Carbon Nanotube (CNT) Enhancements for Aerosurface State Awareness

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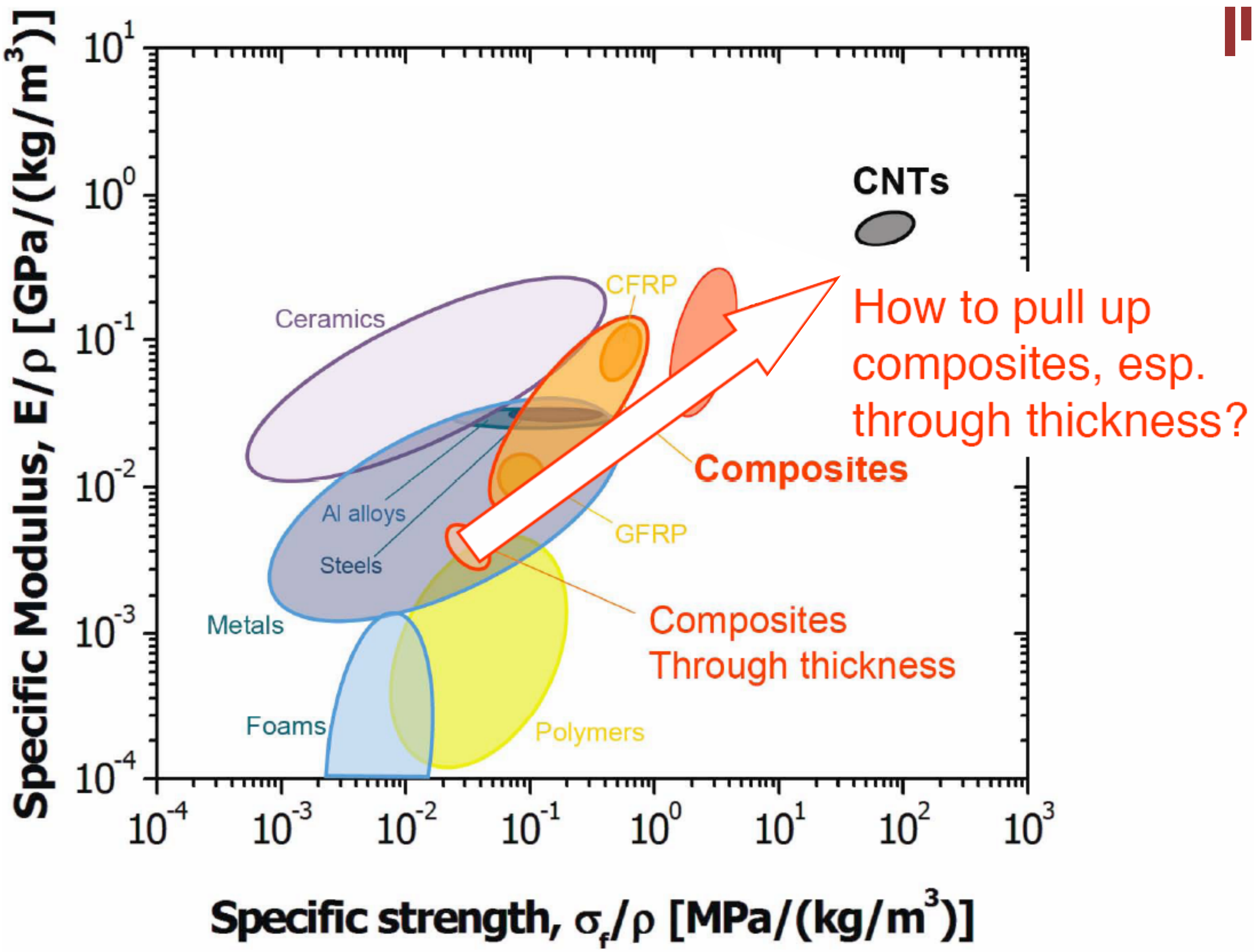
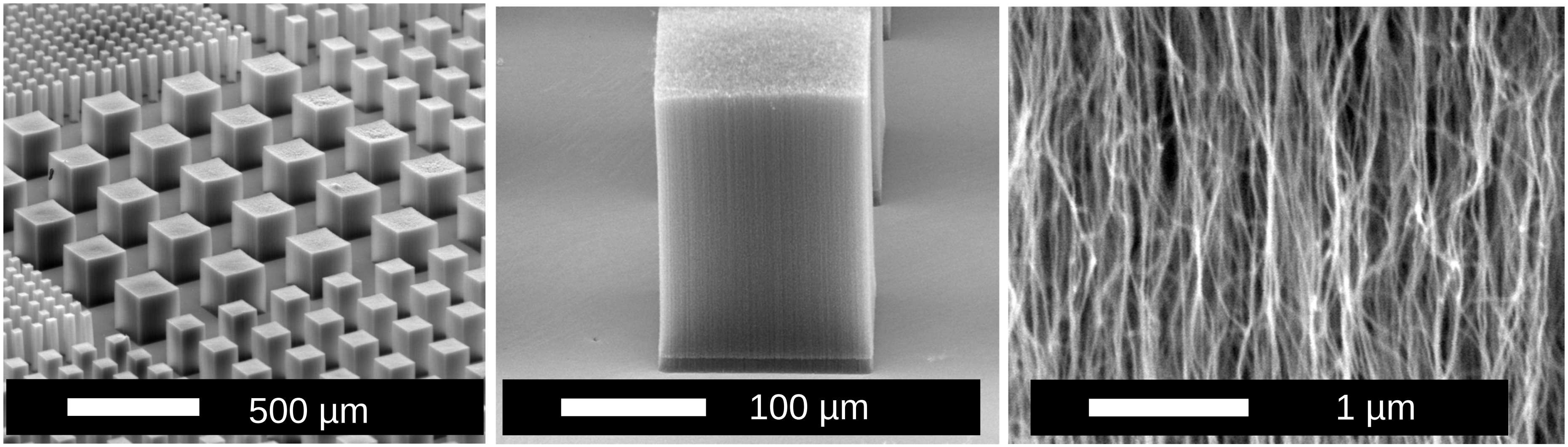
Advanced Composites & CNTs



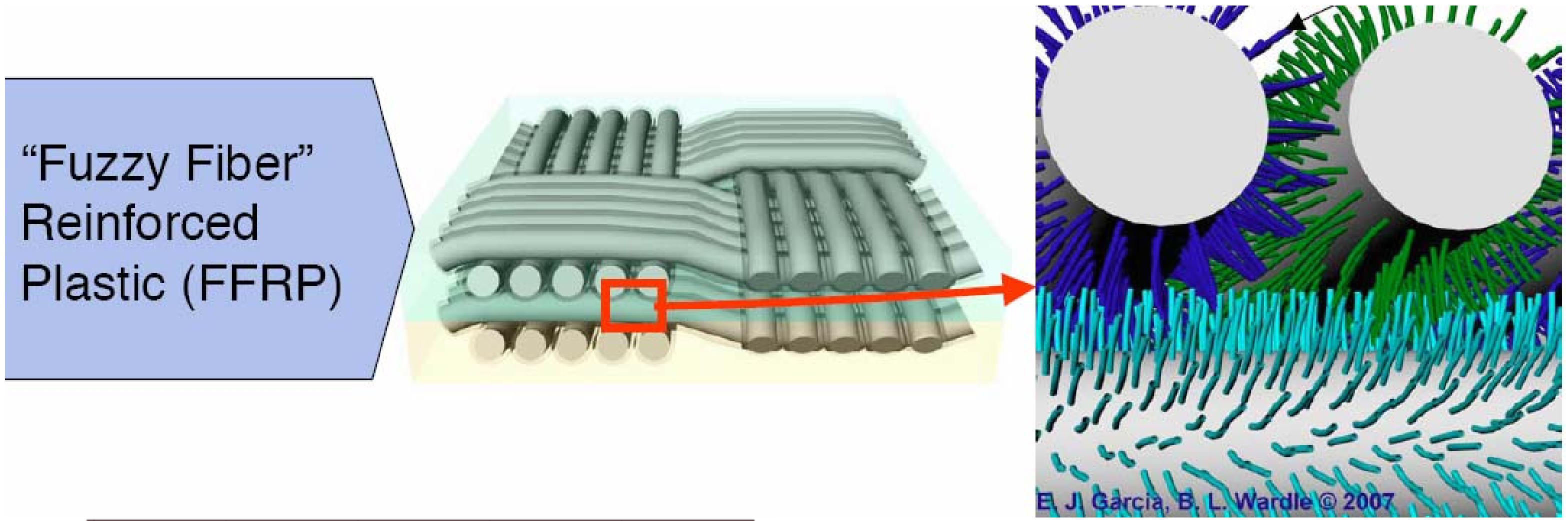
Carbon Nano-Tube (CNT) laminates are a natural progression for aerospace composites due to their superior specific strength & stiffness

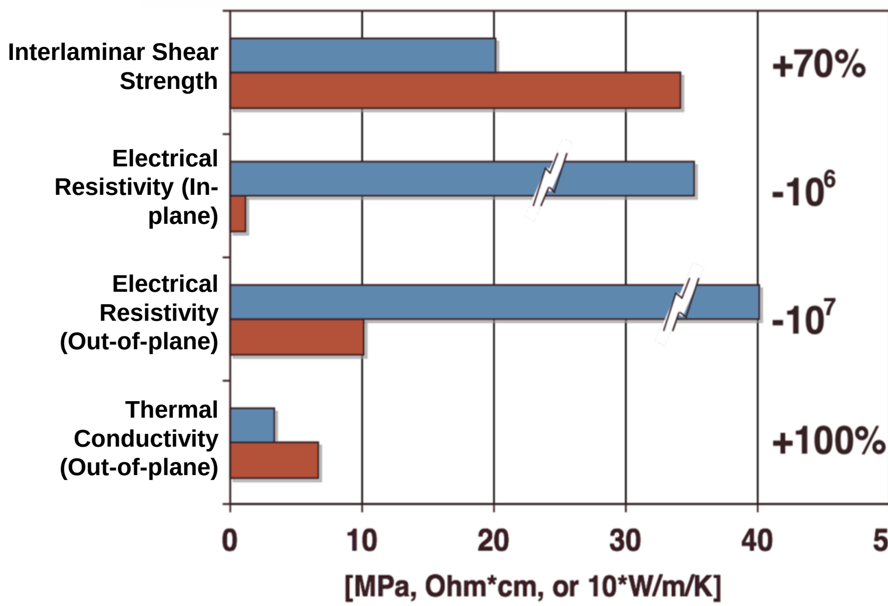
Fabrication of Structured CNTs

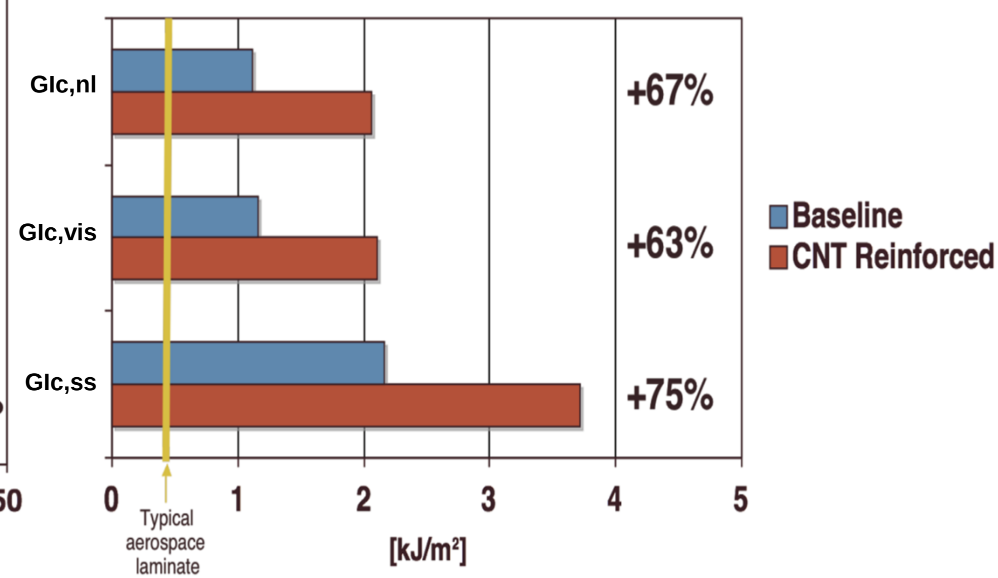


- MIT patented novel CNT fabrication processes
  - CNTs grown aligned directly on fibers or on substrate to be transferred
  - good alignment, dispersion, adhesion & yields high CNT volume fraction
- Atmospheric pressure chemical vapor deposition (CVD)
  - self-aligned morphology 10^{10}-10^{11}/cm^2 of continuous CNTs (7-10 nm OD)
  - rapid forest growth of > 2 microns/second (up to 5 mm long)

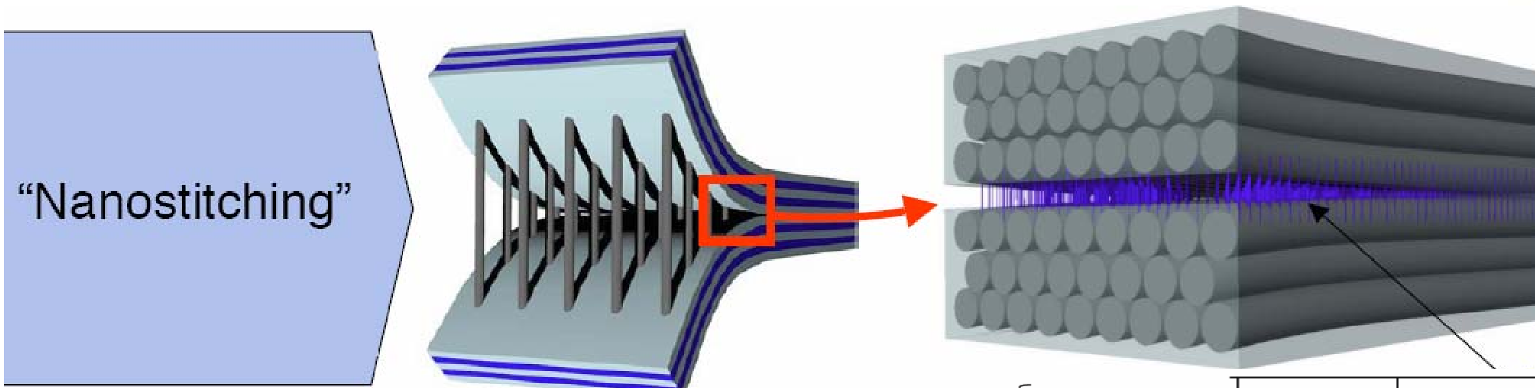
“Fuzzy Fiber” Laminates

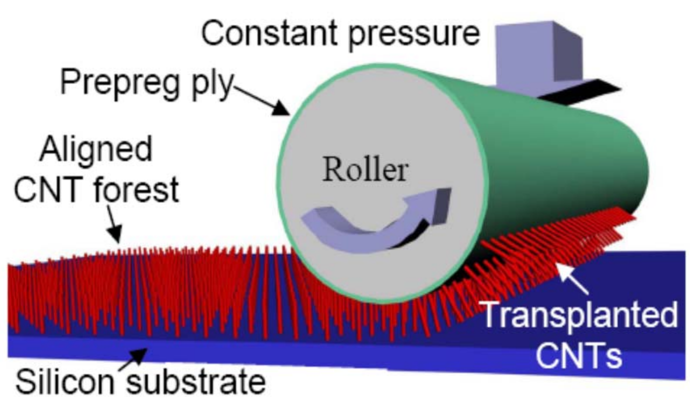


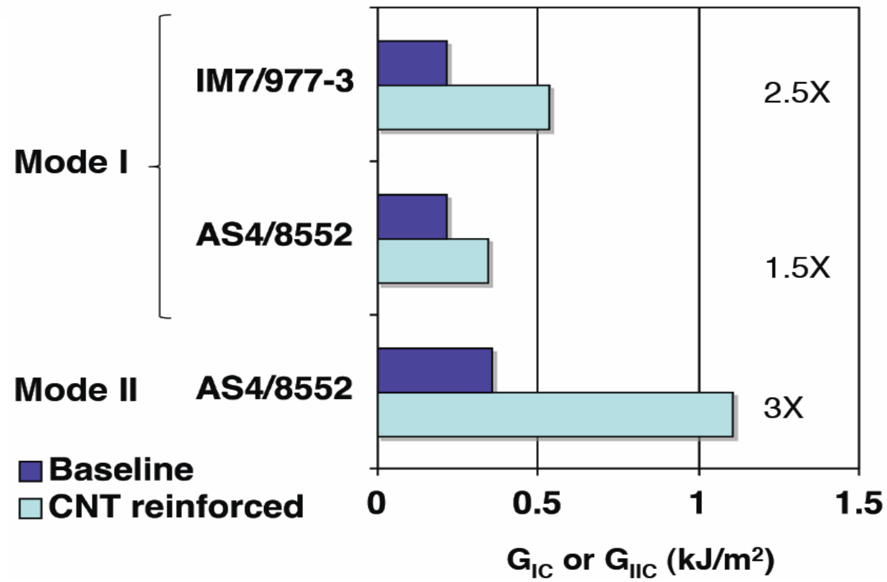




"Nano-Stitched" Prepreg





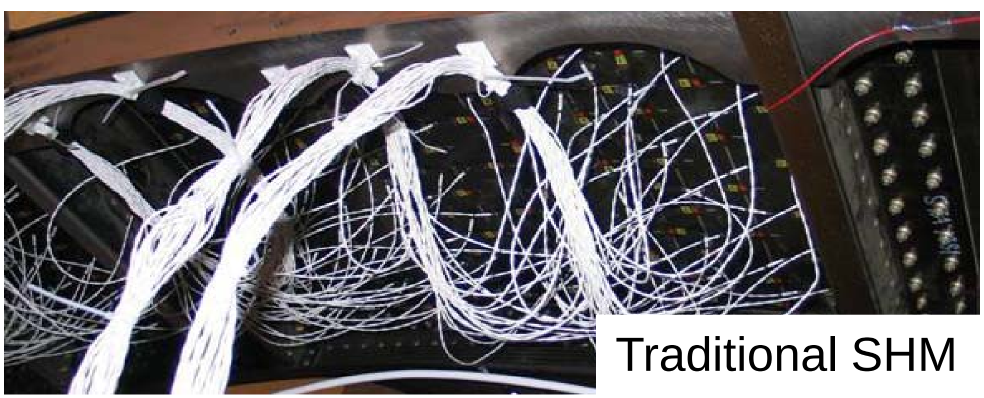


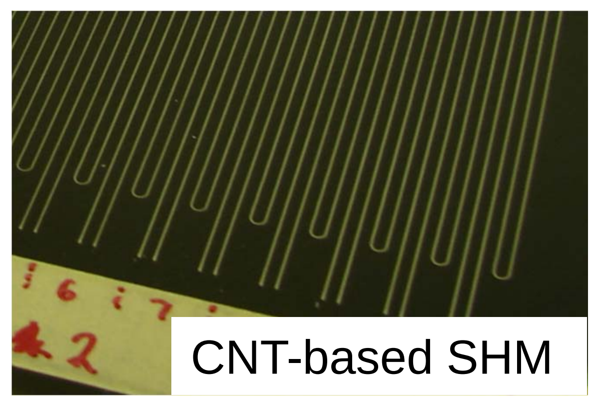
- Grow aligned CNTs on high-temperature substrate
- Transplant CNTs to composite at low temperature
- Process the enhanced composite normally

CNT-based SHM

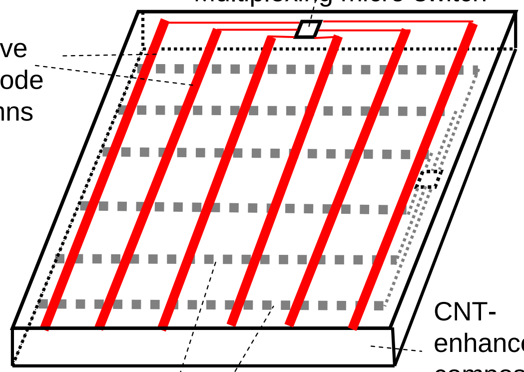
Motivation For CNT-based SHM

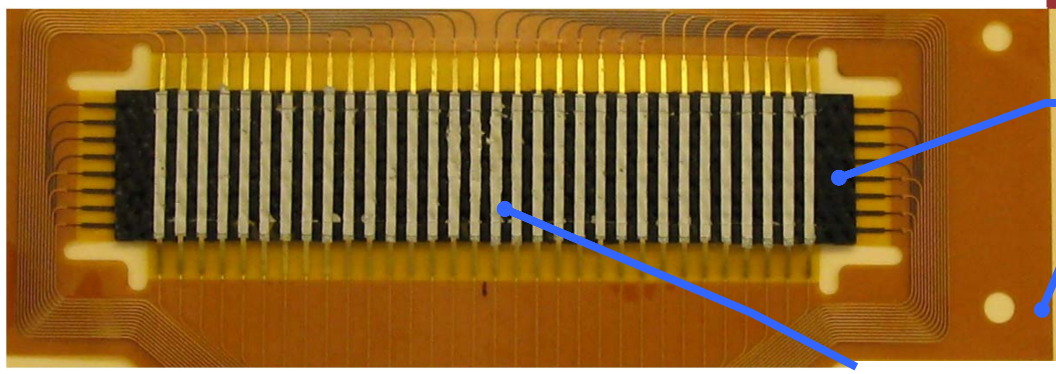
- SHM improves reliability, safety & readiness @ reduced costs
  - ➢ sensors & cables add weight as well as durability & EMI concerns
  - ➢ scaling SHM for large-area coverage has presented challenges
- Advantages of proposed CNT-based SHM methodology
  - ➢ sensing elements actually *improve* specific strength/stiffness of structure
  - ➢ damage alters CNT links around affected zone, impacts resistivity
  - ➢ surface & sub-surface damage images produced in post-processing
  - ➢ simple to scale over large structure, maintains good local resolution


Traditional SHM


CNT-based SHM

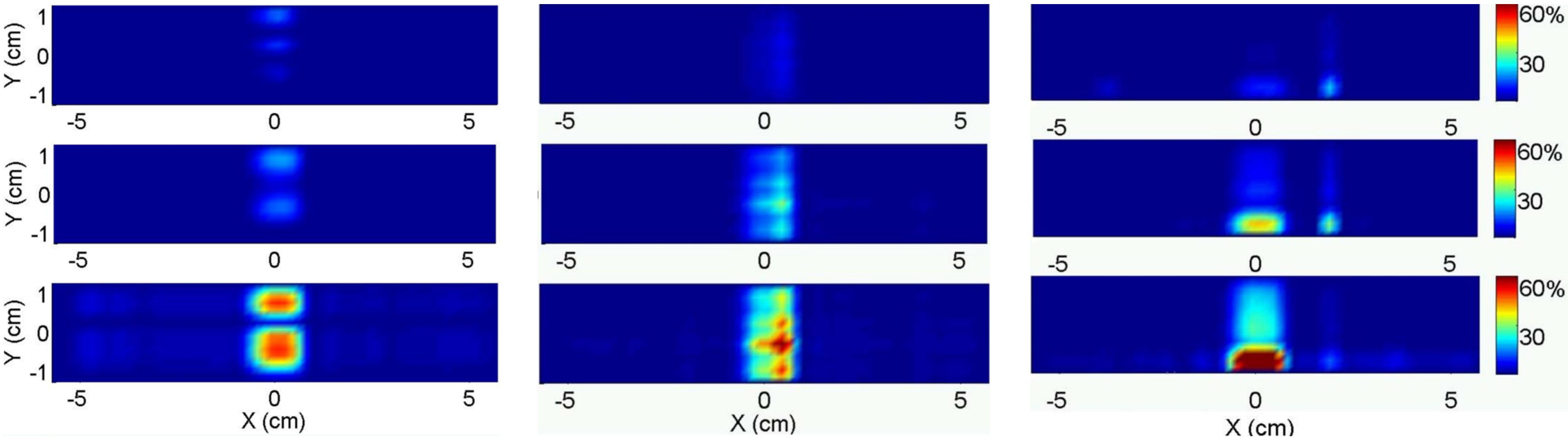
SHM Experimental Setup





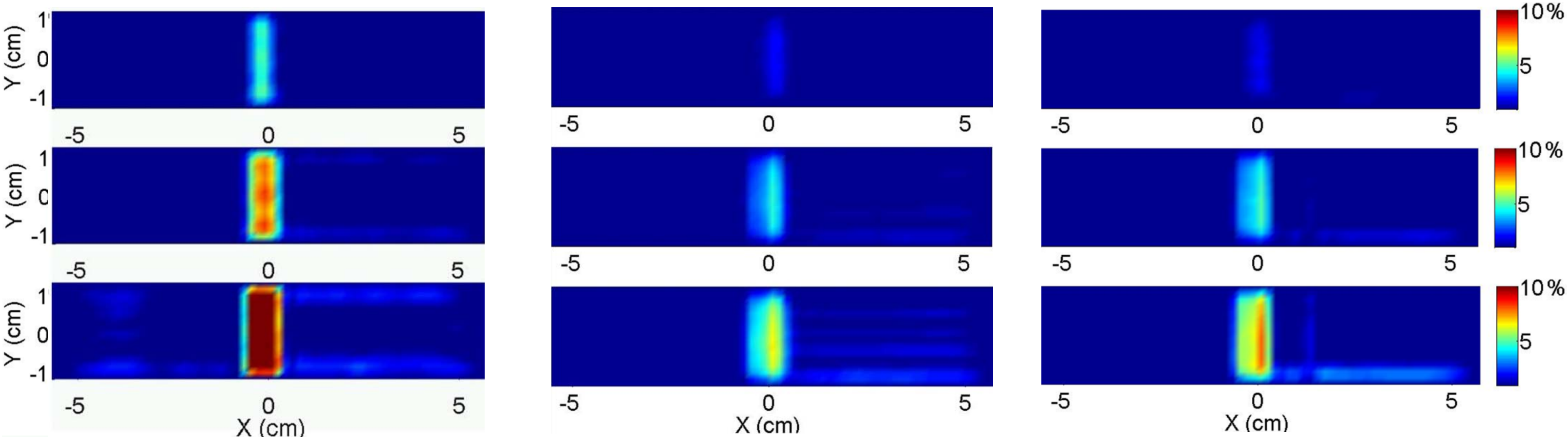
- FFRP laminates fabricated
  - alumina fiber satin-weave cloth dipped in solution of 50 mM iron nitrate
  - CNTs grow radially aligned 20-50 μm with modified thermal CVD method
  - 2 plies stacked by hand layup, infused with RTM-6 for 12-hour RT cure
  - ~50% fiber volume fraction & ~ 2% CNT (115 x 25 x 2 mm)
- Silver-ink electrodes applied w/masked silk-screening process
  - direct-write (DW) electrode grids applied similar to LCD technology
  - 8 x 32 traces 1.5 mm wide, all traces spaced by 1.5 mm
  - in-plane & through-thickness resistance measurements collected

In-plane Resistance Changes



- No visible damage was present in any of these cases
  - nearly linear increase in % resistance change with impact energy
  - < 1% change in resistance away from impact zone
- Appeared relatively localized to the actual impacted region
  - 15 ft-lbs impact caused ~10-20% changes
  - 30 ft-lbs impact caused ~20-30% changes
  - 45 ft-lbs impact caused ~40-60% changes

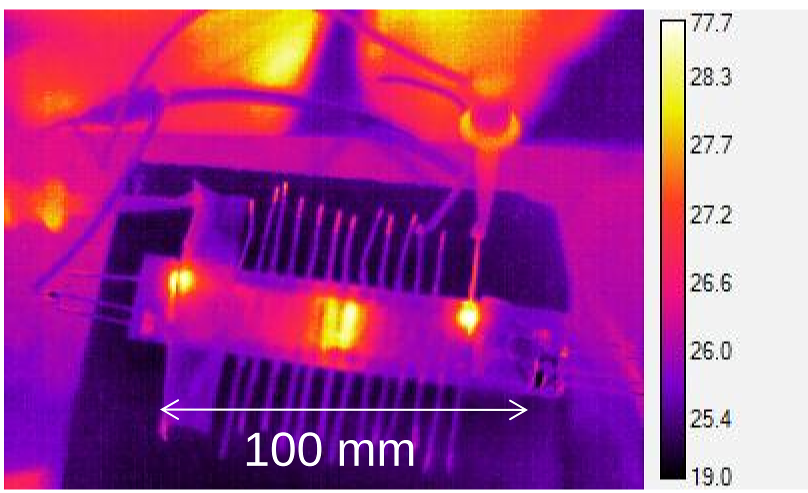
Through-Thickness Changes

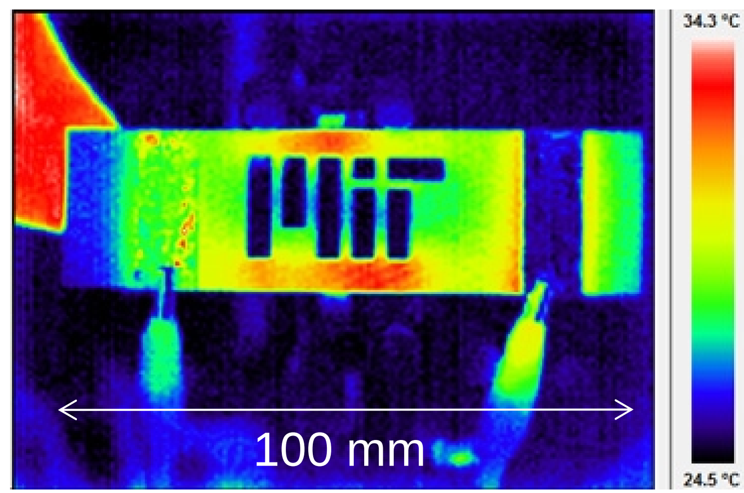


- Same trends observed for in-plane vs through-thickness results
  - witness specimen testing indicated complete fracture at 50-60 ft-lbs
  - no visible micro-cracking until failure
- Appeared to effect width in impact region relatively uniformly
  - 15 ft-lbs impact caused ~2-4% changes
  - 30 ft-lbs impact caused ~4-8% changes
  - 45 ft-lbs impact caused ~8-10% changes

NDE Approaches

- Schemes being explored for NDE & Quality Control
  - ➢ acoustic emission (AE) measuring dynamic piezoresisive changes
  - ➢ enhanced penetrating thermographic NDE with applied voltage
- Same hardware & flex frame can be used to measure dynamic resistance changes or self-induce heating
  - ➢ initial “pencil-tap” experiments verifies that AE can be detected
  - ➢ initial thermographs demonstrate method feasibility





CNT-based IPS

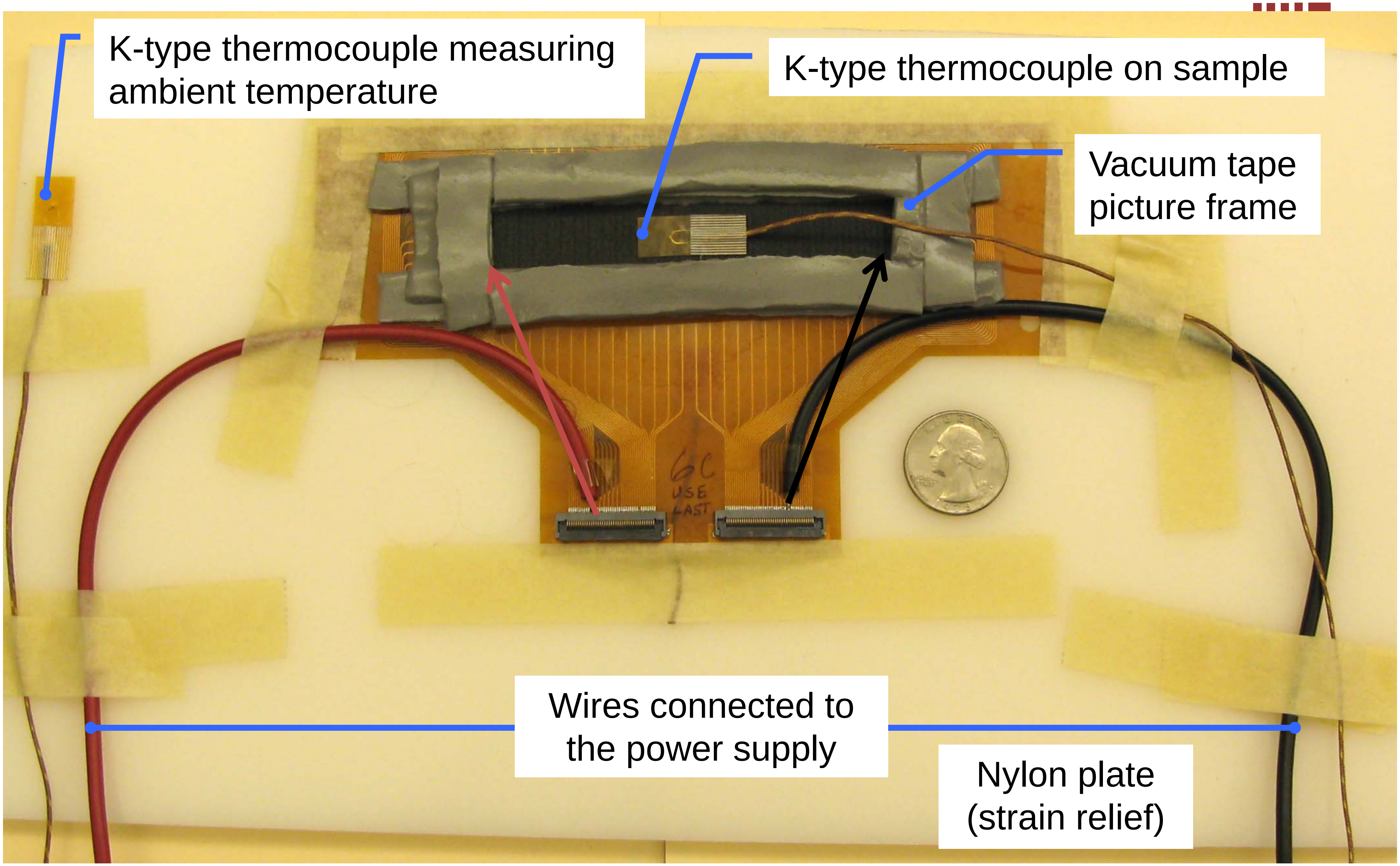
Motivation For CNT-based IPS

- Goal to develop a multi-role system for composite aerosurfaces
  - detection of presence of ice on surface
  - removal of ice and/or prevention of ice (re)formation
  - detection/characterization of structural damage

- Current approaches provides high false positive & failure rates

- CNT-based IPS to produce robust, reliable integrated solution
  - heating/sensing elements are structural
  - solid state (no moving parts)
  - conformal (light & low profile)
  - uniform surface coverage
  - efficient closed-loop feedback possible
  - can improve impact resistance

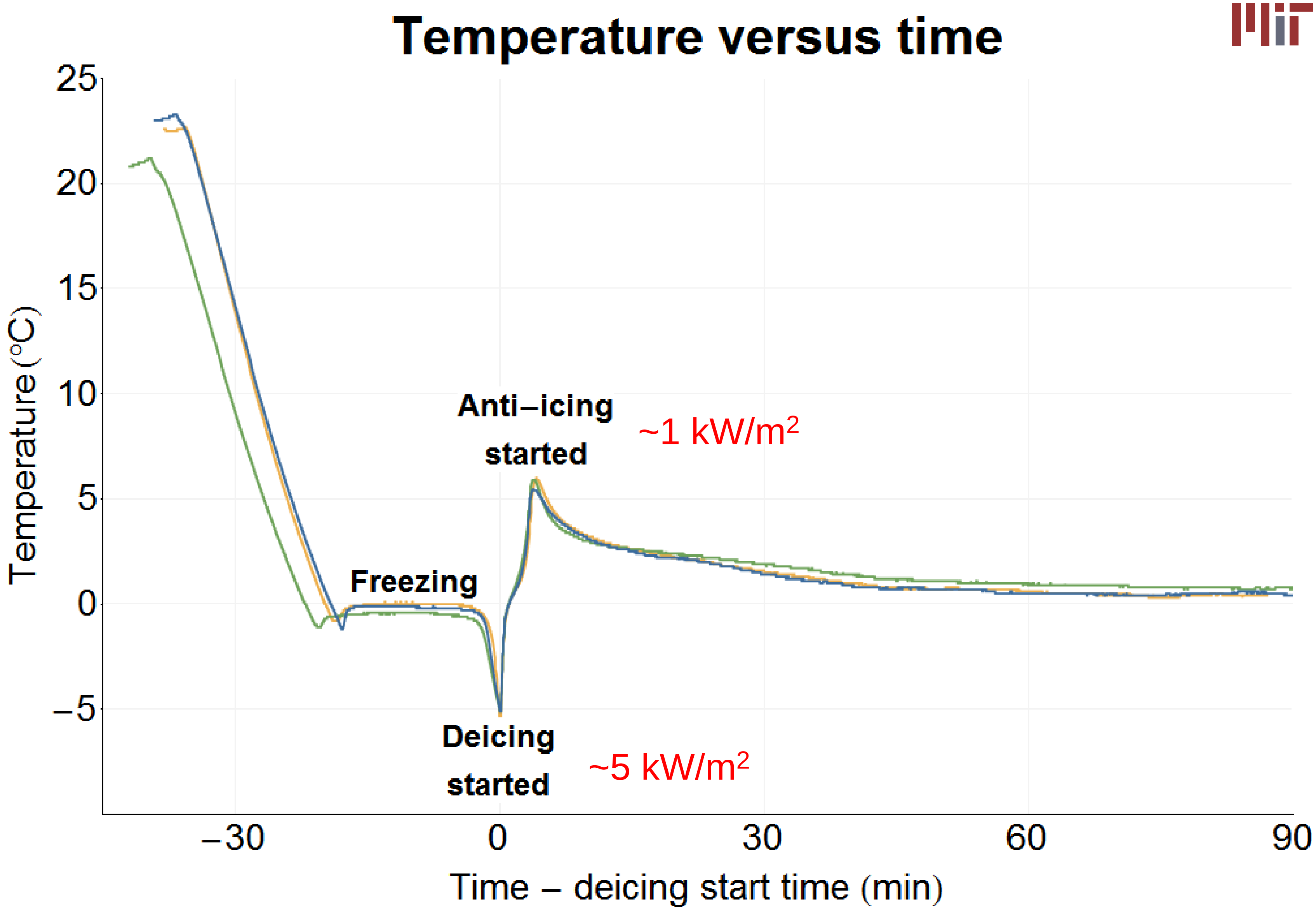
Proof-of-Concept Experiments



Proof-of-Concept Ice Protection

- Anti-Icing @ 4 W input (~2 kW/m^2)
  - without water ~30 °C difference in CNT asymptotic temperature
  - able to maintain sample temperature above freezing with large margin
  - visual confirmation that ice did not form
- De-Icing @ 4 W input (~2 kW/m^2)
  - asymptotic values only a function of power regardless of water/ice
  - time to asymptote only a function of water/ice regardless of power level
  - higher power level provide steeper slope through 0°C (de-ice quicker)
- Ice-Detection @ 4 W input (~2 kW/m^2)
  - while heating with water, distinct phase-related slopes
  - effective heat capacity of melting ice
  - uses anti/de-icing setup without any additional electrodes

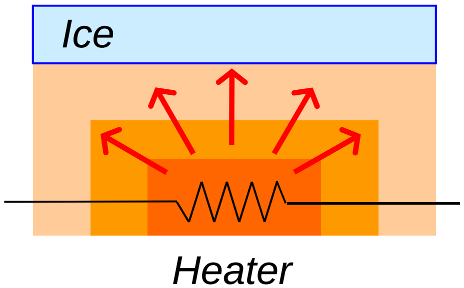
De-Icing & Anti-Icing

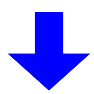


Benefits of CNT Deicing Layer

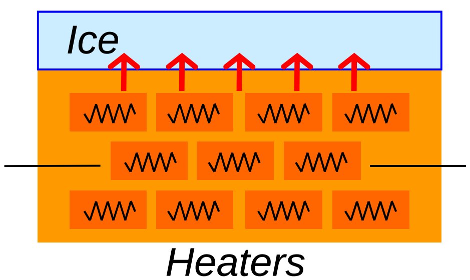
- Quasi-uniform resistive heating across large areas
- Effective heat distribution for large areas
- Tunable resistivity (material property) for optimal power setting

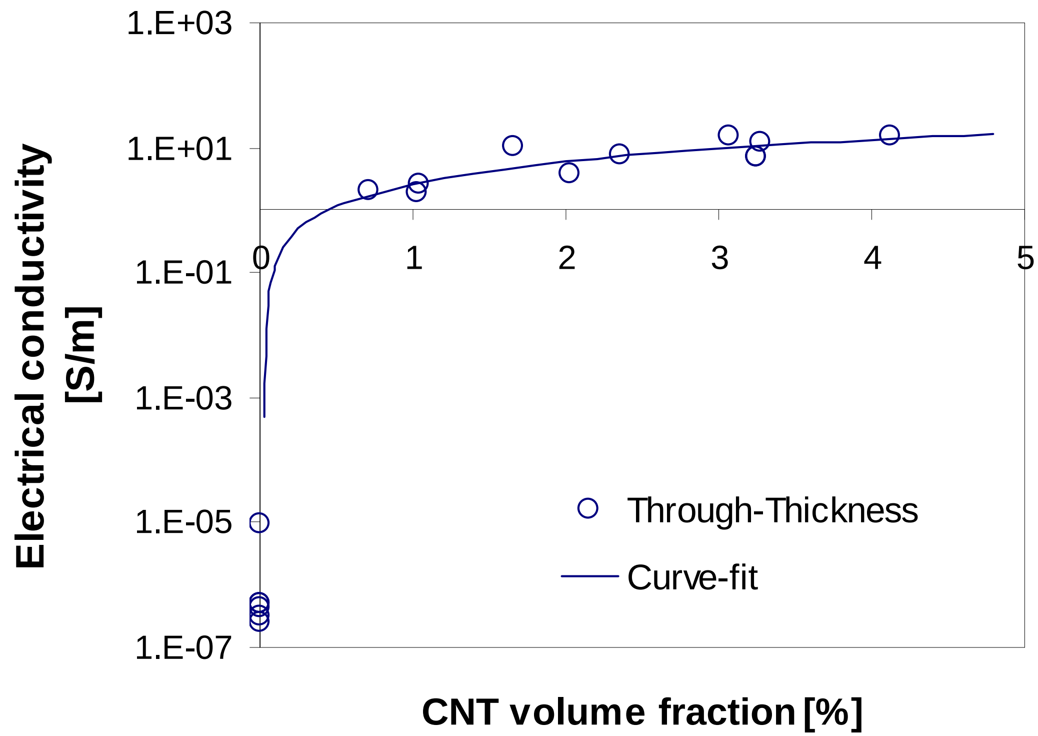
Current deicing design





CNT deicing layer

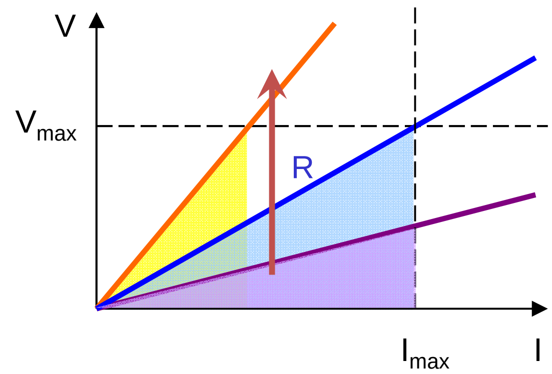




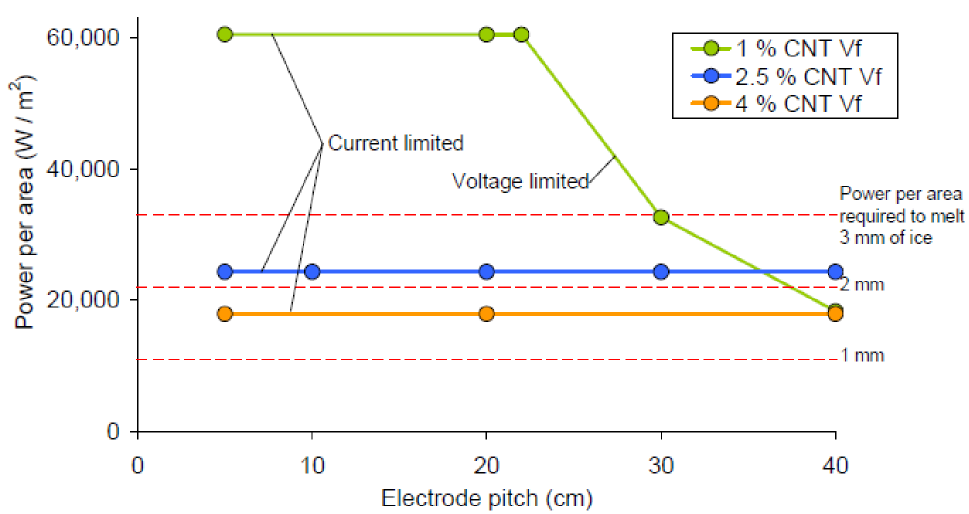
Optimal Resistance for Max Power

If R small, current limited, and thus Power = RI_{max}^2 (linear)

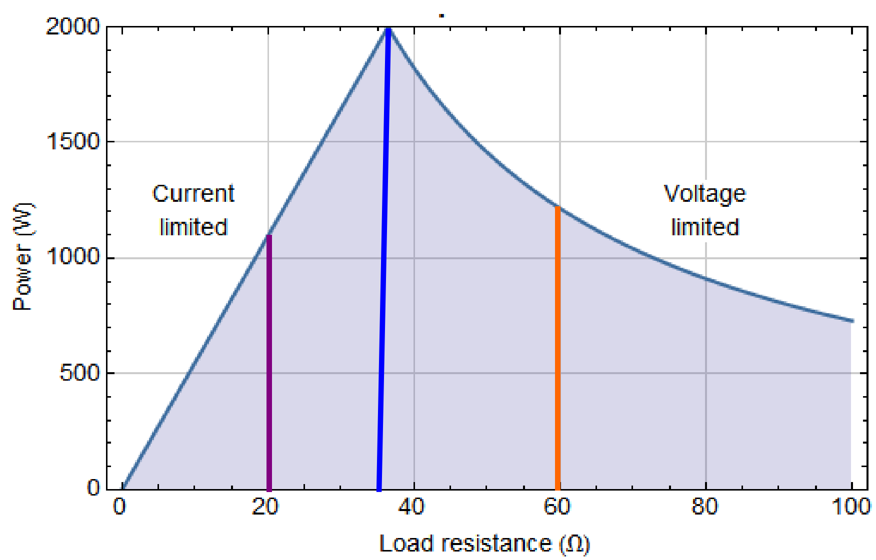
If R large, voltage limited, and thus Power = V_{max}^2/R



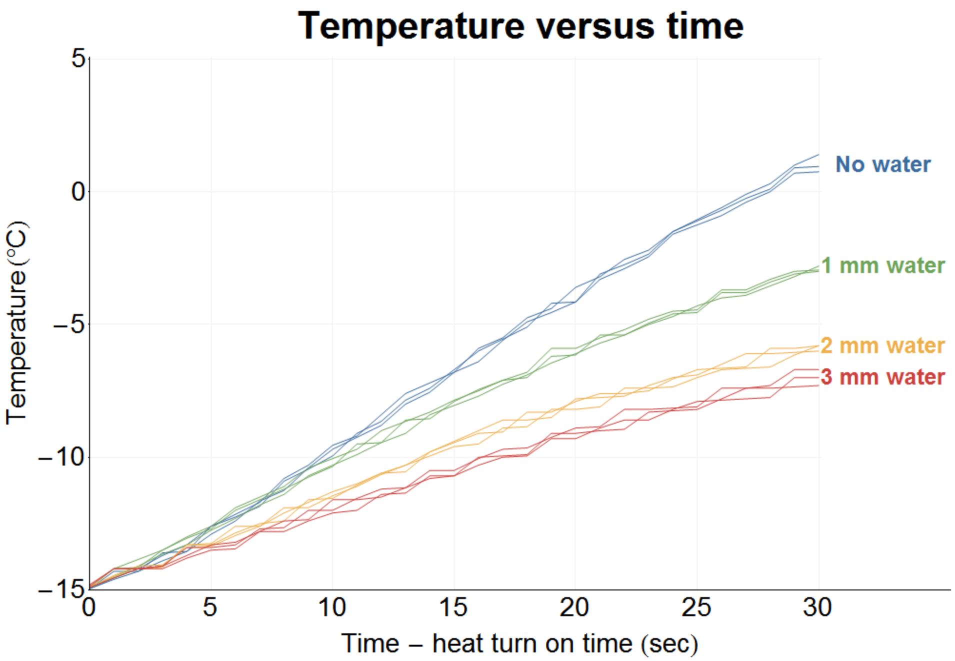
Power/Area with Varying Electrode Spacing

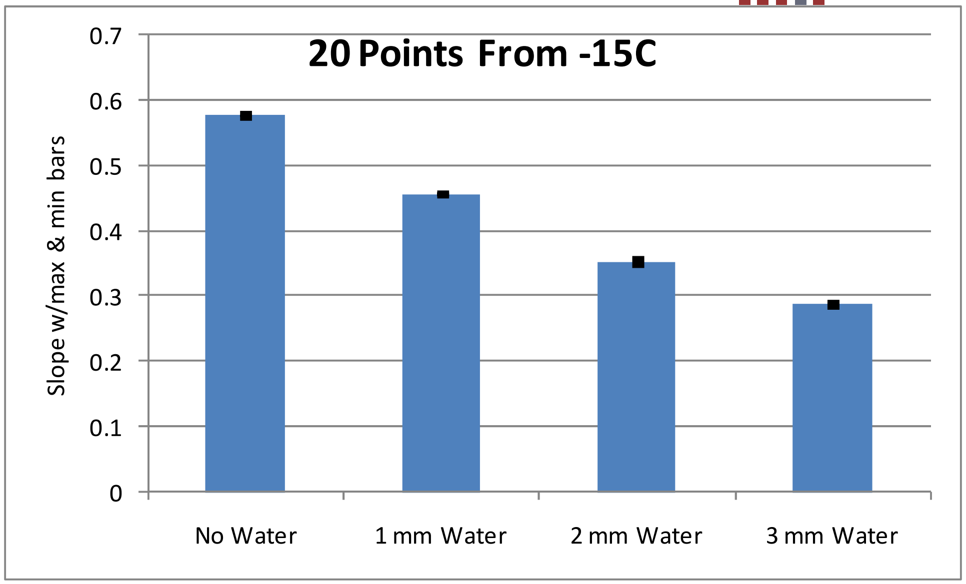


Dissipated Power versus Load Resistance



Ice-Detection Formulation





- Effective heat capacity method
  - ➢ constant current applied to sample for fixed temperature recording time
  - ➢ exponential temperature rise (linear data fit), compared to no-ice case
- Very repeatable results
  - ➢ shallower slope correlates to more ice on specimen
  - ➢ data consistent for multiple detection temperatures

Summary

- Proof-of-concepts for CNT-based SHM & IPS demonstrated
  - Reliable – solid state, structural elements, durability & longevity
  - Minimal impact – low mass & low profile
  - Integrated solution – ice-detection & de-icing + damage detection & NDE
- CNT-based SHM
  - LCD inspired design for in-plane and through-thickness detection
  - damage affects CNT-links, can measure resistivity changes
  - resolution defined by grid spacing; easily modified/expanded
- CNT-based IPS
  - anti-icing @ ~1 kW/m^2 to maintain blade temperature ~5 °C
  - de-icing @ ~5 kW/m^2 , ~2 min from ~-15 °C (not including gravity assist)
  - ice-detection in seconds (faster with faster/finer DAQ)

Continuing Research

- CNT-based SHM system (AFOSR Phase II funding)
  - measure structural & multi-functional properties for CFRP FFRP
  - explore various electroding strategies
  - analytical models to simulate system, parametric iteration
  - find trade between detection resolution & electrode spacing
  - compensation algorithms for temperature & loading
  - demonstrate on UAV wing/tail section

- CNT-based IPS system (NAVAIR Phase II funding)
  - determine electrode spacing versus heating efficiency
  - design of laminate morphology for surface heating
  - development of hardware for deicing and ice detection
  - fabrication & demonstration of BAMS leading edge IPS
  - ice-tunnel testing

Acknowledgments

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