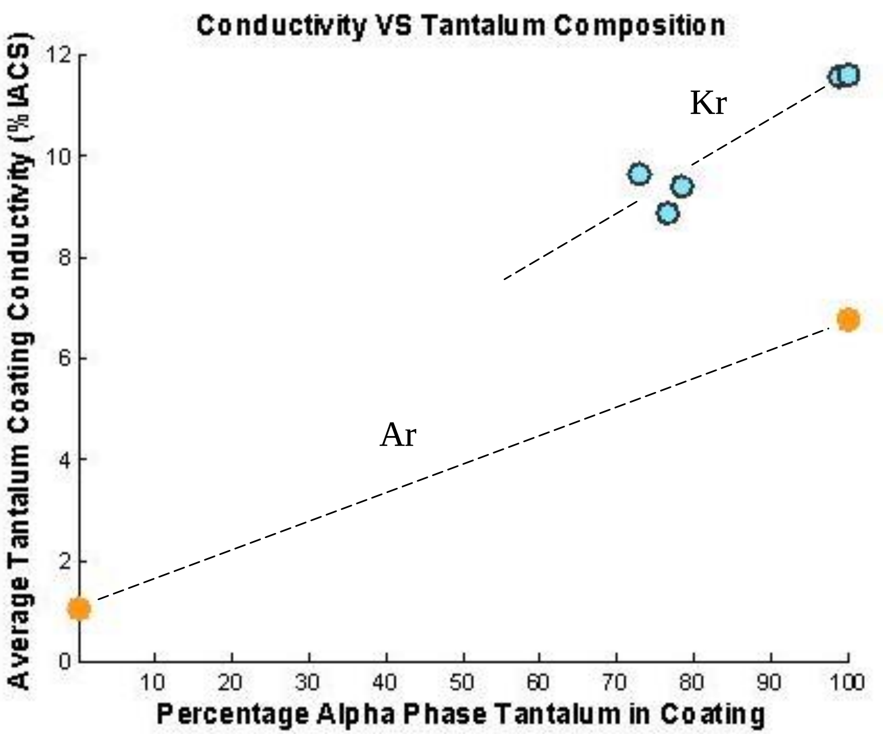


S.5: Independent Thickness & Conductivity for Coatings (2002, transitions continuing)

MWM-Array Measured Tantalum Coating Thickness Values



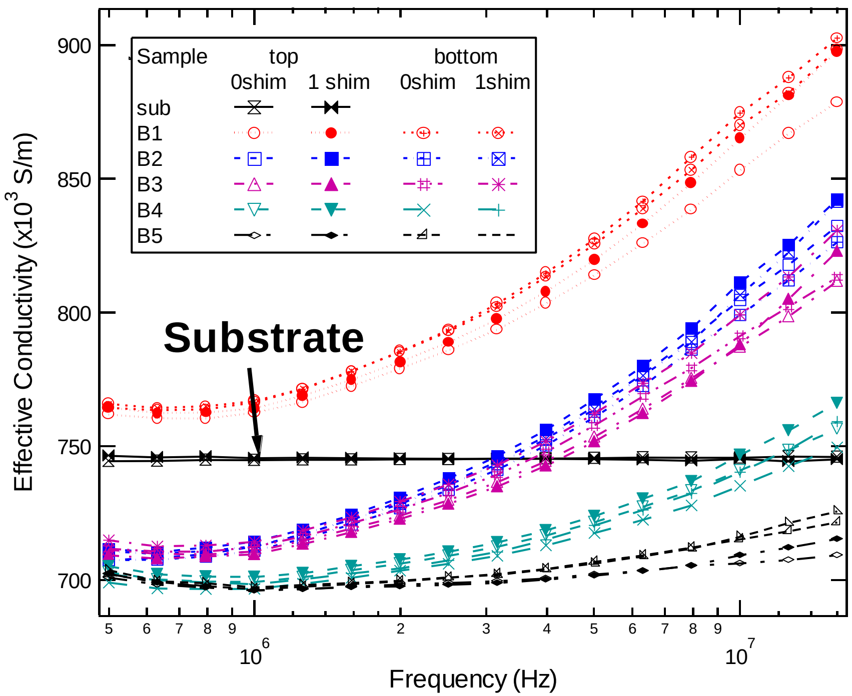
Conductivity vs. Phase Composition for Tantalum Coatings

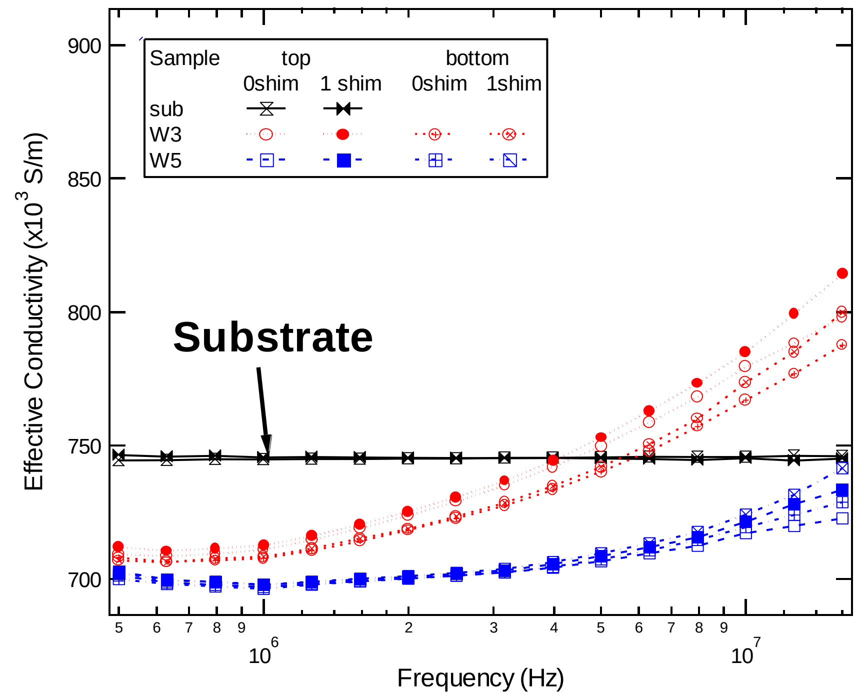


Identified unrecorded process variation!

S.5: Aged MCrAlY Coating (EPRI study)

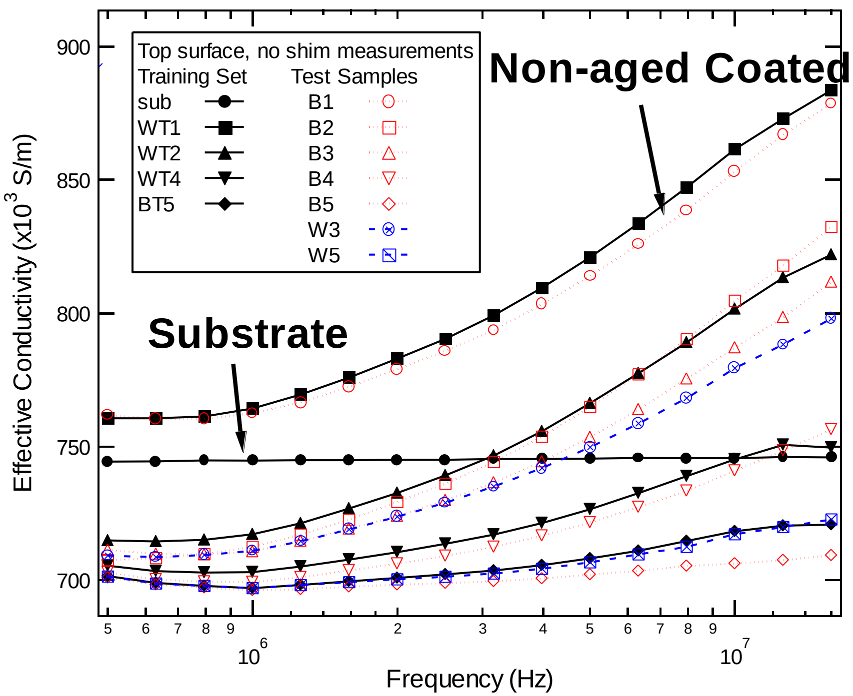
- Measurements on top and bottom of coupons
  - Post-study metallography indicated slight differences between sides
- Measurements with and without shims
  - Highly reproducible effective conductivity measurements

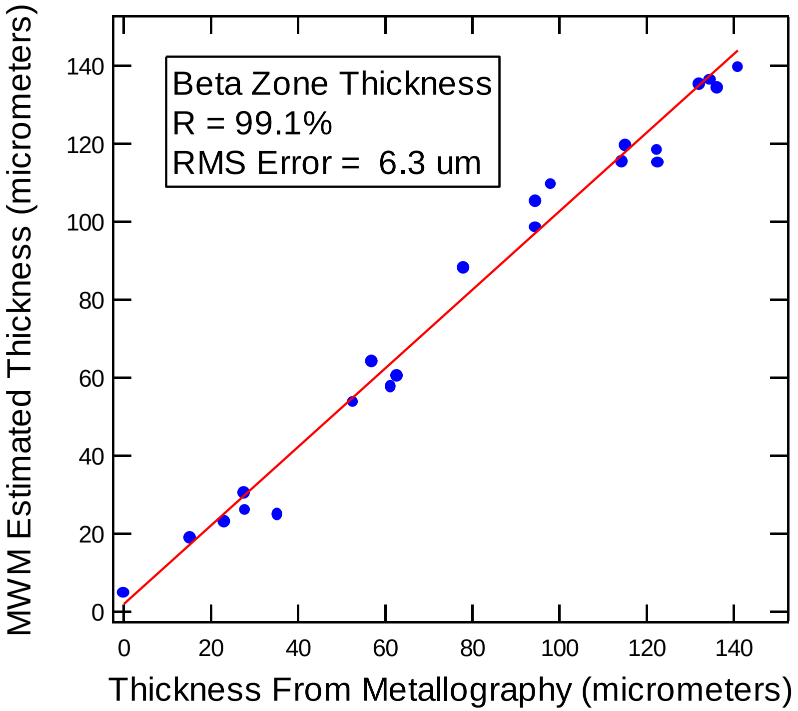




S.5: Aged MCrAlY Coating (EPRI study)

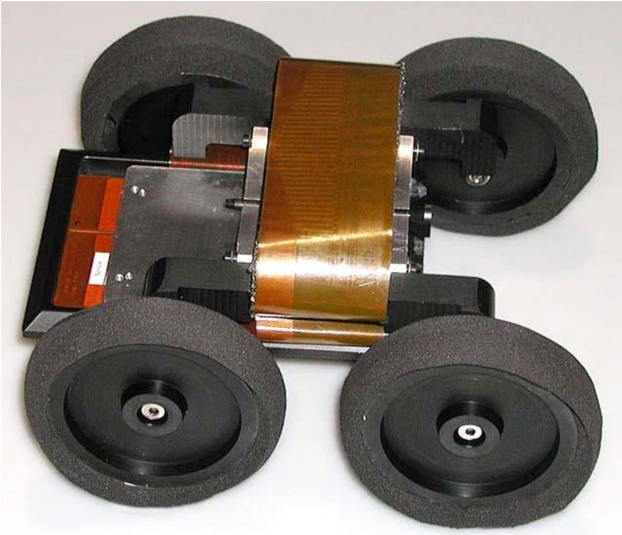
- Blind set samples had frequency variations similar to training set
- For remaining Beta Zone thickness on blind samples:
  - High correlation between MWM estimates and metallography
  - Low RMS error in MWM estimates (6.3 um, 0.25 mils)

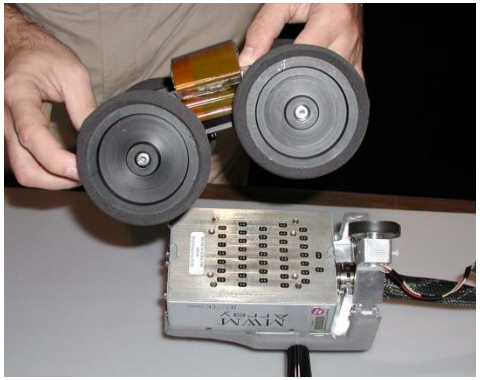


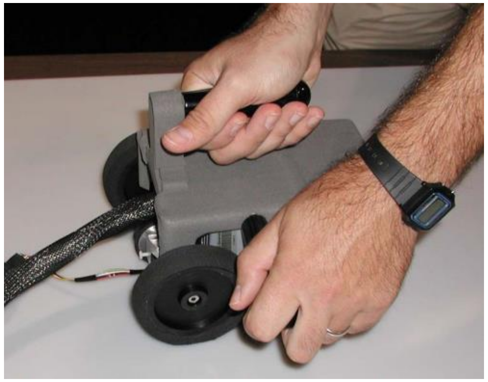


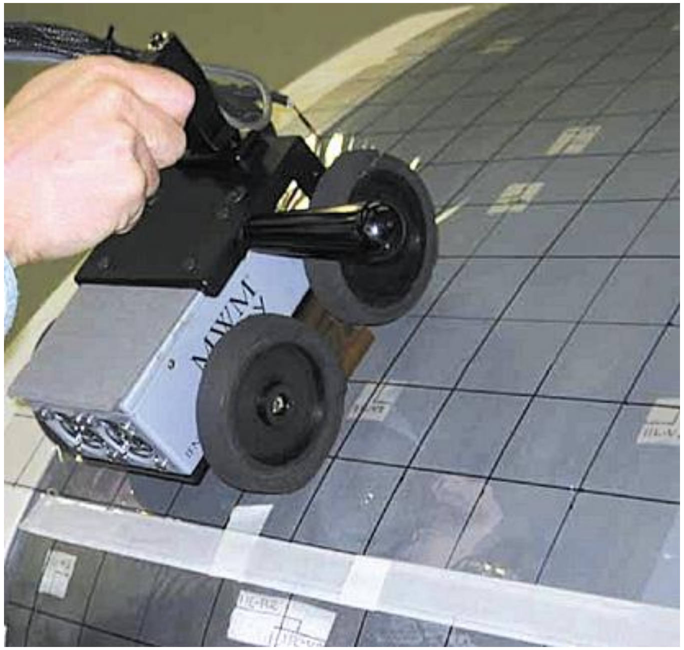
S.6: Complex Composite Surfaces ,Variable Curvatures

(used last 5 yrs of Space Shuttle Program at KSC)





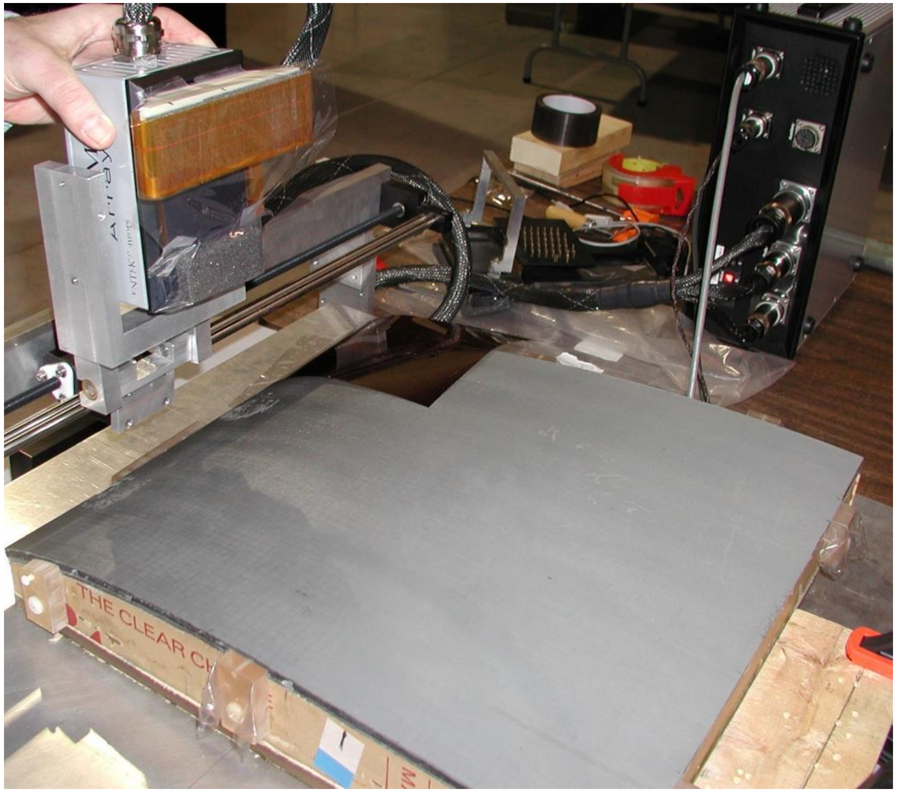




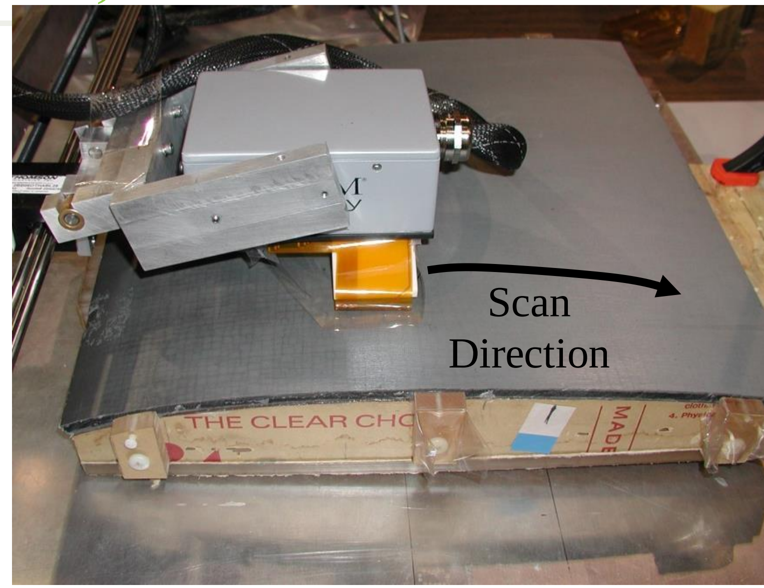
- Foam wheels protect surface
- Manual scanning for complex surfaces
- C-Scan images of wide areas
  built from multiple passes
- Adapts automatically to varied curvatures

S.6: Complex Composite Surfaces ,Variable Curvatures

Test Setup for MWM-Array RCC Inspection Validation

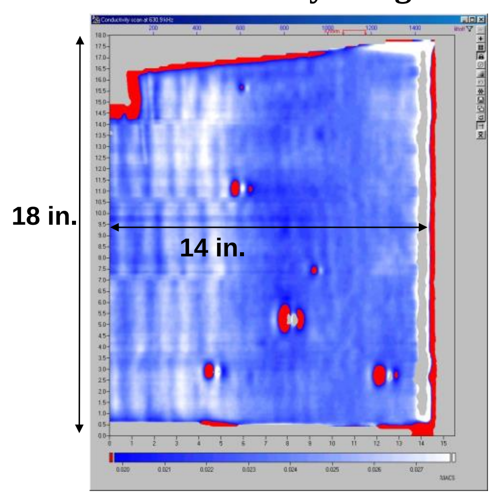


Blind Test RCC Sample Provided by NASA Langley Research Center

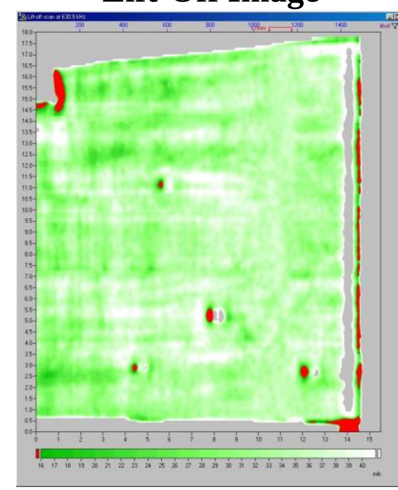


MWM-Array FA24 single-frequency scan at 1 in./sec

Conductivity Image



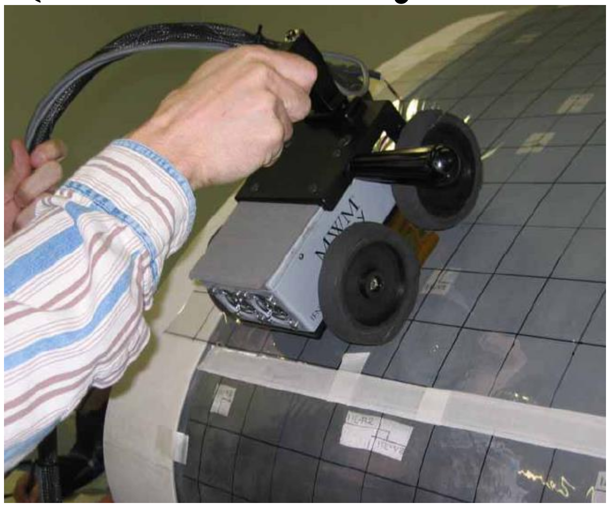
Lift-Off Image

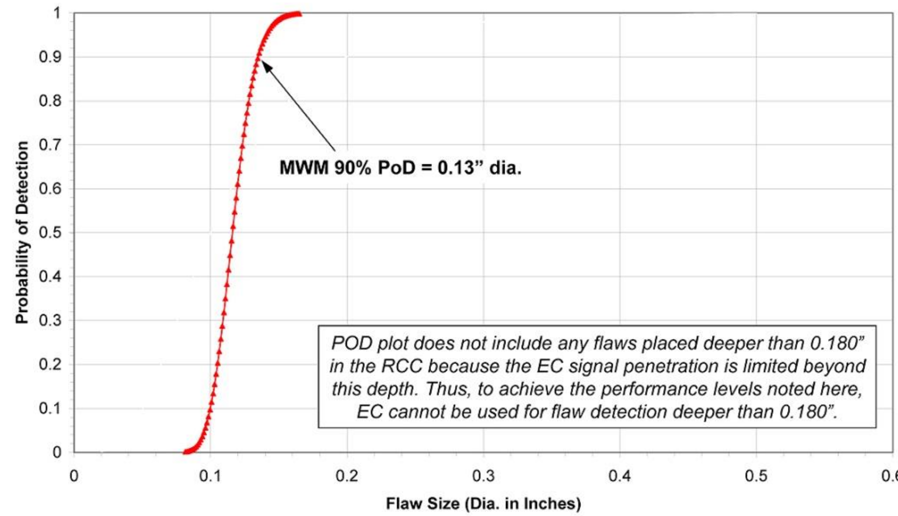


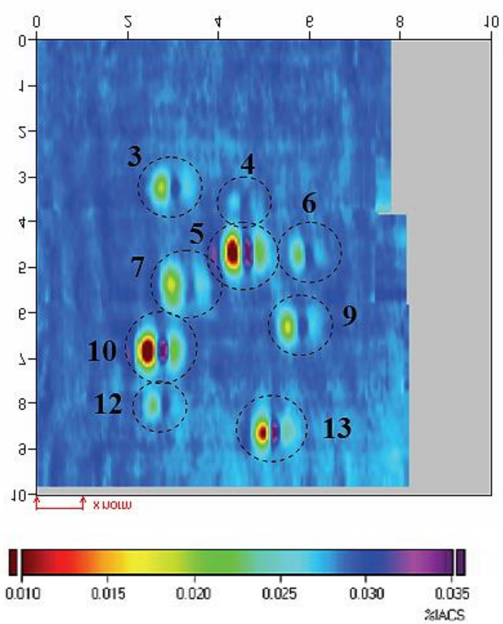
Scan Performed in 2 Minutes.

S.6: Complex Composite Surfaces ,Variable Curvatures

(used last 5 yrs of Space Shuttle Program at KSC)







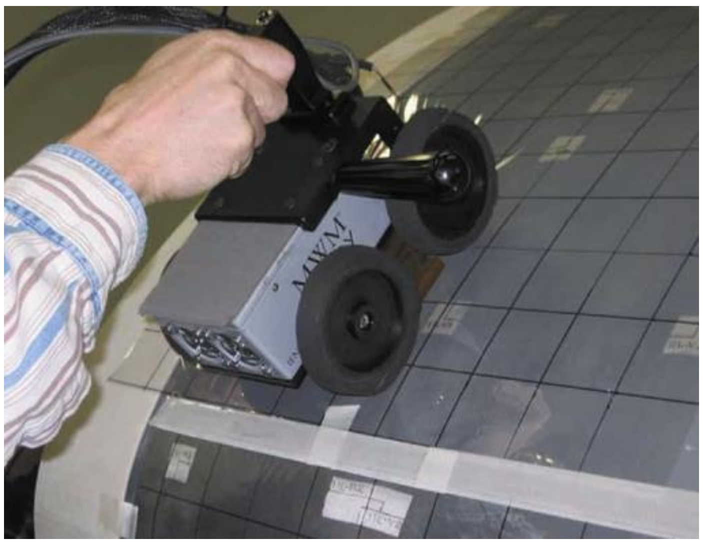
11LFB1 @ UPPER SURFACE				
ZONES	DRILLED FBH	LASER MEASUREMENT		
FEED BACK	Ø @ HOLE DEPTH	Ø	REMAINING MATERIAL THICKNESS	THICKNESS NEAR HOLE
1	3/8 @ 0.040	0.381	0.222	0.251
2	1/2 @ 0.040	0.509	0.220	0.249
3	3/8 @ 0.115	0.383	0.138	0.247
4	1/8 @ 0.115	0.128	0.130	0.246
5	3/8 @ 0.190	0.381	0.057	0.246
6	1/8 @ 0.190	0.132	0.058	0.249
7	1/2 @ 0.115	0.512	0.140	0.249
8	1/4 @ 0.040	0.241	0.215	0.250
9	3/8 @ 0.115	0.384	0.136	0.250
10	3/8 @ 0.190	0.384	0.061	0.251
11	1/2 @ 0.040	0.507	0.212	0.250
12	1/4 @ 0.115	0.235	0.130	0.250
13	1/4 @ 0.190	0.236	0.057	0.250
14	3/8 @ 0.040	0.380	0.213	0.251

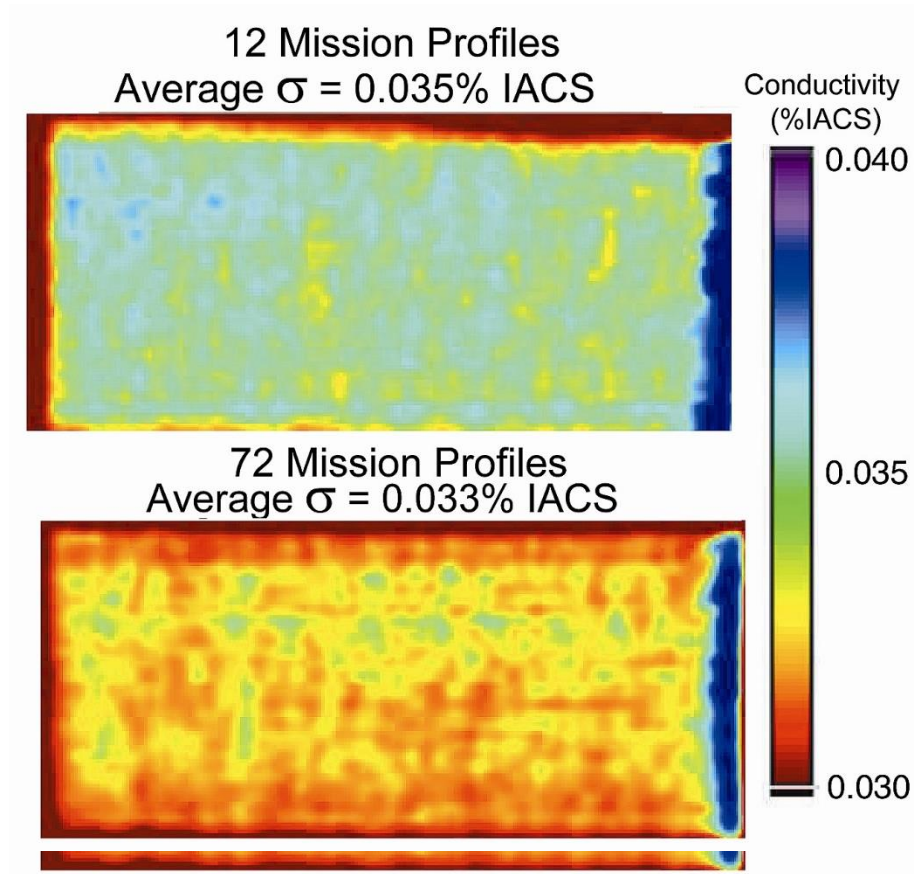
Source:
"Global Mass Loss Characterization Through Eddy Current Analysis," Buzz Wincheski, **NASA** Langley Research Center; Dan Ryan, Jim Landy, **United Space Alliance**; and Neil Goldfine, JENTEK Sensors, Inc.

S.6: Complex Composite Surfaces ,Variable Curvatures

(used last 5 yrs of Space Shuttle Program at KSC)

MWM-Array for Inspecting Complex Composite Surfaces with Variable Curvature





For as-manufactured RCC specimens and the same specimens exposed to thermal cycling equivalent to 12 and 72 shuttle missions

3 Decades of Research and Transitions

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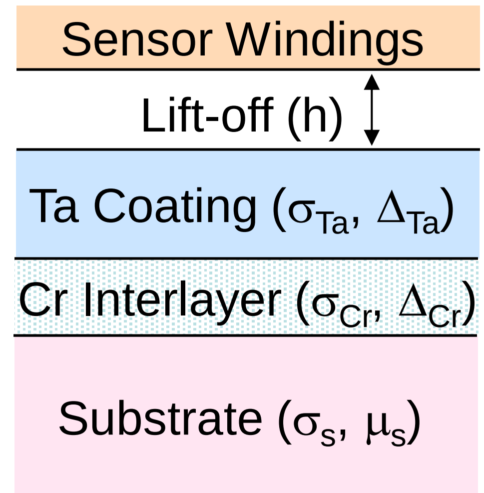
I.1: HyperLattices for Multivariate Inverse Methods (MIMs)

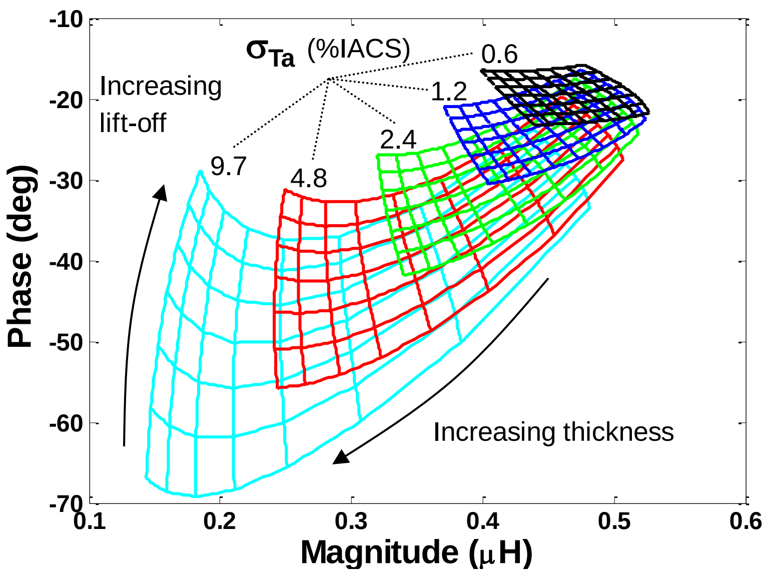
Coatings Example:

- Measure Three Unknowns (Thickness, Conductivity, Liftoff)
- Provide High Resolution image of each unknown
- Automated & Real-Time



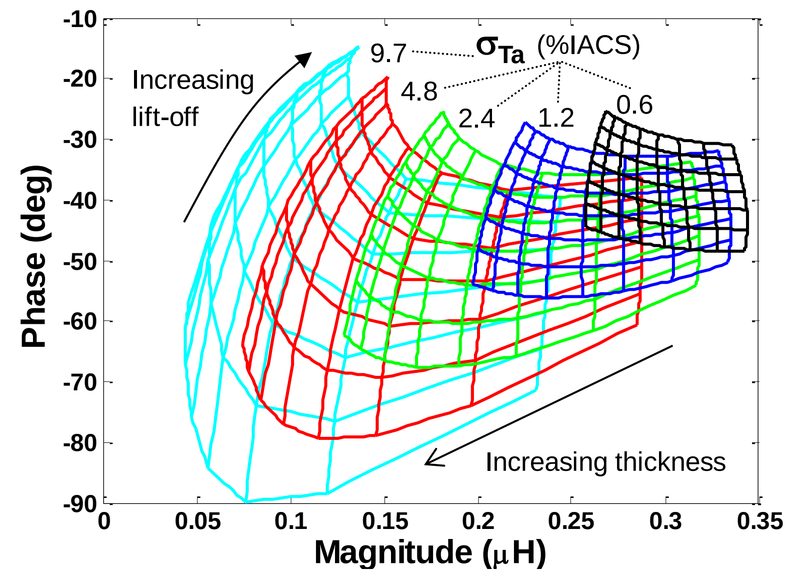
Low *f* σ_{Ta}- Δ_{Ta}- h Lattice

μ_s, σ_s, σ_{Cr}, δ_{Cr} constant



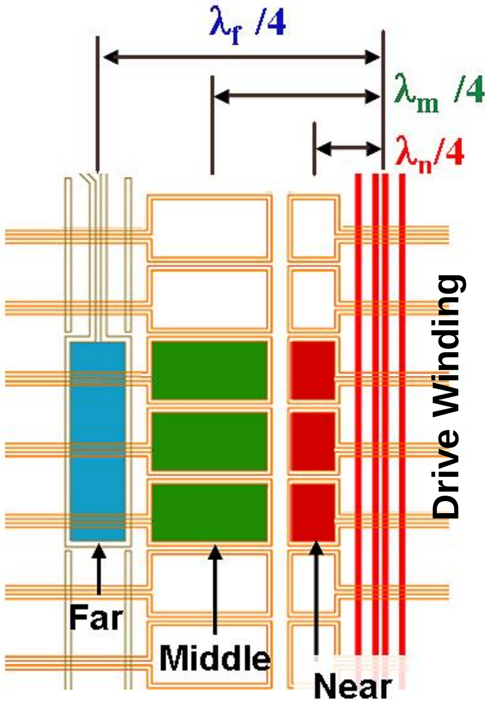
High *f* σ_{Ta}- Δ_{Ta}- h Lattice

μ_s, σ_s, σ_{Cr}, δ_{Cr} constant



I.2: SF-ET-Arrays (Segmented Field) Engineering-Science Innovation

- Enables AM powder characterization
- Enables enhanced Composite characterization
- Enables enhanced multiple layer media characterization

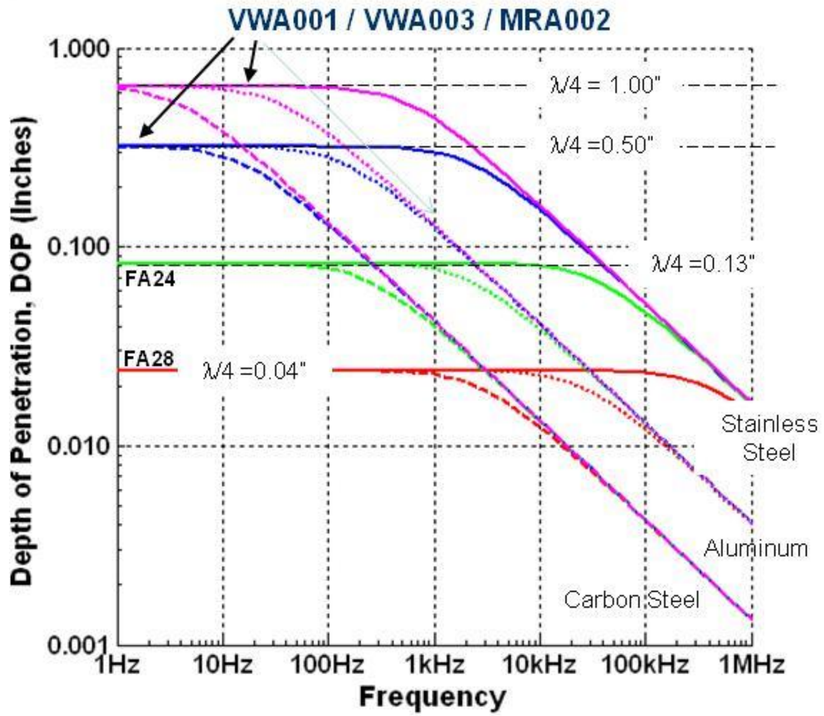


Depth of Penetration = $1/\mathrm{Re}(\Gamma_n)$

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

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

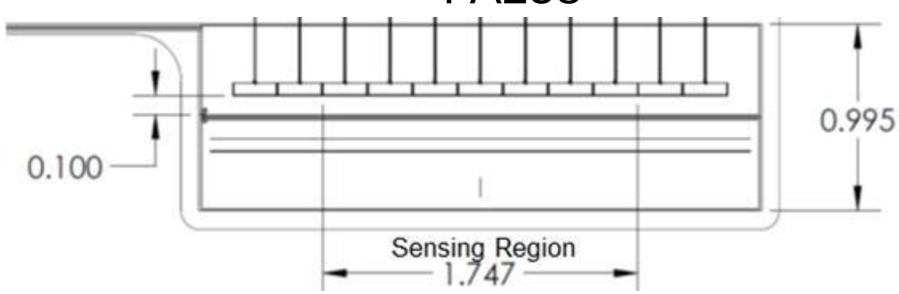
Skin depth: $\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$

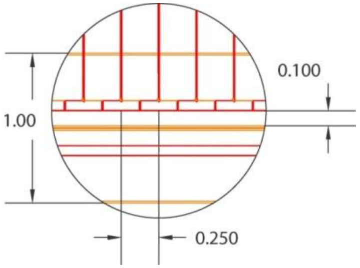


I.3: jET with MWM-Array (larger channel count systems called GS8200 uses same technology)

jET®

MWM®-Array





- 3 frequencies simultaneously
- 7 channels simultaneously
- Up to 1000 measurements/sec per channel

MWM-Array

- Designed for model based methods
- Drive sense gap determines depth of penetration

I.3: Types of Eddy Current Arrays & MWM-Arrays

1. **Compilations of single eddy current testing (ET) coils**
   - Used independently (either in parallel or multiplexed)
   - Mounted on a shuttle that is rigid and shaped similar to the part
   - Challenges include: rigidity, cross talk for parallel operation, variability channel to channel, response variation across array, etc.
2. **Arrays of flat spiral coils** or multiple layered coils that can act as both drive and sense elements
   - Multiplexed in groups of channels (typically 4 or 8 at a time)
   - Must avoid exciting neighboring coils due to cross talk
   - Challenges include: variable channel performance, crack response variations across array, variable directional sensitivity across array, curvature effects and rigidity due to complex cabling issues.
3. **Single rectangular drive with linear array of square sense elements MWM-Arrays**
   - Fully parallel data acquisition from all channels
   - No significant cross talk
   - Designed for physics model-based analysis methods
   - Challenges include: larger cables for many channels, culture change is a hurdle for some customers

I.3: Fully Parallel Digital electronics, with MWM-Array Advantages

1. **Sensor: Designed for model-based multivariate inverse methods (MIMs)**
   - Designed with simple linear drives and square sensing elements
   - No significant cross talk between elements.
   - Enables more robust results, such as **rescaling of the crack response** for variable liftoff when scanning a curved surface.

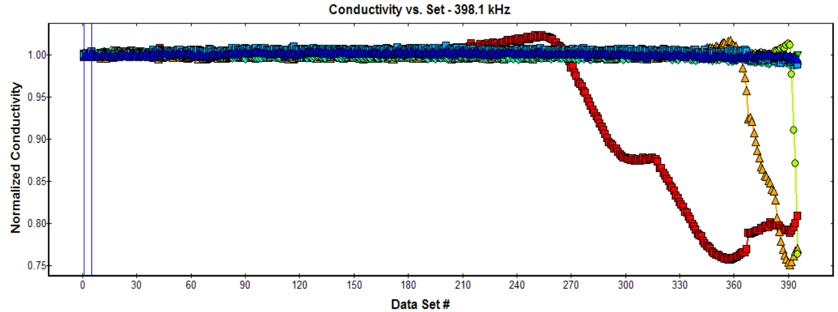
2. **Electronics: Simultaneous data acquisition at up to 3 frequencies**
   - Needed to measure multiple properties, such as independent 1st and 2nd layer corrosion imaging independent of gap between layers.
   - Both complex impedance components simultaneously to retain data integrity and support model based methods

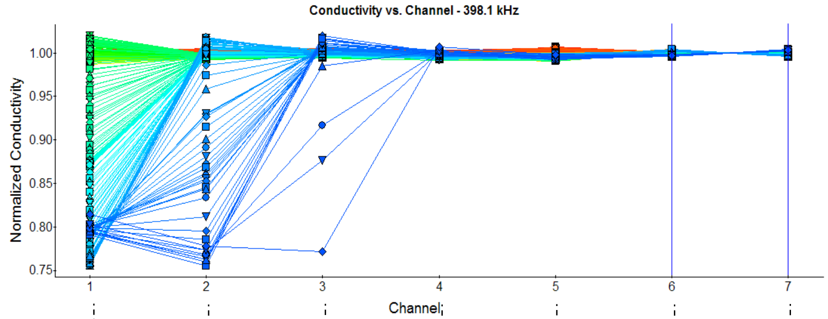
3. **Electronics & Sensor: Enable fully parallel (simultaneous) acquisition from 7 sensing elements**
   - Needed to reliably detect and size cracks
   - Needed to reliably detect cracks at edges
   - Needed to ensure consistent coverage of the inspection surface
   - Needed to rescale crack response for position within the array

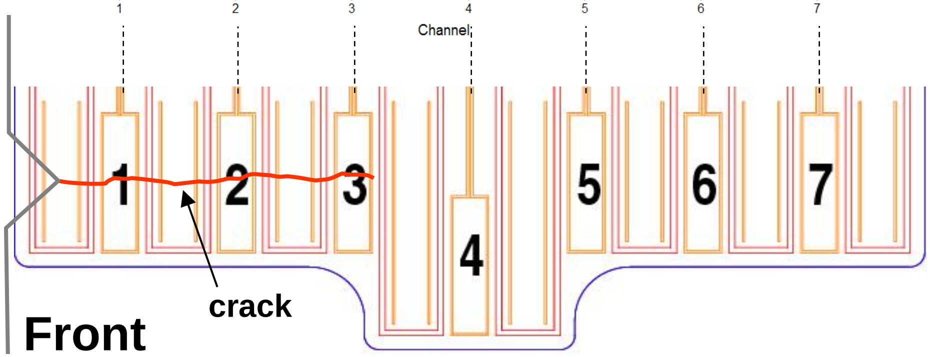
I.4: Fatigue Test: Al Compact Tension Specimen

MWM-Array FA65

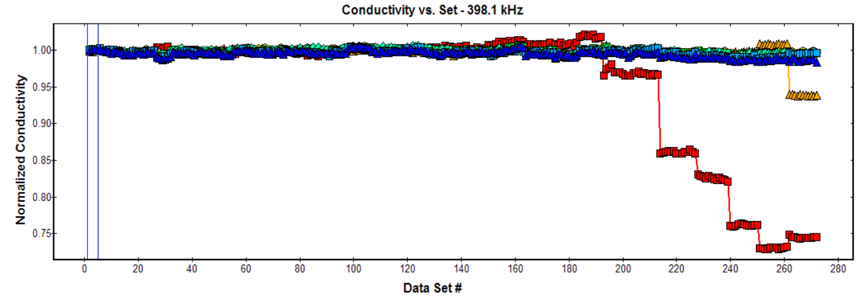
Continuous Monitoring

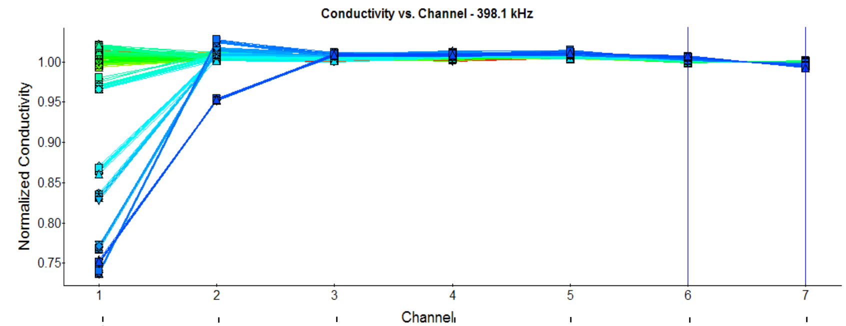


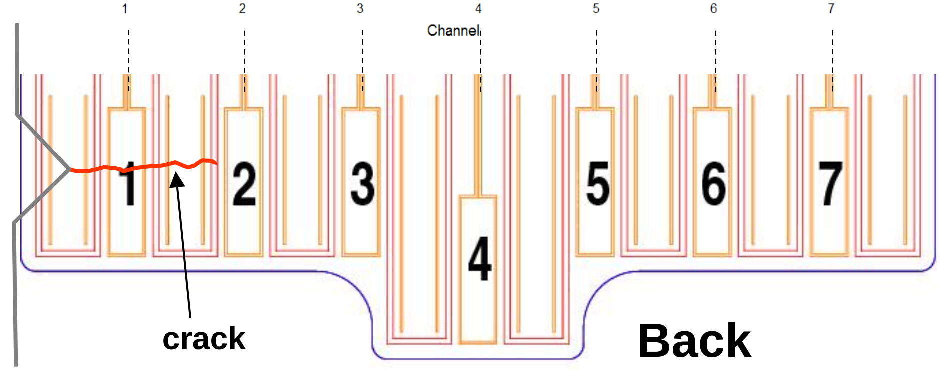




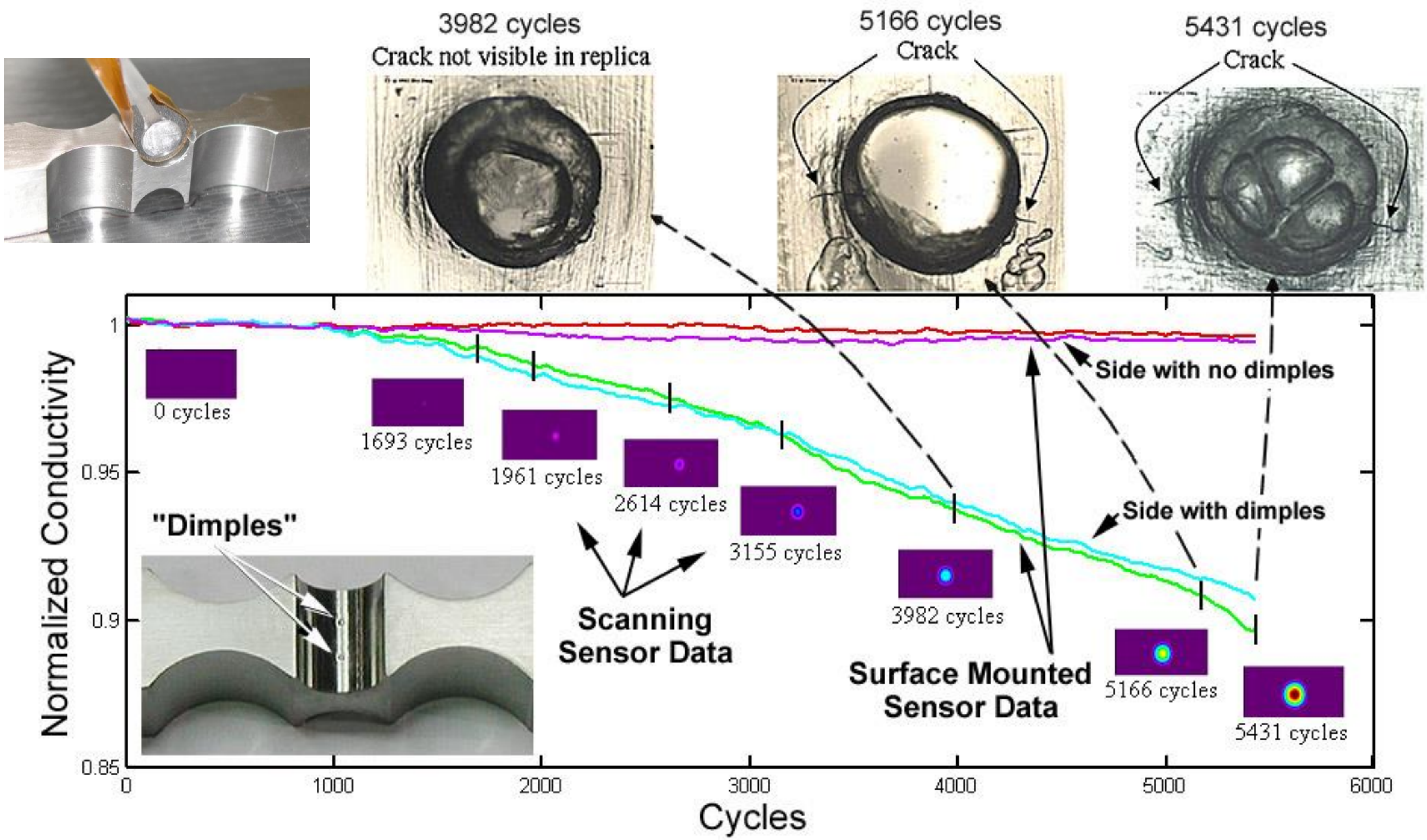
Scheduled Inspections to simulate on-aircraft use





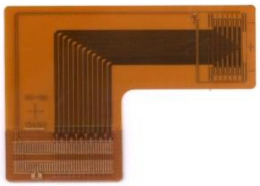


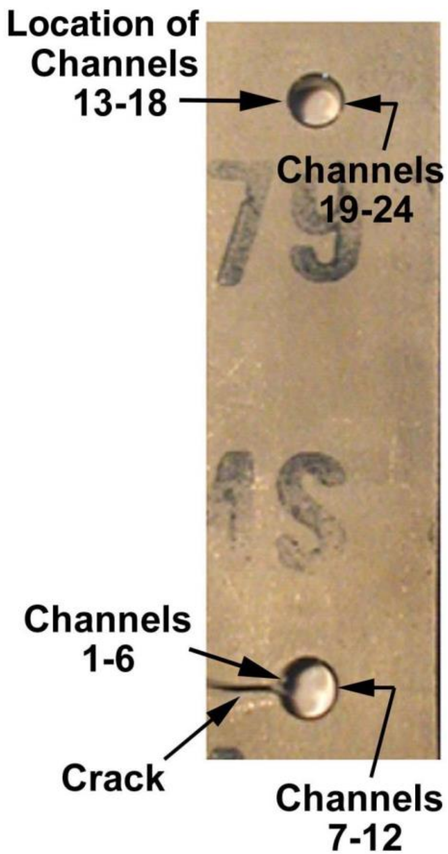
I.4: Mapping and Tracking of Crack Initiation and Growth at "Dings" in Ti-6Al-4V

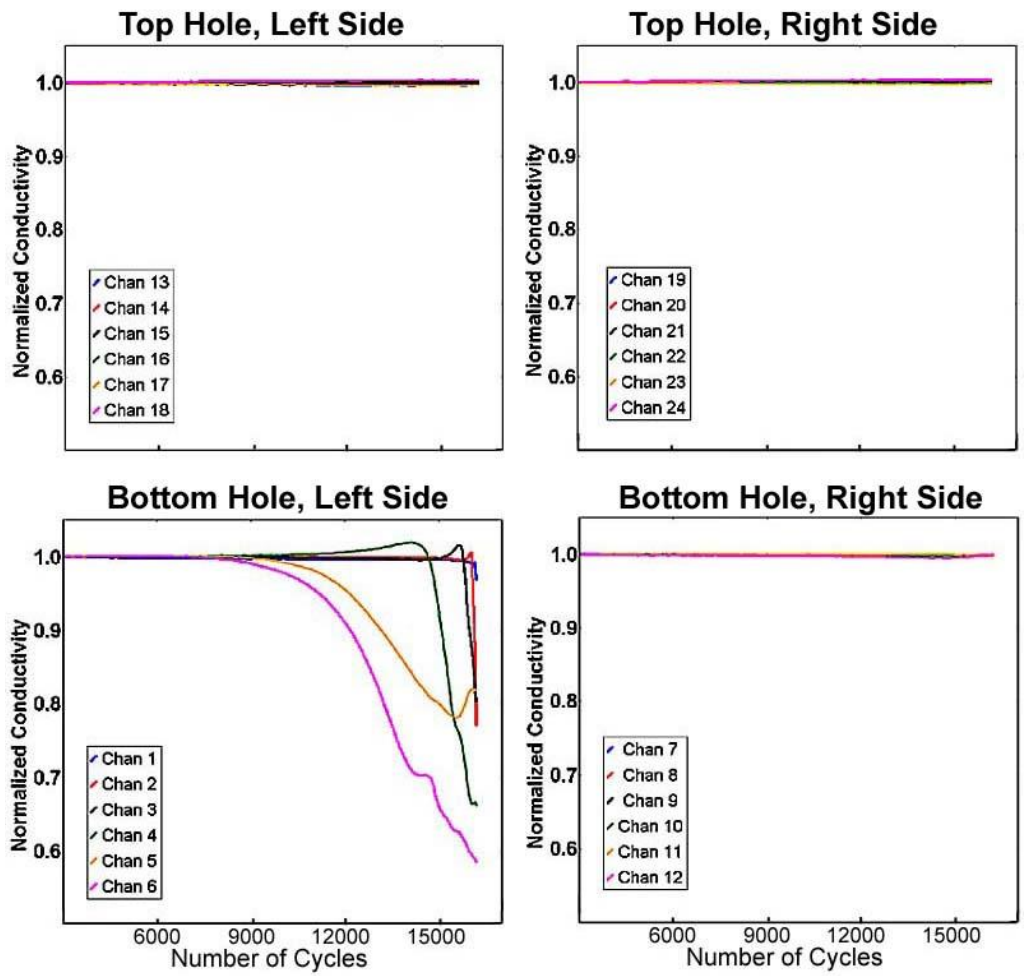


I.4: Generation of “Real Crack” Specimens

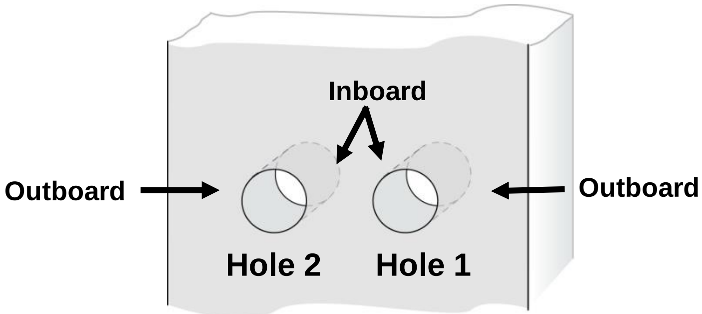
MWM-Array
FA75



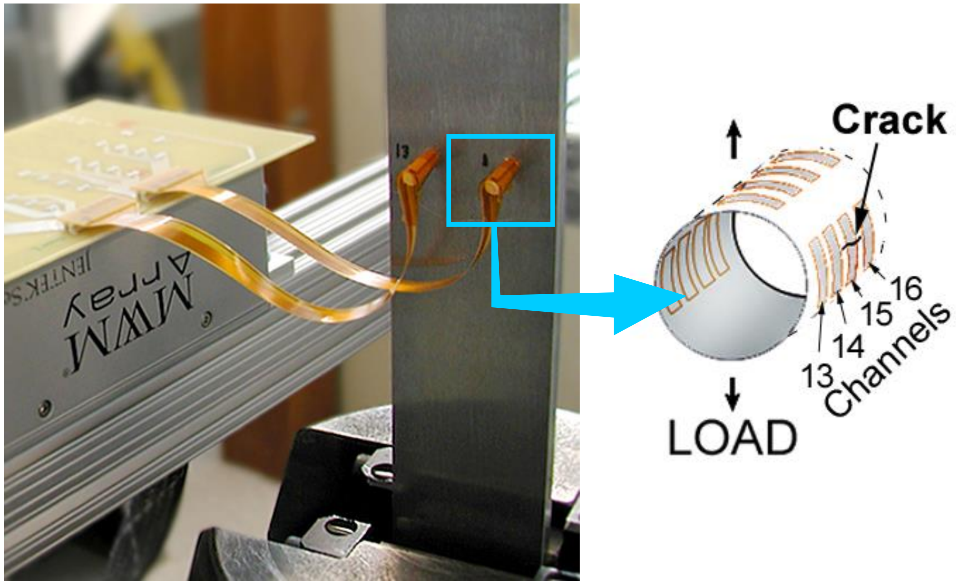




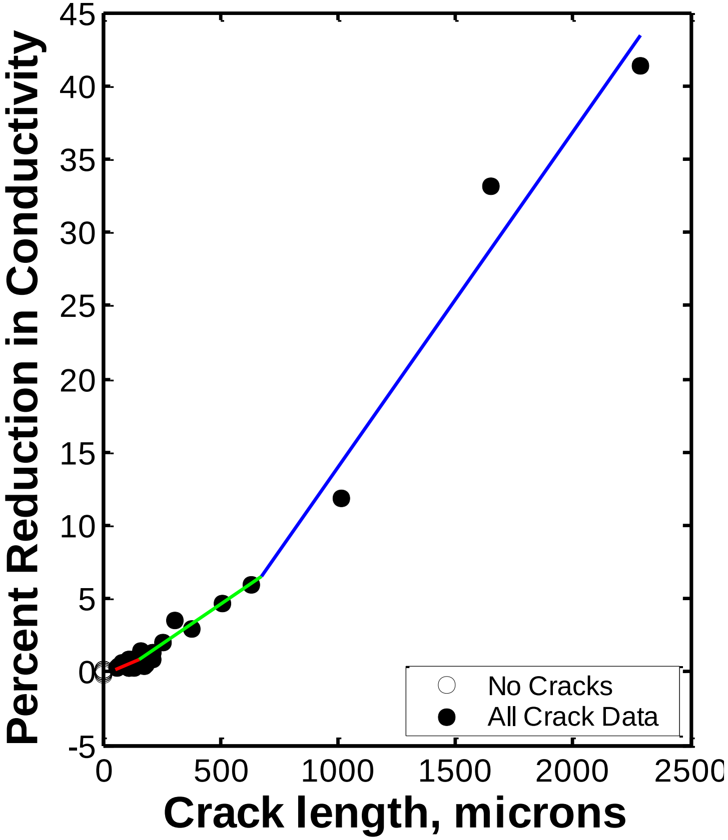
I.4: Fatigue Monitoring Holes Aluminum Alloys



4 hole-sides per specimen



MWM Response vs. Crack Length



I.4: Fatigue Monitoring Holes Aluminum Alloys

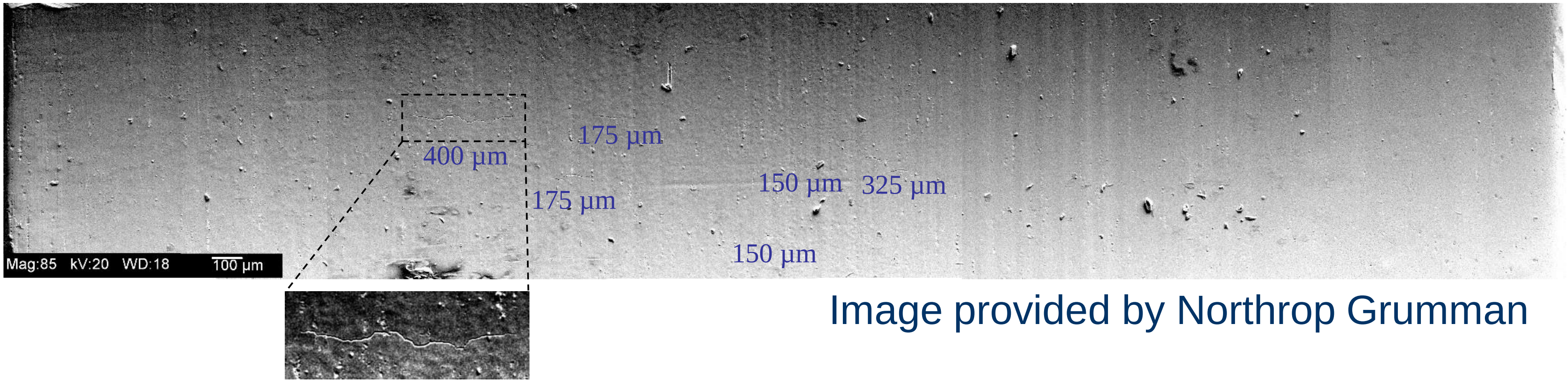
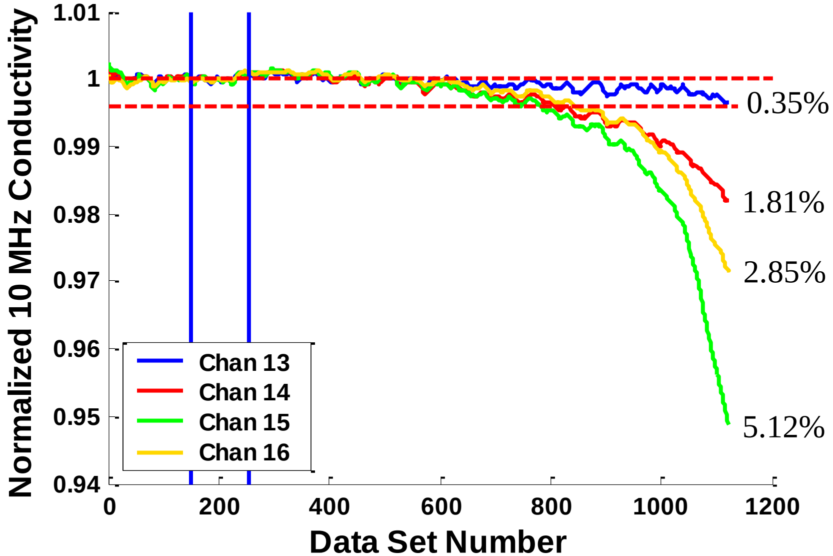
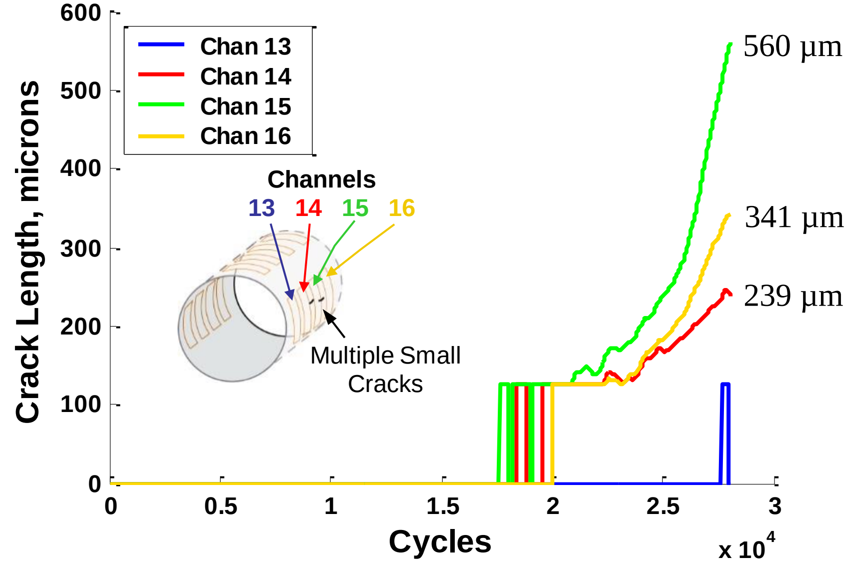


Image provided by Northrop Grumman

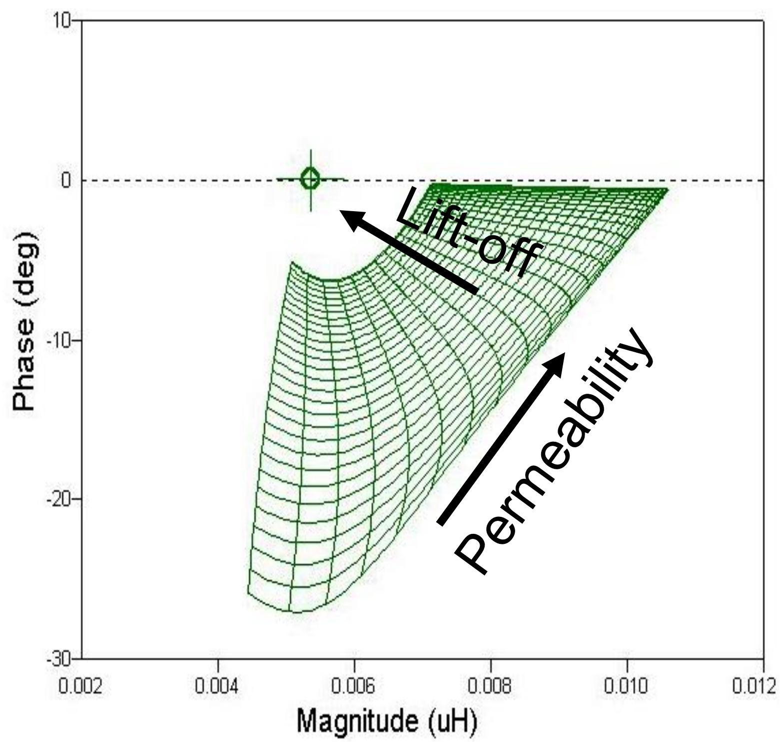


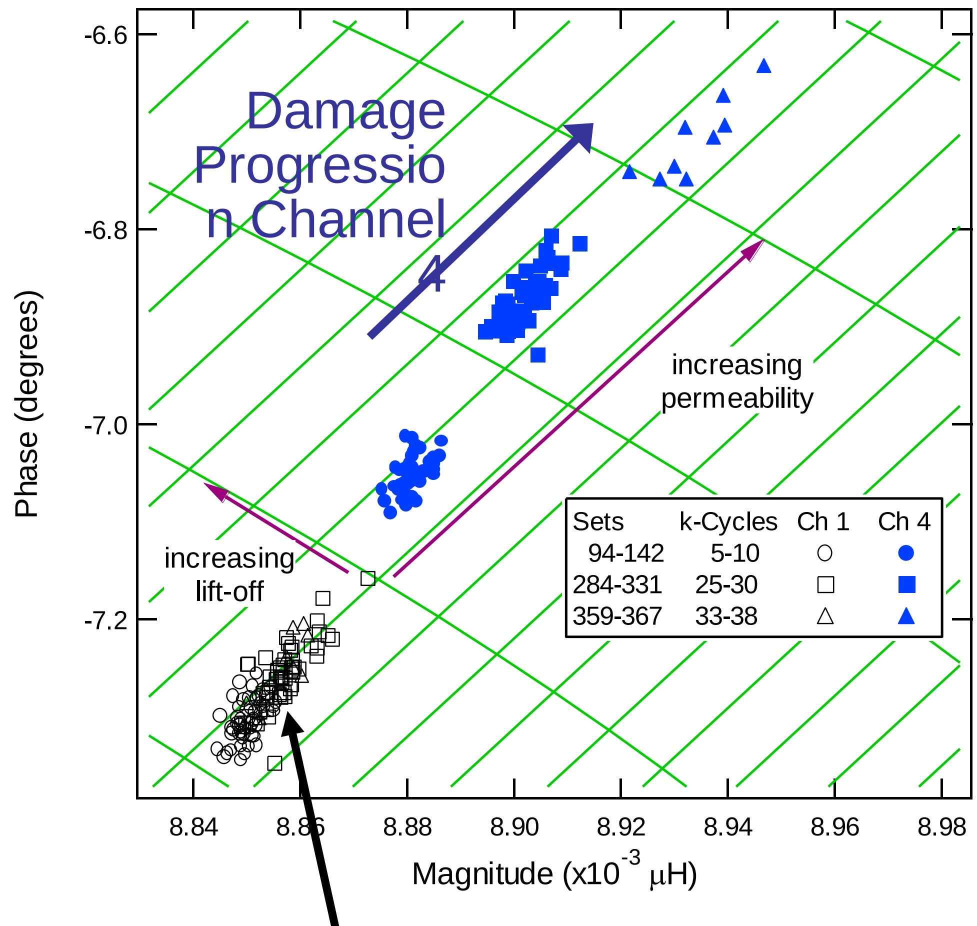


125 µm Crack Length, Detection Threshold

I.4: Steel Alloy Fatigue Monitoring

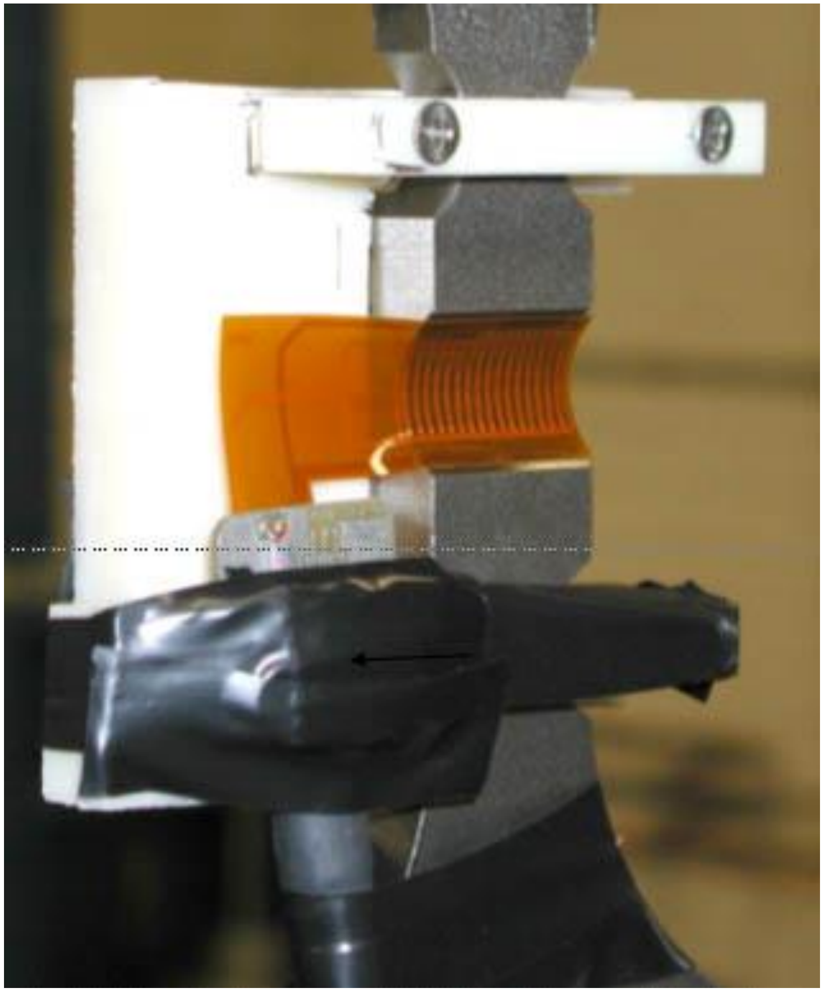
Precomputed Response Databases



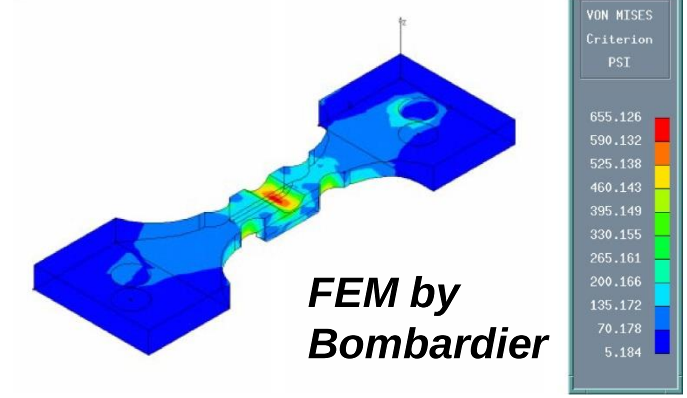


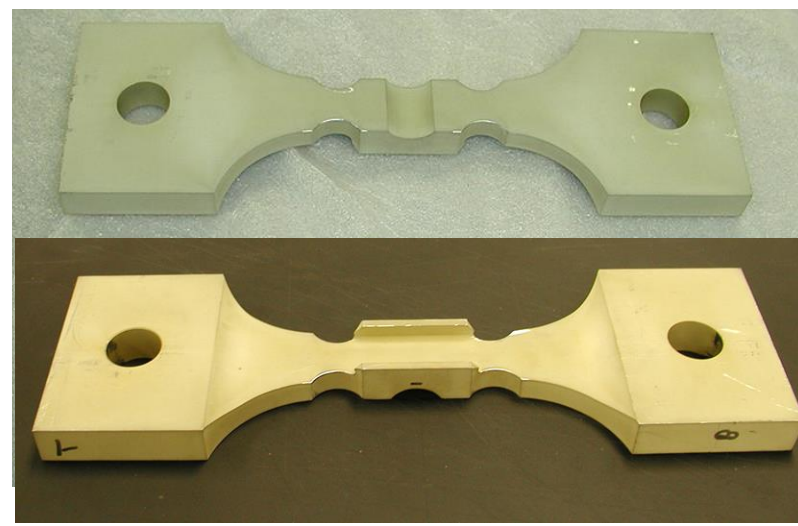
Minimal Damage at Channel 1

I.4: Steel Alloy Fatigue Monitoring



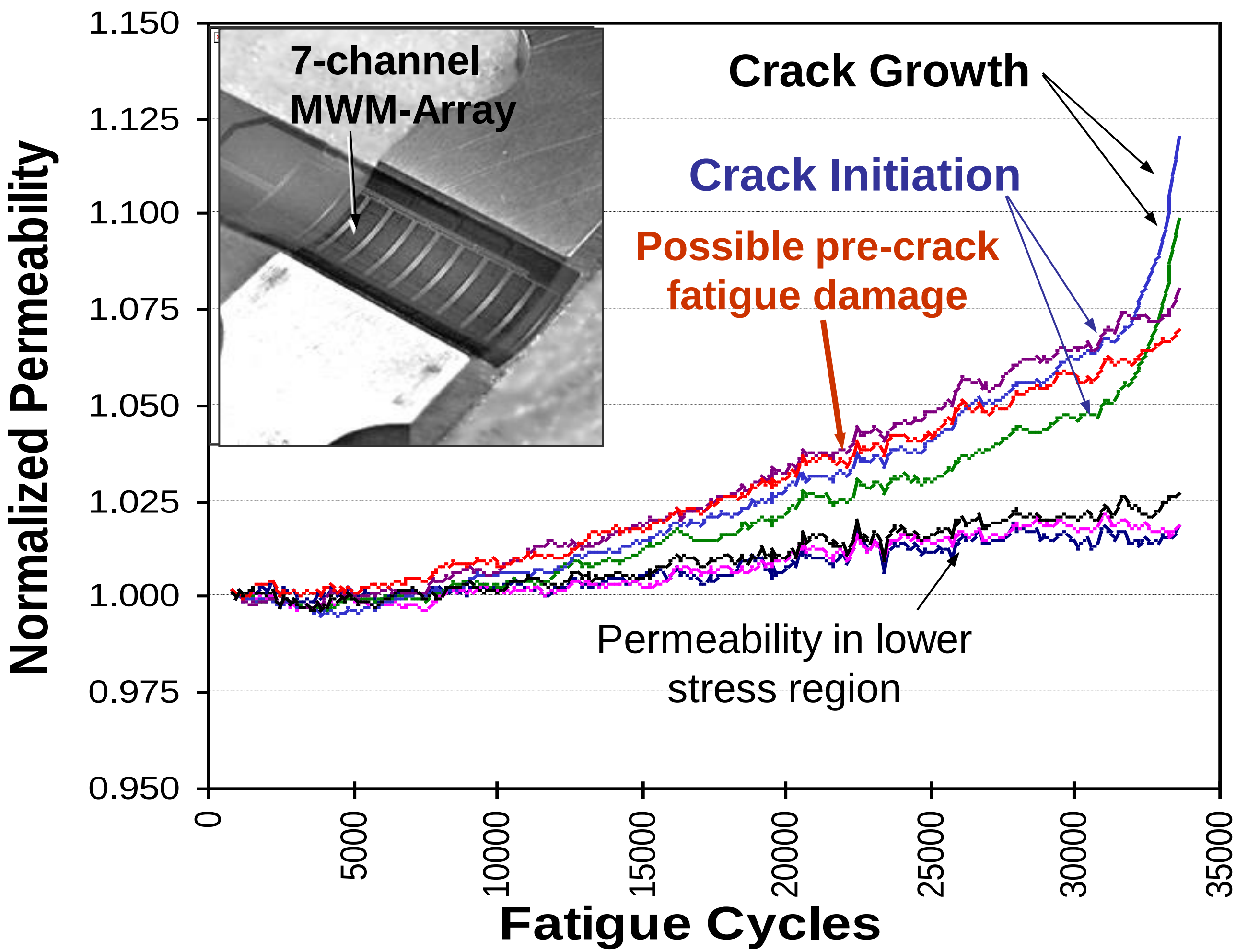
Finite Element Analysis of Stress Distribution



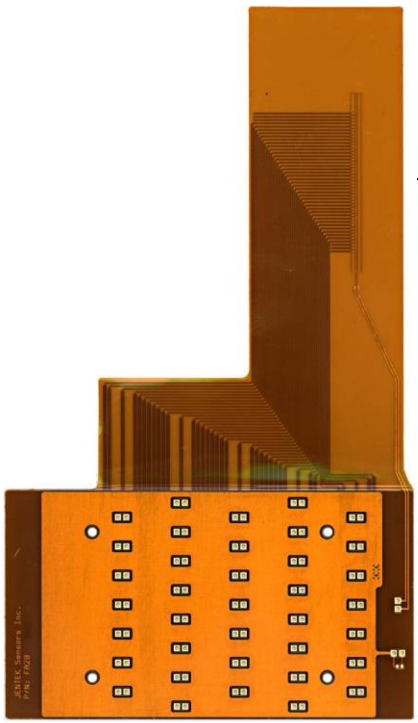


coupon design, JENTEK patent pending

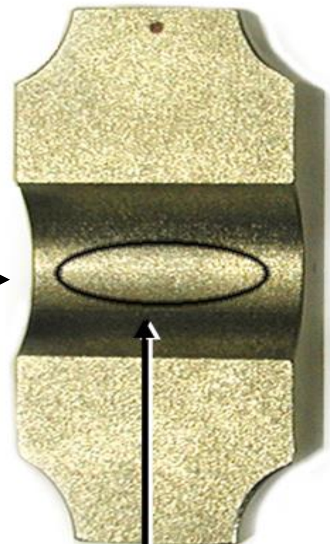
I.4: Steel Alloy Fatigue Monitoring



I.4: Steel Alloy Fatigue Monitoring

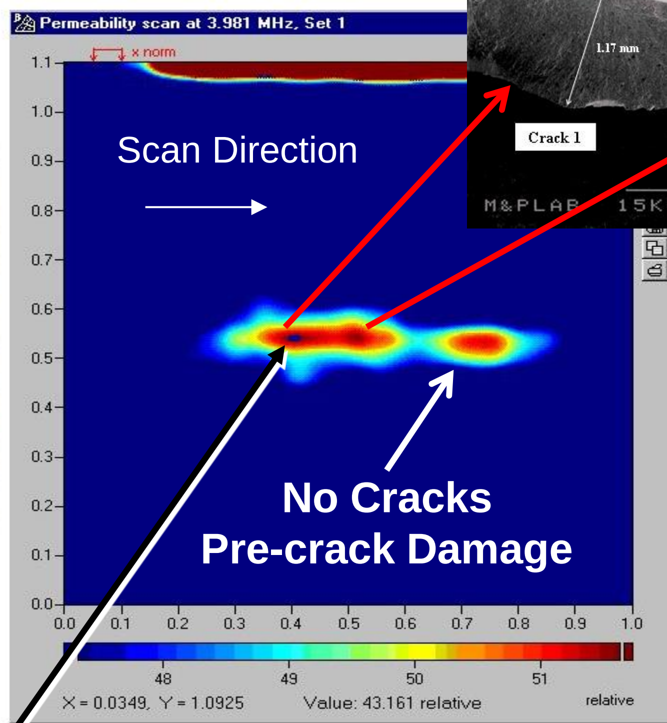


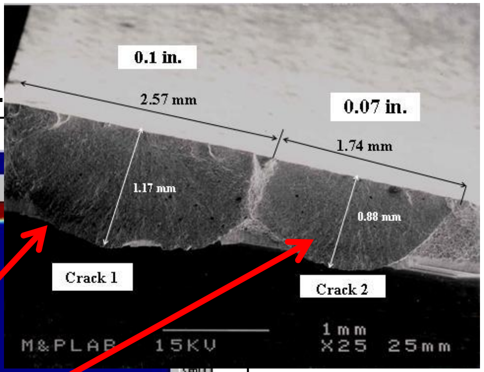
4340 Steel
Specimen



High Stress
Region

25.4 mm (1 in.)



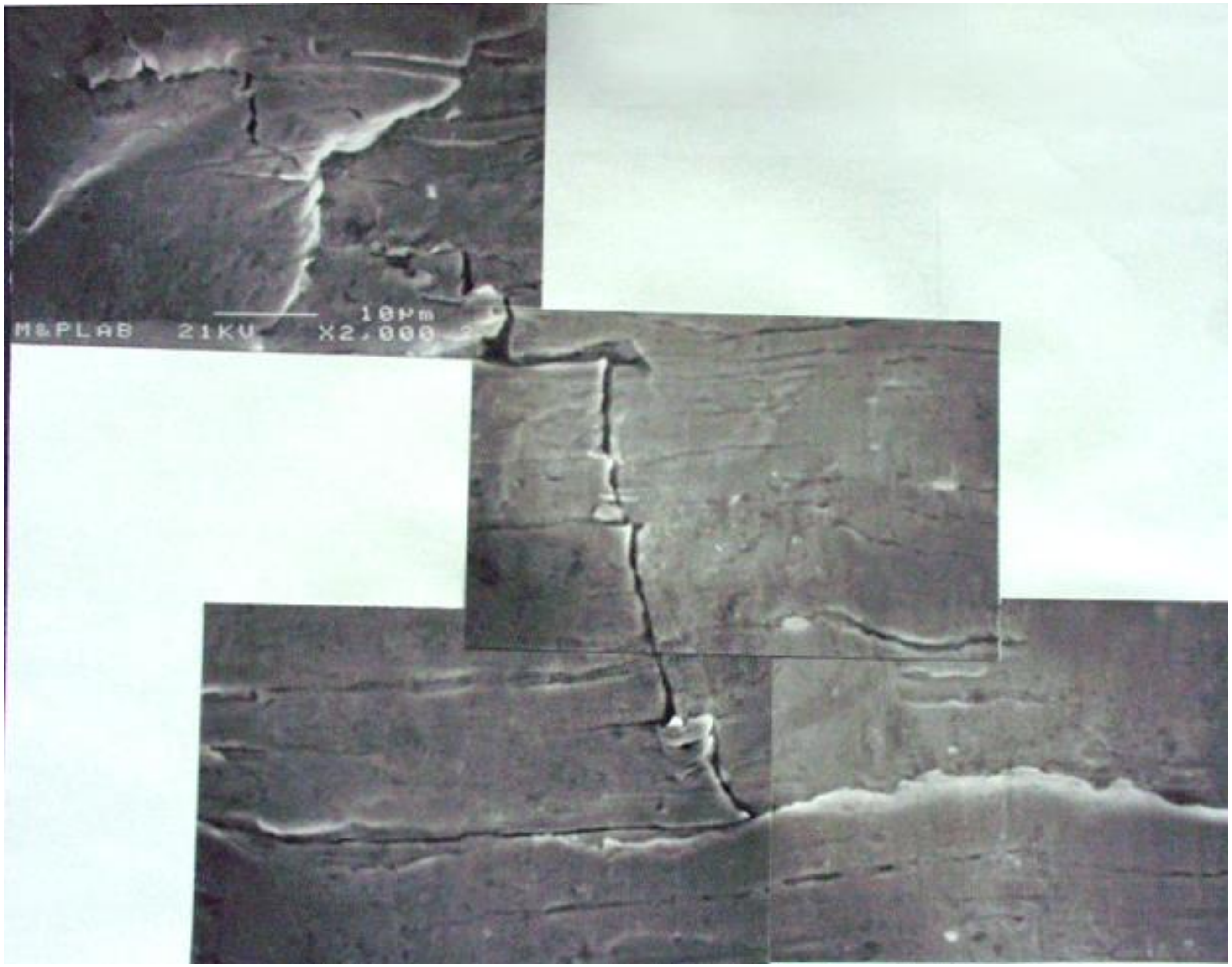


27.9 mm
(1.1 in.)

SEM found only 0.008
inch crack

UT, ET, LPT, Detected
NO cracks

I.4: Steel Alloy Fatigue Monitoring

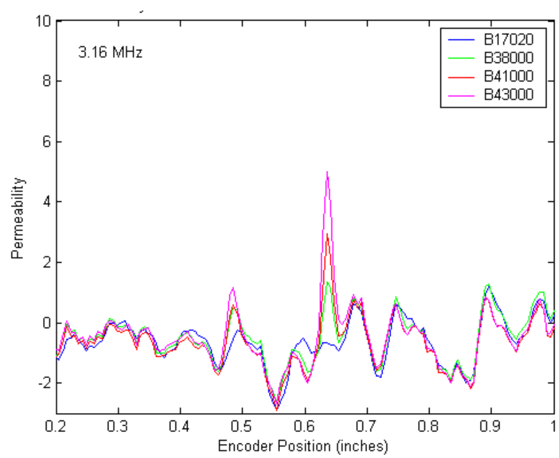


I.4: Difference Imaging or Baseline Subtraction

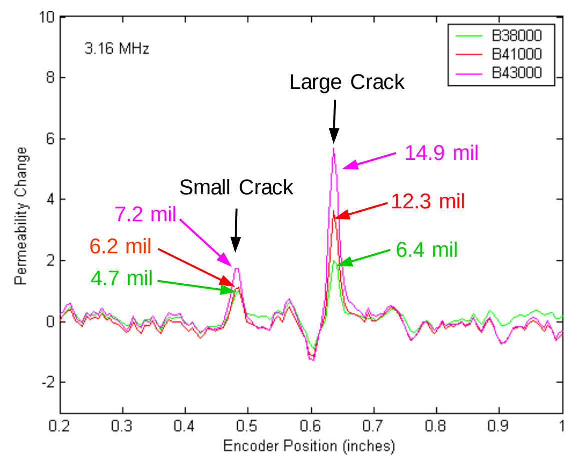
Improves Signal-to-Noise Levels to Reliably Detect Smaller Cracks

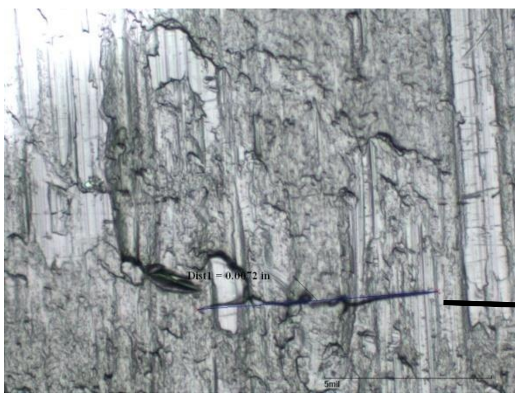
A514 Grade B Steel

Raw data

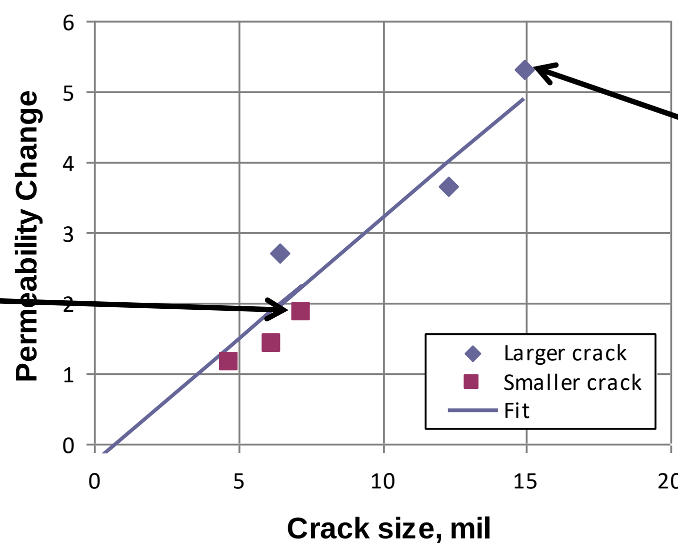


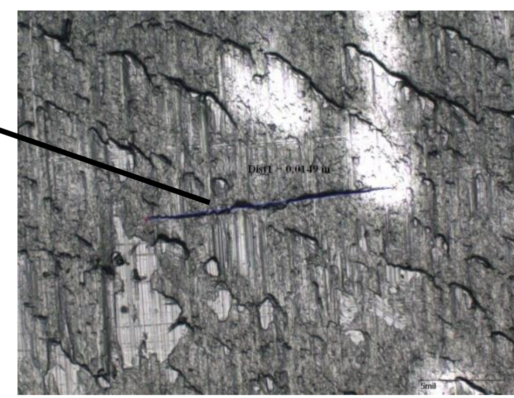
Data with baseline subtraction





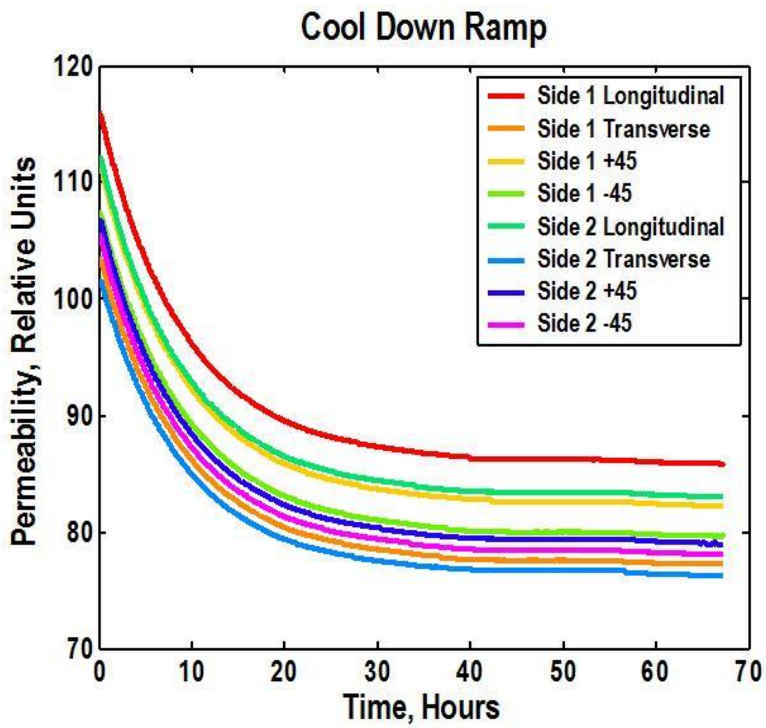
Crack on front side at 43,000 cycles

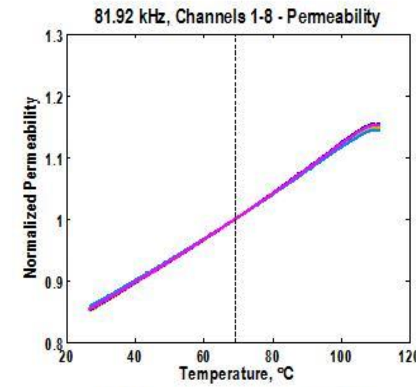


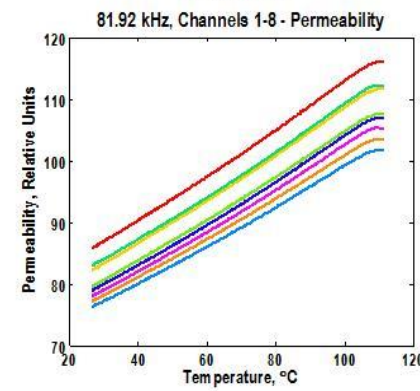


Crack on back side at 43,000 cycles

I.4. Stress & Temperature Monitoring for Steel Alloys with BD-MSGs or QD-MSGs



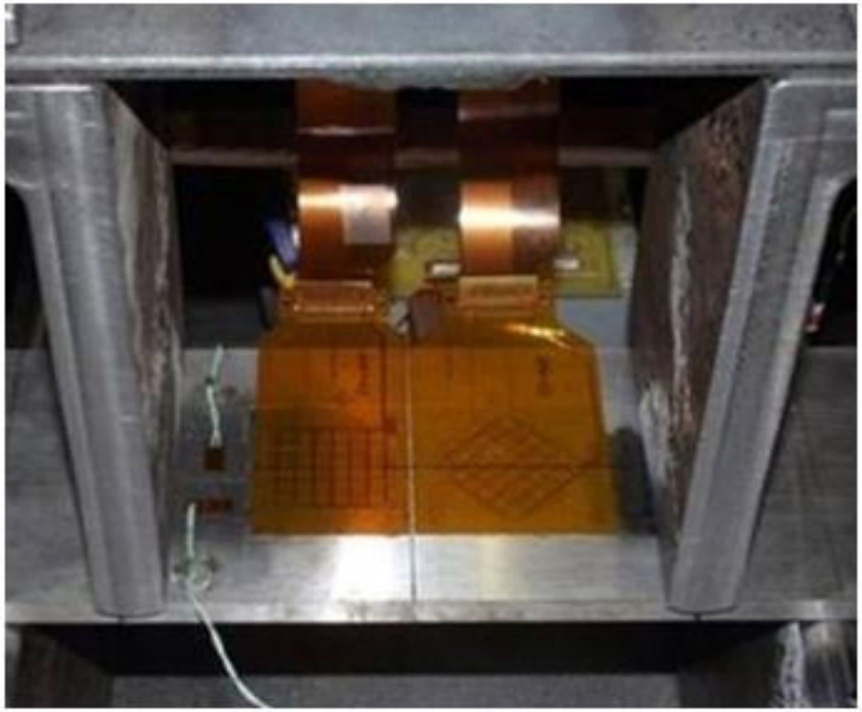


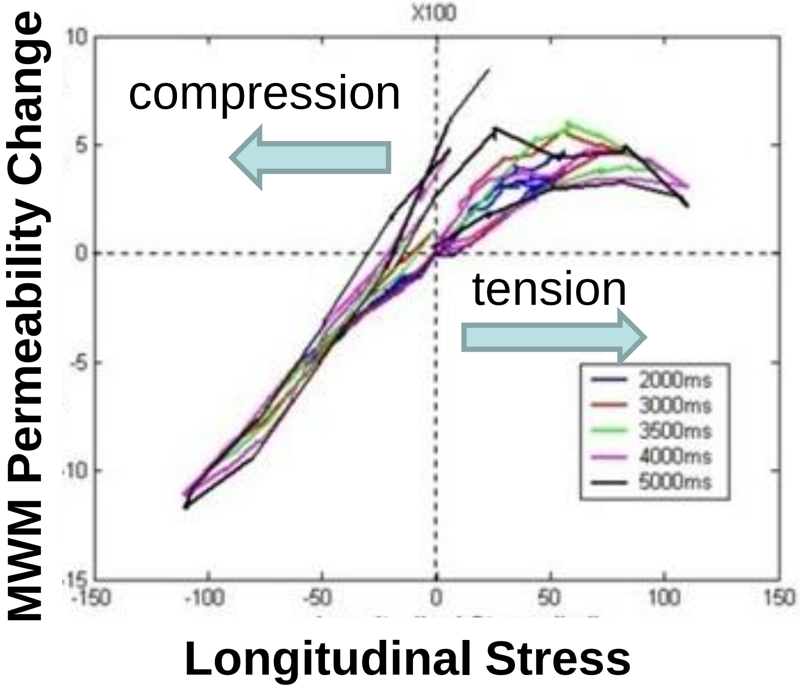


Test Setup for Calibration Derivation in Oven

Magnetic Permeability vs Temperature Plots

I.4. Stress & Temperature Monitoring for Steel Alloys with BD-MSGs or QD-MSGs



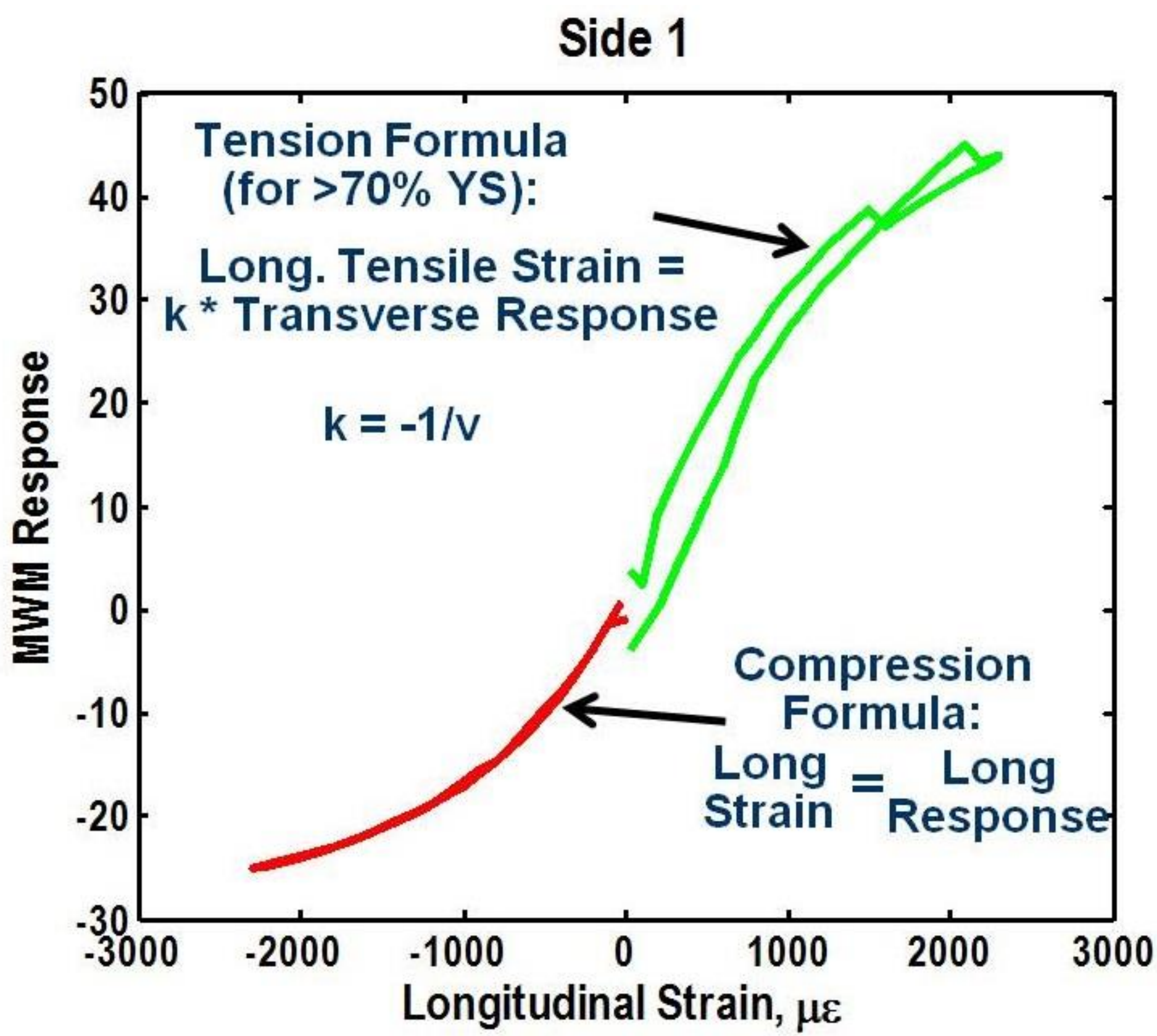


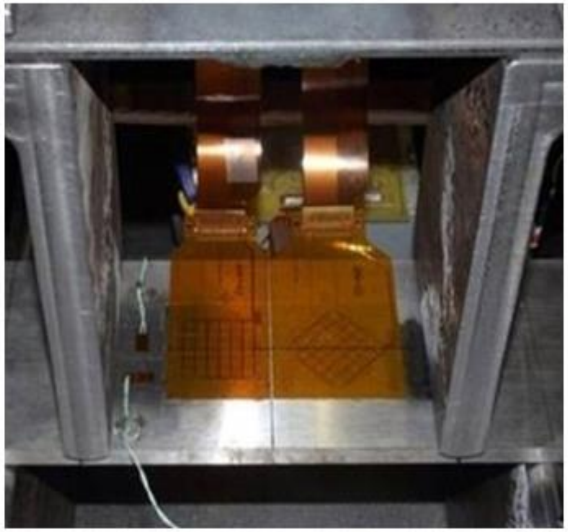
Two BD-MSGs at ± 45 degrees and 0/90 degrees on bending coupon

Compression response is monotonic

Tension response peaks at about 70% of Yield, and Hysteresis occurs after approaching yield

I.4: Need to Combine Longitudinal and Transverse Permeability Responses for Stress Monitoring



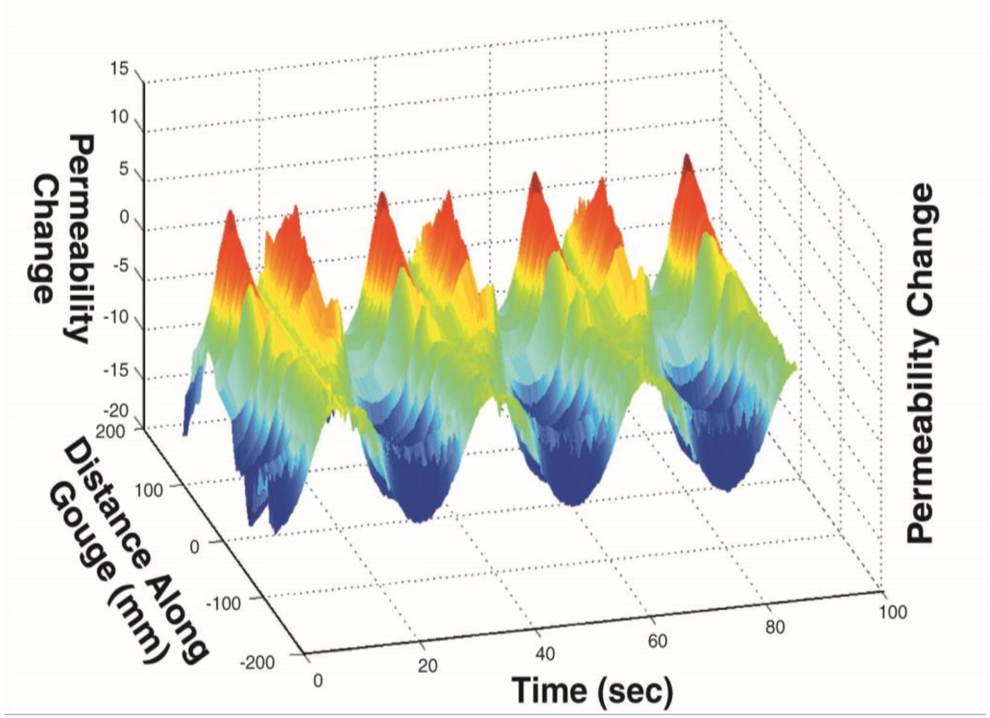


BENDING COUPON TEST WITH MOUNTED BD-MSGs

I.4: Dynamic Stress Testing on a Pipe at GDF Suez

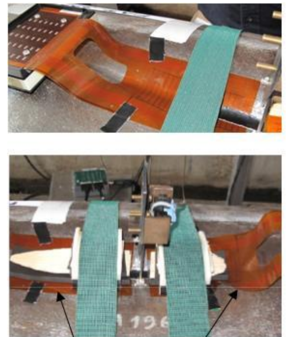
PHOTOGRAPH GDF TEST SETUP FOR CRACK GROWTH AND STRESS MONITORING USING AN INSTALLED MWM-ARRAY AT A MECHANICAL DAMAGE SITE

DYNAMIC STRESS DATA SHOWING VARIABLE PERMEABILITY AS THE PIPE SECTION PRESSURE IS VARIED CYCLICALLY OVER TIME.

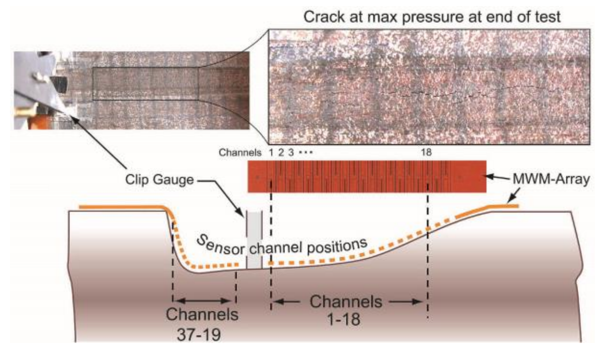


I.4. Pipe Fatigue Test at Mechanical Damage Site

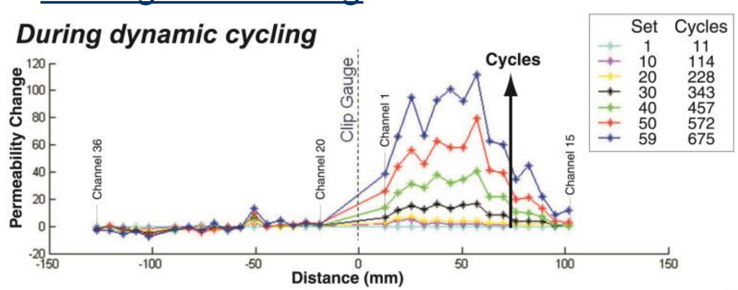
under DOT and PRCI funding with GDF Suez

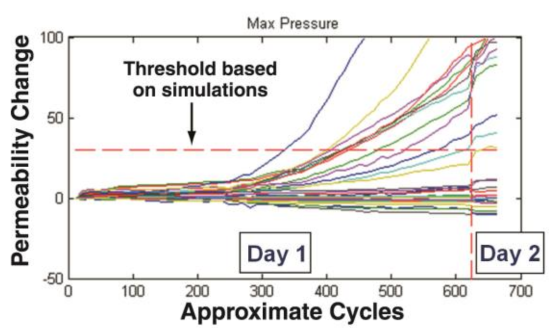


FA178 MWM-Arrays



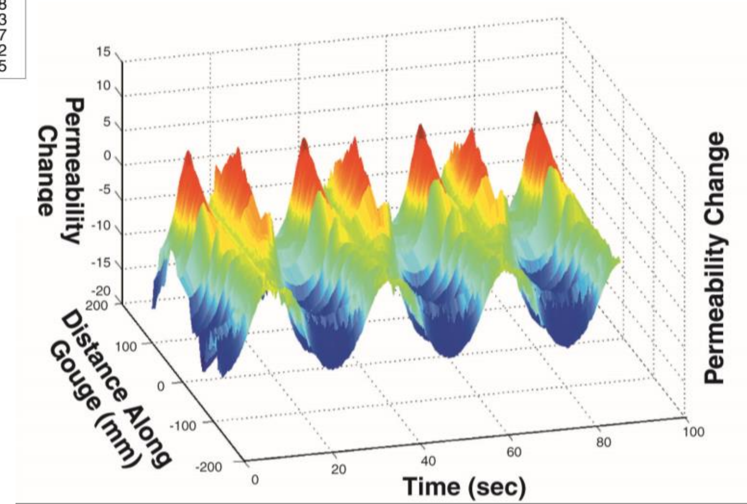
Damage Monitoring



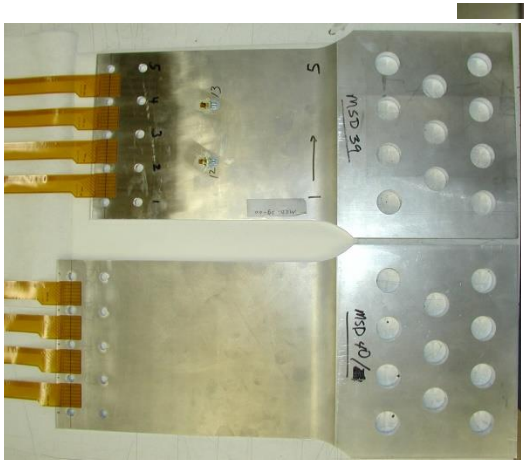


Stress Monitoring

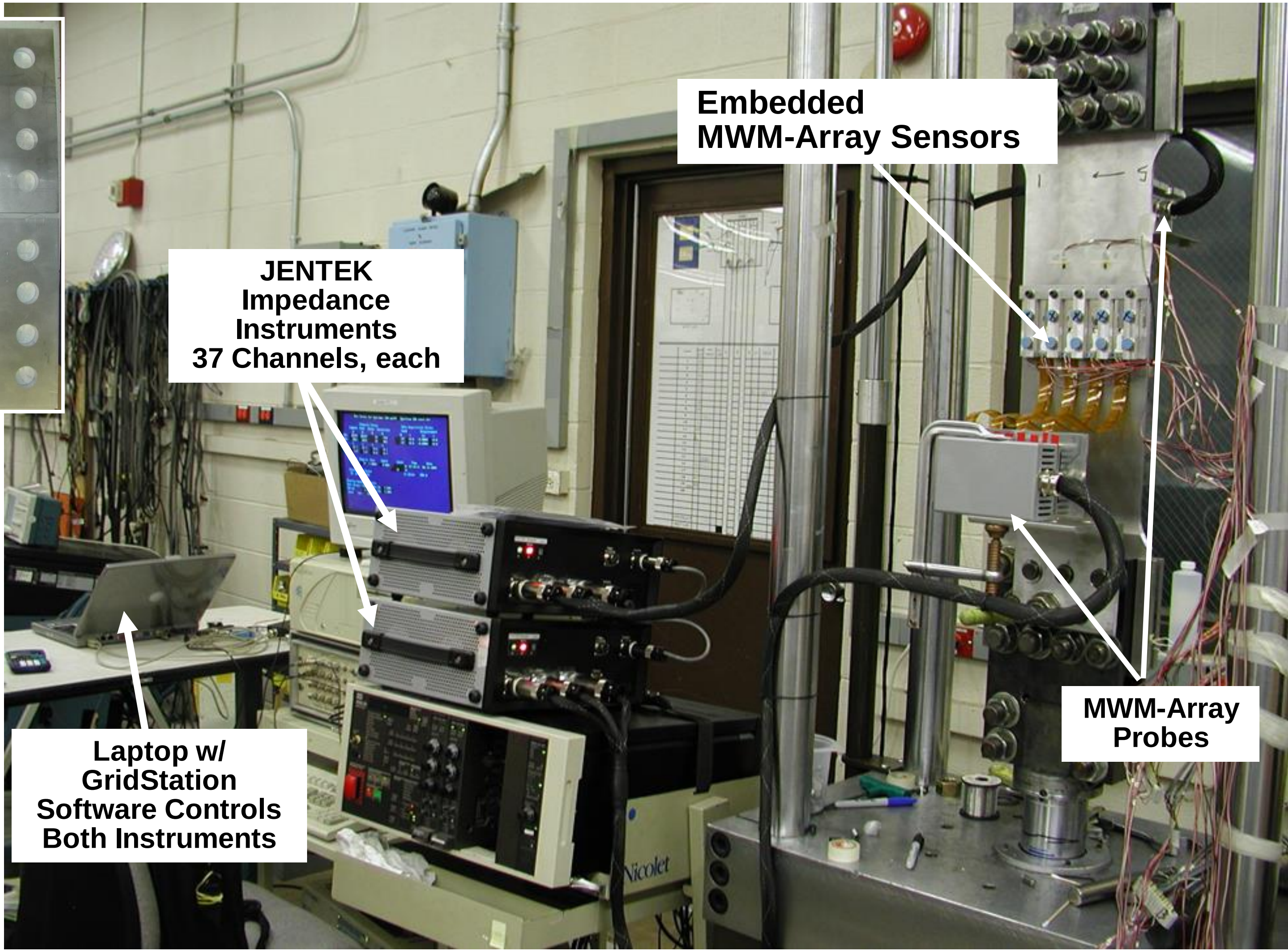
Dynamic pipeline pressure testing



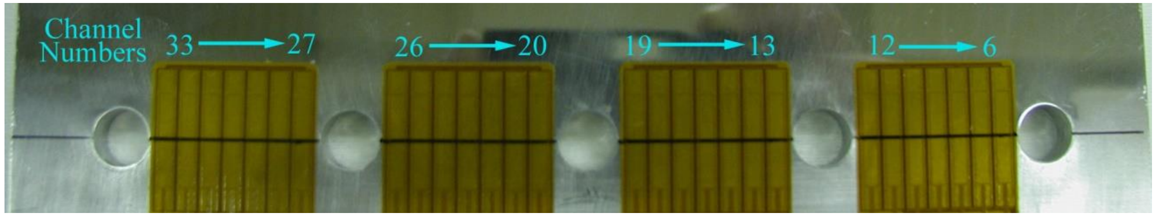
I.4: 10-Hole Specimen Fatigue Test Setup

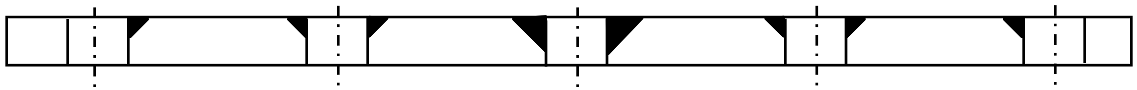


10-Hole Specimen with MWM-Array Networks



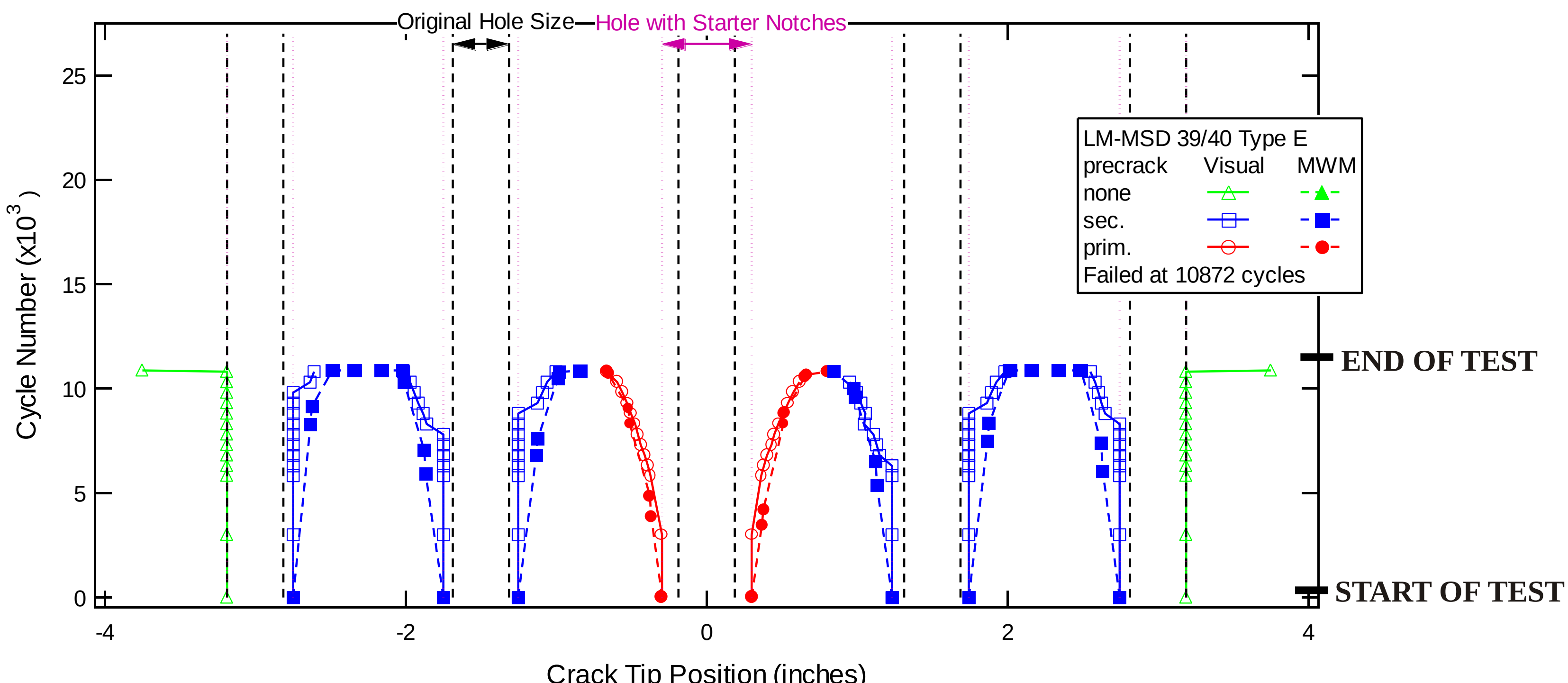
I.4: MWM-Array & Visual Crack Tip Position Results



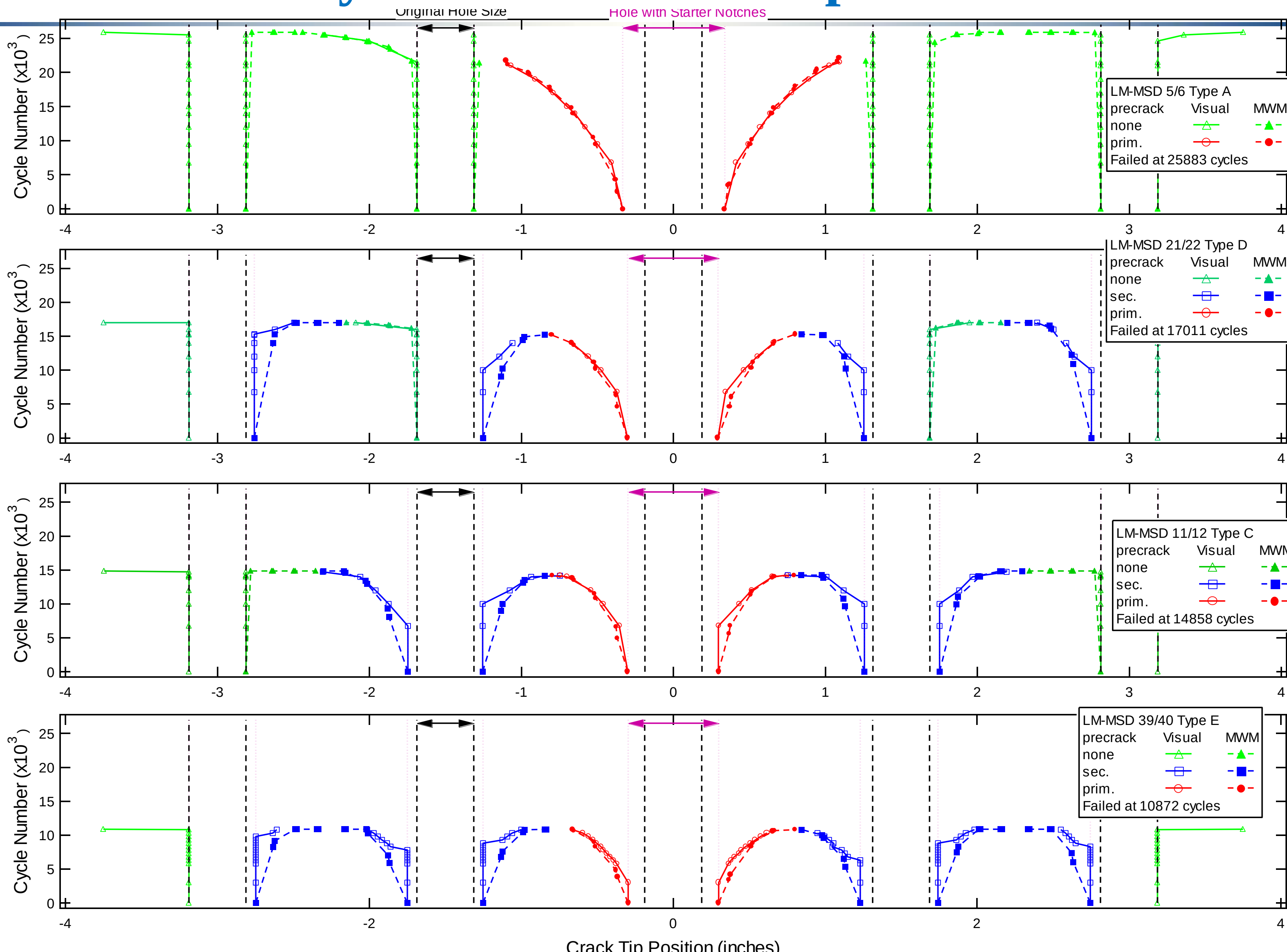


START OF TEST

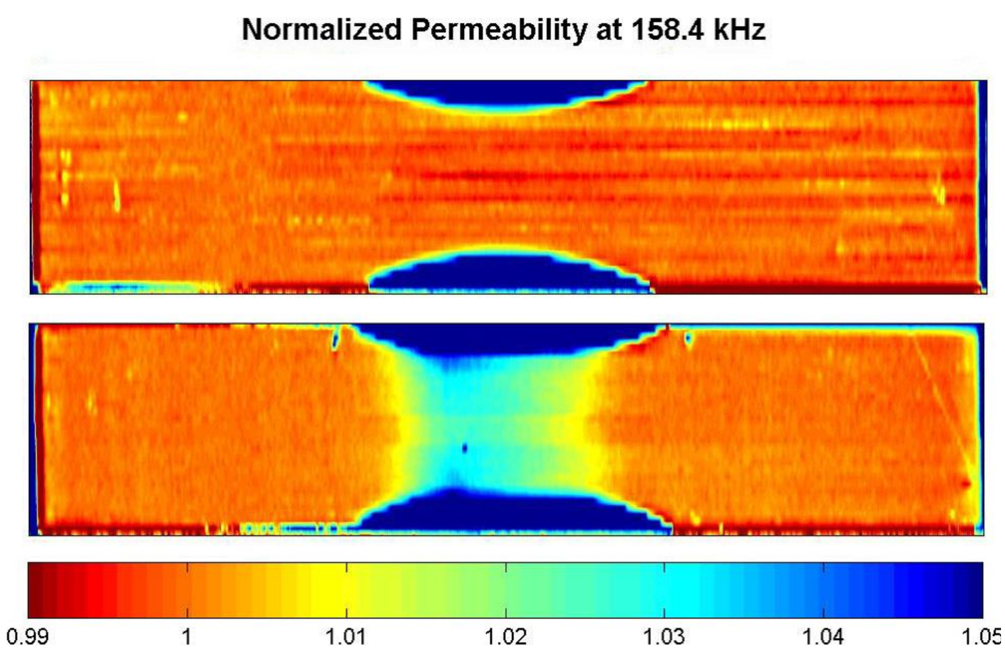
Fracture Surface

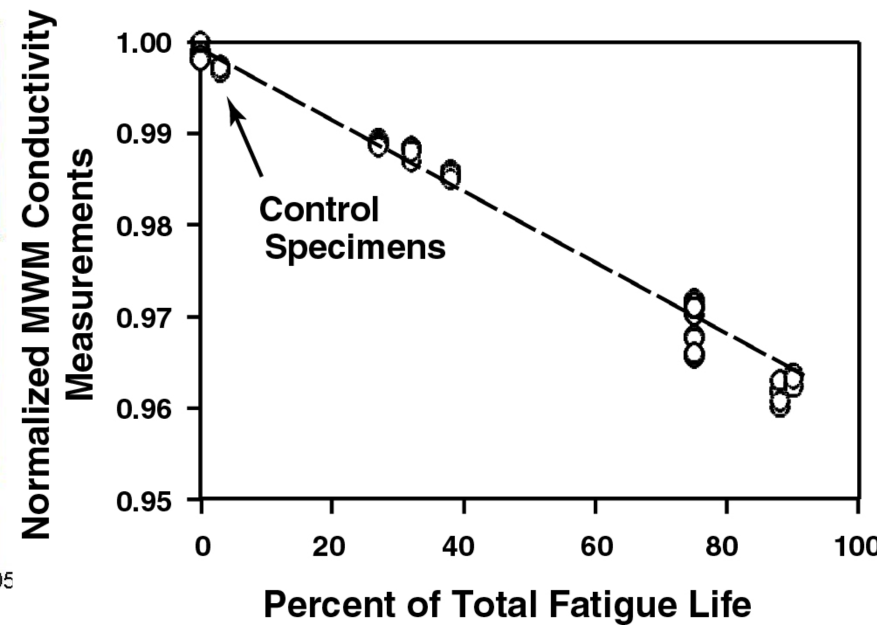


I.4: MWM-Array & Visual Crack Tip Position Results



I.4: SS304 Pre-crack Fatigue Monitoring

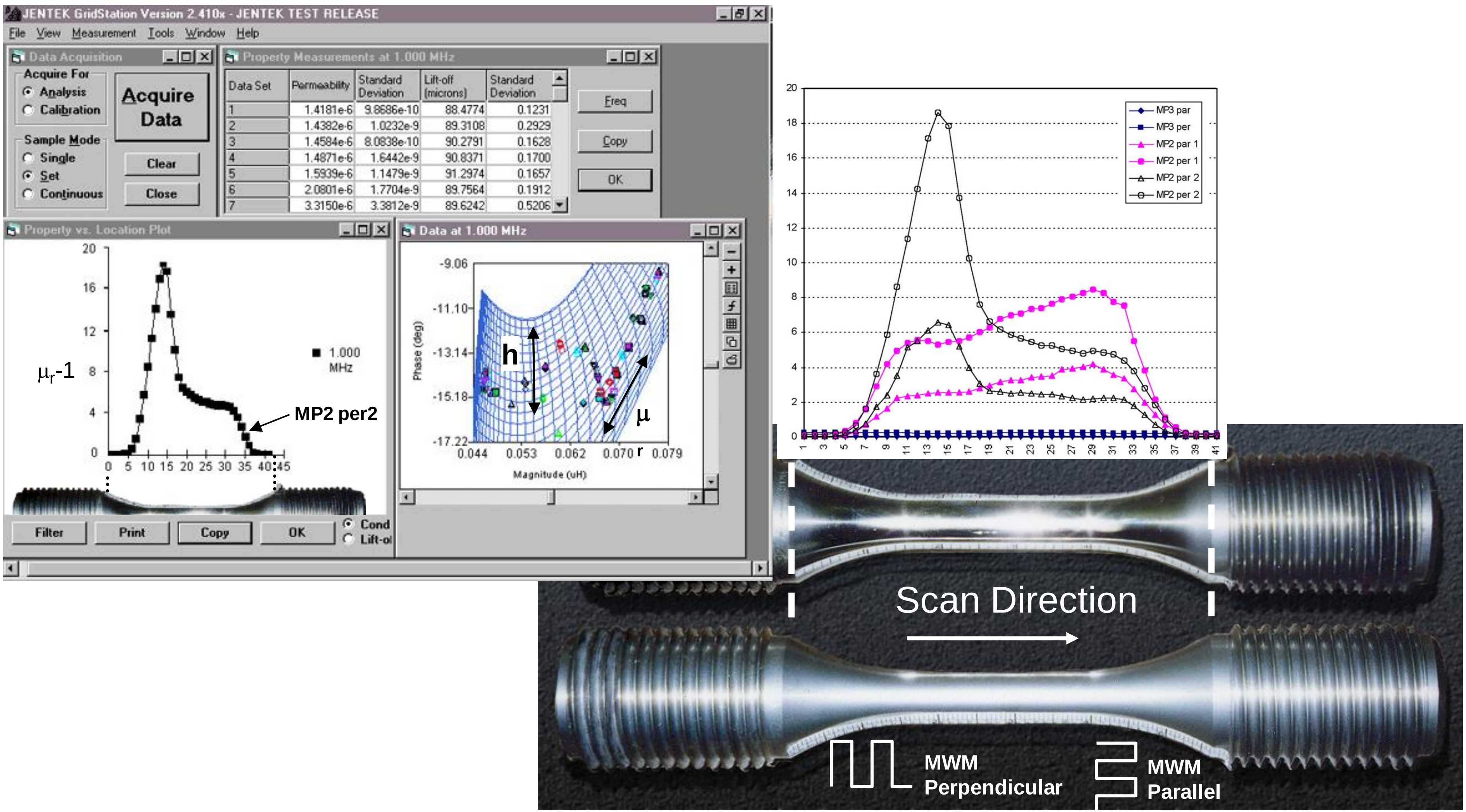




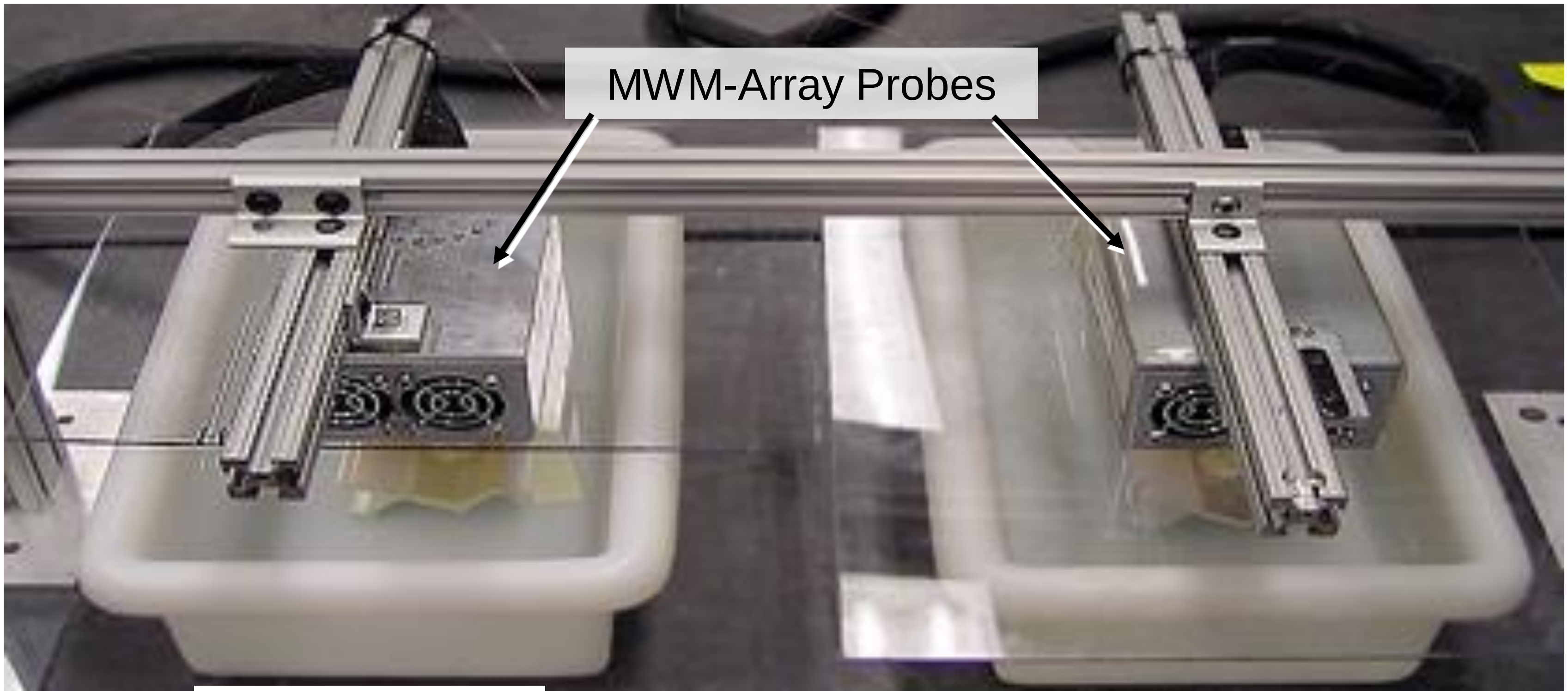
Magnetic permeability image for a control specimen that has not been subject to fatigue testing. (Top)

Magnetic permeability image for the specimen tested to 88% of fatigue life. (Bottom)

I.4: SS304 Anisotropic Permeability for Pre-crack Fatigue Monitoring



I.4: In-Situ Monitoring Set-Up (Test Performed at Alcoa with JENTEK Support)



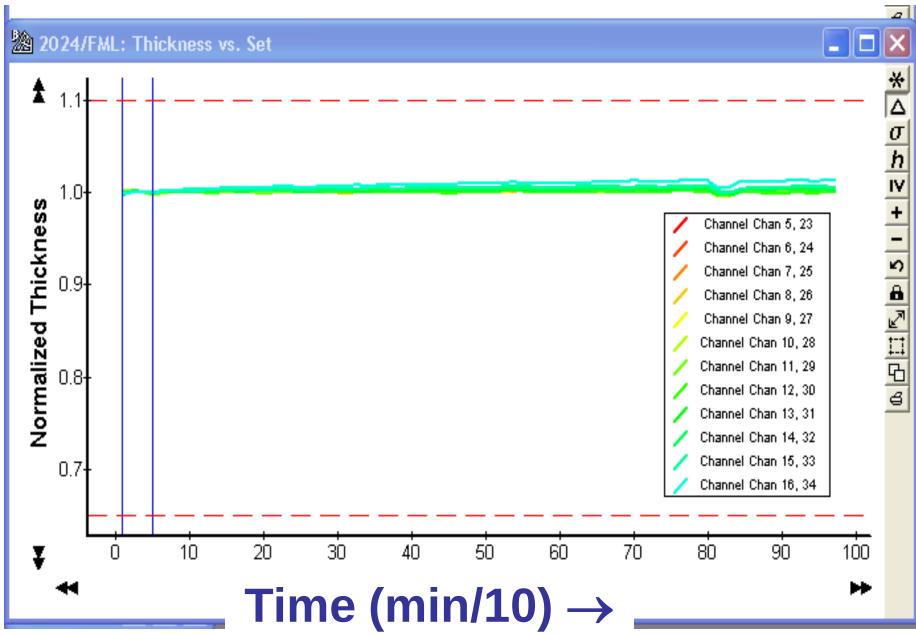
EXCO Solution

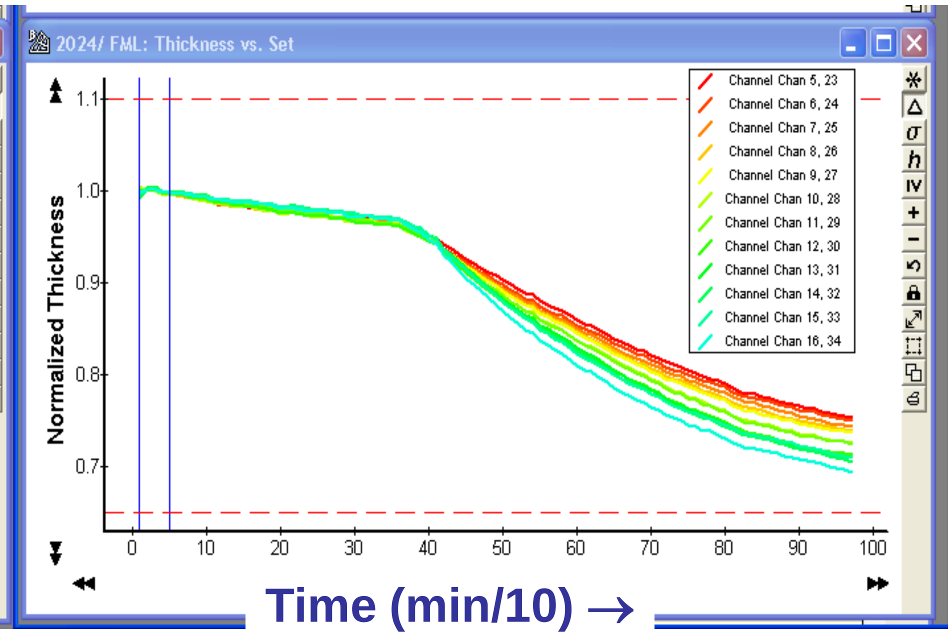
Control: Water

I.4: In-Situ Monitoring Set-Up
(Test Performed at Alcoa with JENTEK Support)

Control (Water)

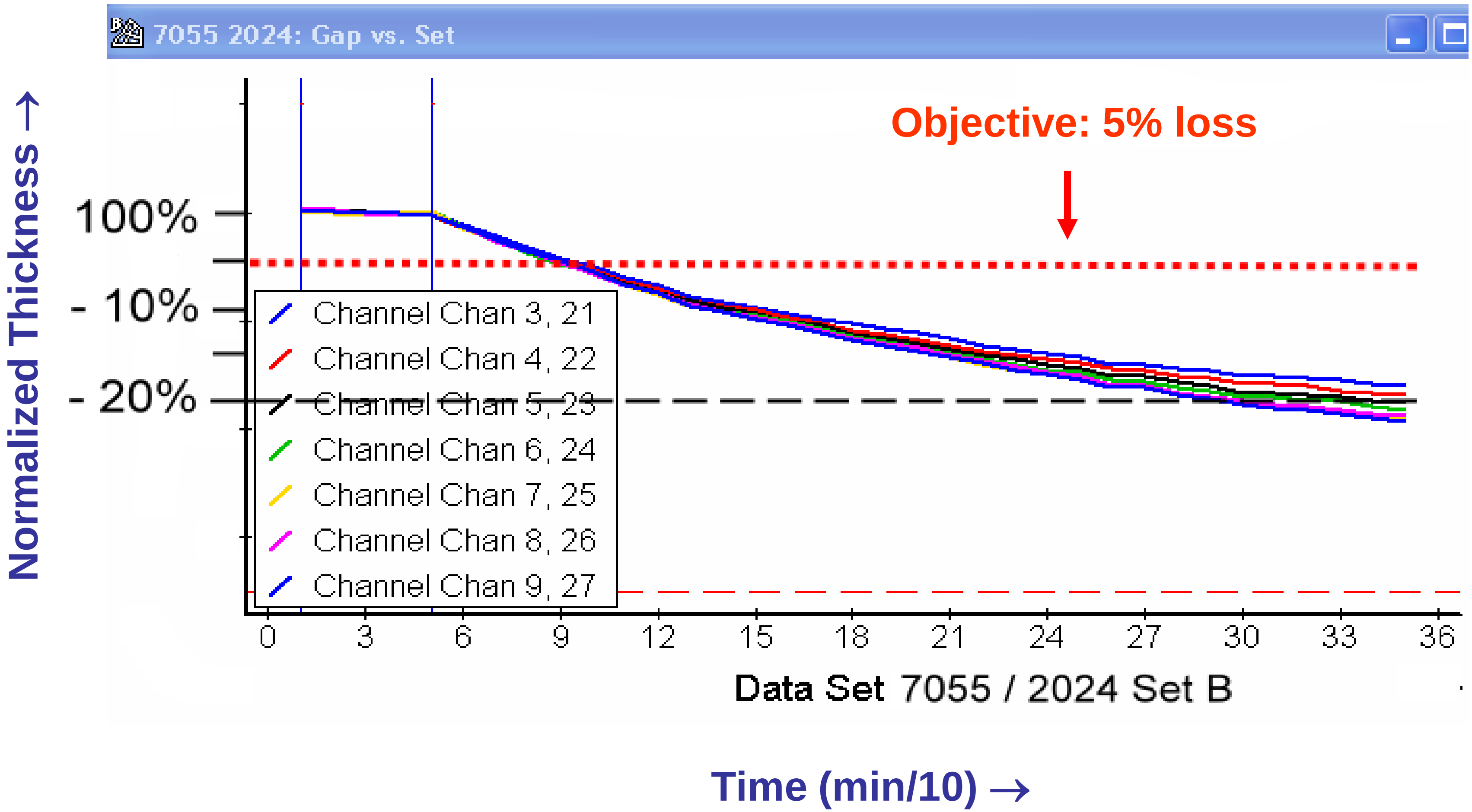
Corrosion



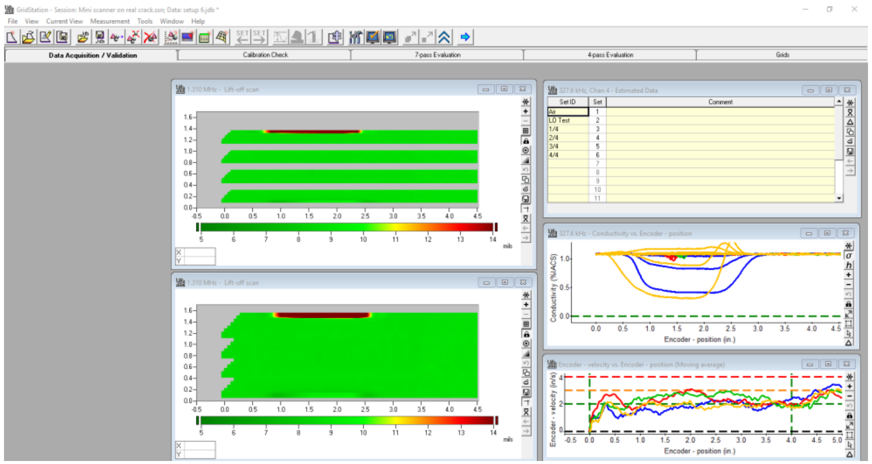


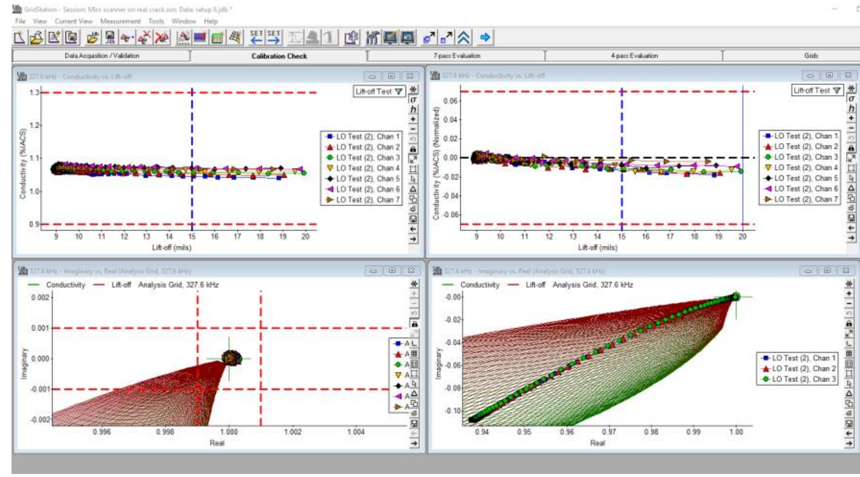
2024 joint to Composite

I.4: In-Situ Monitoring Set-Up
(Test Performed at Alcoa with JENTEK Support)



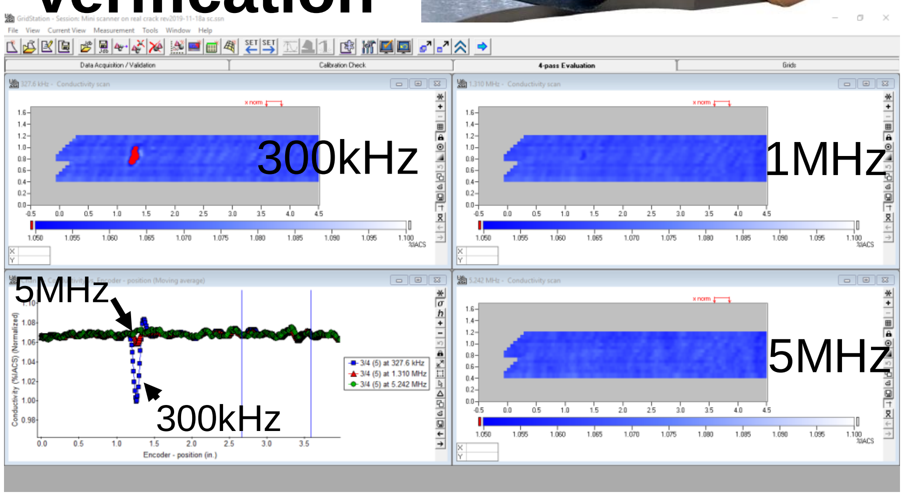
I.5: Software "Tabs" and data visualization tools with automated analytics & training feedback

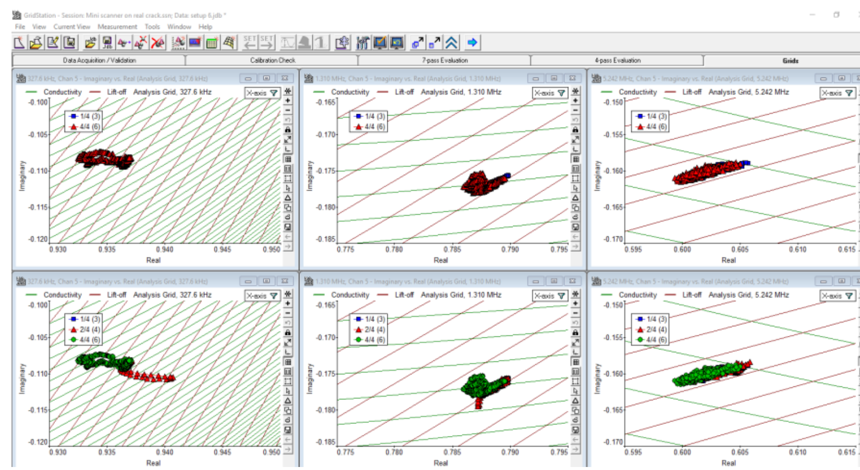




Liftoff and coverage verification

Air Calibration & Verification (Air and liftoff checks)





Crack detection

Model-Based visualization

I.6: Example Aircraft Structures NDT/NDE/NDI

1. **Corrosion imaging**
2. **Buried crack detection**
3. **Bolt hole inspection**
4. **Surface crack detection**
5. **Coating characterization**
6. Detection of cracks in steel through coatings
7. Friction Stir Weld (FSW) and other weld inspection
8. Detection of 1st and 2nd layer cracks at fasteners
9. Layer-by-Layer in process additive manufactured (AM) metal part inspection and post process NDT
10. Residual stress/stress monitoring, and cold work assessment for various but not all alloys

I.6: Picking the Right MWM-Array Sensor
(Depth of Penetration is NOT Depth of Sensitivity)

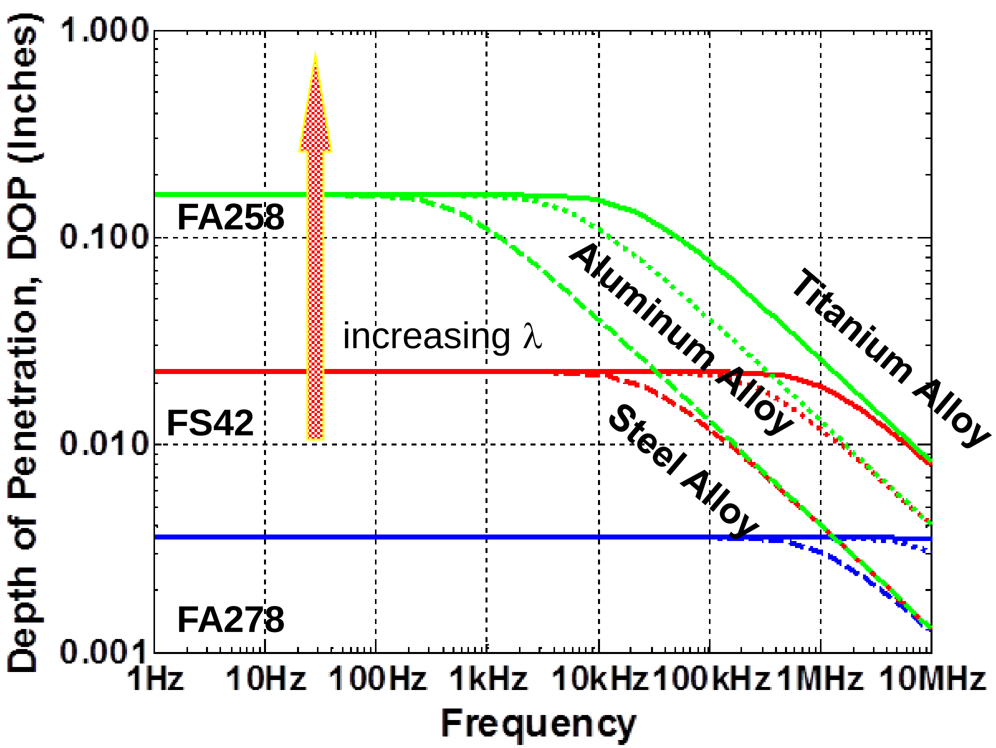
Field Variation with Depth ≈ $e^{-\Gamma_n z}$

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

Spatial Fourier Mode Depth of Penetration = $1/\mathrm{Re}(G_n)$

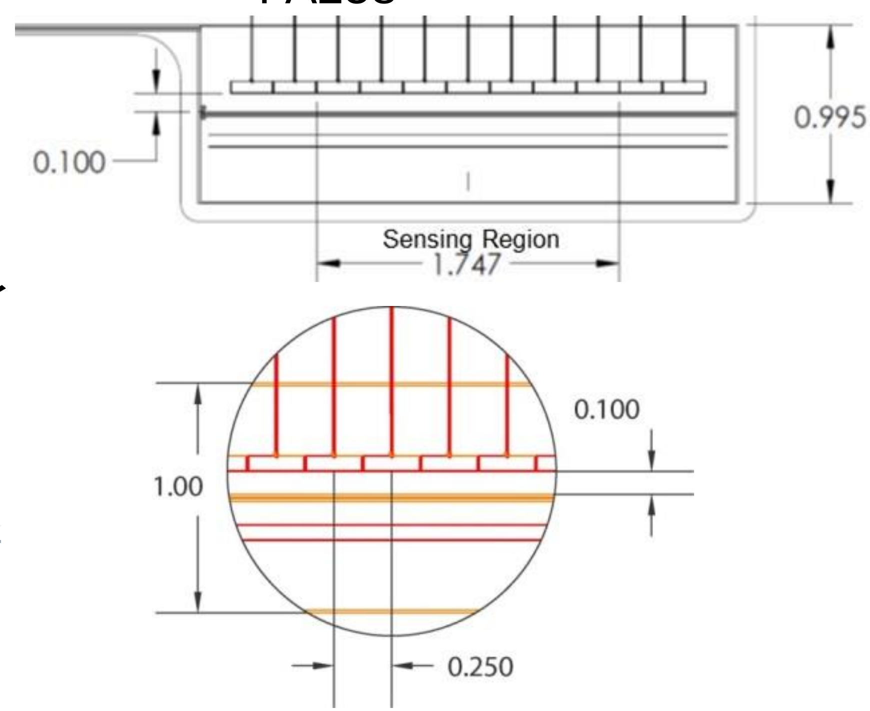
Low frequency asymptote = $\lambda/2\pi$

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

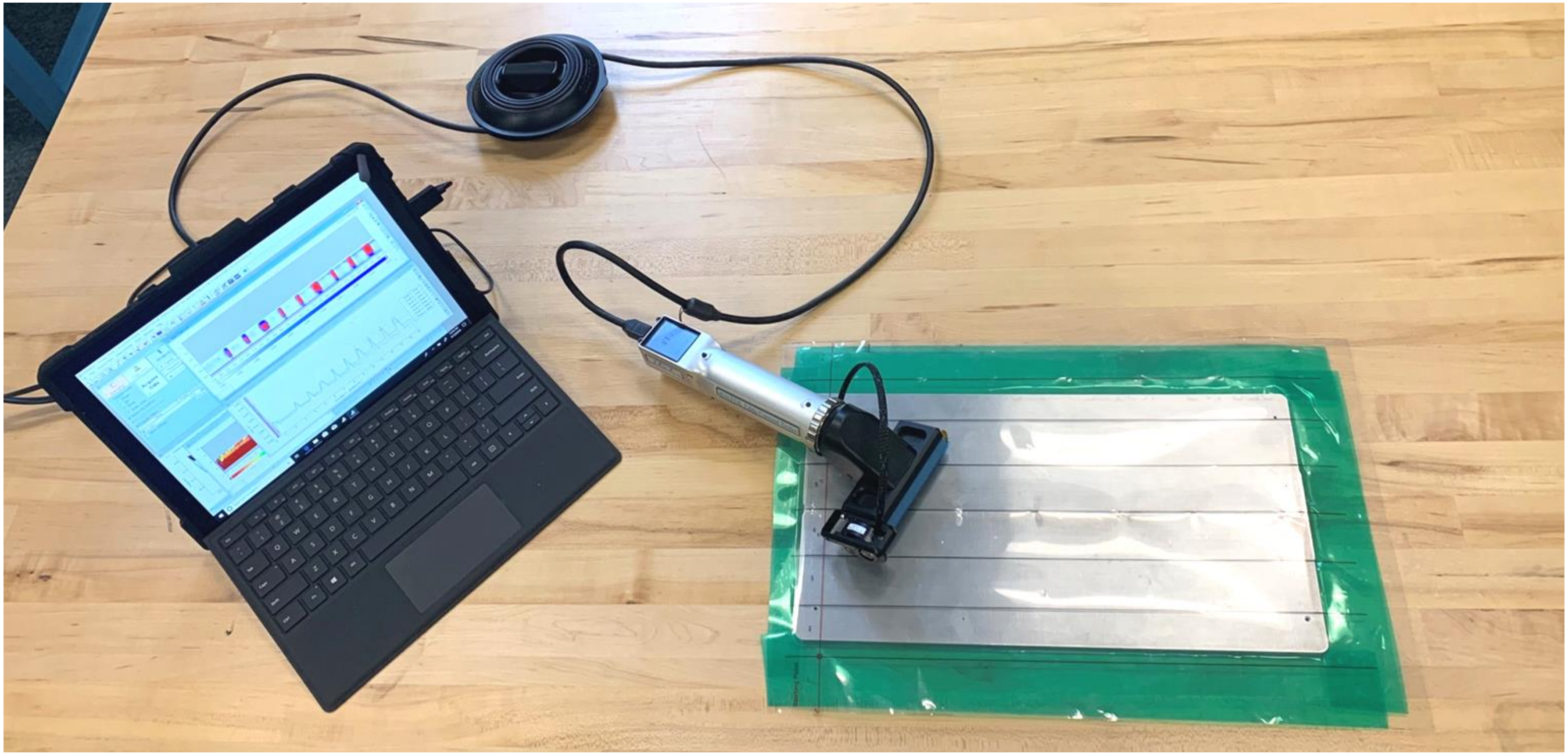


MWM®-Array

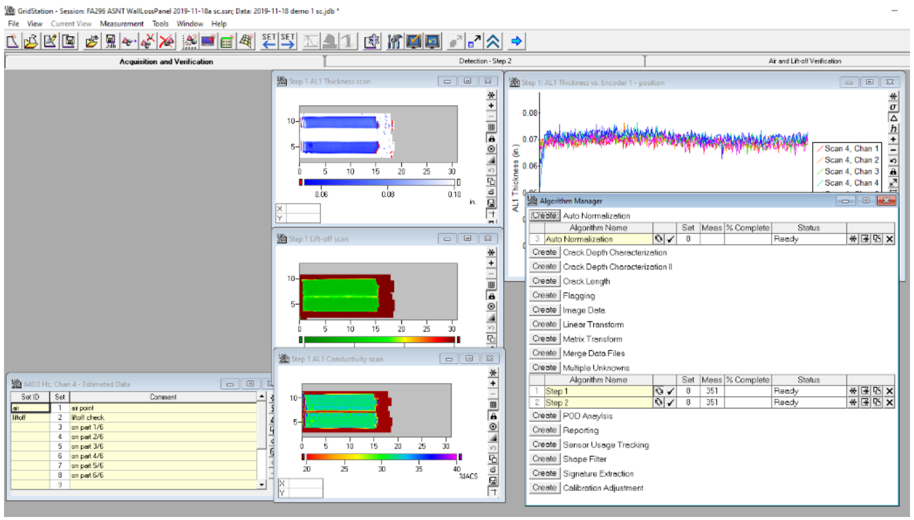
FA258



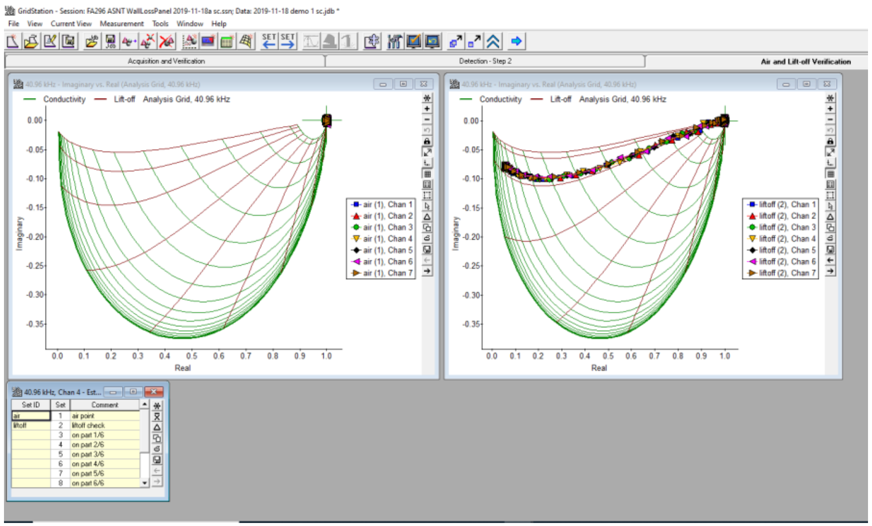
I.6: Corrosion Imaging Performance Study Ongoing



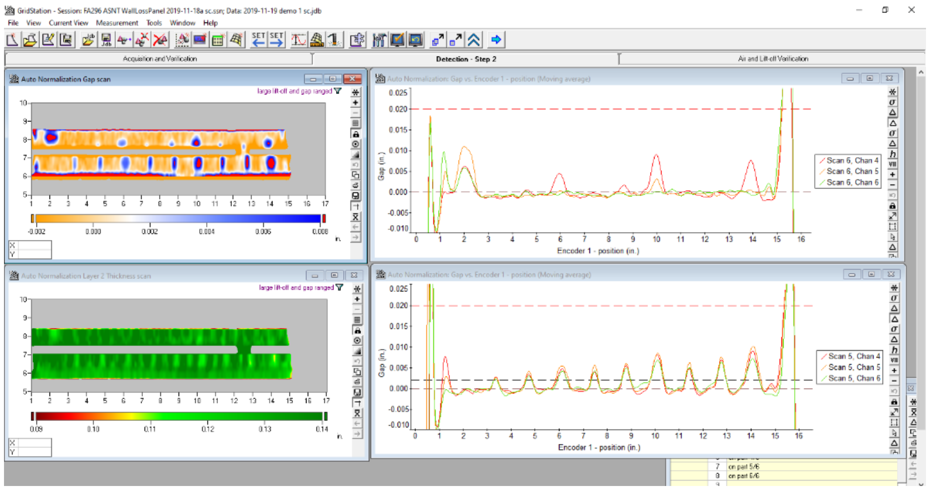
I.6: Corrosion Loss Imaging and POI Verification



Liftoff & coverage verification

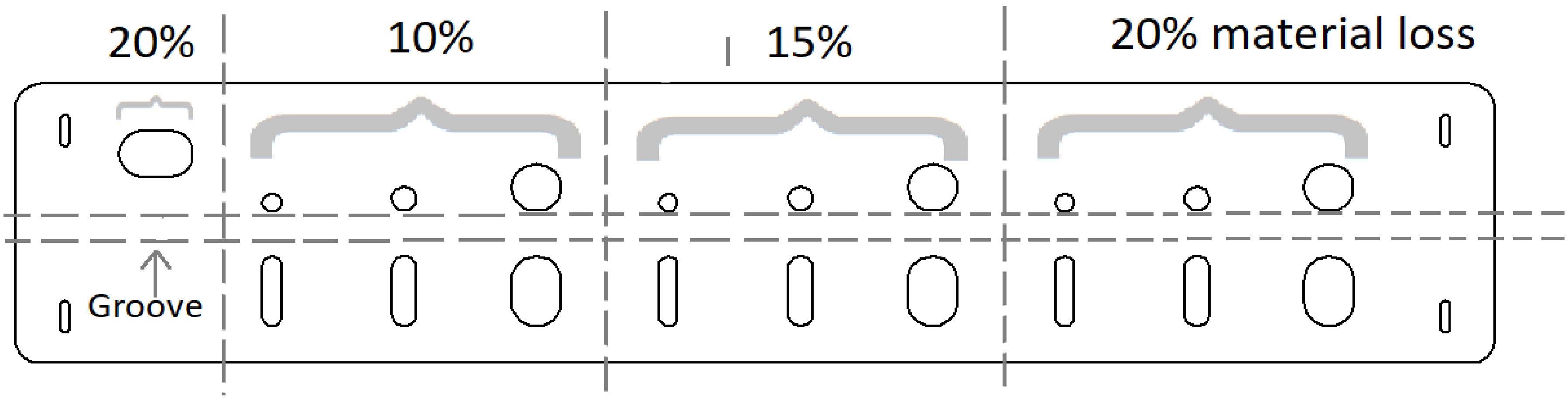


Air Calibration & Cal Check (Air and liftoff)

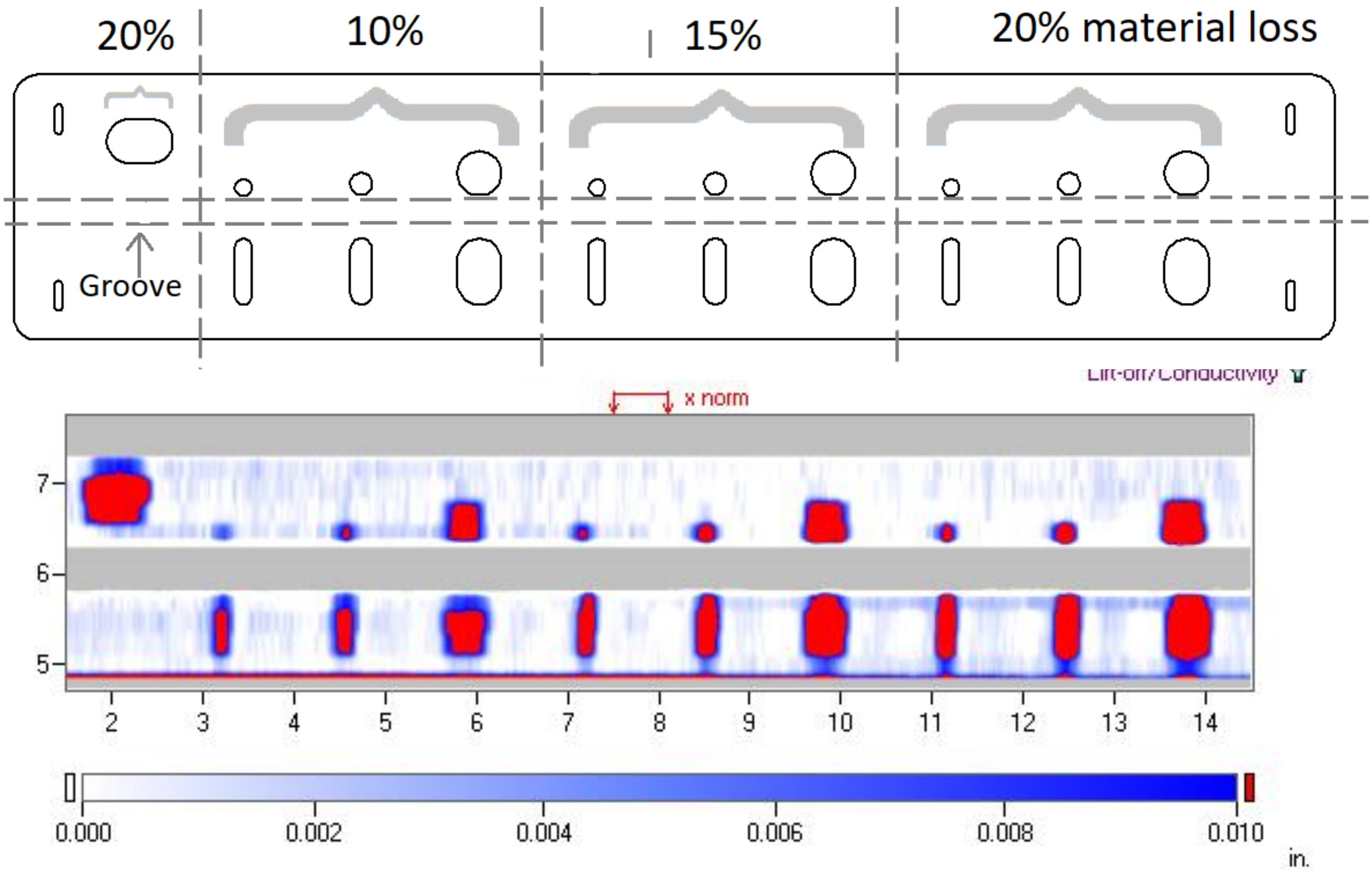


C-Scan and B-Scan data visualizations

I.6: 15 inch Corrosion Loss Sample

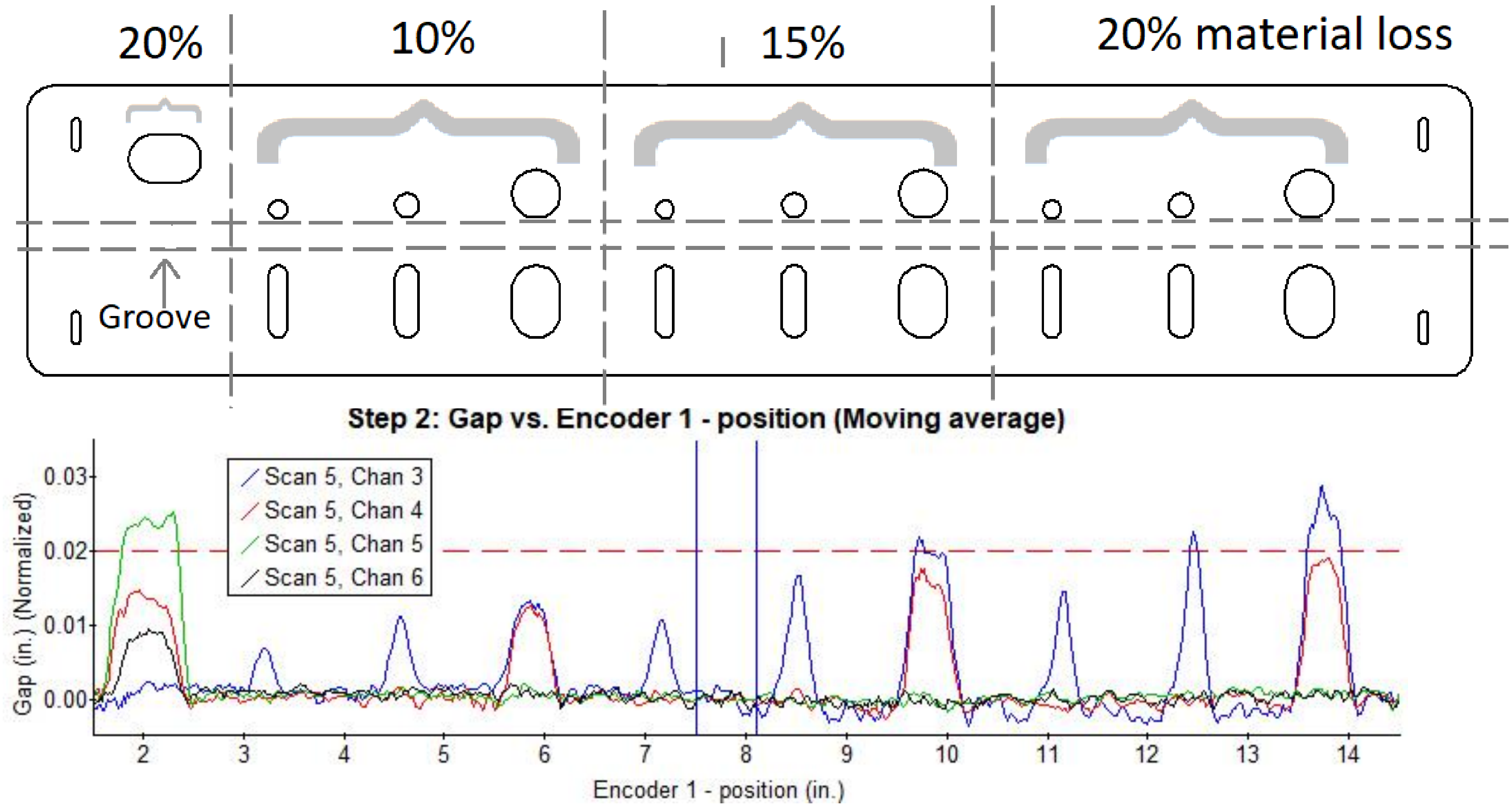


I.6: FA296: 15 inch Corrosion Loss Sample (1)



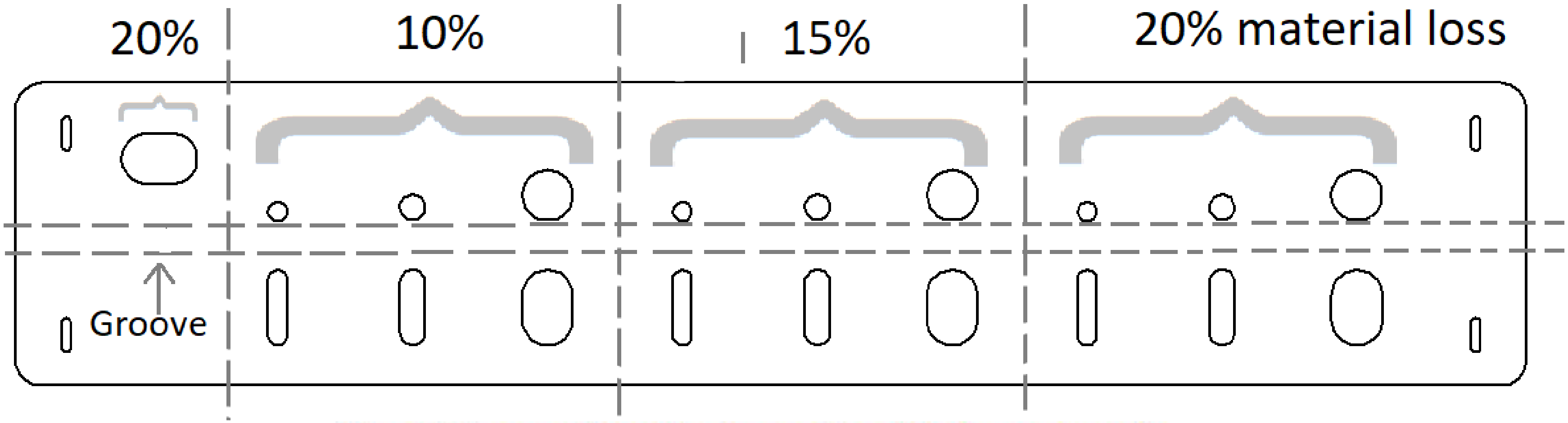
Filtered and normalized C-scan of Gap data across the corrosion defect locations.

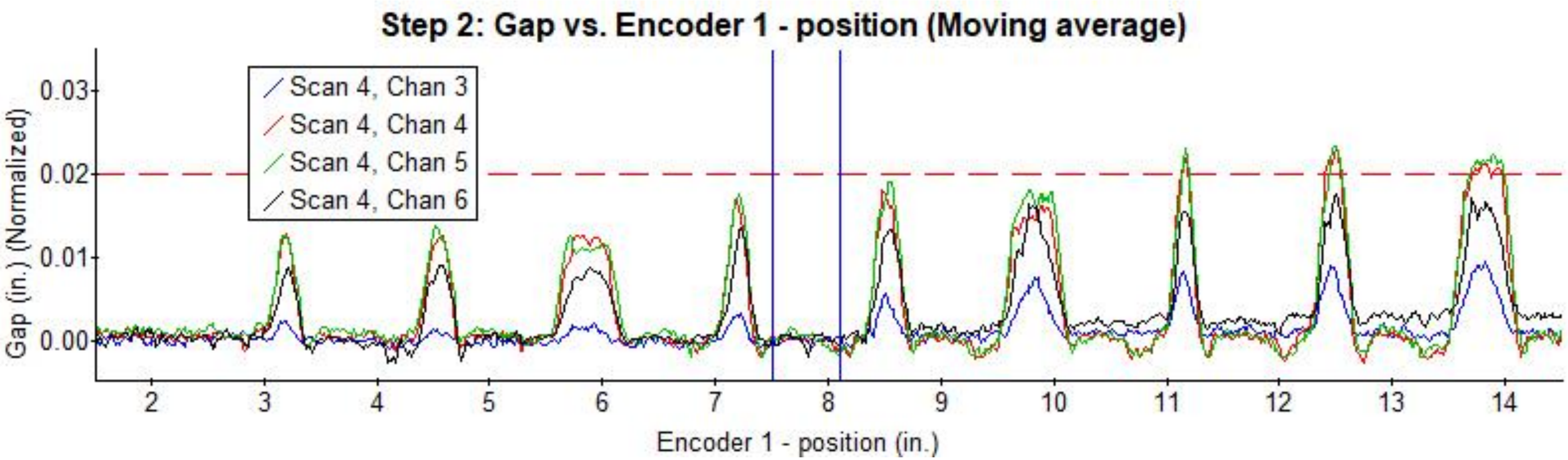
I.6: FA296: 15 inch Corrosion Loss Sample Holes (2)



Normalized B-scan of Gap data across the flat bottom hole defect locations.

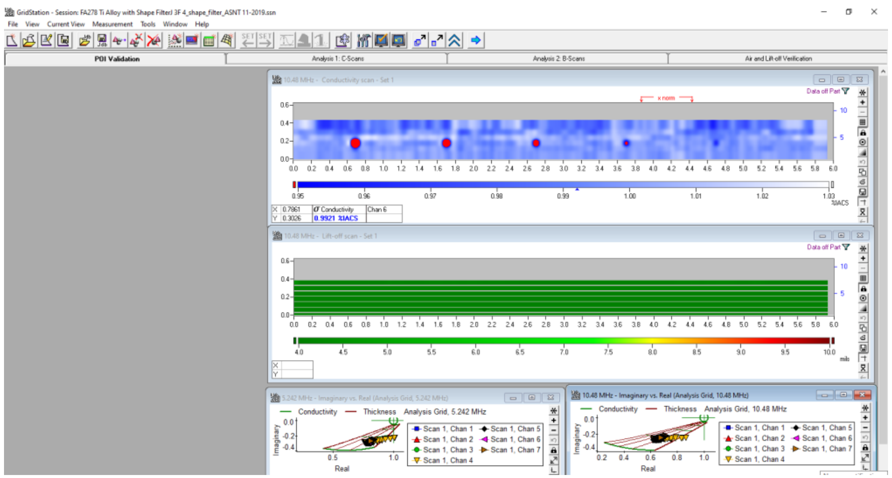
I.6: FA296: 15 inch Corrosion Loss Sample Slots (3)



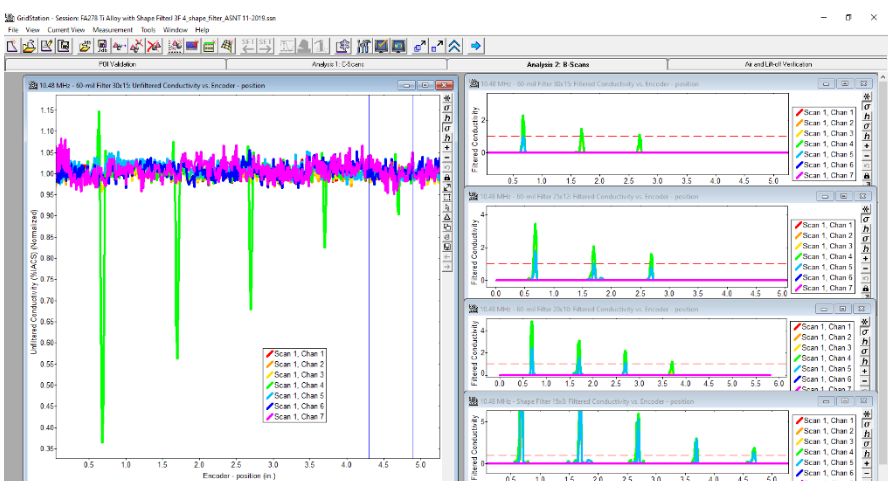


Normalized B-scan of Gap data across the flat bottom slot defect locations.

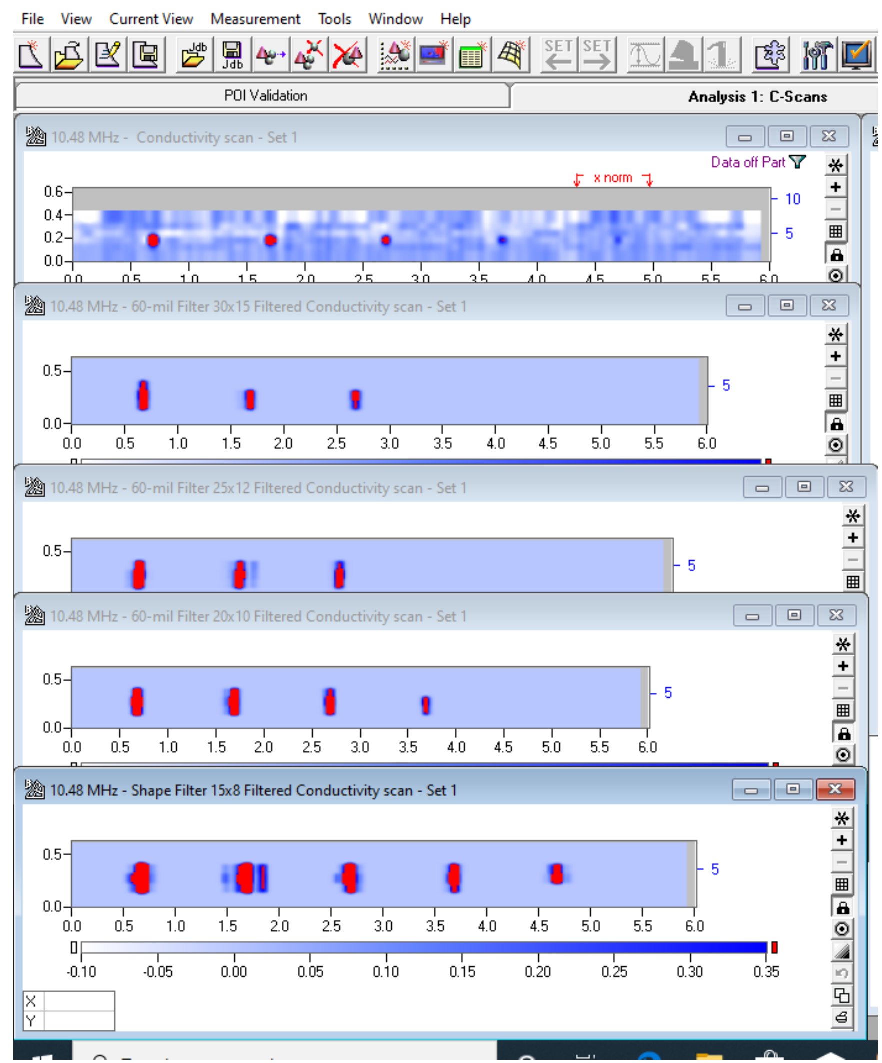
I.6: Surface Crack Detection Interface for POD verification and Inspection



Liftoff & coverage verification

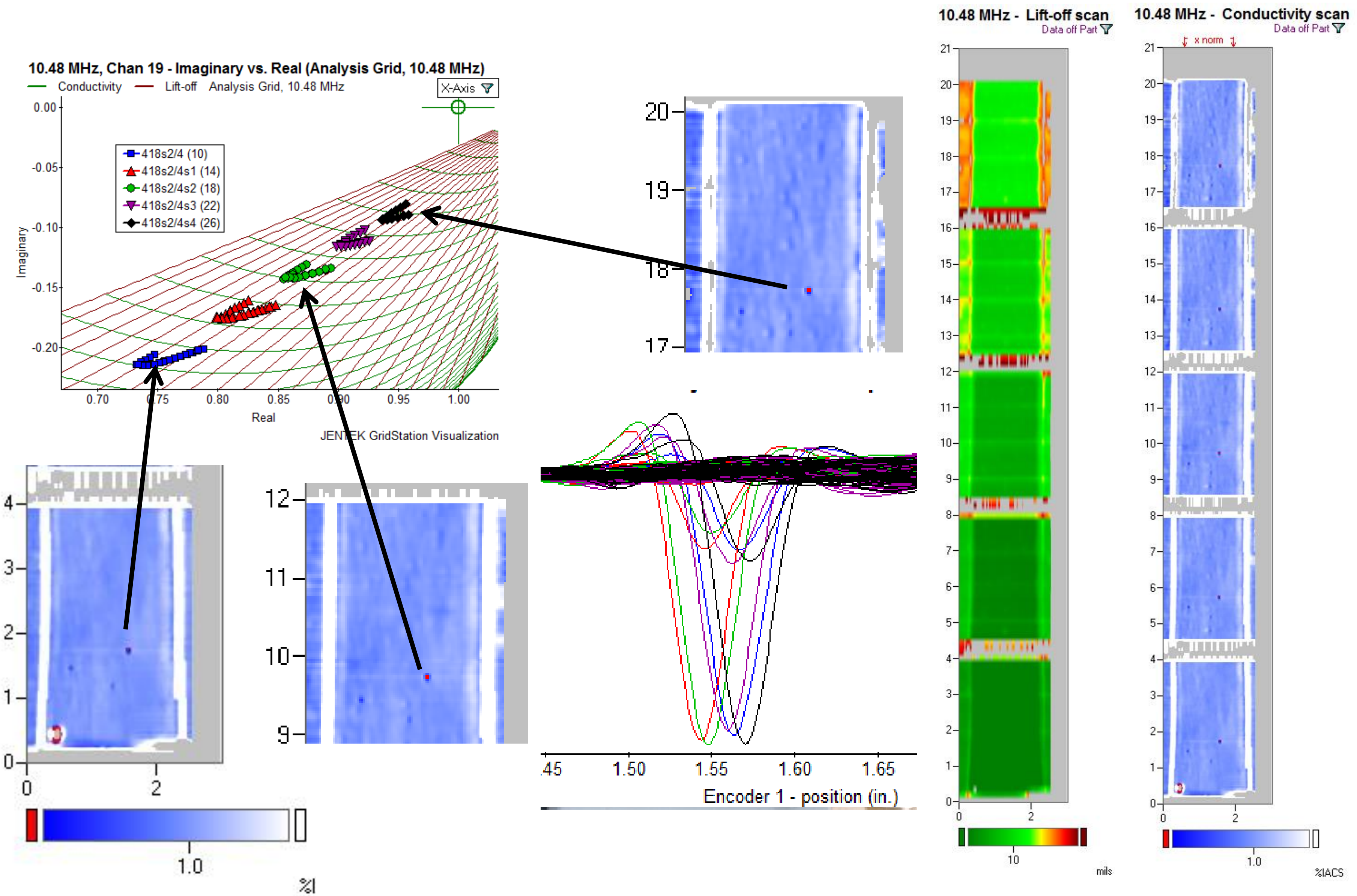


Unfiltered and Filtered B-Scans

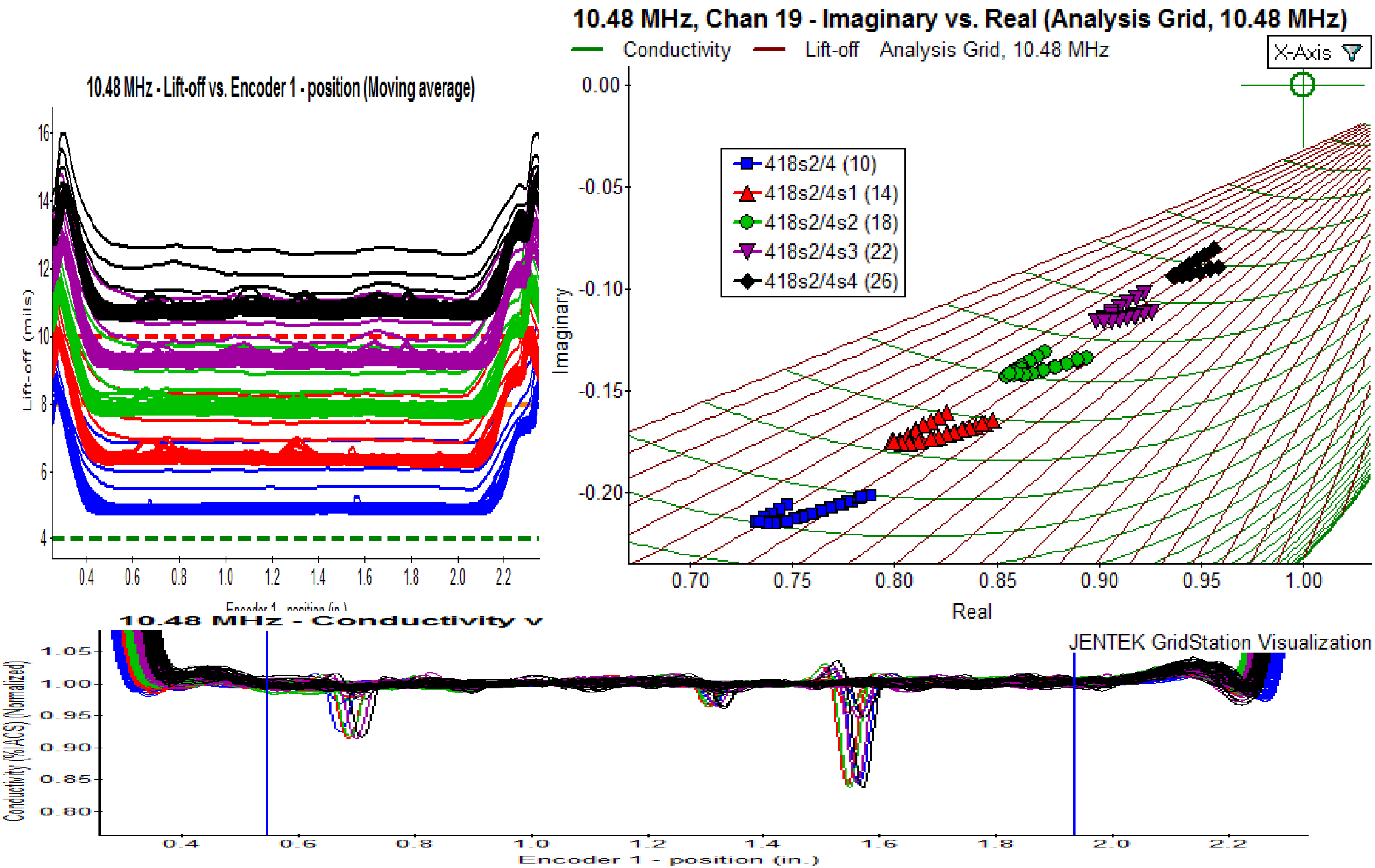


Unfiltered and Filtered C-Scans

I.6: Surface Cracks: Rescaling of Conductivity Response

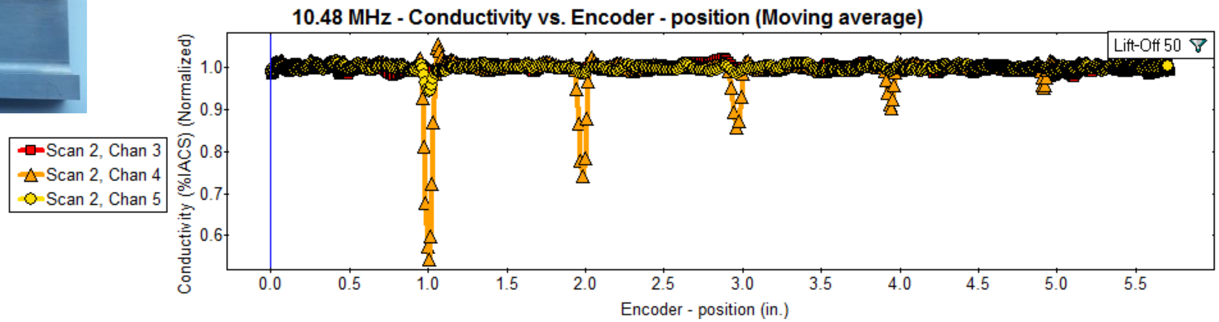


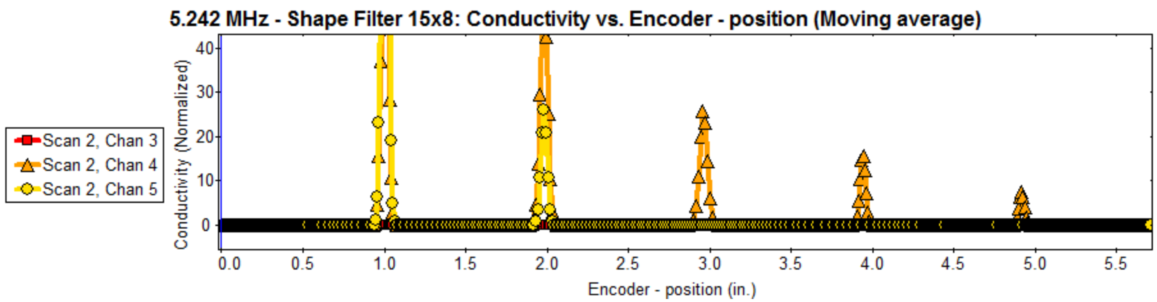
I.6: Surface Cracks: Rescaling of Conductivity Response

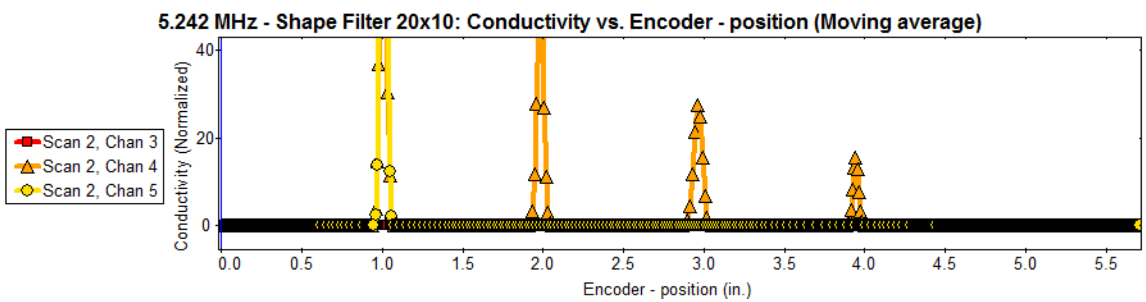


I.6: Titanium Alloy Unfiltered and Shape Filtered Results

EDM Notch Sizes:						
	length	0.06	0.04	0.03	0.02	0.015
	depth	x0.03	x0.02	x0.015	x0.01	x0.0075



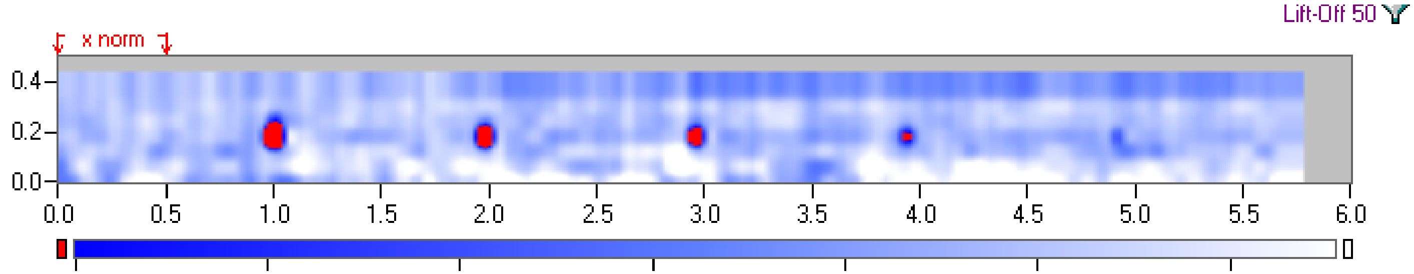




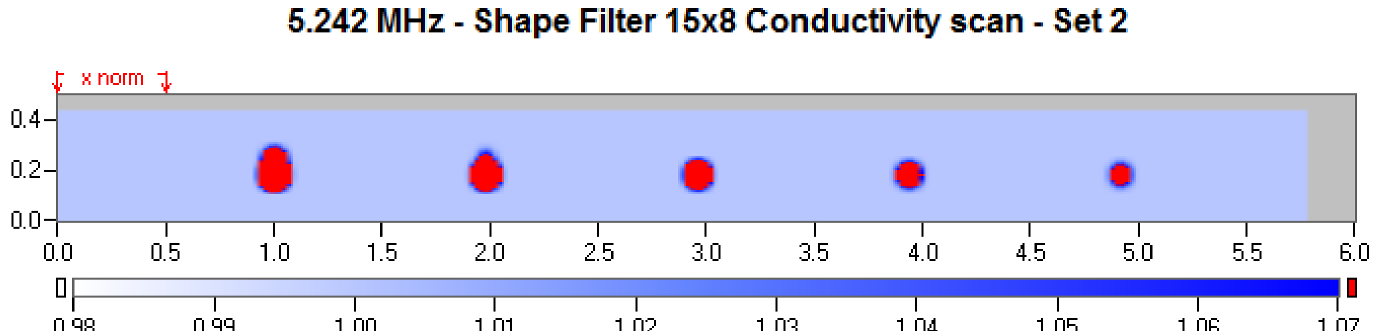
I.6: Titanium Alloy, air calibration, unfiltered and shape filtered results *(with rescaling for position within array)*

EDM Notch Sizes:	length / depth	0.06 x0.03	0.04 x0.02	0.03 x0.015	0.02 x0.01	0.015 in. x0.0075 in.

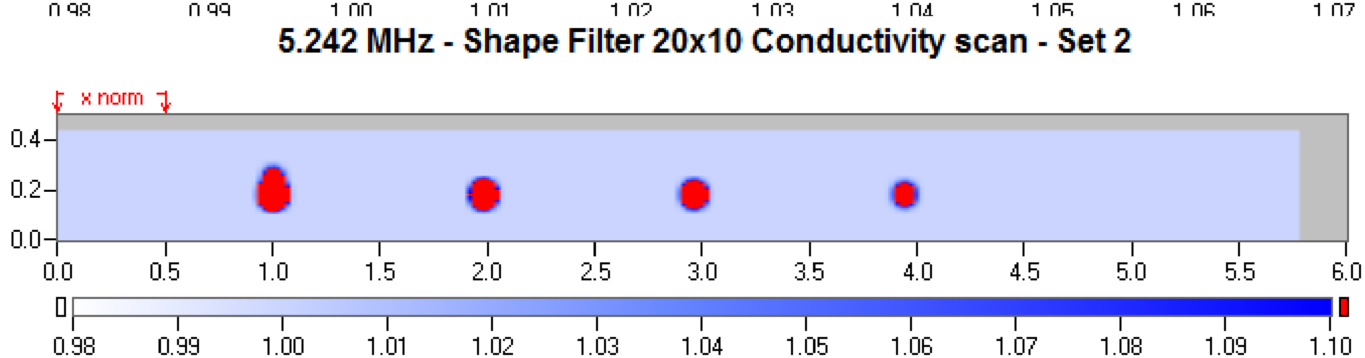
Unfiltered 5.2MHz Conductivity



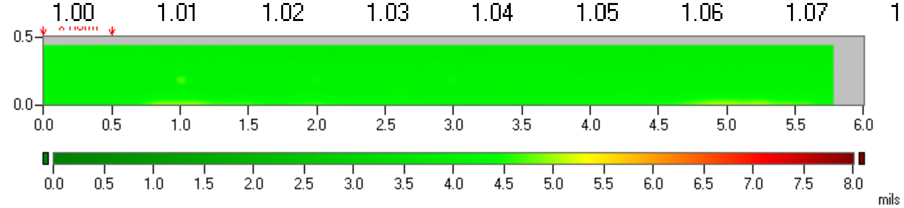
Shape Filtered 0.15 x 0.008



Shape Filtered 0.2 x 0.01



Lift-off Verification



I.7: Additive Manufacturing and Weld Inspection

Additive manufacturing Initiatives Ongoing

- Layer-by-layer NDT
- Fatigue life management
- Post process NDT
- In-process control for AM (metal powder characterization, non-contact temperature, weld pool monitoring, metallurgical assessment, geometry tracking).

Weld inspection initiatives

- FSW inspection as replacement for penetrant testing ((PT)
- Inspection of welds with crowns as replacement for PT
- Volumetric inspection of welds for thin layers to replace (UT and Radiagraphy)
- In-process control for welding (non-contact temperature, weld pool monitoring, seam tracking, metallurgical assessment, geometry tracking).

3 Decades of Research and Transitions

- **Example Successful Transitions of Research In-Use Today**
  - **S.1** Engine blade weld repair identification (2002 thru 2020+)
  - **S.2** Propeller cold work quality assessment (2002 thru 2020+)
  - **S.3** Friction Stir Weld (FSW) qualification (intermittent 2005-2020+)
  - **S.4** Engine component NDT (2005-2020+)
  - **S.5** Coating characterization (intermittent 2007-2020+)
  - **S.6** Space Shuttle Leading Edge at KSC (2007-2010)
- **Example Engineering-Science Innovations & Ongoing R&D**
  - **I.1** Model-based Multivariate Inverse Methods Using HyperLattices
  - **I.2** Segmented Filed ET-Arrays (SF-ET-Arrays)
  - **I.3** MWM-Array and Parallel architecture impedance instruments
  - **I.4** Fatigue, Stress and Corrosion monitoring
  - **I.5** Accessible ET-Array systems, software and training
  - **I.6** Aircraft NDT for cracks and corrosion
  - **I.7** Additive manufacturing and weld inspection