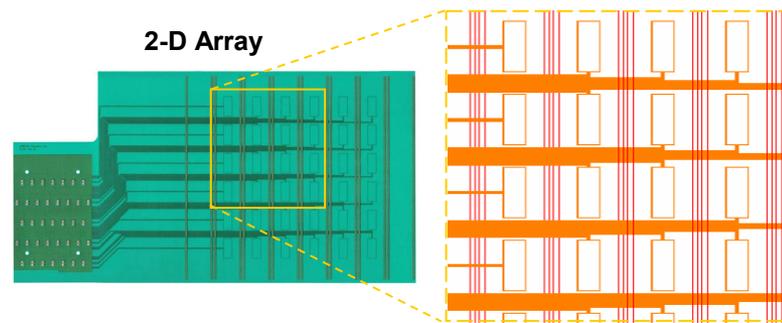
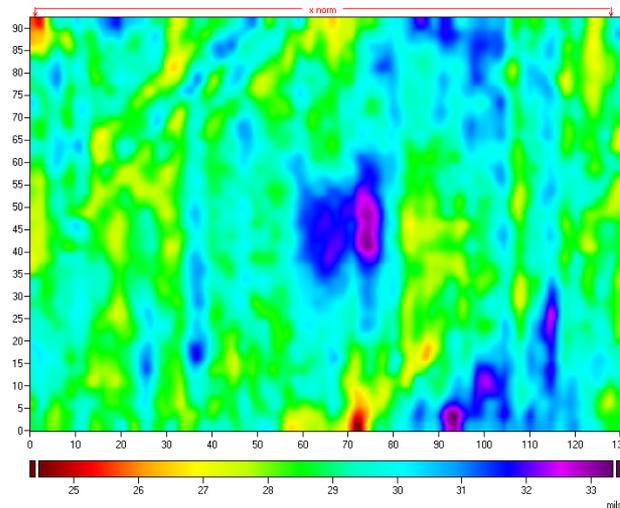


Magneto-Thermography and Temperature Measurement using MWM-Arrays

November 15, 2007

JENTEK Sensors, Inc.
Waltham, MA 02453
Phone: 781-642-9666
Email: jentek@shore.net

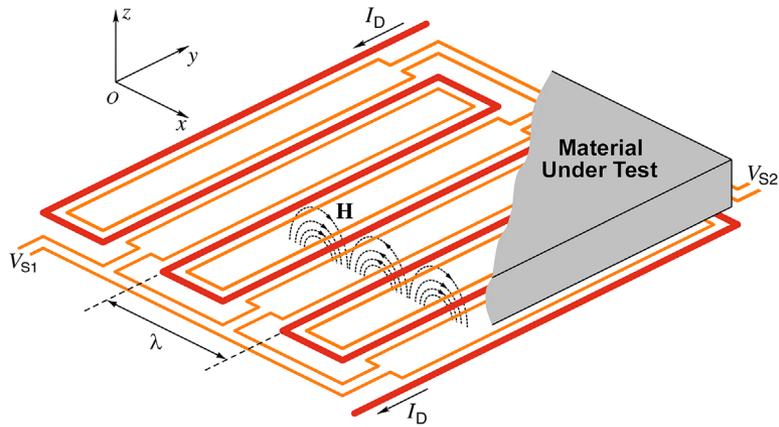


Outline

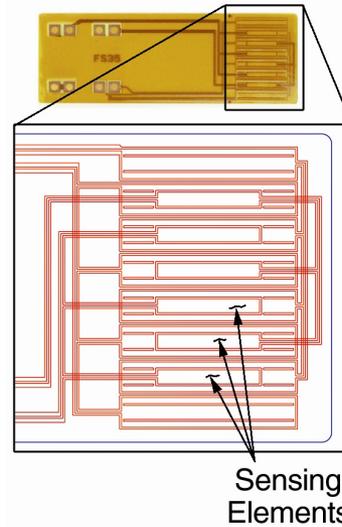
- **Background**
 - Magnetoquasistatic (MWM[®]-Array) sensing
 - Measurement grid methods
- Magneto-Thermography Method
- Applications
 - Through-wall temperature monitoring
 - Missing adhesive in lapjoint
 - Graphite/Epoxy composites
 - Simulation results
- Summary

MWM[®] and MWM-Array Eddy Current Sensors

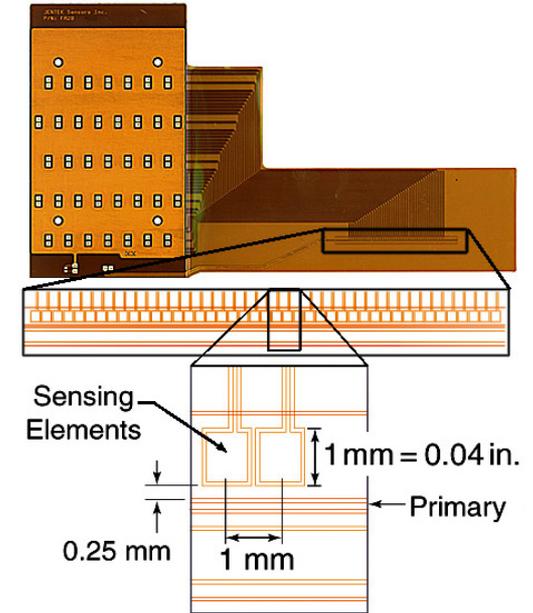
Schematic diagram of an MWM Sensor



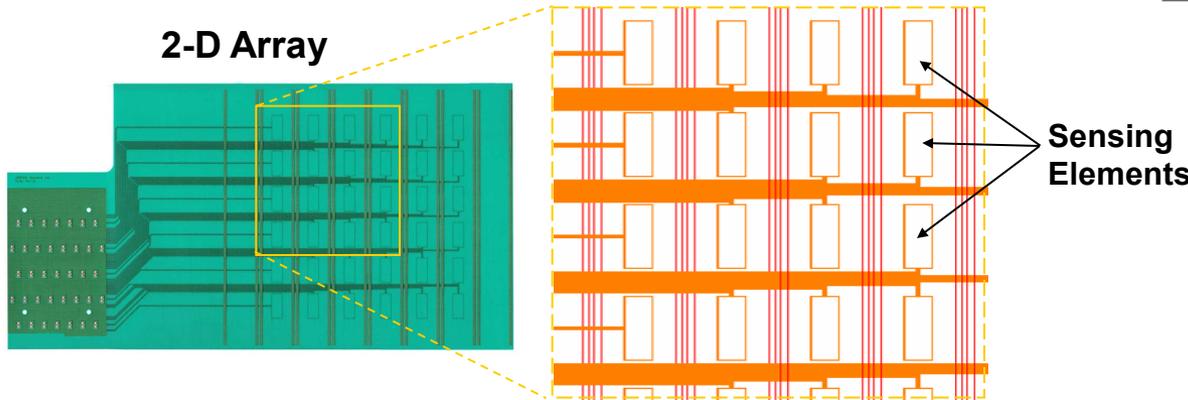
Single-channel MWM sensor FS35



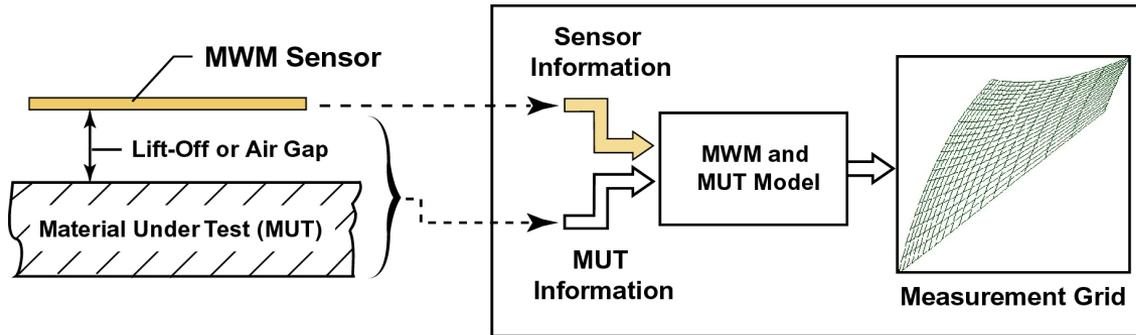
Multiple channel MWM-Array sensor FA28



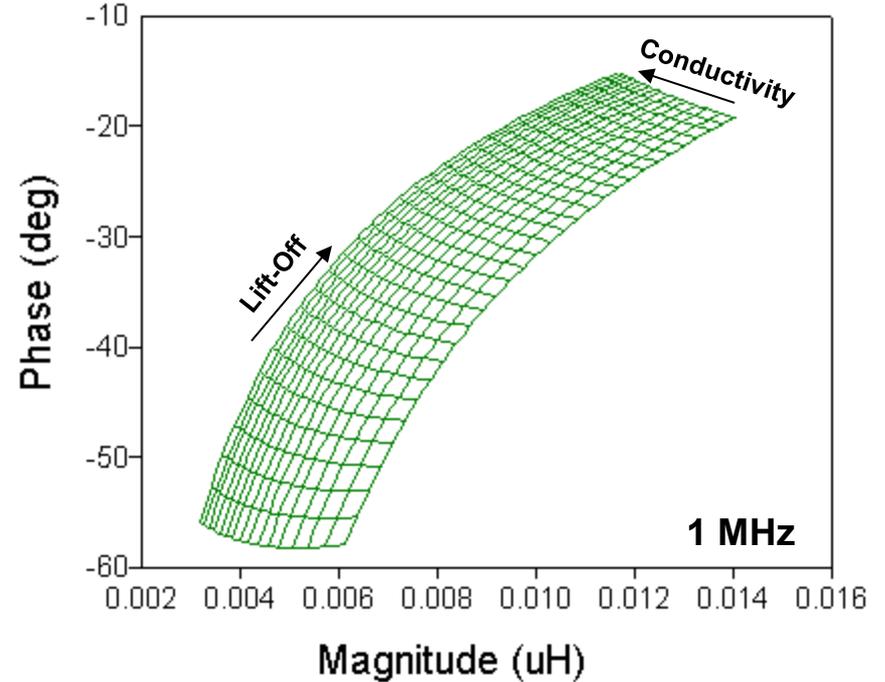
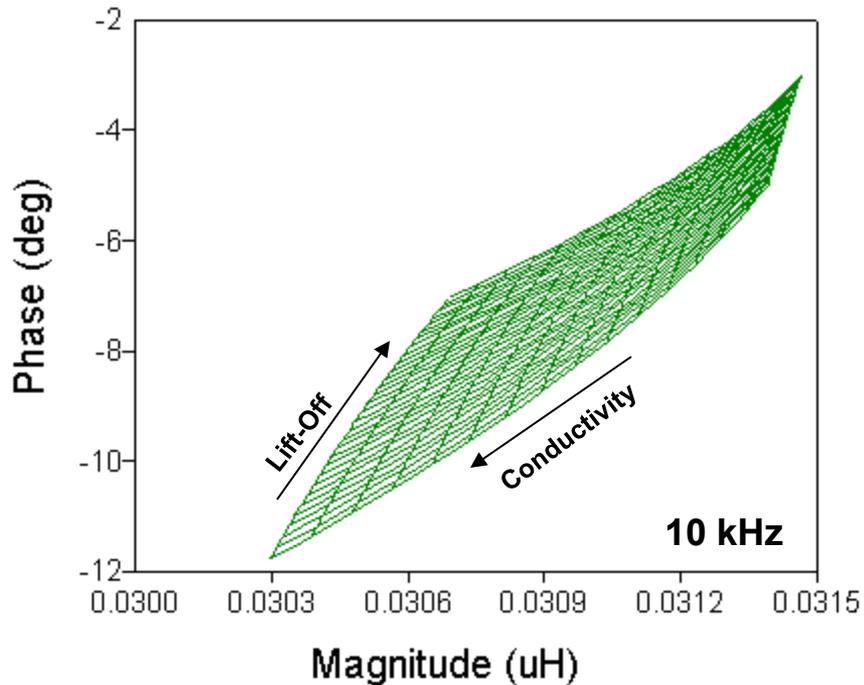
2-D Array



Conductivity / Lift-off Measurement Grids



Example Grids for the MWM-FS35 Sensor and Aluminum



Outline

- **Background**
 - Magnetoquasistatic (MWM[®]-Array) sensing
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New Magneto-Thermography Method

(Patents pending)

- Monitor subsurface temperatures and temperatures at buried interfaces
- Reduced cost and improved portability over IR cameras
- Capability to inspect thicker structures, up to 0.75 in. or more, with higher sensitivity than conventional thermography
- Capability to inspect curved and complex structures
- Capability to measure temperatures at different depths by varying frequencies
- Capability to inspect through air gaps and coatings, for multi-layered structures

Representative Applications

- Magneto-thermography suitable when at least one material is conducting (e.g., graphite fiber composites)
- Approaches incorporating magneto-thermography
 - Hybrid (MWM with conventional thermography)
 - Combination has value in specifying damage type
 - e.g., MWM responds to fiber damage but thermography responds to fiber and composite. If seen in thermography but not MWM, then composite and not fiber damage
 - Surface mounted or embedded MWM sensing
 - Monitoring of material condition with “normal” thermal exposures
 - Perforated sensor designs may enable embedding in adhesive layers
 - Scanning sensor applications
 - complex curvature areas or areas inaccessible to conventional methods
e.g., engine cowlings

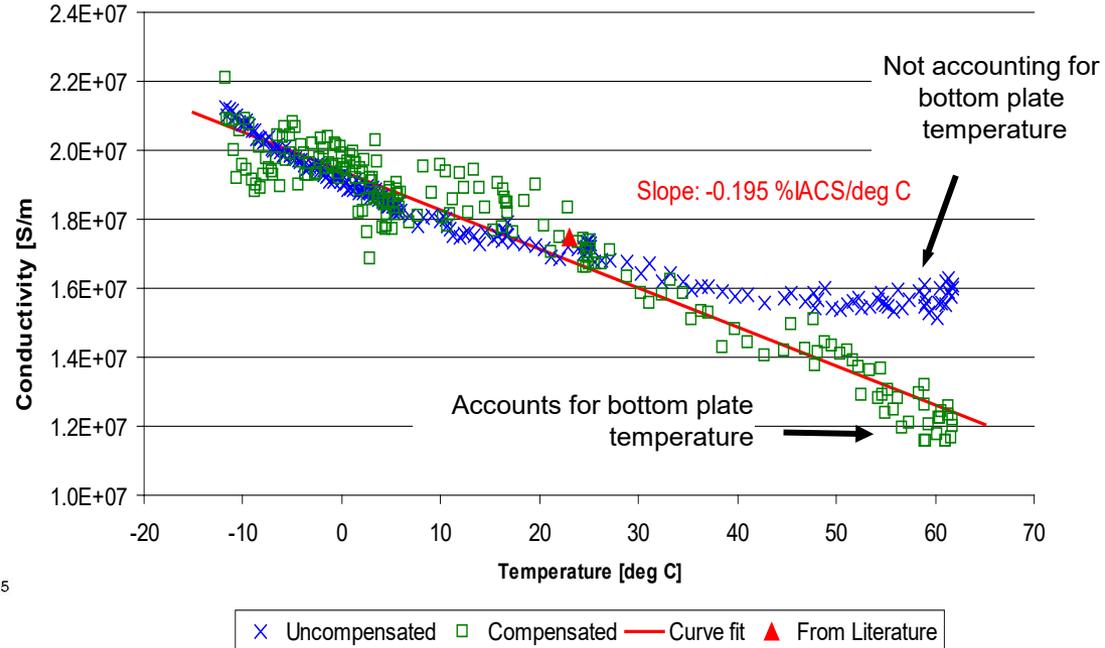
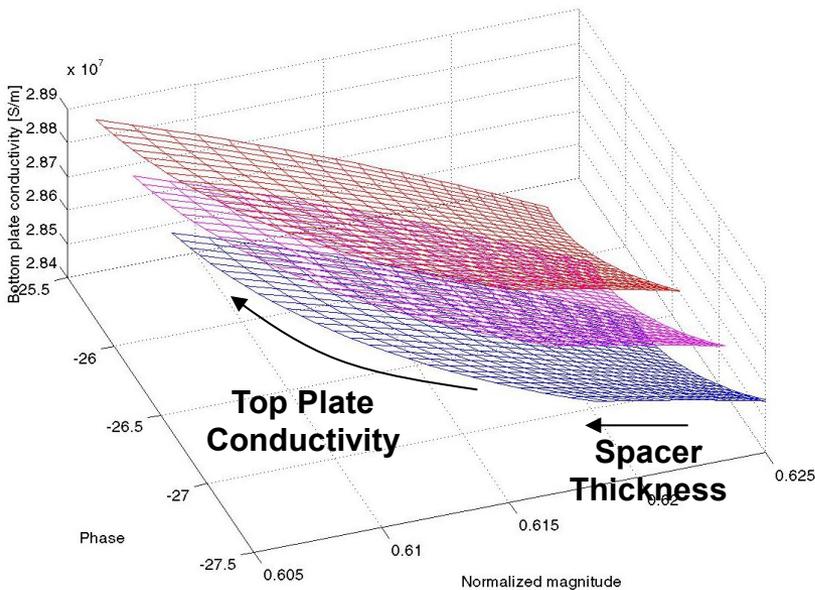
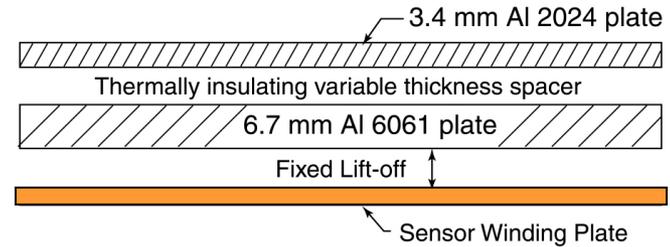
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Through-Wall Temperature Monitoring

Need: Non-invasive through-wall temperature measurement at inaccessible locations

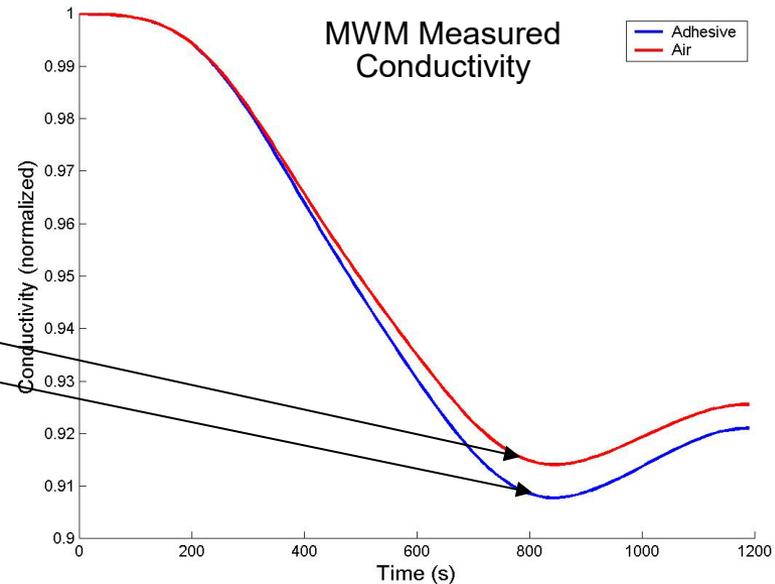
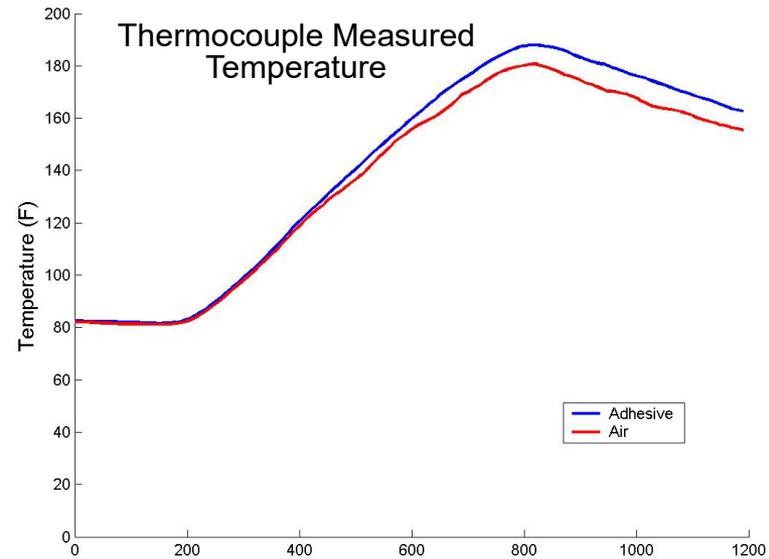
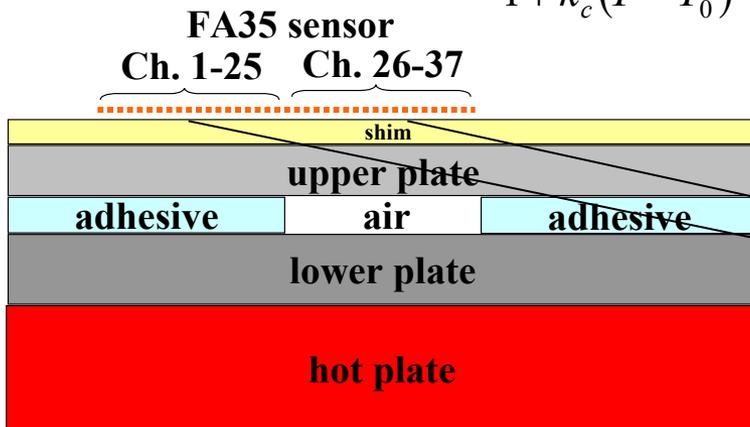
ONLY Known Solution for this Problem



Missing Adhesive in a Lap Joint

- Surface mounted sensor
- Monitored conductivity of top metal layer in lap joint over areas with and without adhesive
- Through-transmission heating test
 - Thermal conduction is different between areas with and without adhesive, leads to temperature gradient on the top plate
 - Metal conductivity varies with temperature:

$$\sigma = \frac{\sigma_0}{1 + k_c(T - T_0)}$$

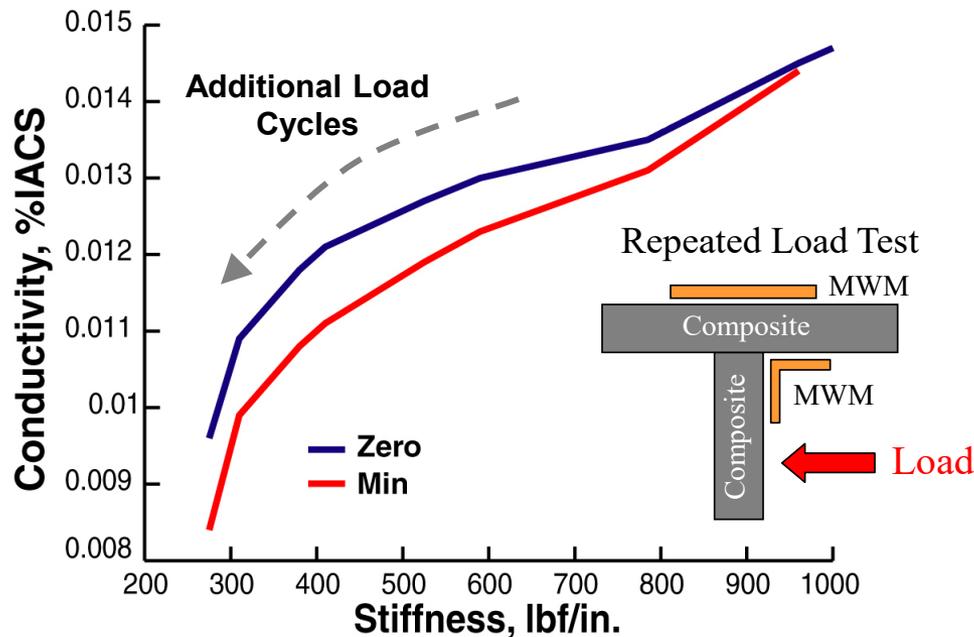
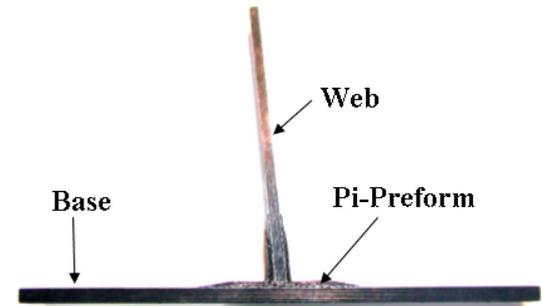
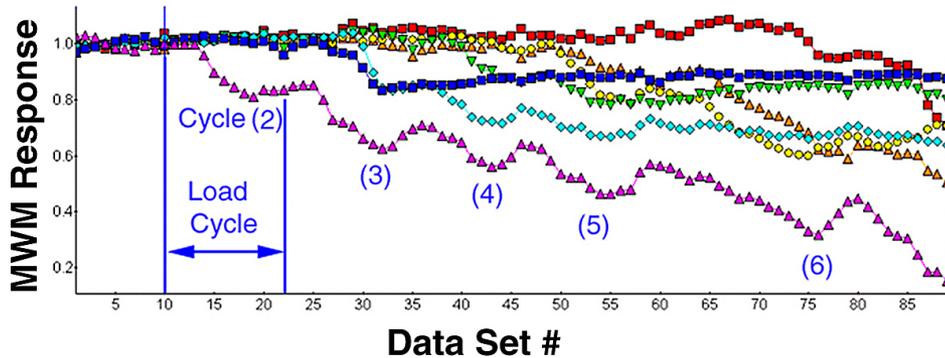


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Composite Disbond Growth Monitoring

- Graphite fiber composite joint damage monitoring
- MWM-Arrays mounted on both sides of the joint

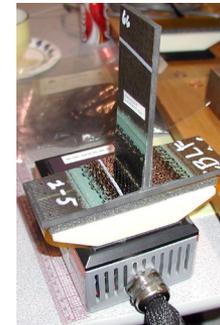


FA24 Sensor
Element Locations

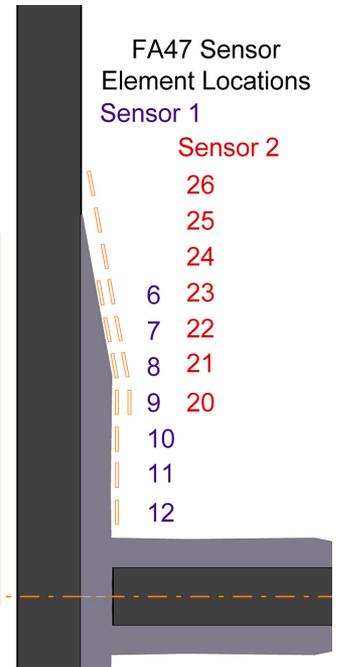
FA47 Sensor
Element Locations
Sensor 1

Sensor 2

- 26
- 25
- 24
- 23
- 22
- 21
- 20

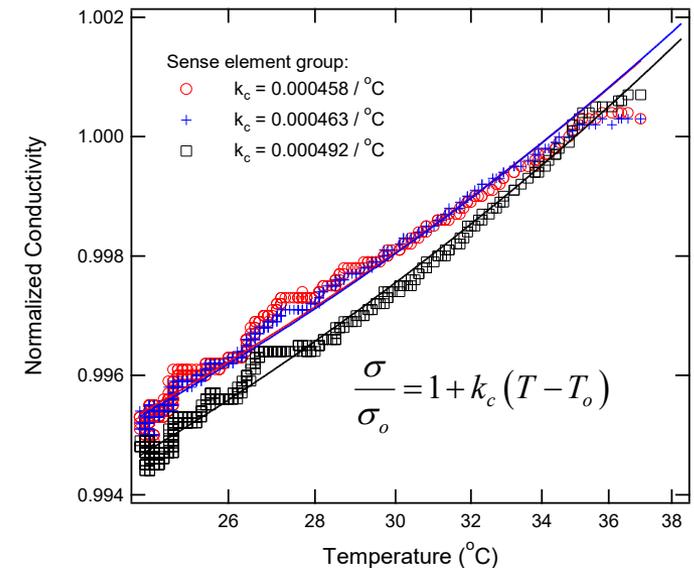
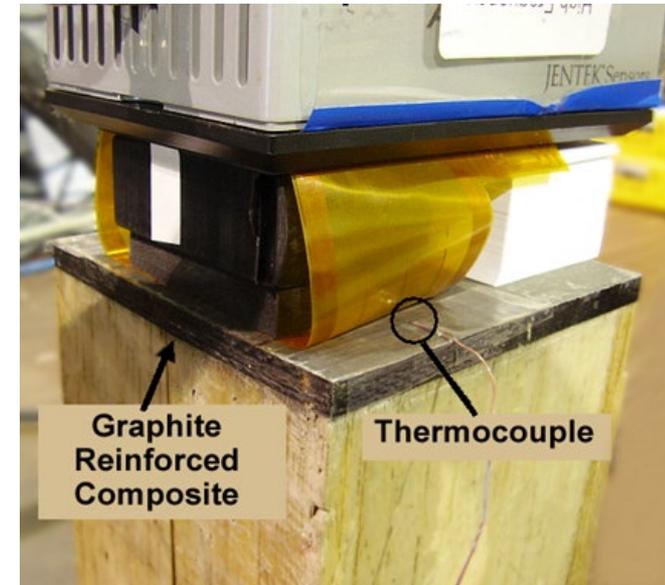
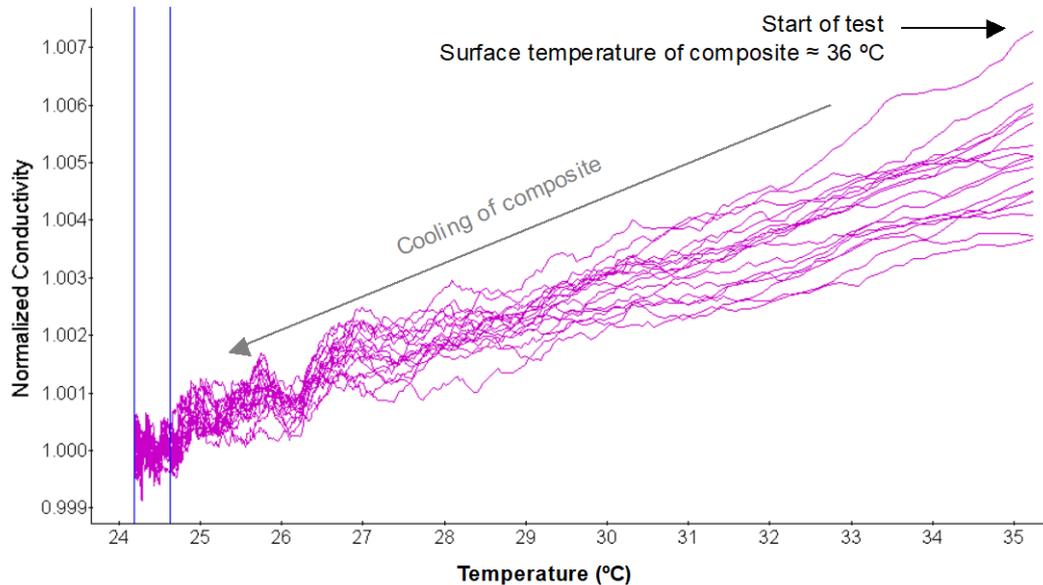


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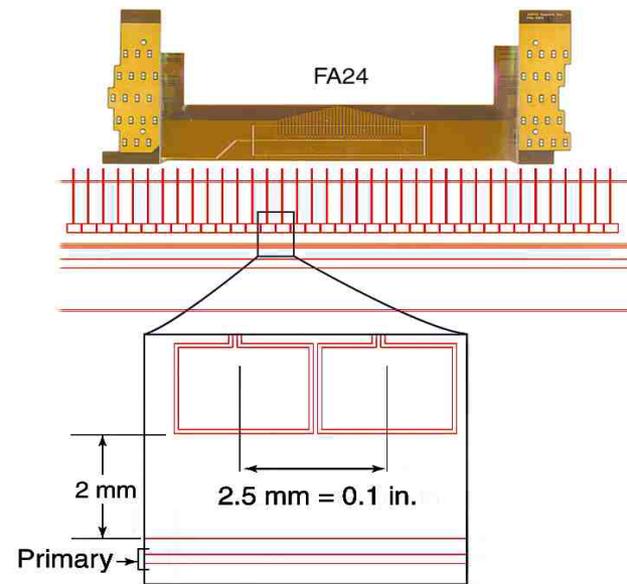
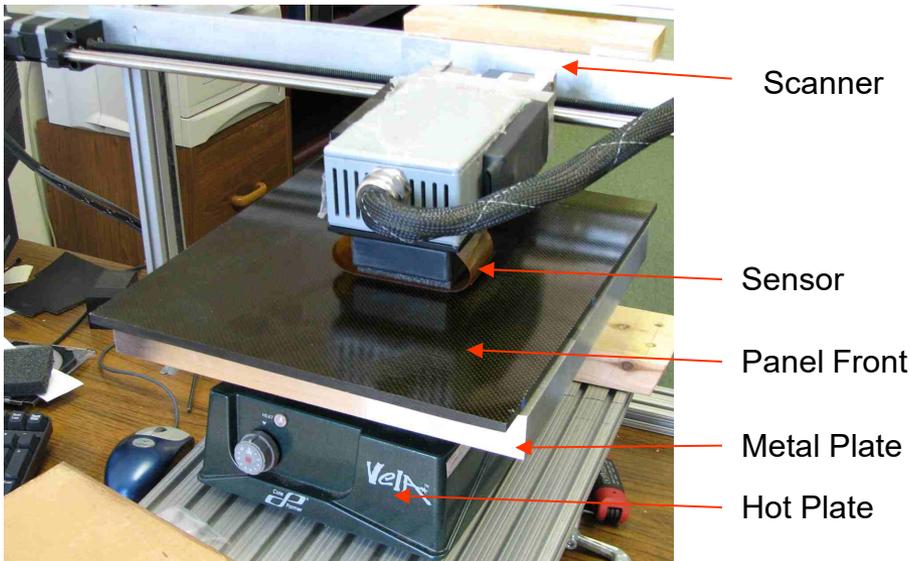
Composite Fiber Temperature Monitoring

- MWM-Array placed against surface of graphite fiber composite
- MWM-Array measured electrical conductivity varies with the temperature of the composite
 - Fibers are electrically conducting and the fiber properties are being monitored
- Indicates basic feasibility for the magneto-thermal approach



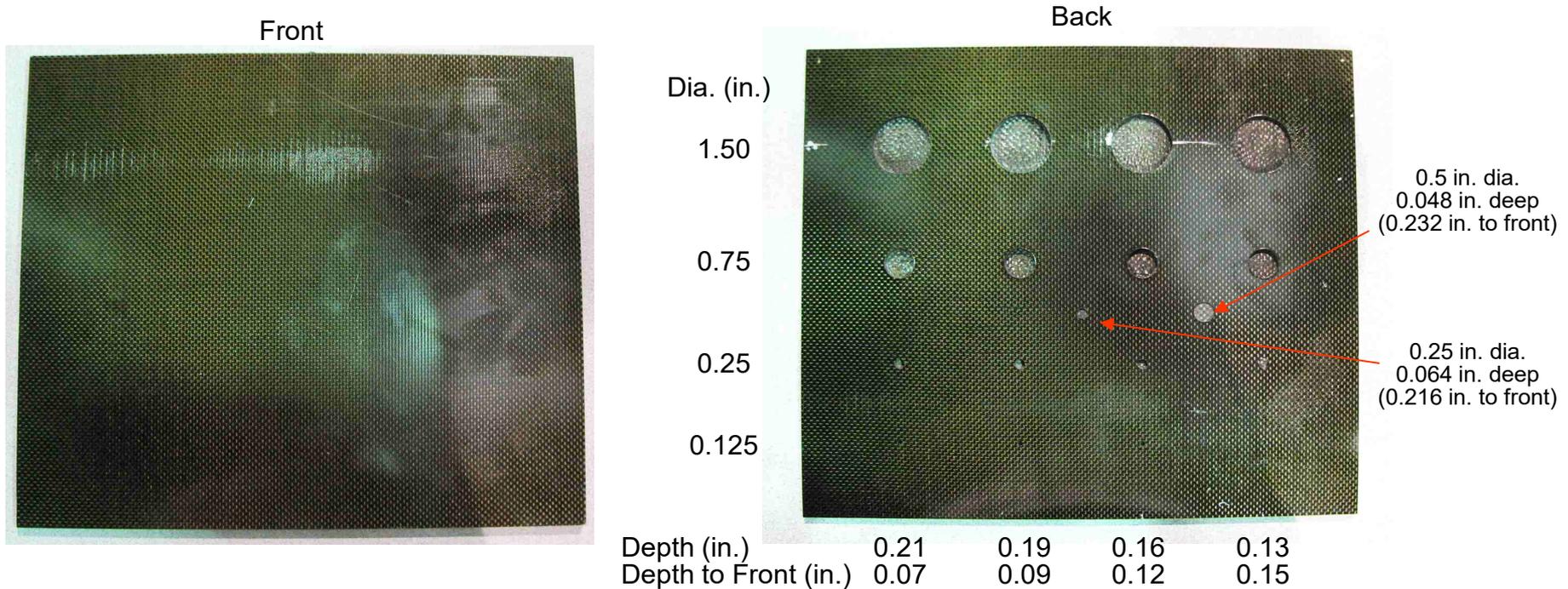
Basic Measurement Apparatus

- MWM-Array scanned used to scan over the front surface
 - Scan width of approximately 3 inches with 37 sense elements
- MWM-Array mounted in automated scanner
 - Allows mapping of wide areas and permits repeated measurements at same location
- Through-transmission heating responses obtained
 - Panel placed on hot plate
 - Intermediate (thick) metal layer to help provide uniform heating of composite
 - Other heating mechanisms (resistive, inductive, flash) also possible
 - Temperature measured with thermocouples



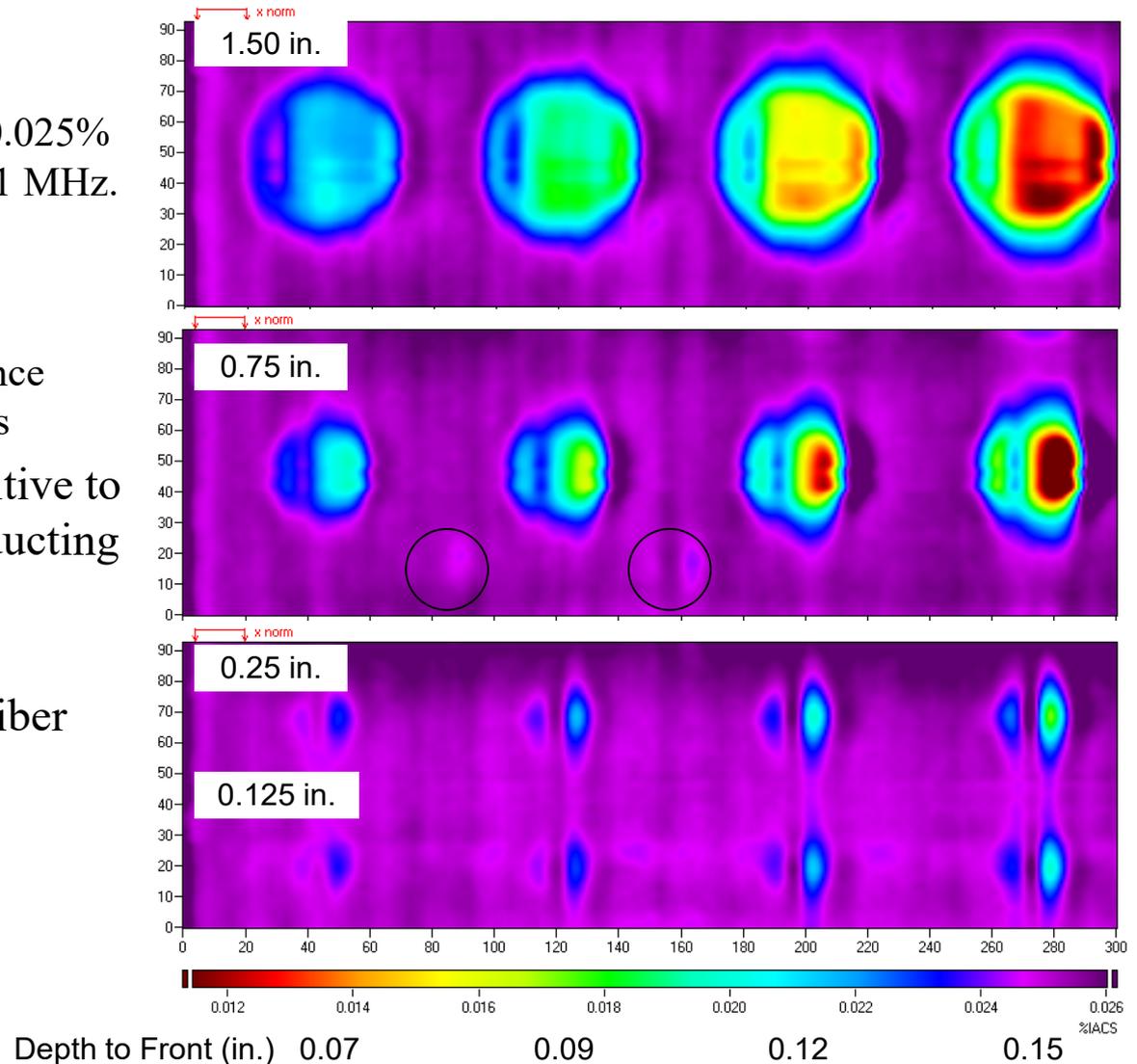
Graphite/Epoxy Panel with Artificial Defects

- 0.28 in. thick solid laminate
 - Provided by Thermal Wave Imaging
 - Initially part of a test with an induction heating apparatus
- Flat bottom holes milled out of back side
 - Various diameters and depths
 - Note that the deeper and smaller diameter holes are considered challenging for thermography.



Graphite/Epoxy Panel with Artificial Defects (2)

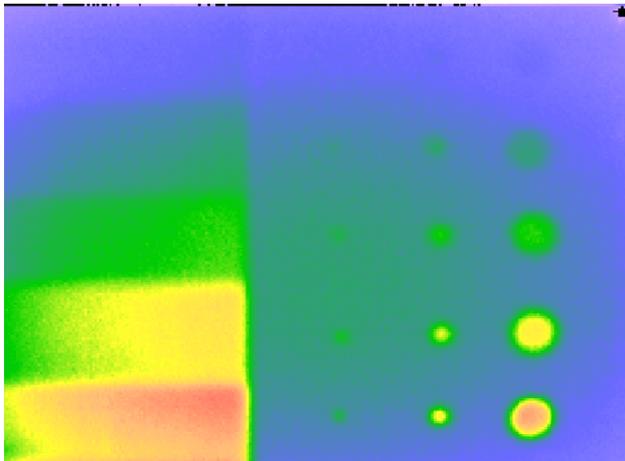
- Baseline measurements
 - Skin depth is 0.16 in. for a 0.025% IACS nonmagnetic MUT at 1 MHz.
- Room temperature
- Clearly detect artificial flaws
 - Shape filtering should enhance response to small/deep flaws
- Indicates sensor array is sensitive to the missing and weakly conducting fibers
- Relatively “friendly” to eddy current measurements since fiber damage is extreme
 - i.e., fibers are missing



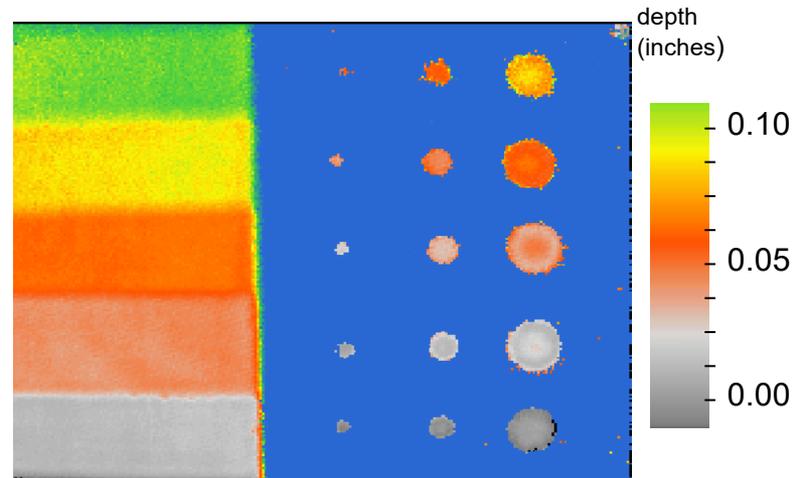
Graphite/Epoxy Panels with Thermography

- Representative thermographic images
- Classification possible with hybrid MWM-Thermography
 - MWM response to damaged/missing fibers
 - Thermography responds to damaged/missing matrix and fibers

Raw IR image of the panel 1.6 seconds after flash heating

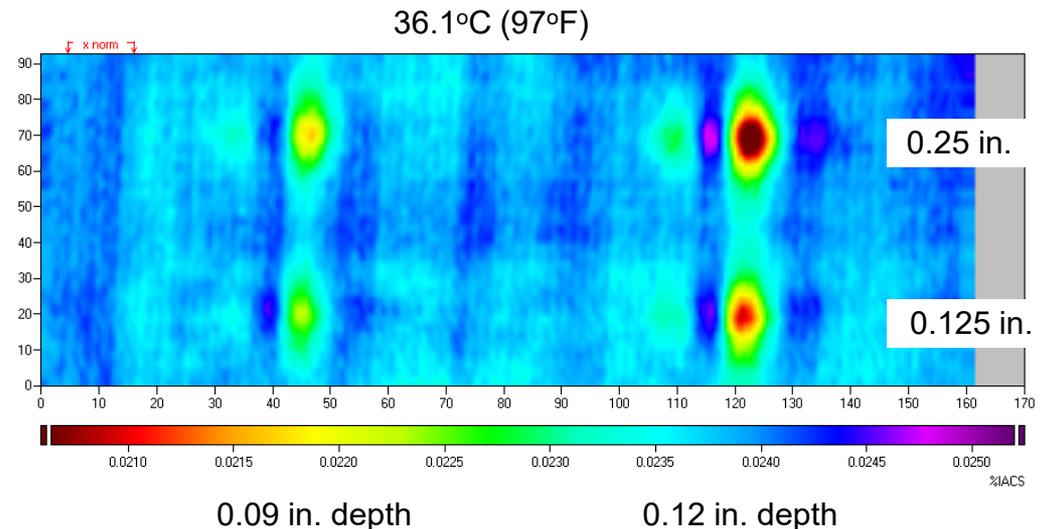
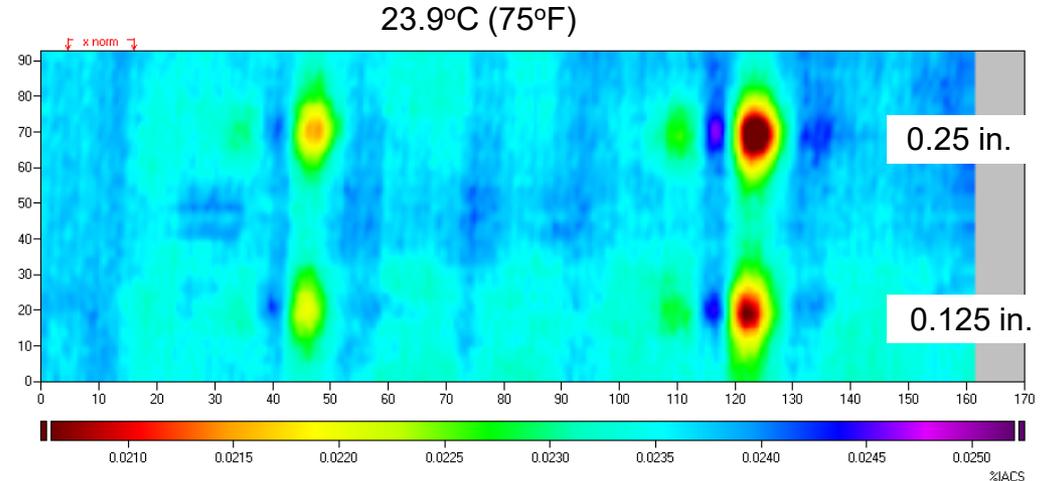
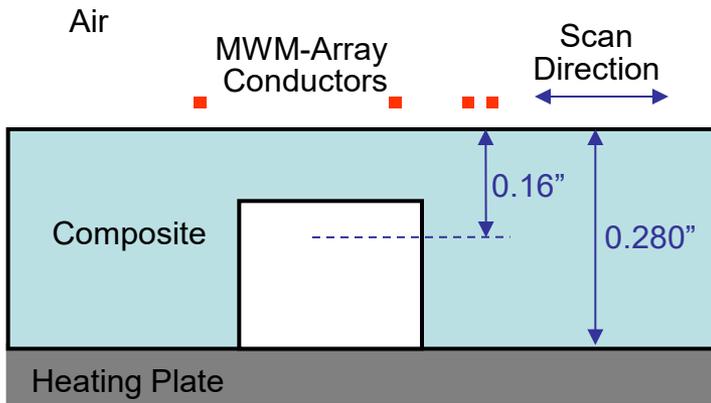


Depth map created from original data using TWI Thermographic Signal Reconstruction (TSR®)



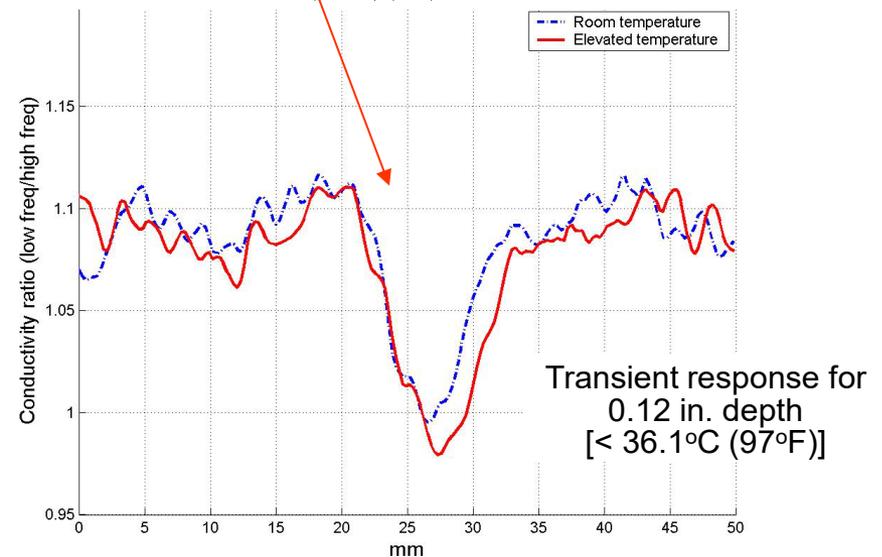
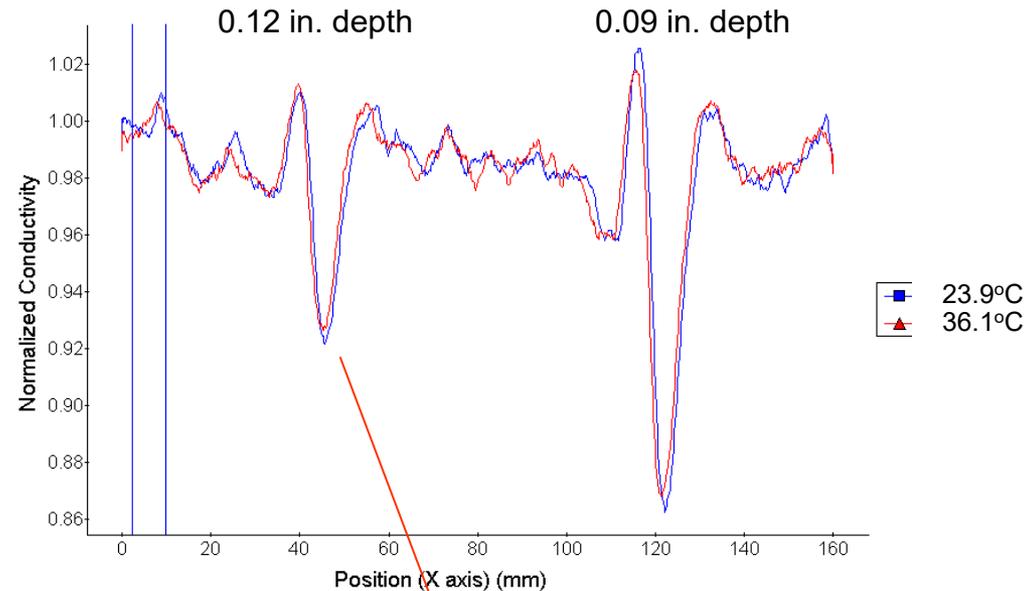
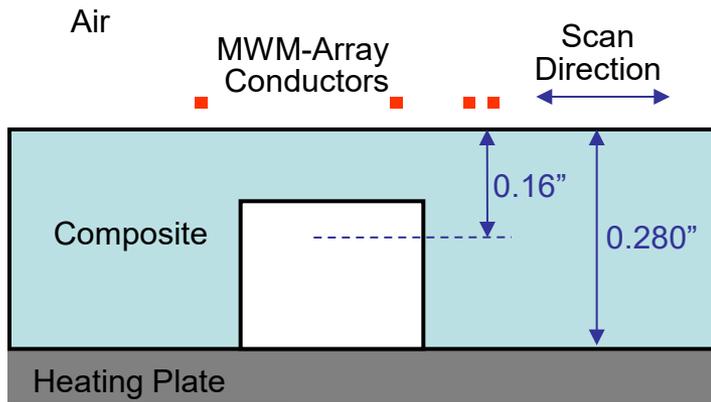
Graphite/Epoxy Panel with Artificial Defects (3)

- Measurements at two different temperatures
 - Initial (ambient) and near steady-state after heating
- Slight increase in background conductivity of panel with increased temperature
 - $k_c \sim 1.05 \times 10^{-3}/^{\circ}\text{C}$
 - $\sigma = \sigma_0 [1 + k_c (T - T_0)]$
- Small change in flaw contrast with elevated temperature



Graphite/Epoxy Panel with Artificial Defects (4)

- B-scans for 0.125-in. diameter holes
- As with images, small change in flaw contrast with elevated temperatures
- However, during the heating transient there is a modest improvement in flaw contrast
- This enhancement is consistent with model analysis

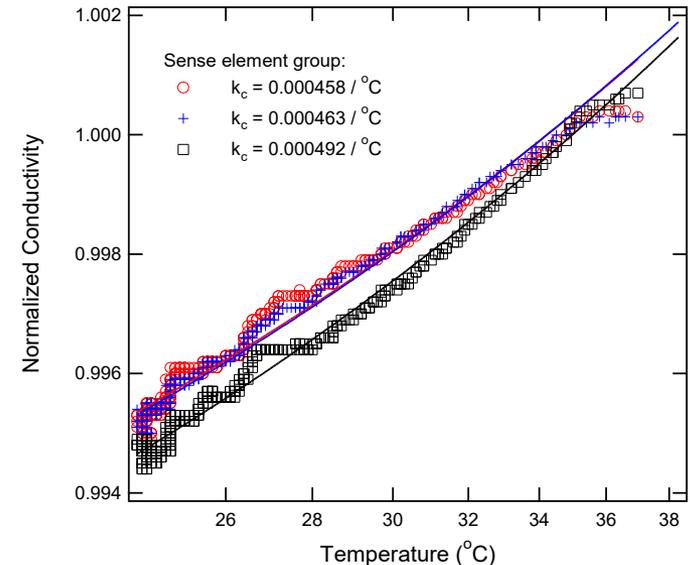
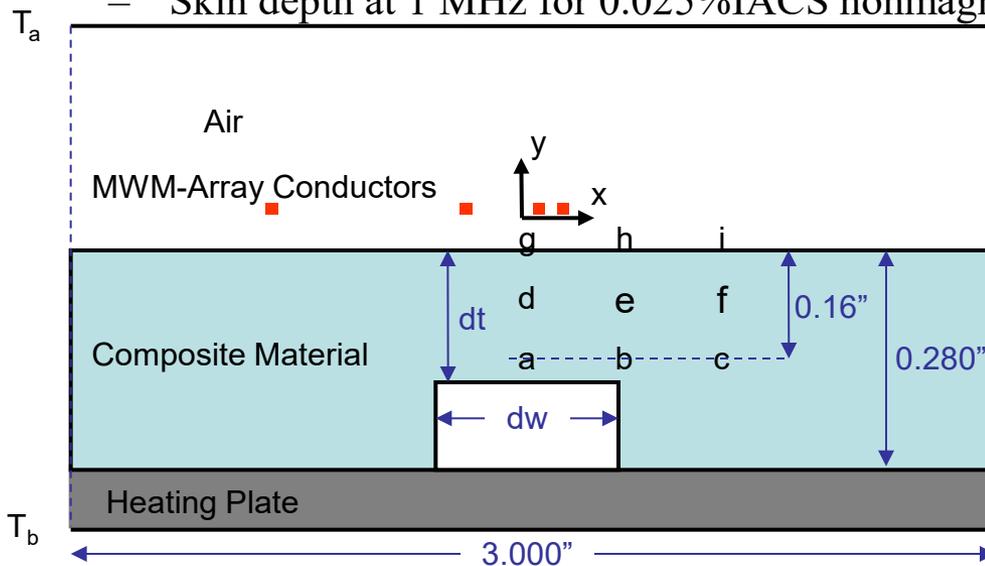


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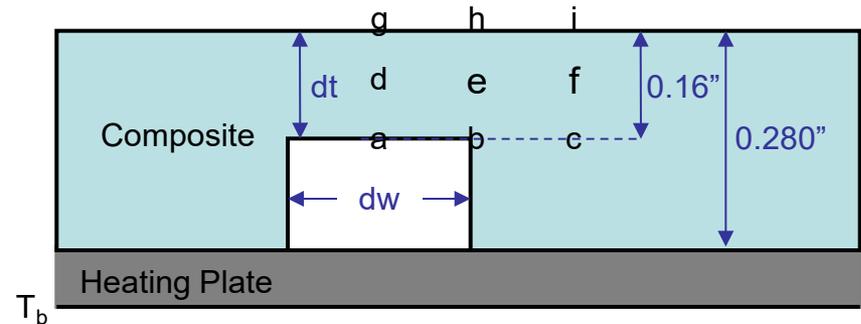
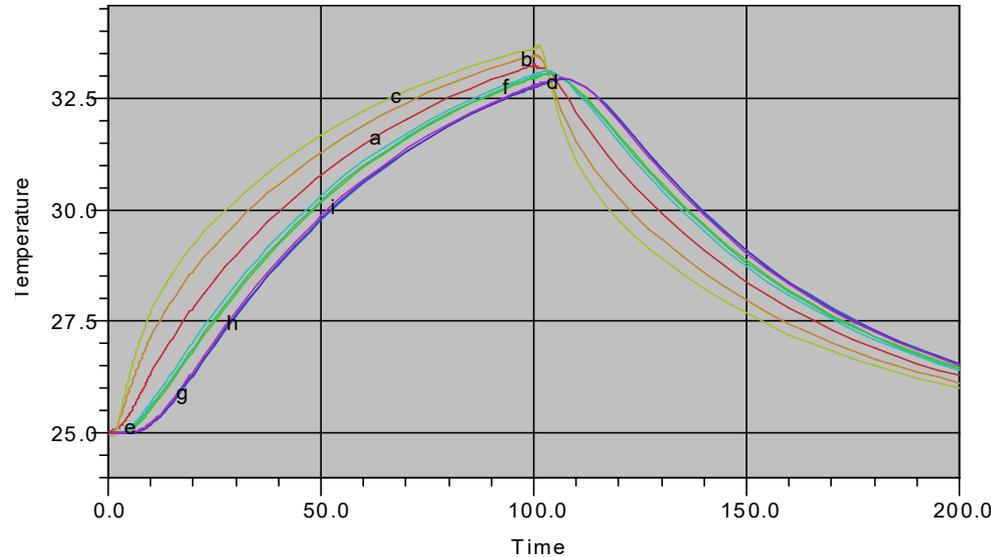
Magneto-Thermal Simulation Case Studies

- Premise of this analysis:
 - Scanning an MWM-Array over the flaw tends to show a decrease in conductivity.
 - Since the graphite/epoxy conductivity tends to increase with temperature, if the volume above the defect is lower in temperature than on the sides, an enhanced decrease in conductivity should be observed
- Used 2D FEM to find the transient temperature distribution
 - Anisotropic conduction
 - Boundary conditions:
 - Assumed a step change in temperature at $t=0$ for the lower surface of the heating plate
 - $T_a = 25\text{ }^\circ\text{C}$, $T_b = 35\text{ }^\circ\text{C}$ $u(t)$
 - No heat flow out of sides of simulation geometry
- Temperatures plotted at several locations (as indicated by a-i)
 - Skin depth at 1 MHz for 0.025%IACS nonmagnetic material is 0.16"



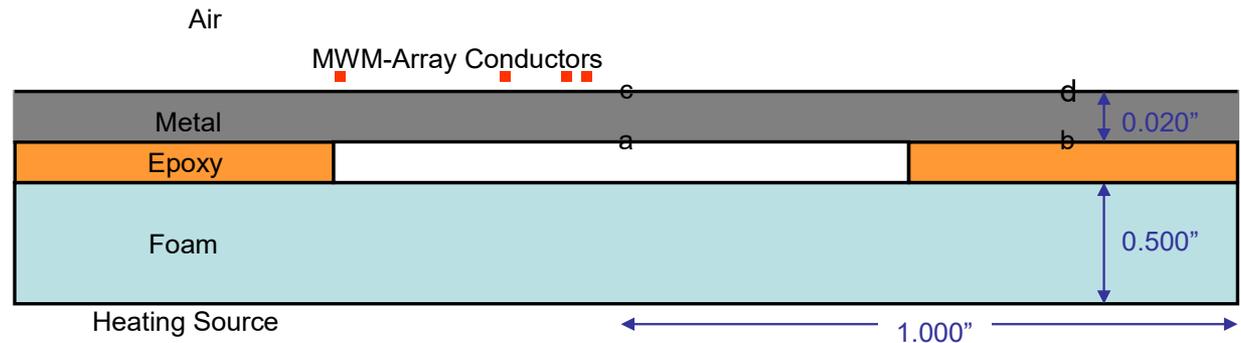
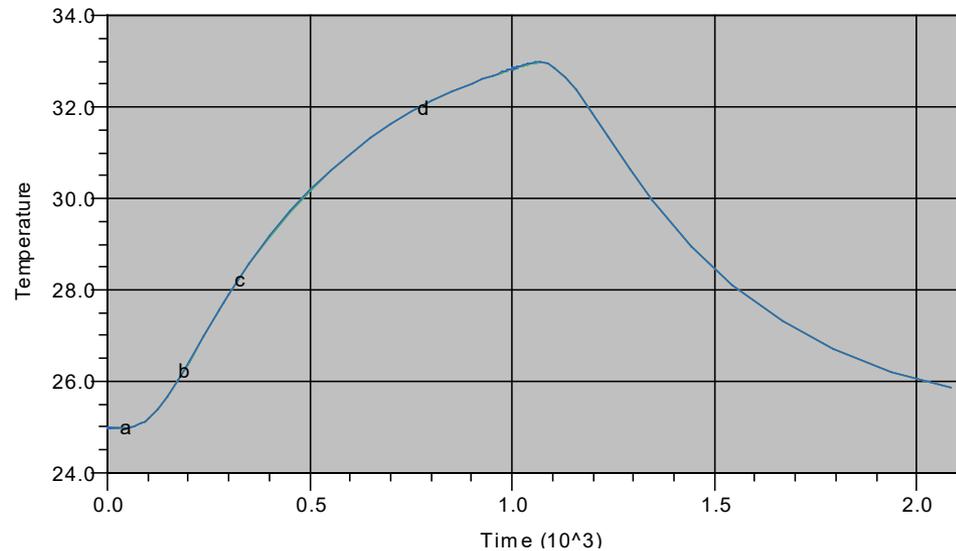
Case 1: 0.25" diameter, 0.16" deep hole

- Material properties:
 - Composite: $k_x = 5.3 \text{ W / m K}$, $k_y = 0.61 \text{ W / m K}$, $\rho c_p = 1.44\text{E}6 \text{ J / m}^3 \text{ K}$
 - Air: $k_x = k_y = 0.025 \text{ W / m K}$, $\rho c_p = 1.17\text{E}3 \text{ J / m}^3 \text{ K}$
 - Metal: $k_x = k_y = 120 \text{ W / m K}$, $\rho c_p = 2.42\text{E}6 \text{ J / m}^3 \text{ K}$
- Several degree temperature gradient across the top of the defect
 - Most significant in the 10-30 sec range
 - By 100 sec the gradients across the sample are small
- Set heating plate to ambient after 100 sec
 - Similar gradients with heating and cooling transients
- Surface remains essentially uniform in temperature
 - Suggests an advantage to a method that can interrogate the volume of the material
 - To compare surface and volume measurement methods, must compare temperature measurement sensitivity.



Case 2: Missing Adhesive under Foam

- Basic geometry for a missing adhesive attaching foam to a metal
 - Disbond width of 0.500" and a thickness of 0.040"
- Heating from the back side and MWM measurements on opposite surface
 - A step change in temperature at $t=0$
 - A step change down in temperature at $t=1000$ sec
- Material Properties:
 - Adhesive (Epoxy assumed): $k = 0.35$ W / m K, $\rho c_p = 2.16E6$ J / m³ K
 - Foam (90% air, 10% epoxy assumed): $k = 0.058$ W / m K, $\rho c_p = 2.17E5$ J / m³ K
 - Air: $k = 0.025$ W / m K, $\rho c_p = 1.17E3$ J / m³ K
 - Metal: $k = 120$ W / m K, $\rho c_p = 2.42E6$ J / m³ K
- Minimal temperature gradients over disbond.
- Better to heat from surface rather than through transmission



Summary

- MWM-Arrays have shown an imaging capability for some flaw conditions in graphite fiber/epoxy composites
- Initial thermal simulations indicate some conditions where magneto-thermography shows **enhanced responses**
- Ongoing work:
 - Explore other heating mechanisms
 - Comparison to capabilities of conventional thermography
 - Surface temperature versus volume measurement
 - **Embedded/surface mounted sensors** on graphite/epoxy composite