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NASA

Development of Meandering Winding Magnetometer (MWM®) Eddy Current Sensors for the Health Monitoring, Modeling and Damage Detection of High Temperature Composite Materials

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32nd HIGH TEMPLE Workshop

February 2, 2012

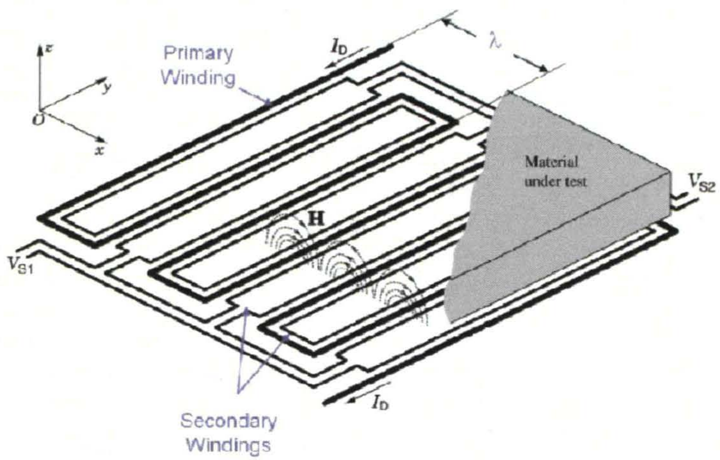
Palm Springs, CA

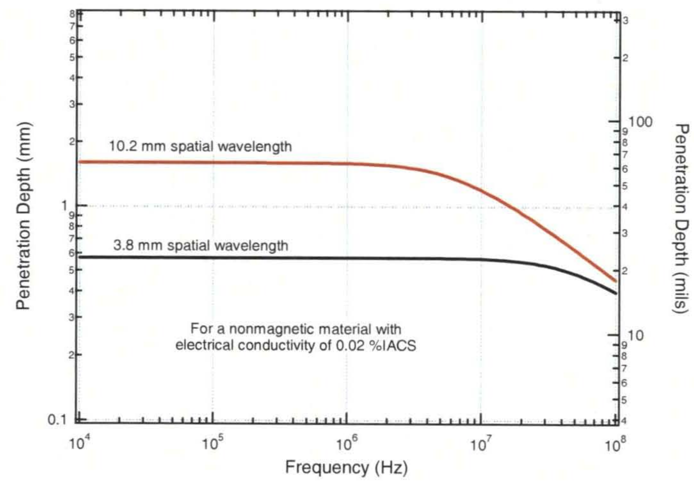
Agenda

- Overview of MWM® Technology
- Historical application – Space Shuttle RCC
- Recent Developments for COPVs
  - Health Monitoring
  - NDE
- High Temperature Development

MWM® Technology

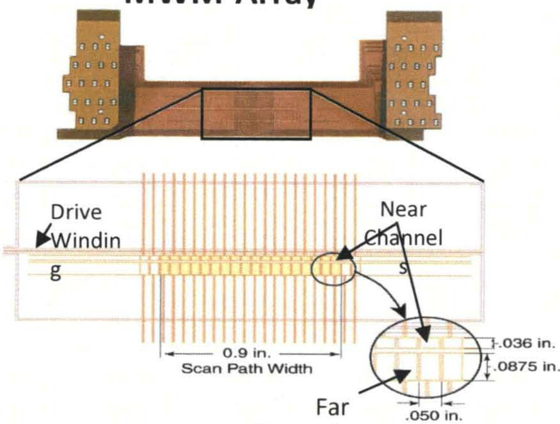
- What is a Meandering Winding Magnetometer (or MWM)?
  - Primary winding is a linear construct that can be aligned with fibers
  - Secondary windings for sensing the response
  - Fabricated on thin flexible substrate creating a conformable sensor
  - Can be manufactured in various array configurations
  - Depth of penetration varies with sensor wavelength (spacing) and frequency
  - Vendor has capability to perform computer simulations





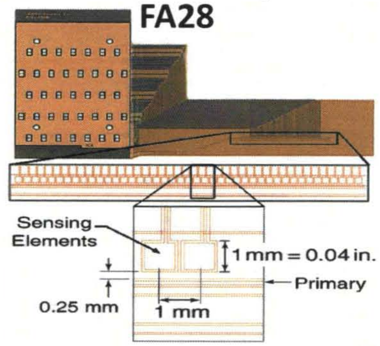
MWM® Arrays and Grid Methods

MWM-Array



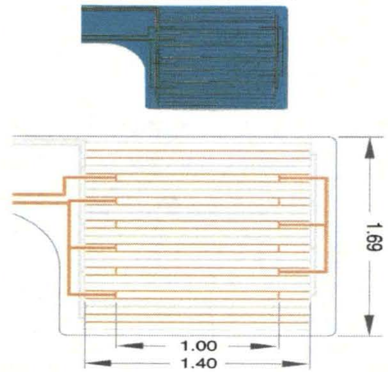
FA41 λ ≈ 480/190

MWM-Array FA28



FA28 λ ≈ 150 mils

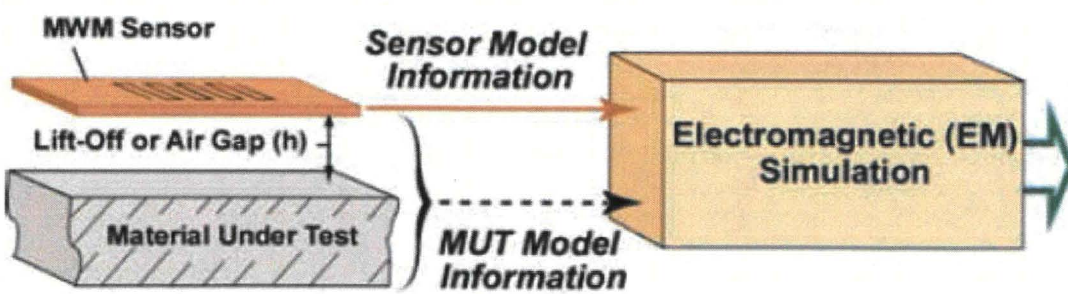
MWM FS36



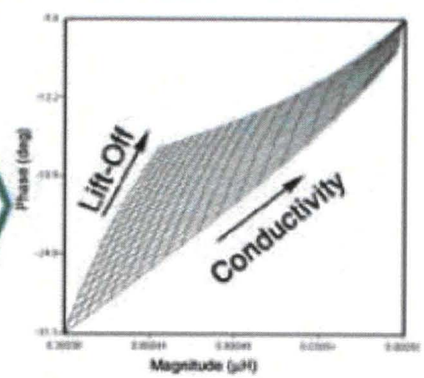
FS36 λ ≈ 400.0

JENTEK Grid Methods

MWM and MUT Model

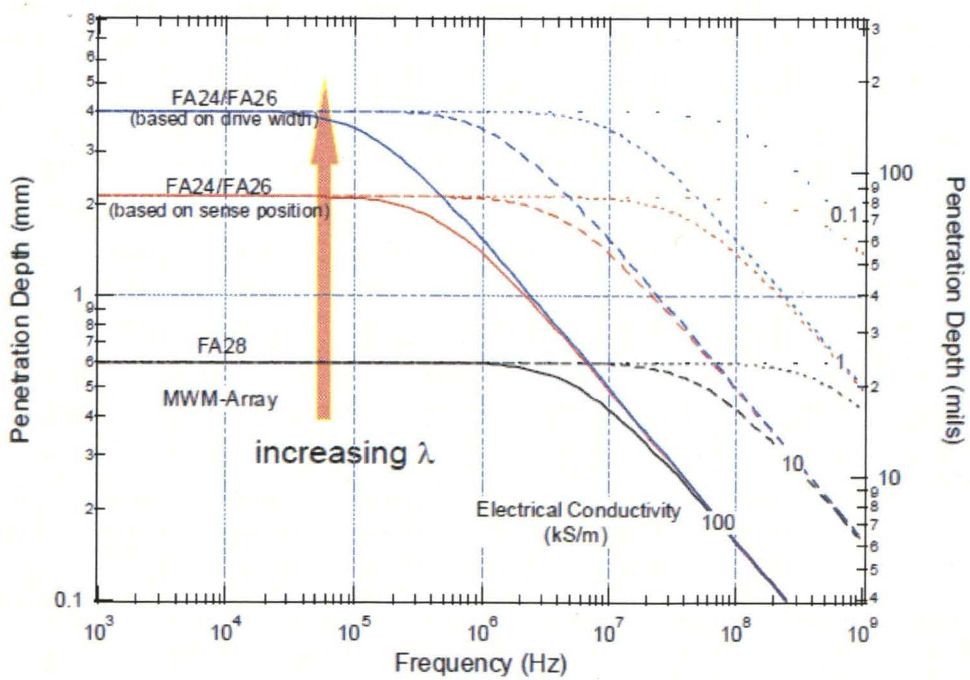


Measurement Grid

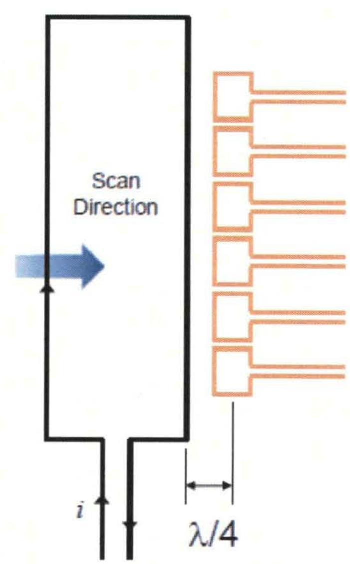


MWM Sensor Selection

- Magnetic field Decays exponentially with distance away from the sensor
  - Decay rate determined by skin depth at higher frequencies and sensor dimensions at lower frequencies
- Higher frequencies needed to induce significant eddy currents
- Large dimensions needed for thick composites



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



Application: Space Shuttle Orbiter RCC Panels

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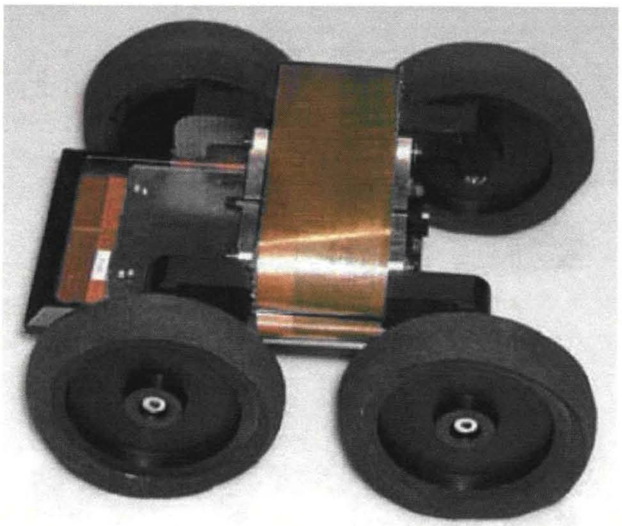
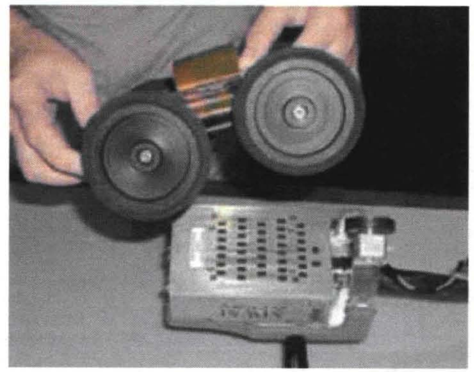
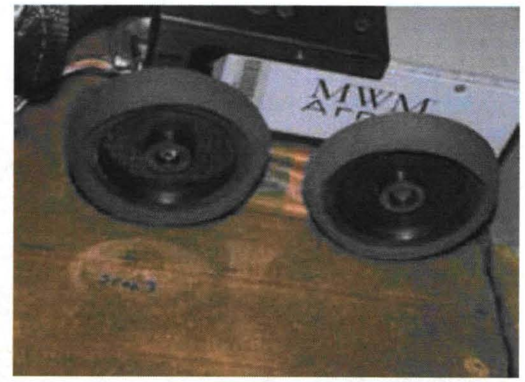
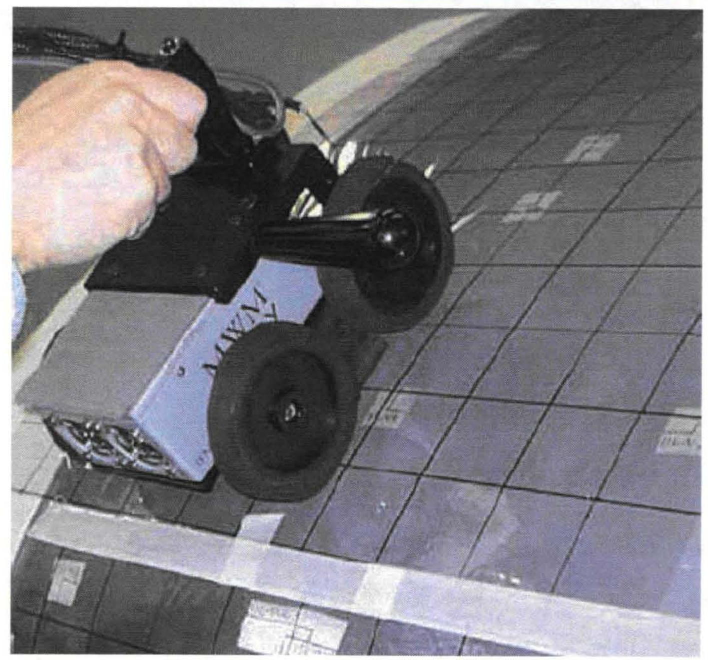


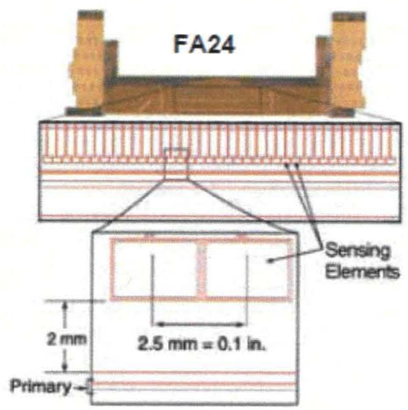






- Foam wheels protect surface
- Manual scanning for complex surfaces
- C-Scan images of wide areas built from multiple passes
- **Adapts automatically to varied curvatures**

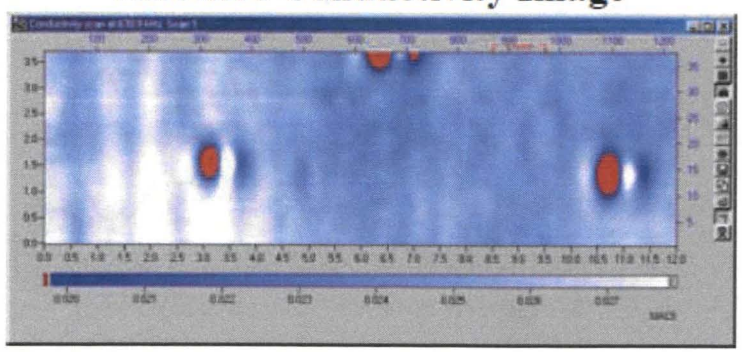
Application: Space Shuttle Orbiter RCC Panels



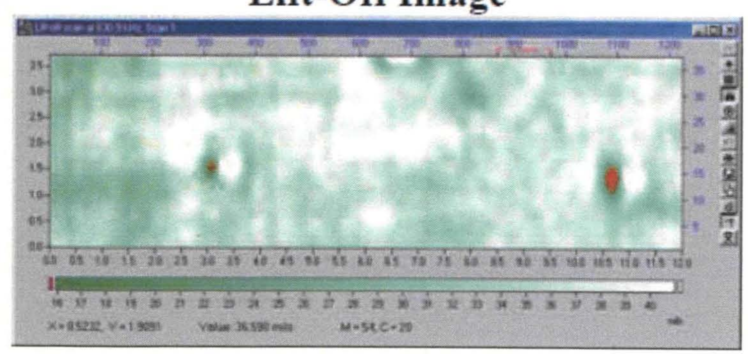
Blind Test RCC Sample Provided by NASA Langley Research Center

- Scan width = 37 sensing elements = 3.7 in.
- Scans performed at 1 in./sec.

Effective Conductivity Image



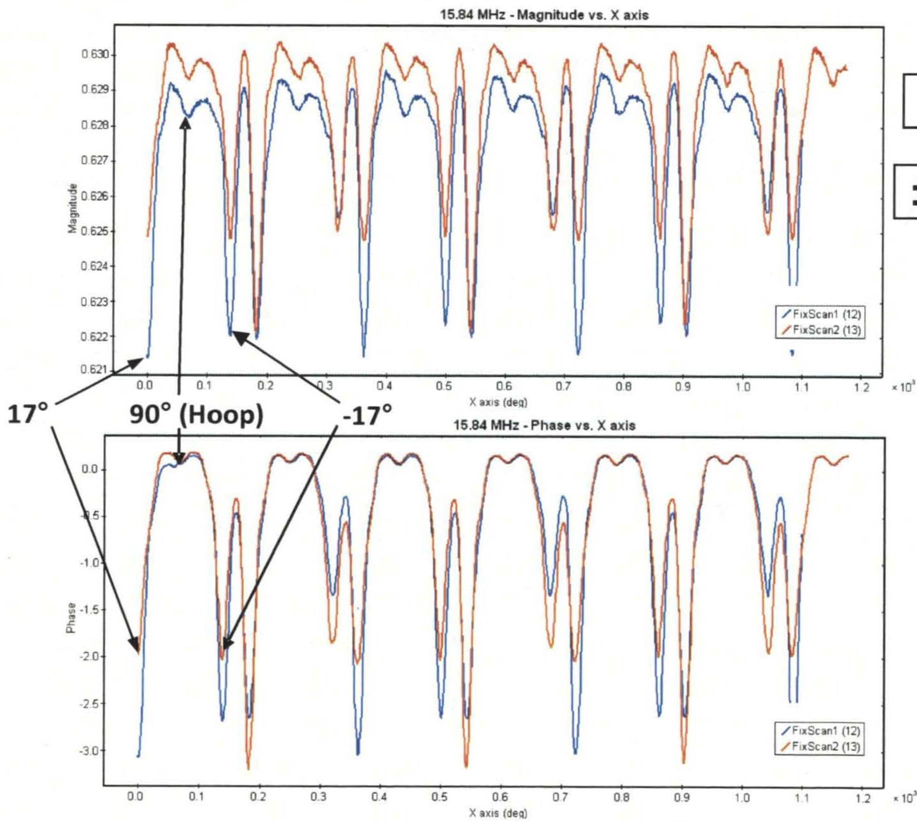
Lift-Off Image

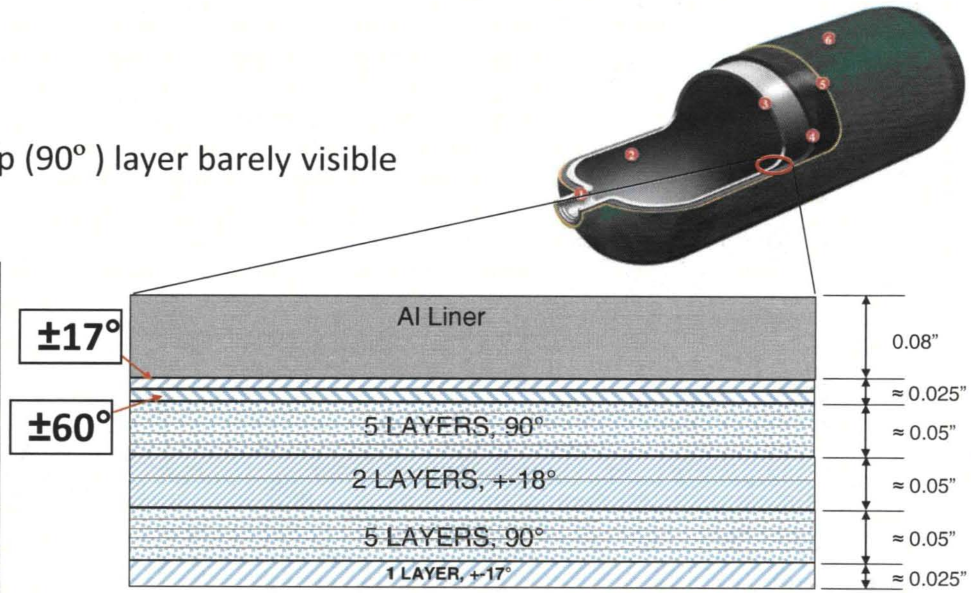


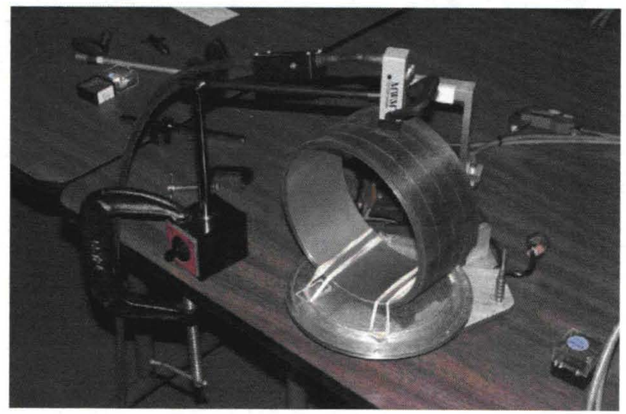
Throughput: 3.7 in. x 12 in. scan in 12 seconds = 3.7 sq. in./sec

COPV Testing – Effect of Fiber Orientation

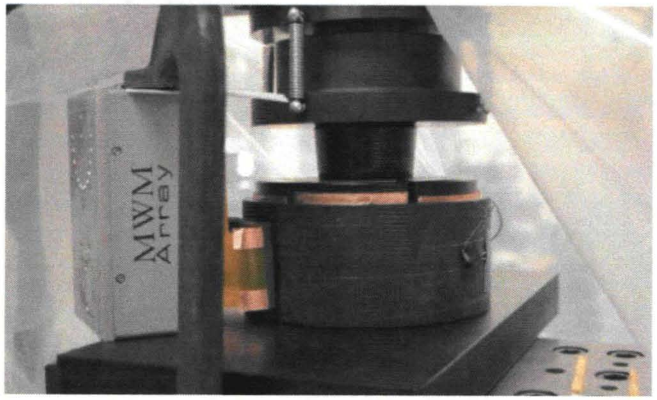
- Multiple fiber orientations in several different layers
- Orientation measurements with FS33
  - 15.8 MHz data indicated
- Limited penetration depth of MWM so outermost hoop (90°) layer barely visible





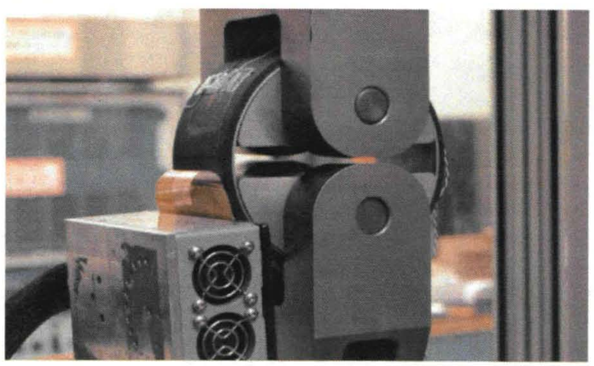


COPV – Health Monitoring Proof of Concept Coupon Testing

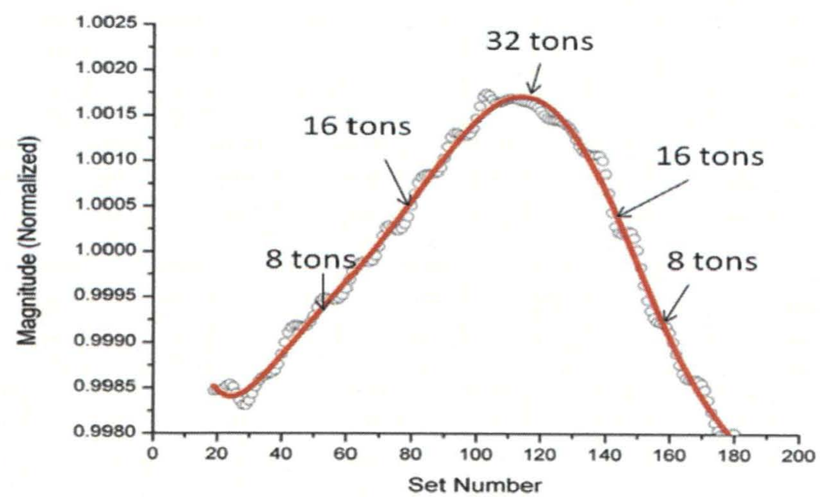


Stresses produced by compressive loading of tapered wedges

- Coupon cut from center section of COPV (~4" wide)
- Two test fixtures designed
- Due to cutting only hoop direction could be measured
- Several different sensor designs and orientations were tested



Stresses produced by tensile loading of specially design test fixture



Example of results from compressive loading of tapered wedges test

COPV – Health Monitoring Proof of Concept Hydrostatic Test

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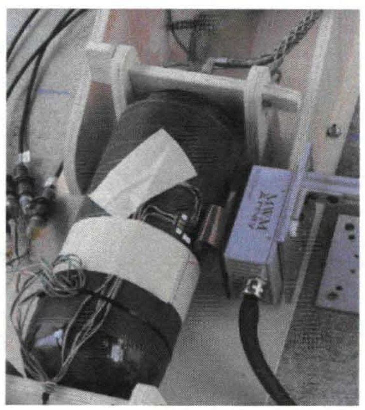
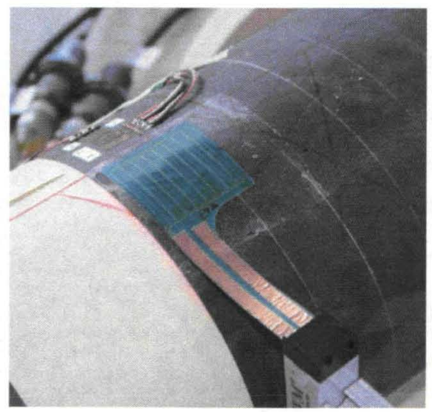
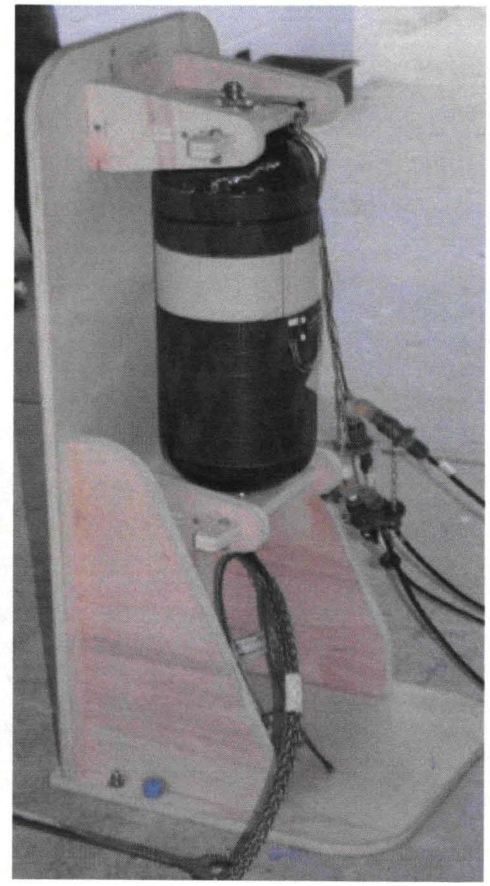
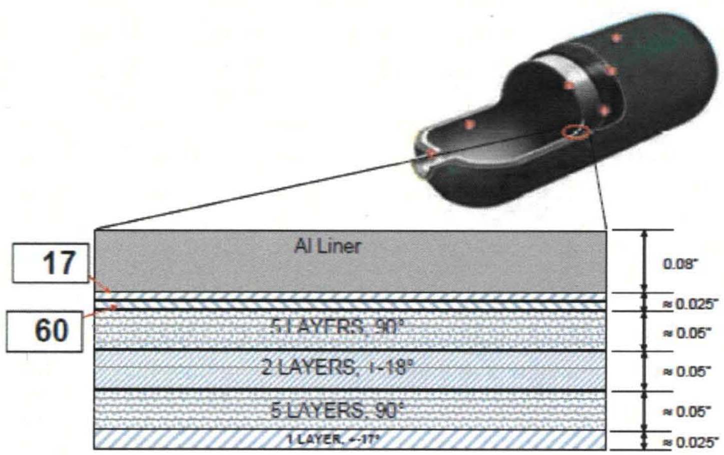
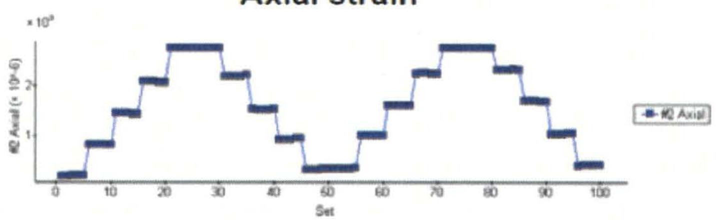
- Full COPV tested hydrostatically at KSC on February 5, 2011
- Vessel cycled to 8,000 psi and back to zero stopping at 2,000 psi increments
  - Pressure chosen to mimic MEOP
  - Estimated design burst pressure of COPV is 16,000 psi
- Based on coupon tests 3 sensor configurations were chosen
  - Different wavelength to obtain various depth of penetration
- Tests were performed with 3 sensor orientations
  - 90º, 60º and 17º to align sensor drive with fiber orientations

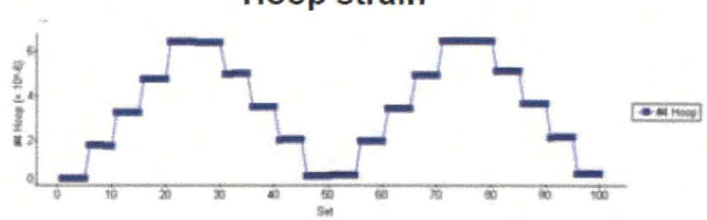
COPV – Health Monitoring Proof of Concept Hydrostatic Test

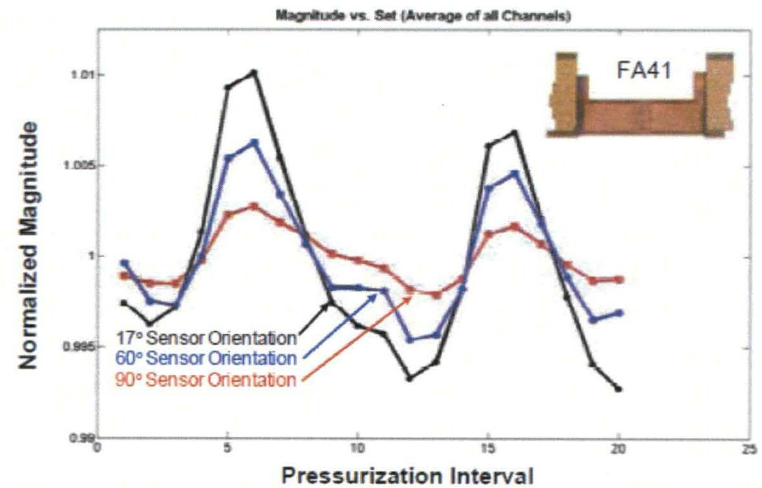


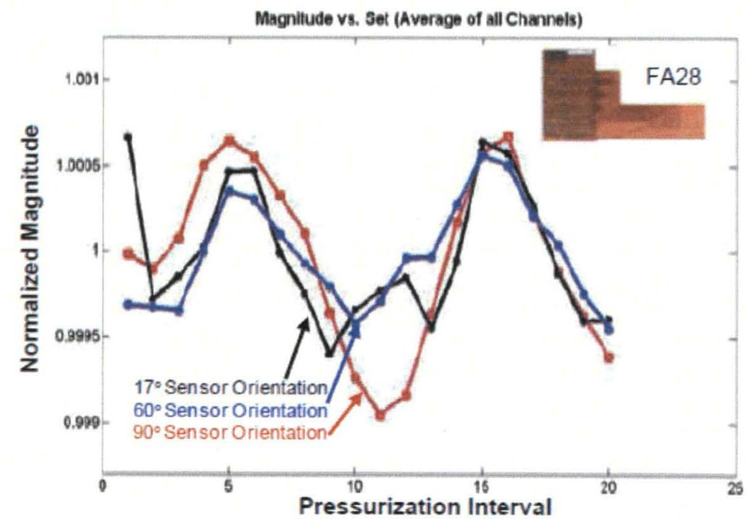
Axial strain



Hoop strain

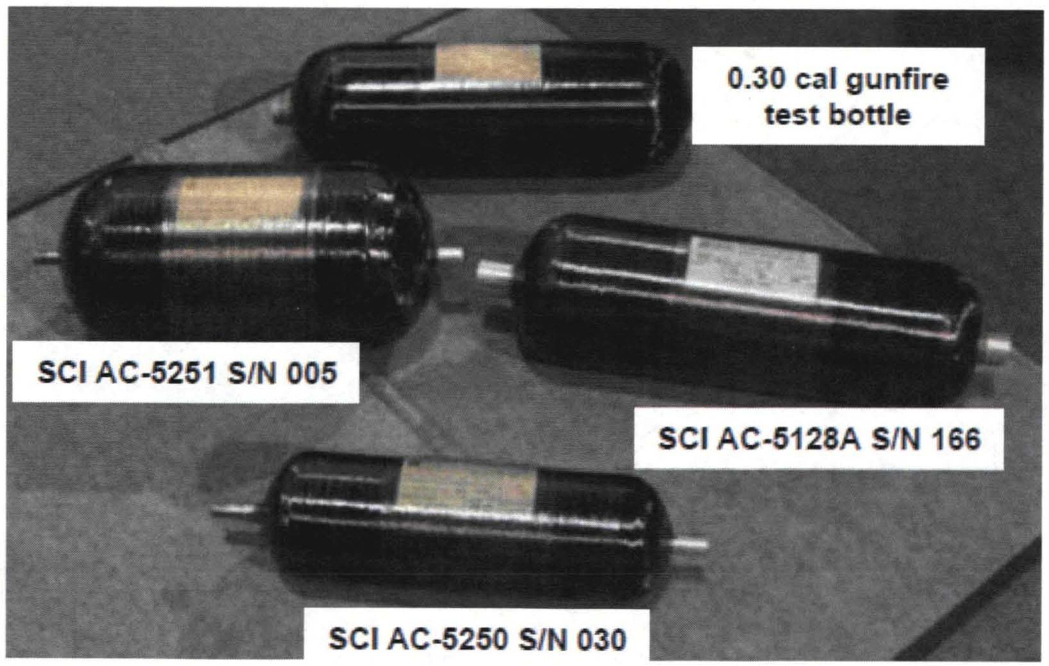




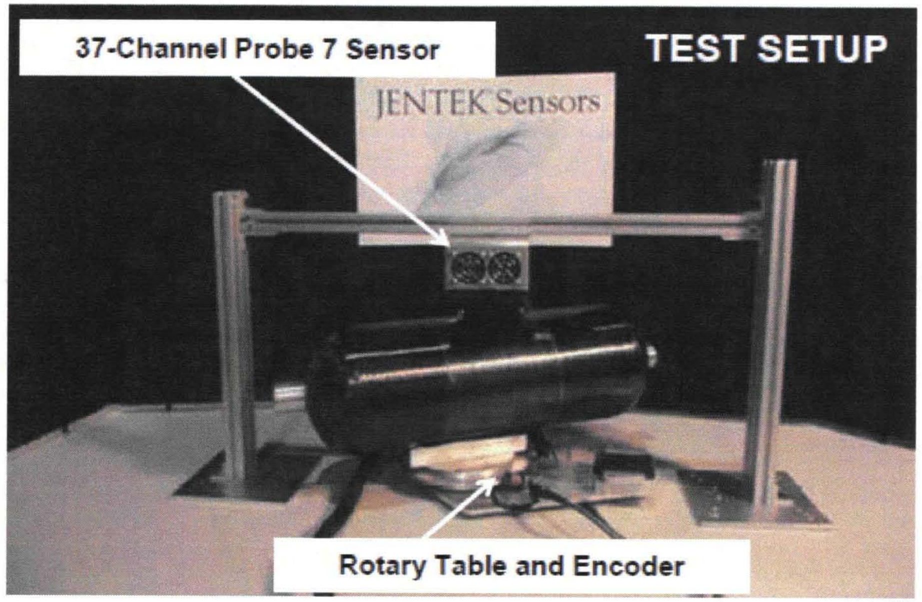


COPV NDE

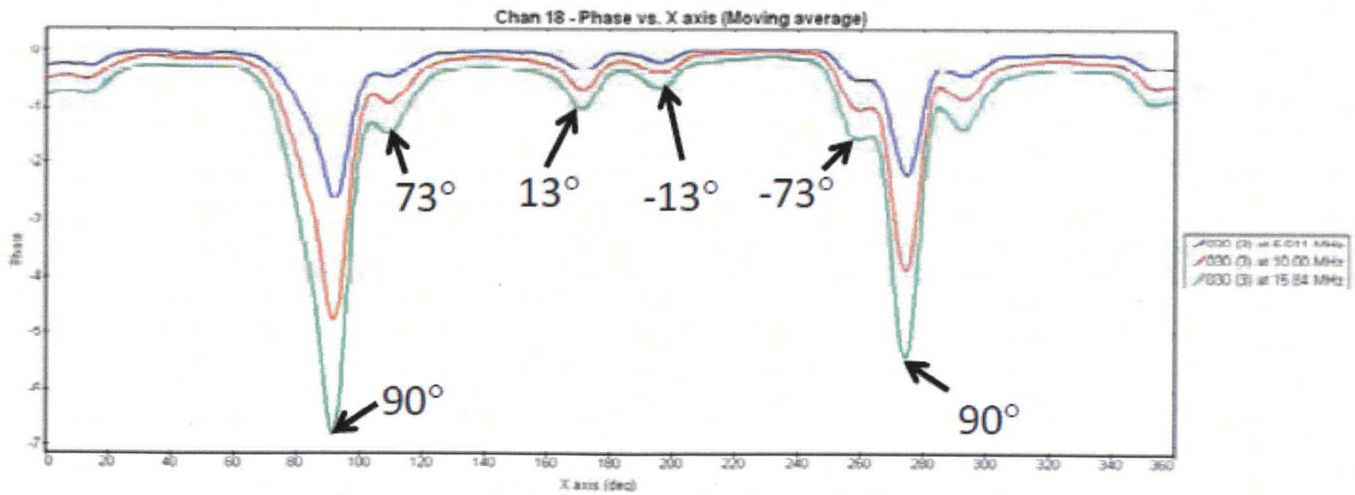
- Four COPVs selected from NASA White Sands inventory
- Scanned via MWM before and after impact testing



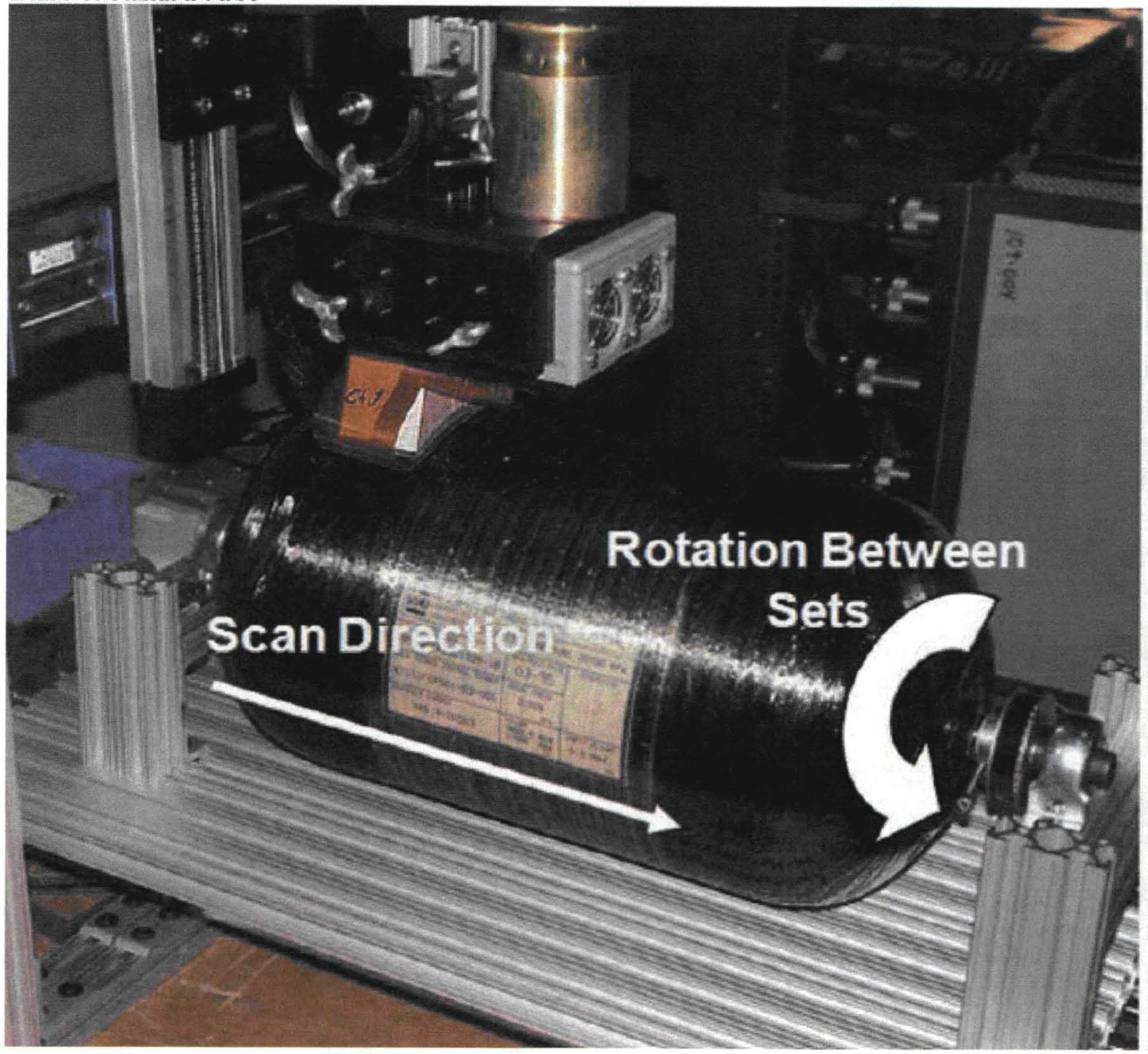
Rotation Scans

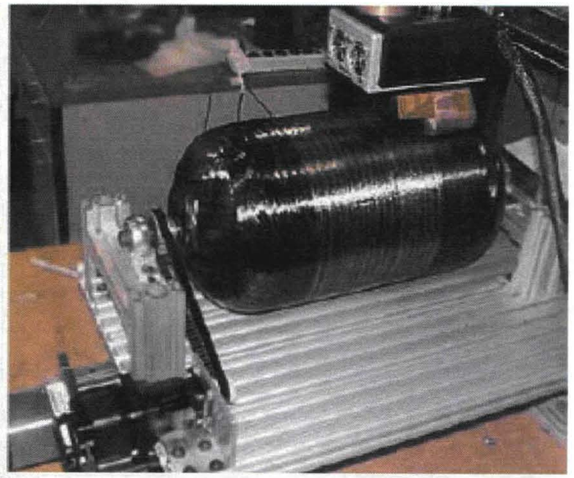


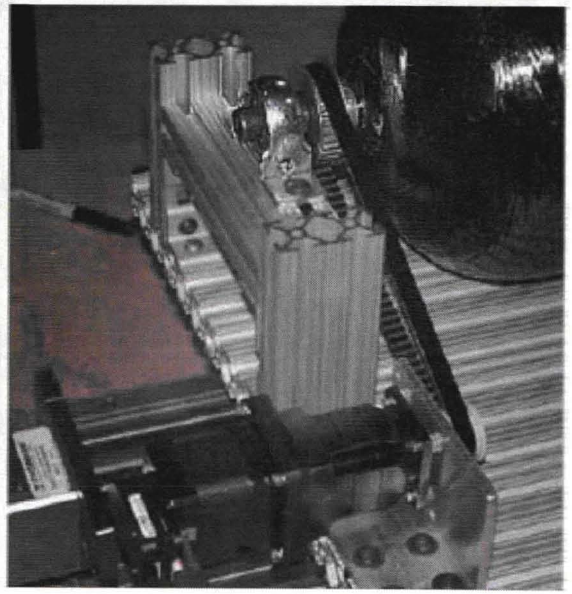
FA28 MWM-Array Scan



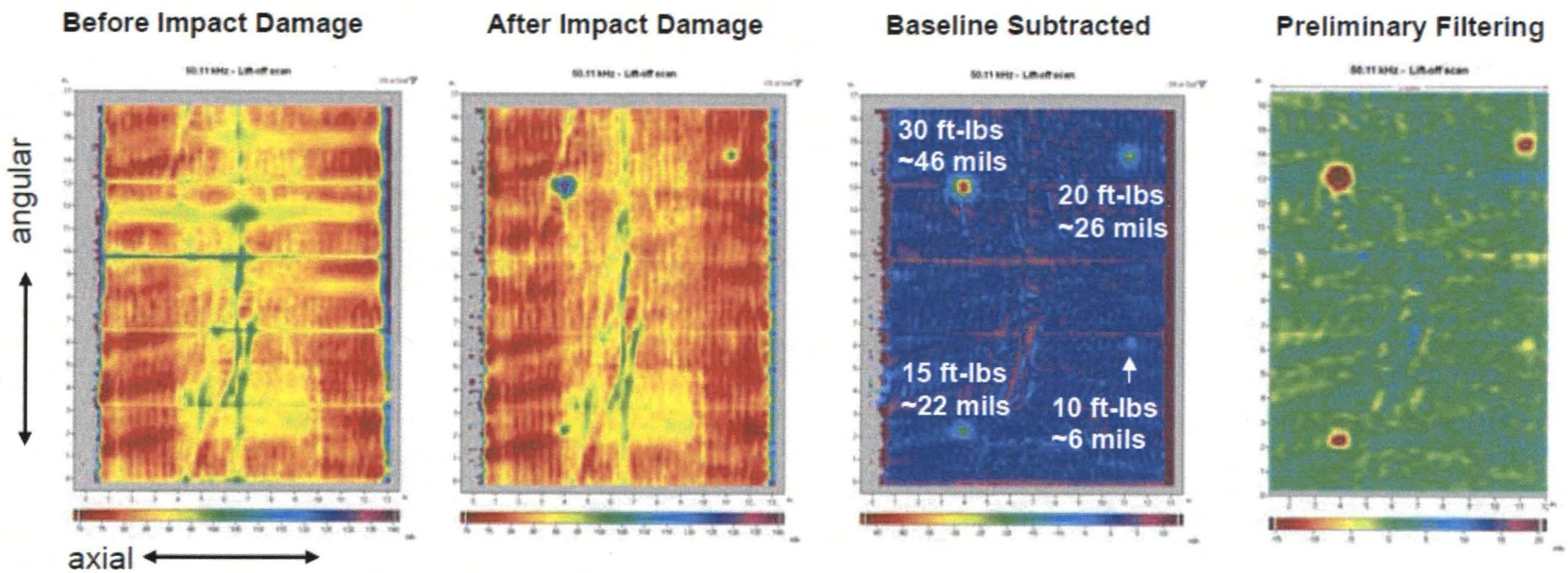
Test setup for hoop oriented fibers





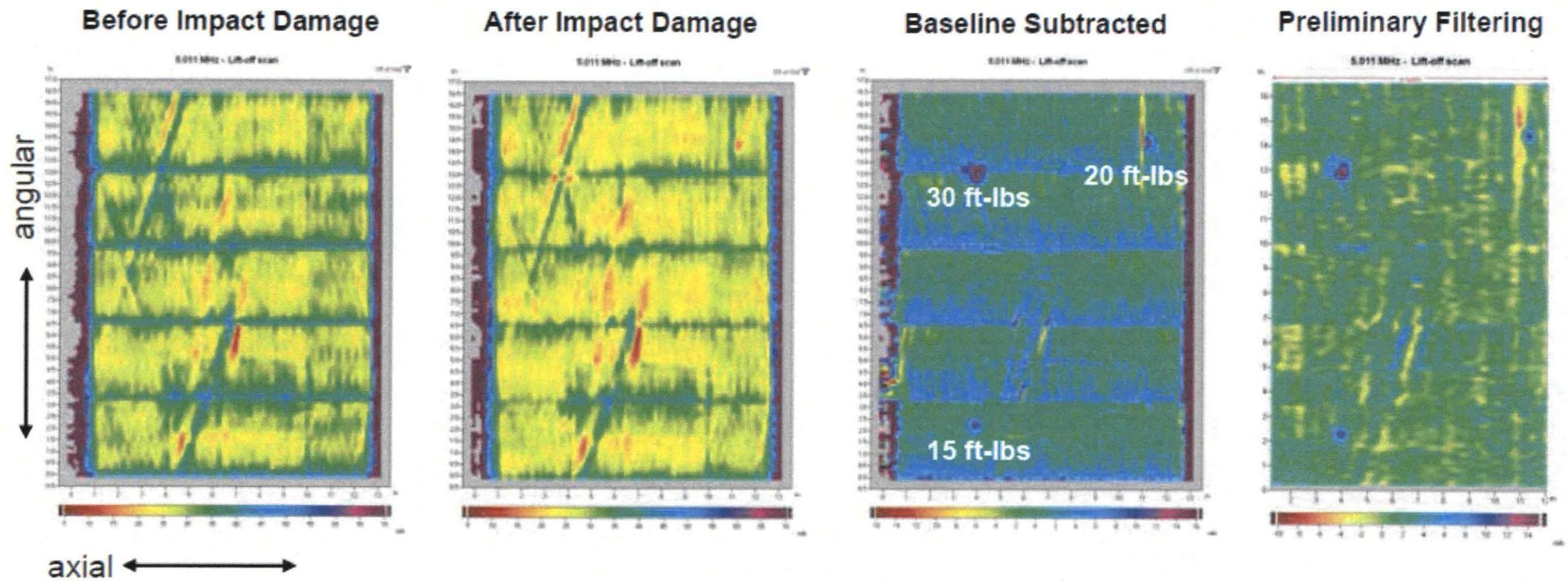


Lift-Off Image Low Frequency



- Sample AC5250-030; 90° Sensor drive orientation
- Higher impact energy results in larger dents in the aluminum liner
- Sensor: MWM-Array FA24
- 50.11 kHz

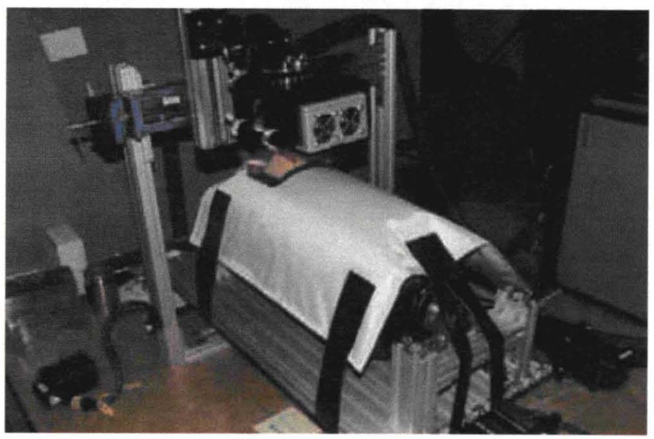
Lift-Off Image High Frequency



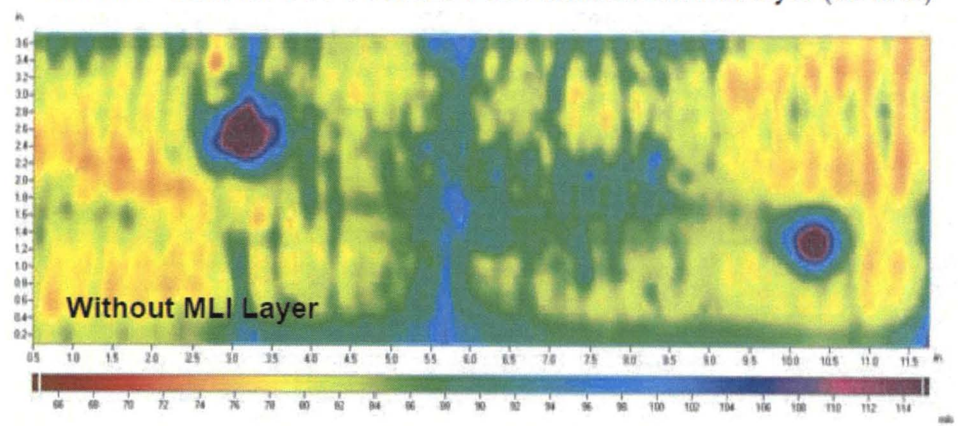
- Sample AC5250-030; 90° Sensor drive orientation
- Sensor: MWM-Array FA24
- 5.011 MHz

Scan of COPV with Insulation Blanket

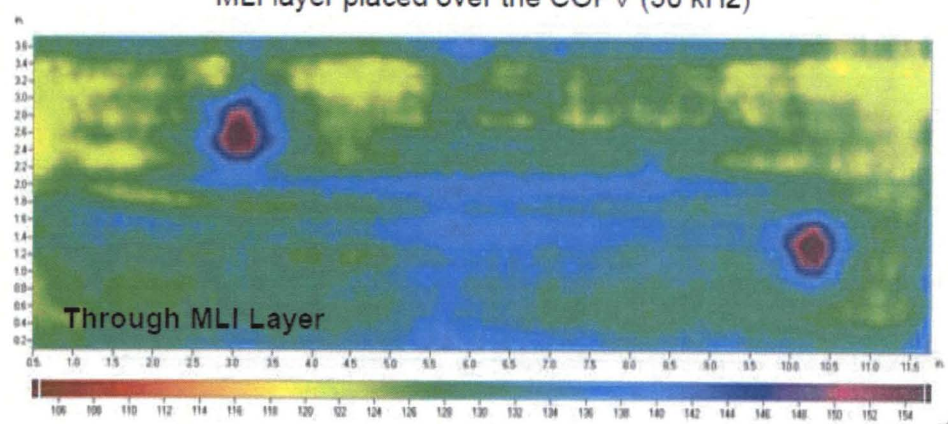
Test Setup



Lift-off C-scan for COPV AC5251-005 **without** an MLI layer (50 kHz)

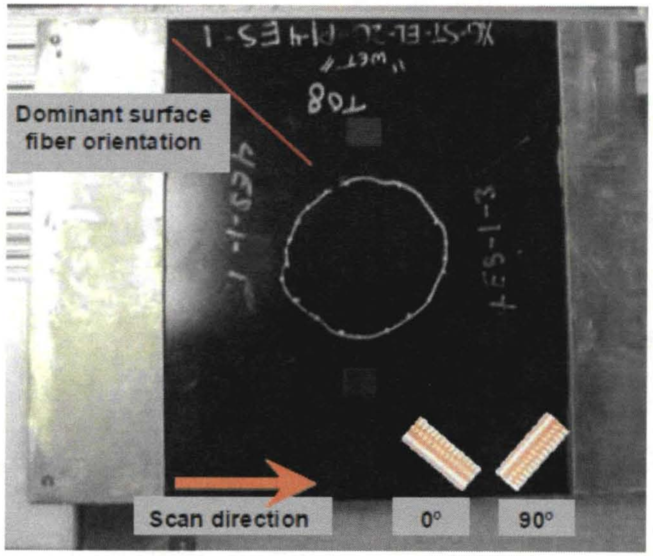


Lift-off C-scan for COPV AC5251-005 **with** a conductive MLI layer placed over the COPV (50 kHz)



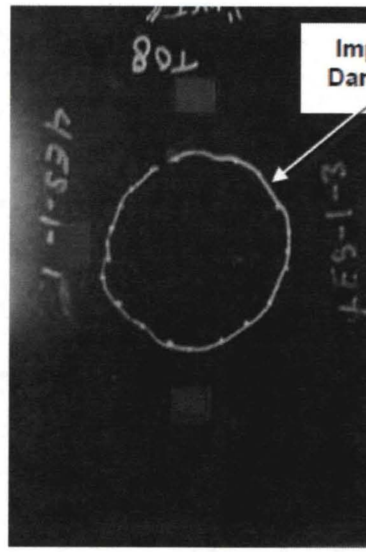
Composite Structure Impact Damage Detection

Composite Specimen with Impact Damage on Scanning Bed

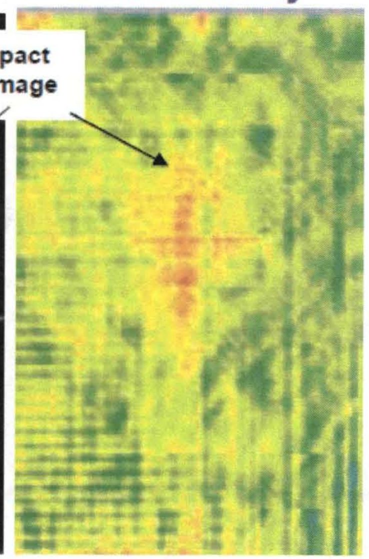


Specimen provided by Lockheed Martin

Sample

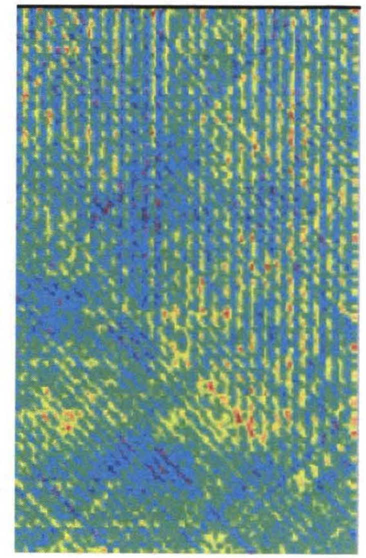


Conductivity



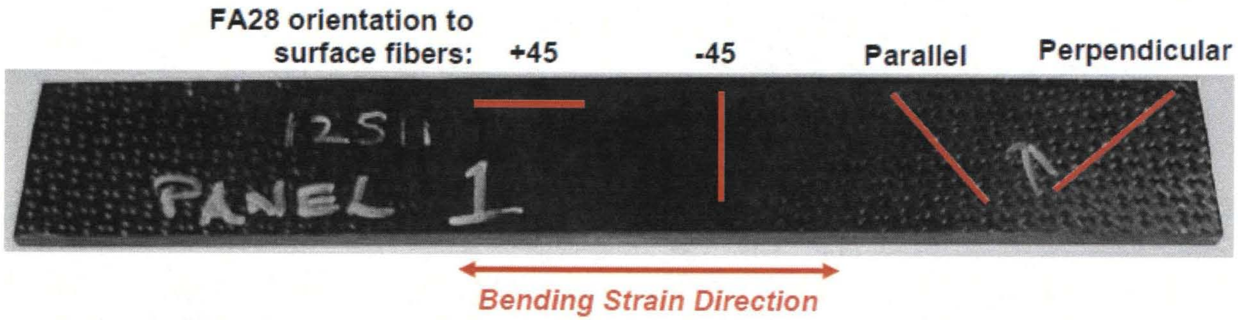
15.84MHz image taken with scanning MWM-Array for effective conductivity

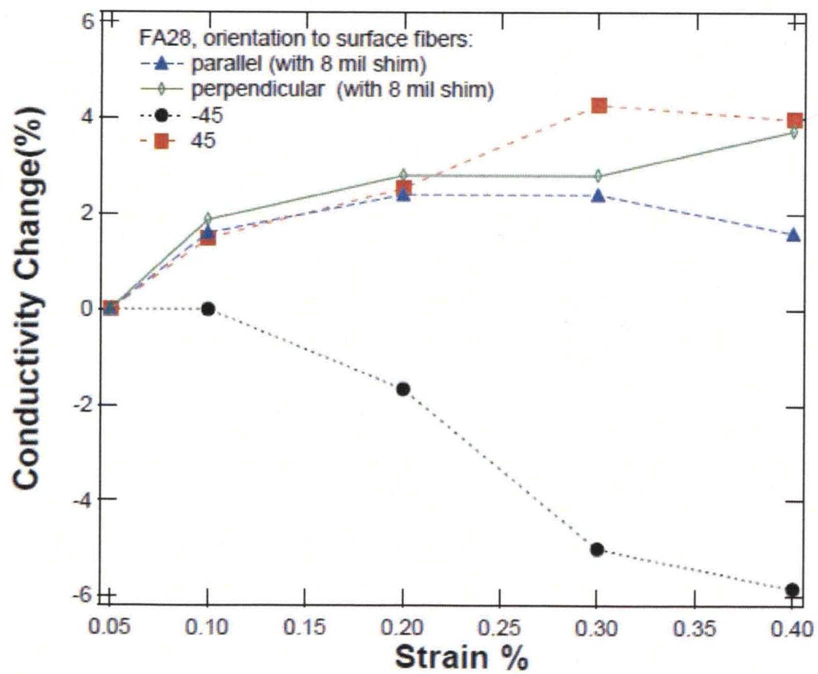
Proximity



MWM-Array image of proximity to first fiber layer

Composite Property Variation with Stress

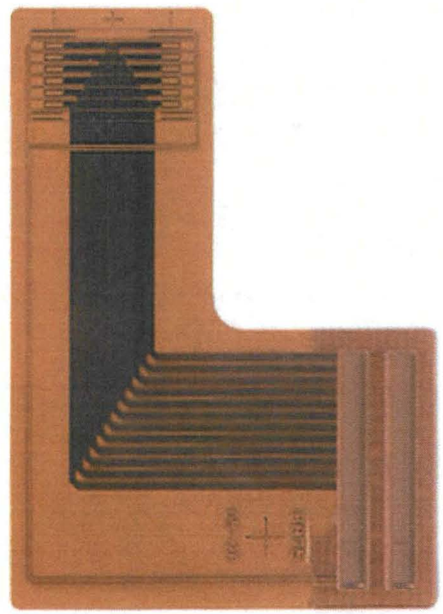




Development of a High Temperature MWM Array Sensor

- Designed for continuous use at 1000° C by proper selection of high temperature materials.
- Ceramic substrate and high-temperature metal deposited conductive winding constructs.
- Prototype 7-channel MWM-Array sensor built and tested at 850° C with no degradation observed.
- Demonstrated crack detection with prototype high temperature sensor.
- High temperature cabling issues require further development

Room Temperature MWM-Array Sensor



High Temperature MWM-Array Sensor