U.S. AIR FORCE

USSF

AFRL

Quantifying Performance Under Extreme Environments

Hilmar Koerner

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Materials & Manufacturing Directorate

Extreme Environments

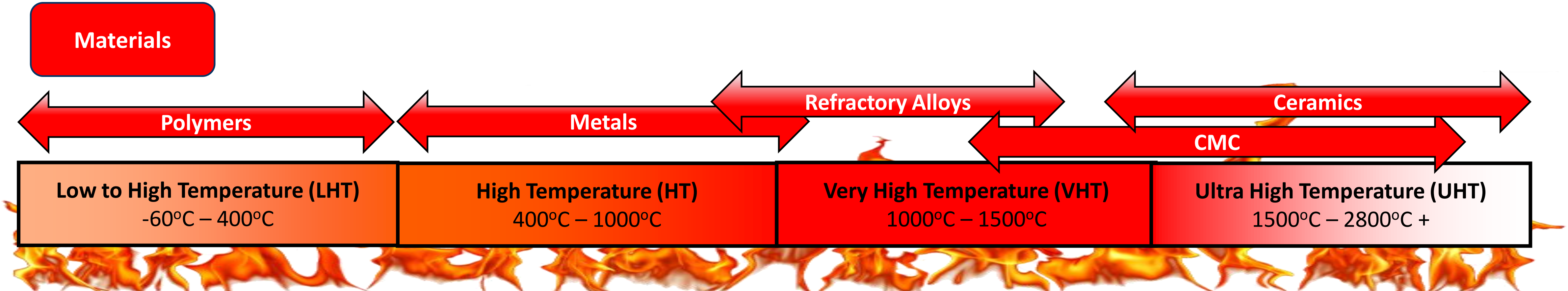
- Temperature, something we can immediately relate to

- Everybody has their own definition of Extreme Environment. RX and is Materials and Mfg focused

Materials

- metals
- polymers
- ceramics
- layered hard/soft materials
- additively manufactured structures
- architected structures

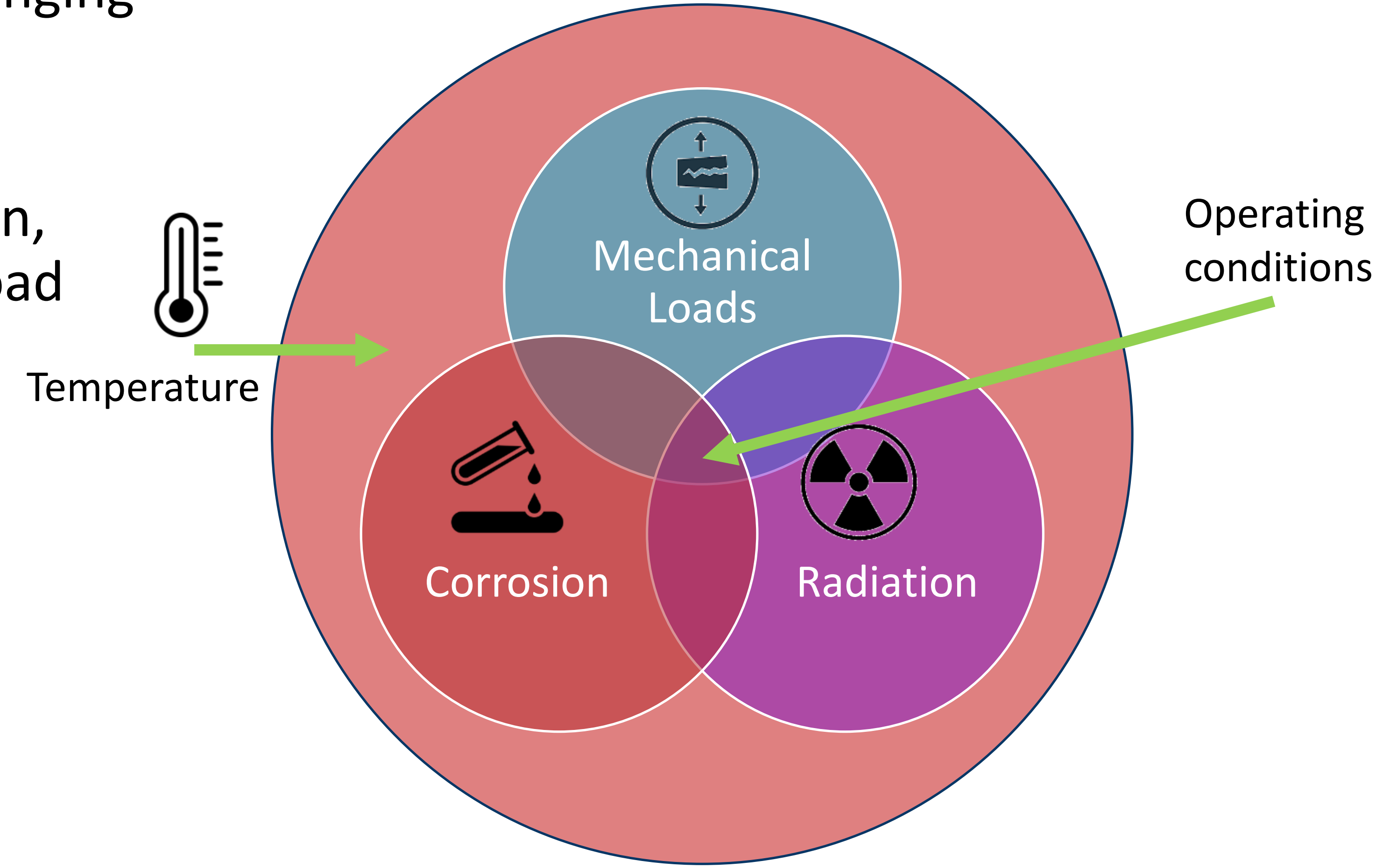
Limits on materials behavior are among the greatest technical obstacles to achieve required performance



Definition of Extreme Environments

Materials behave in unexpected and unpredictable ways
Combinations are most challenging

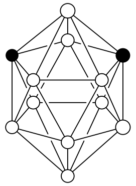
- Temperature
- Mechanical impact, vibration, acoustic, shock, pressure, load
- High energy EM impact, impulse, discharge, pulse
- Radiation
- Chemical environments
- Combinations

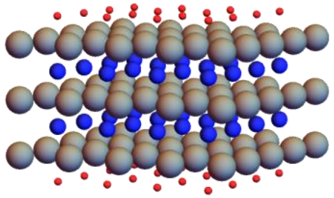


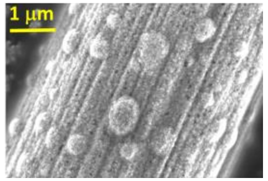
Multi-scale Dimensions

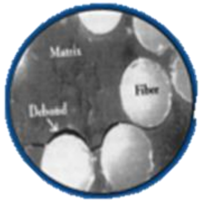
- Performance dictated by defects over length and timescales
- Loads over seconds vs loads over milliseconds. E.g. impact vs load.

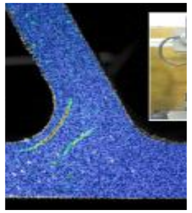
Atomic Nano Micro Macro











ns µs ms s

Length Scale / Time Scale

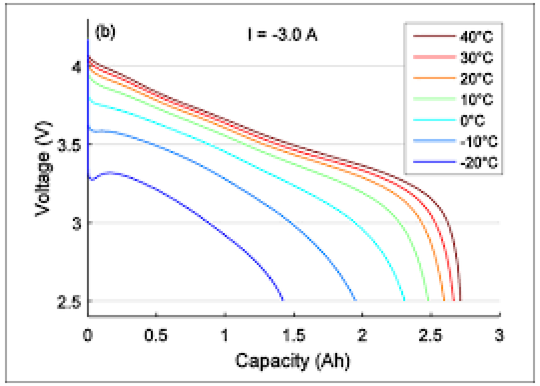
Arctic – Human Performance Aided by Materials Science

DAF ~ 80% of DoD resourcing to the Arctic

Provides access to harsh and remote locations (-60 F)

Airmen first to the scene

- tight spaces, little mobility
- thermal insulating
- waterproof, keeping folks dry
- temp resistant (so no brittleness); heat providing (heated textiles);
- lightweight
- battery issues in cold

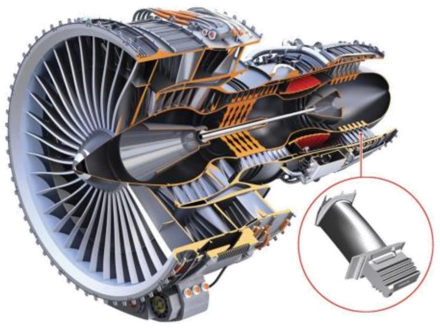


Nancy Kelley-Loughnane
Jorge Chavez Benavides

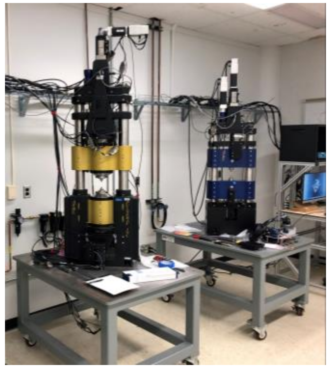
Jet Engines (Metals)

Turbine blades in jet engines operate close to melting point in an oxidative environment;

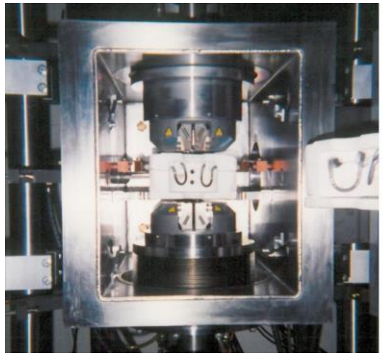
- Need **integrated** characterization tools, ability to get to 1000C in a load frame and **combine** with mechanical loading, with +- 5C certainty in temperature with minimal gradients
- Explore new techniques that **exploit physics** to characterize material state in extreme environments
- In non-inert gas backfills



Robotic Testing



RAMS IV - Testing

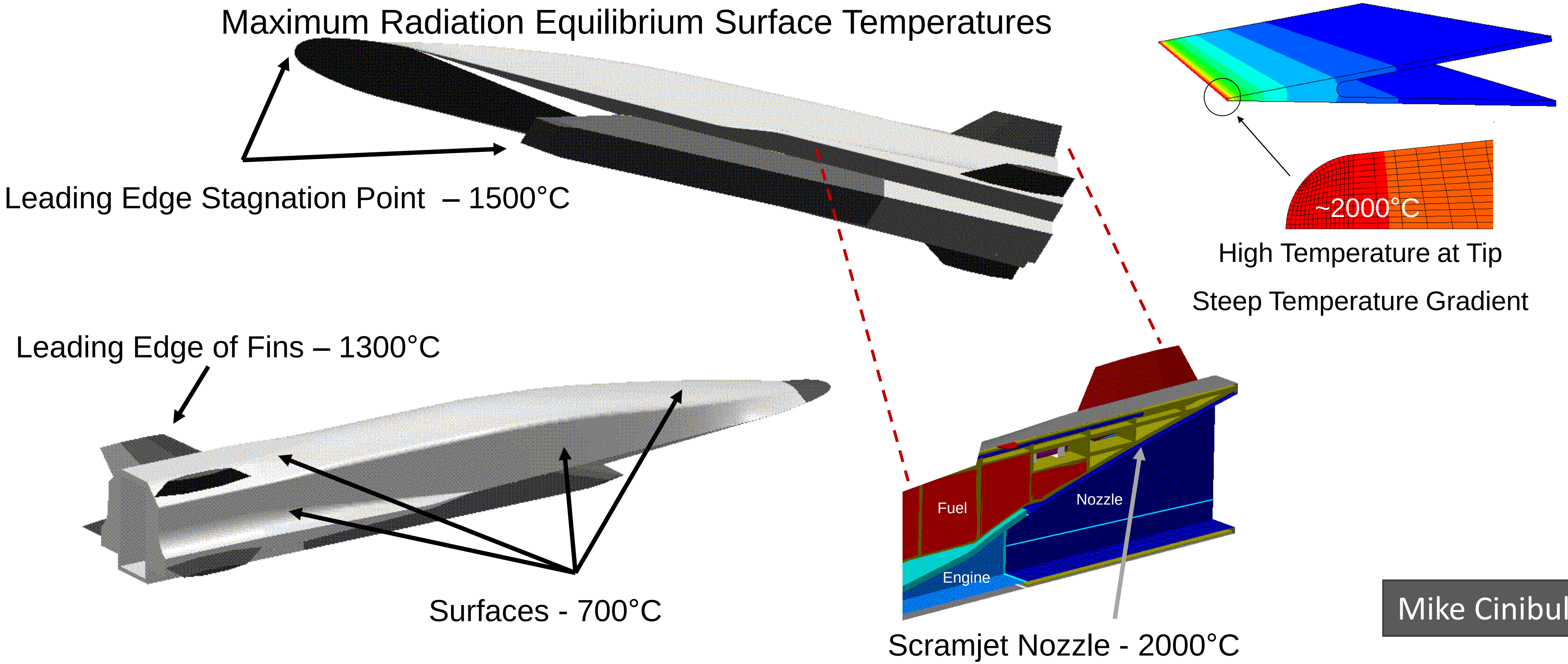


HT Vacuum Furnace

Todd Turner

Hypersonic Flight (Ceramics)

Material Temperature Requirements for Scramjet Powered Flight, 5 < M < 10



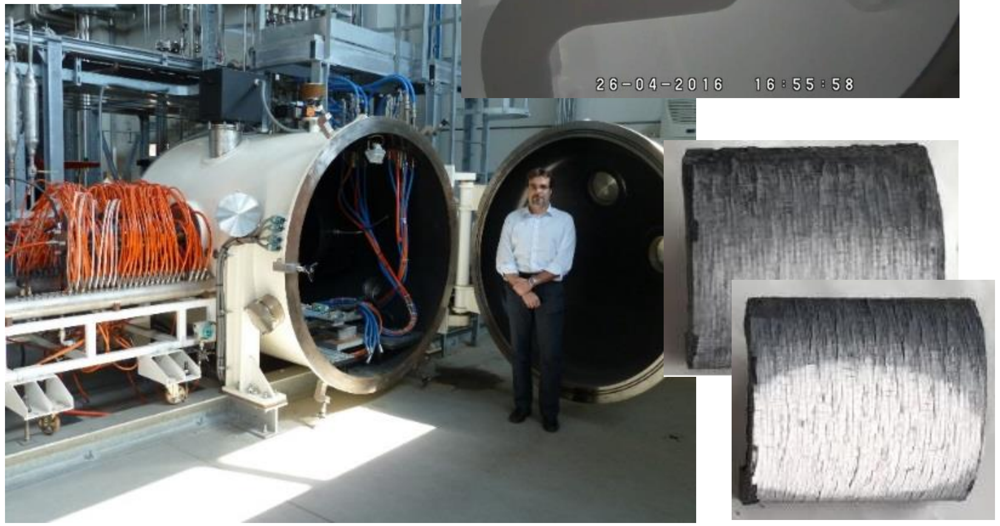
Mike Cinibulk

Lower speeds, yet similar temperatures as blunt re-entry vehicles

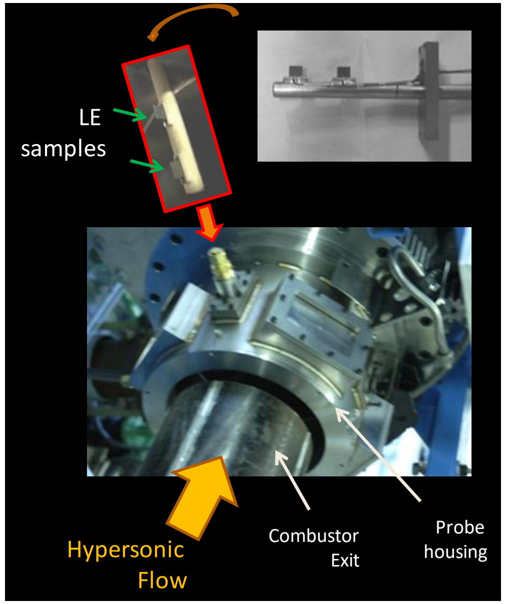
Hypersonic Flight (Ceramics)

- Understand Effect of Environment on Material Behavior and Performance
- Improvements in ground-based testing required to better understand material behavior

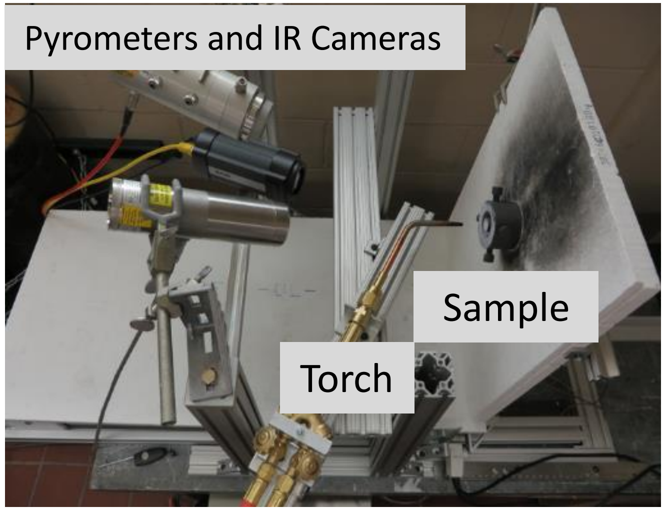
Arc Jet Testing



Italian Aerospace Research Centre (CIRA): Ghibli Arc Jet



Scramjet rig at Mach 7



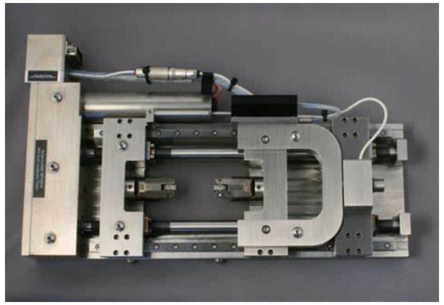
Torch Testing

Mike Cinibulk

Characterization
Relevant environment (torch, arc-jet)
Microstructure before & after testing
Mechanical before & after testing

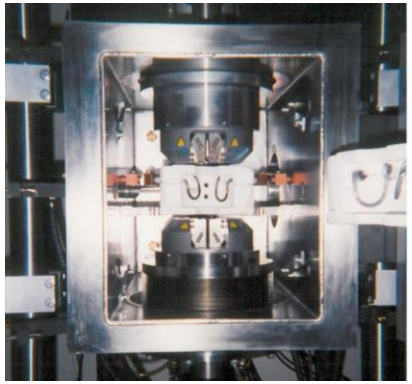
Measurement Science for EE

in situ optical load Stage



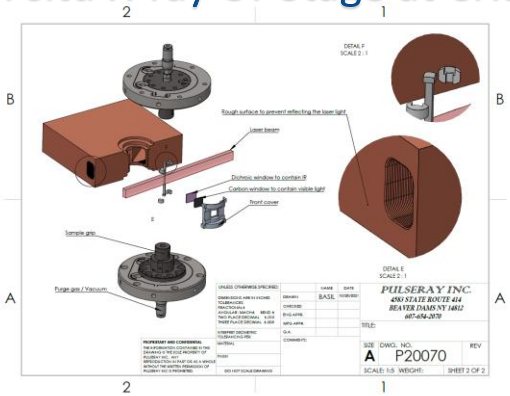
- *Low profile*
- *Two sided imaging*
- *Dual actuators*

High Temp Vac Furnace Mechanical Test Frame



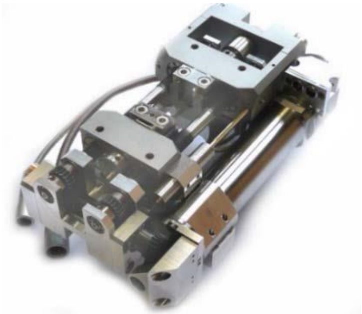
- *2500°C Temperature Capability*
- *8 in diameter by 10 in high hot zone*
- *Vacuum/inert environment*

in situ X-ray CT Stage at CHESS



- *Laser heating*
- *Vacuum/inert environment*

in situ High Temperature SEM Stage (5k Newton)



- *1200°C Temperature Capability*
- *Edge on sample viewing*
- *Vacuum environment*

Nextgen xCT

Desired features...

- *Larger samples (up to 12”)*
- *Higher power*

Craig Przybyla

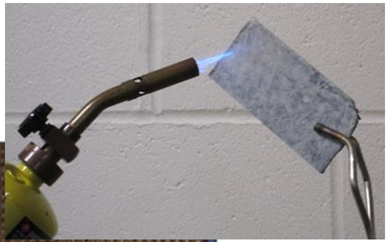
Simulating Hypersonic Flight (Ceramics)

No single test facility accurately simulates hypersonic flight

- Factors affecting performance
  - Heat flux
  - Stagnation temperature
  - Stagnation pressure
  - Fluid velocity at material surface
  - Fluid composition
  - Chemical recombination
  - Mechanical vibrations
  - Thermal shock

Mike Cinibulk
Carmen Carney

Geopolymers for rocket cargo



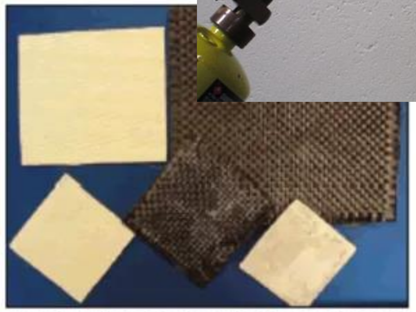


Figure 2. Various geopolymer-based composite panels fabricated with aluminum oxide, carbon, and steel fiber reinforcements

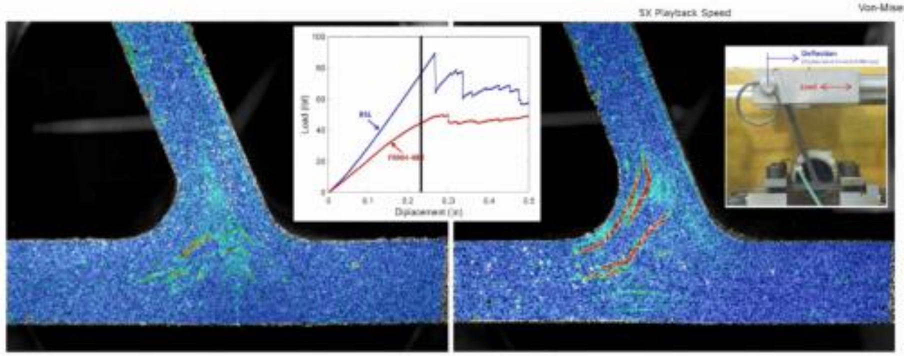
- emissivity above ~1500C ?
- direct measurements of thermal conductivity ?

Jacob Monzel

Biggest challenge is to accurately simulate in a cost-effective way. Develop combined environments (thermal-mechanical-ablative-vibratory)

Performance of Complex Polymer Matrix Composites (Polymers)

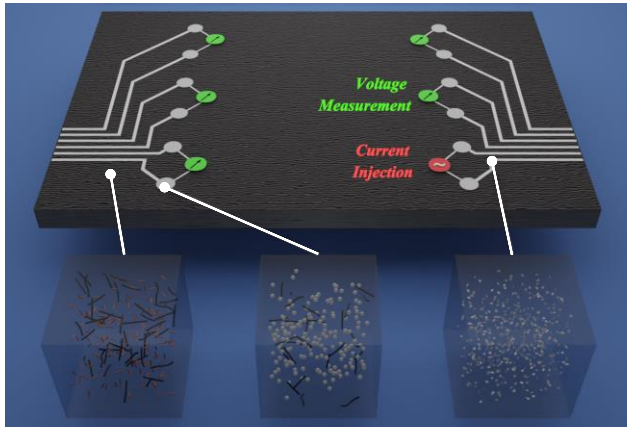
- Couple real-time experiments to damage physics and validate predictive models of crack propagation and initiation
- Combined real-time experiments (X-ray CT, SAXS, mechanical)
  - Measurement at temperature (up to 500C)
  - Beyond 2D surface characterization



Davide Simone
Hilmar Koerner

- Need ability to probe complex shapes using real-time X-ray CT.. Mechanical rigs that fit into environmental chambers and characterization equipment (e.g. beamlines).

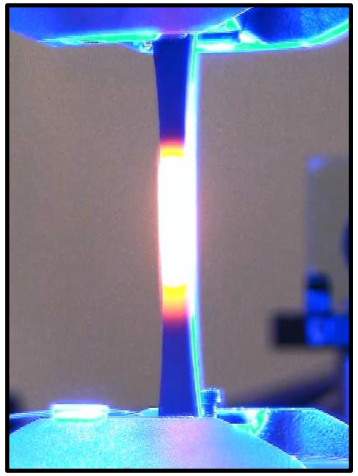
- Detect and localize defects in additively manufactured limited life technologies, such as drones. Structural health monitoring under EE in spatially confined systems. Example: electrical impedance tomography; short lifing for attritables

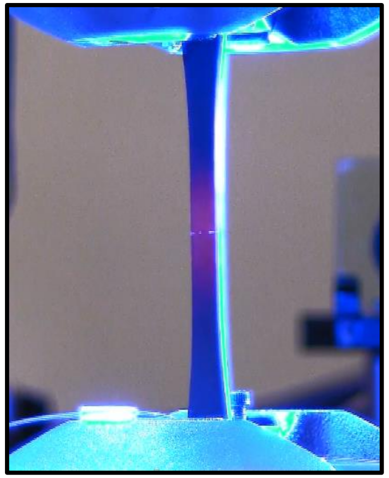


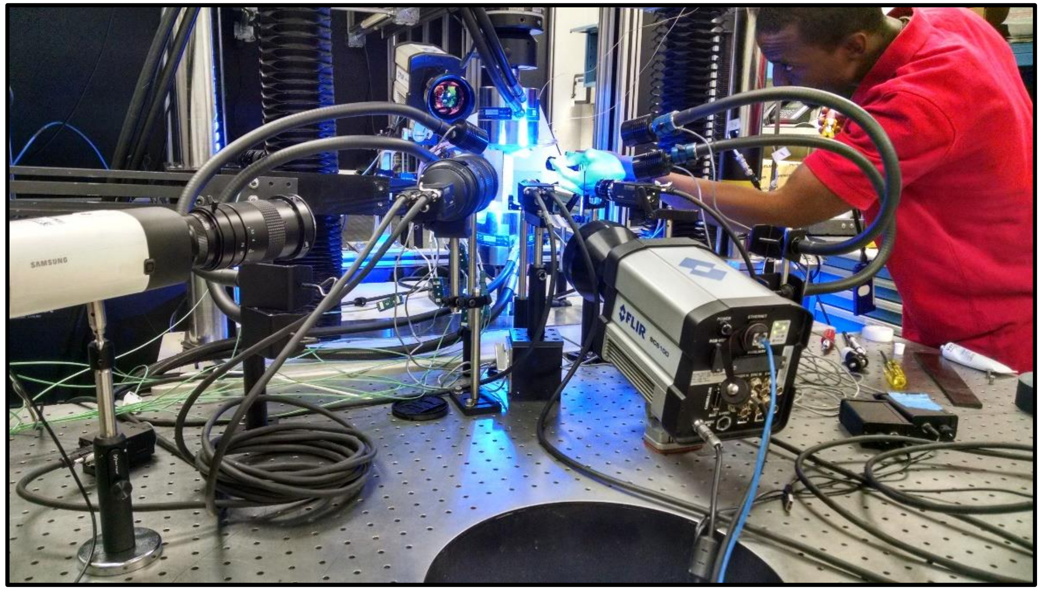
John Wertz

RHINO (Rapidly Heated INvestigation Of) Materials Laboratory

- Variety of high temperature (via laser heating) mechanical, chemical, and optical experiments
- Key limiting factor is not having *in situ* microstructural data in addition to the time and limited utility of post-test microstructural data alone
- *In situ* microstructural evolution with laser heating would be traceable to thermal/mechanical testing in realistic and relevant environments @ the LHMEL facility.







Jonathan Vernon

Modeling Performance (Material Degradation)

Flight Trajectory
Altitude (t)
Velocity (t)
Sample geometry

↓

Aerothermal Conditions →

Experimental Data from Diagnostics →

↑

Ground Test
MOATR, LHMEL, Scramjet, Arcjet

Test Environment
Heat flux (t)
Total temp (t)
Fluid velocity (t)
Static pressure (t)
PO_2 (t), PH_2O (t)
PO (t), PO^+ (t)

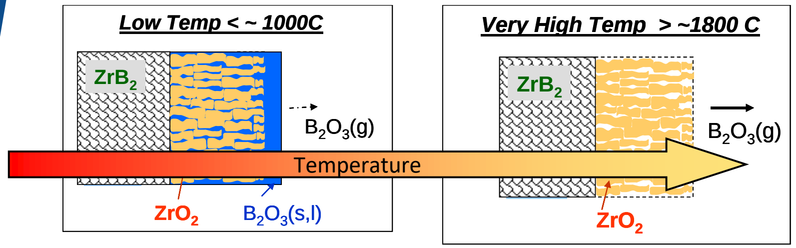
Environmental Effect

Oxidation Model
I: External glass layer,
II: MeO_2/glass layer,
III: Internal depletion zone

Scale composition, viscosity ↓ ↑ Scale loss

Recession Model
Static pressure (t)
Fluid velocity (t)
Glass viscosity (t)
Oxide scale integrity => Erosion (t)

Material Life Prediction Model
Oxidation and Recession
Erosion of Lead Edge
Mechanical Failure (thermal stress)



~1000˚C ~1800˚C

Reliable experimental data needed for many model parameters

- Permeabilities of CO and H_2O in borosilicate glass
- Better data on interdiffusion in borosilicate glass
- Quantification of glass fraction in MeO_2 scale
- Explore machine learning, statistics, and artificial intelligence strategies

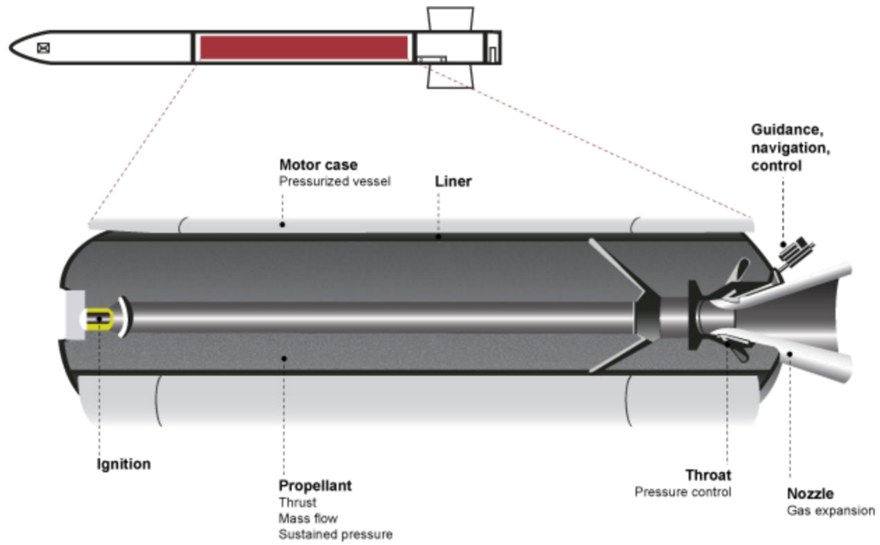
Mike Cinibulk

Rocket Propulsion (Polymers)

RQ West challenges:

- Skin temperatures of 1000 F at Mach 5 for short durations (20 s) on surfaces that are polymer-based in their composition. Goal is to eliminate required parasitic protective mass on booster surfaces
- Interior of solid rocket motor during combustion, temperatures of 5000 F with heat fluxes up to 800 BTU/ft^2-sec are encountered, for periods up to 30 seconds
- Additively manufacturable elastomers that retain their properties in extreme hot and cold environments as binders in solid rocket motors

Simplified Illustration of a Solid Rocket Motor

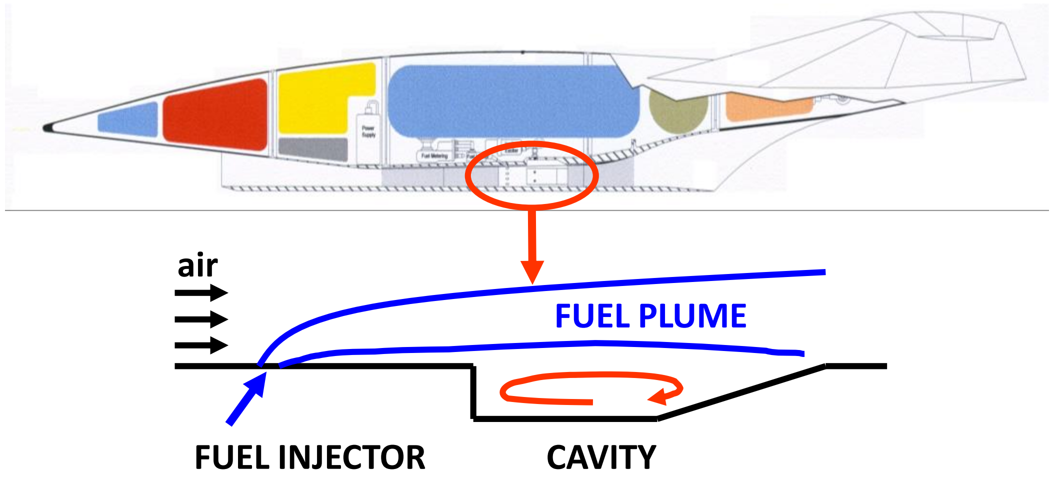


Source: GAO rendering of information provided by Orbital ATK and Department of Defense. | GAO-18-45

Greg Yandek
Levi Moore

Liquid-fueled High-speed Air-breathing Propulsion System (Organics)

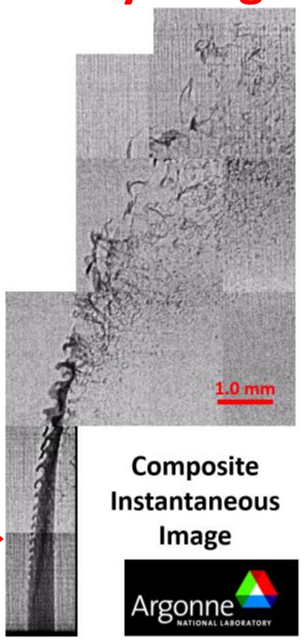
- Pure- and Aerated-Liquid Jets in Supersonic Crossflow



- Diagnostics are needed for plume properties
  - Column breakup dynamics
  - Liquid mass distributions
  - Needs of data for developing numerical predictive tools in supersonic crossflows
  - Explore with different surface tension, viscosity or Mach number

X-Ray Imaging

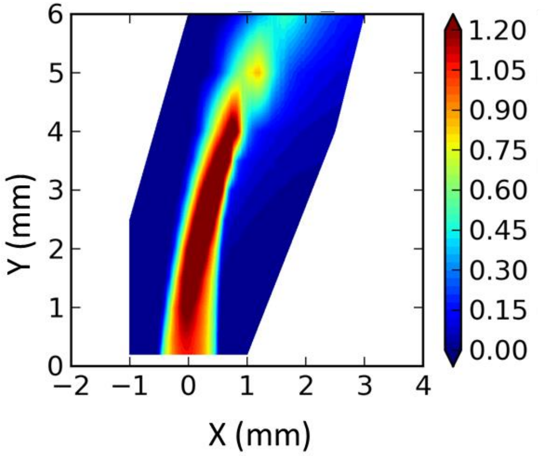
Mach-0.3 Crossflow



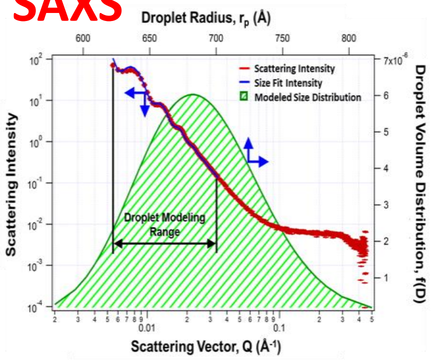
X-Ray Radiography

M=0.3, d_0=1.0 mm, $\dot{m}_L$=10.7 g/s, q=13.8, GLR=0

Time-Average EPL



SAXS

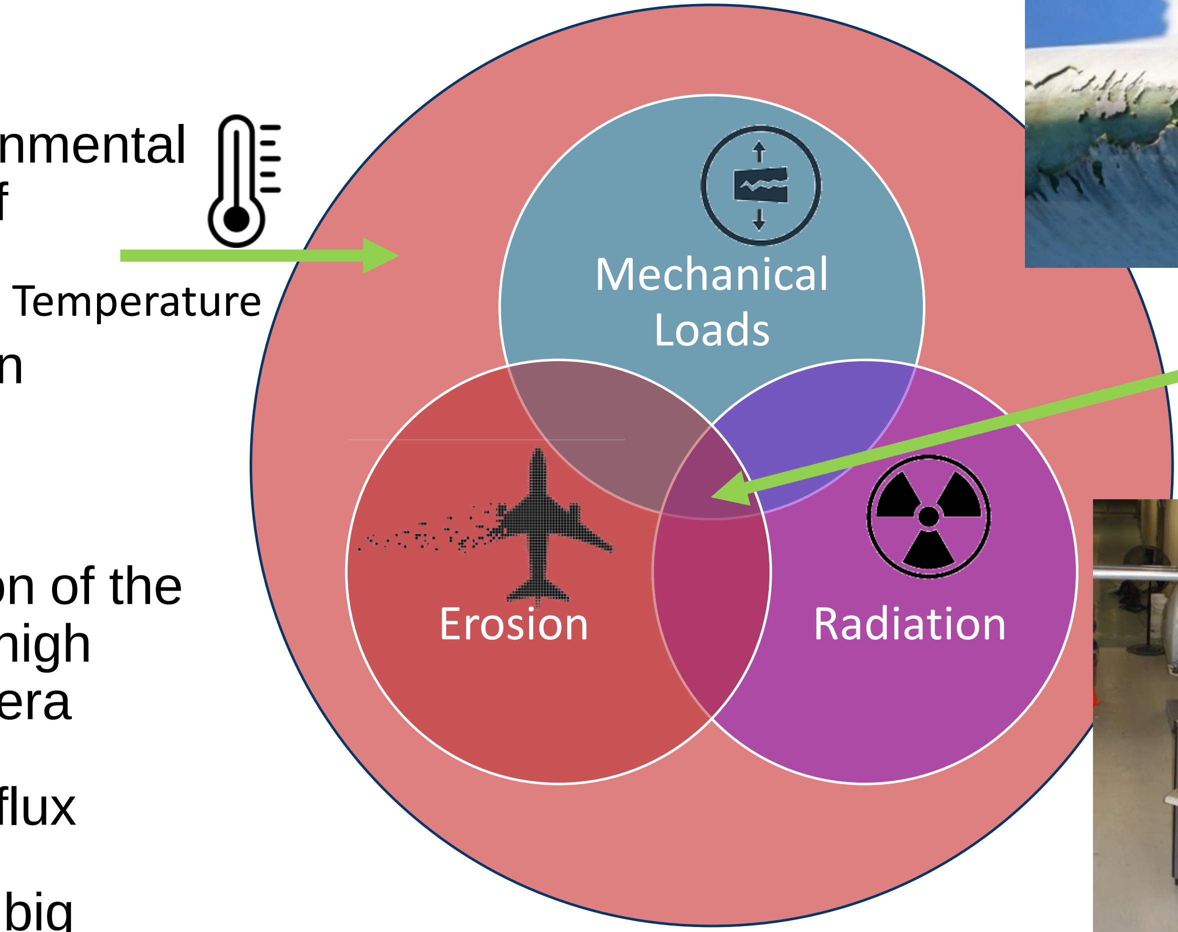


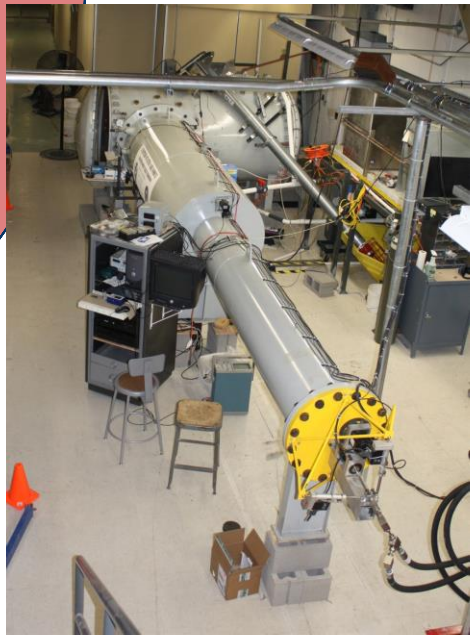
Cam Carter
campbell.carter@us.af.mil

Aerospace Propulsion Division

Erosion under EE

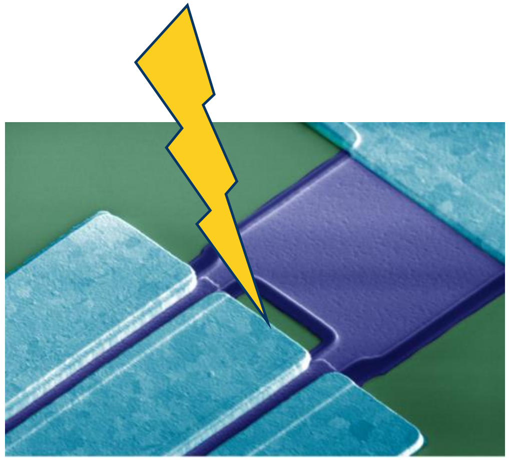
- Hot erosion rig can test environmental particulates at temperatures of ~1300C
- Supersonic rain erosion rig can perform rain impact testing at velocities of ~mach 2.3
- Need for better characterization of the velocity and path of particles, high speed or multispectral IR camera
- Need burner rig to study heat flux
- Currently no modeling done – big opportunity





Chad Hunter
Matthew Hartshorne

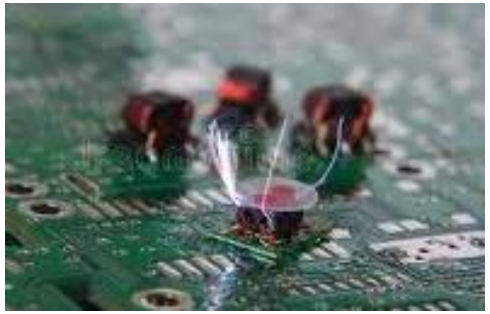
Semiconductor Devices (Inorganic/Organic)



- Challenges in determining failure mechanisms via in-situ IV characterization at high temperatures
  - Under microwave/RF.
  - Contacts, feed-throughs, and/or wiring (passive components) fail above 300 C
  - Maintaining homogeneous temperature (>500 C) over large wafers (limited commercial solutions)

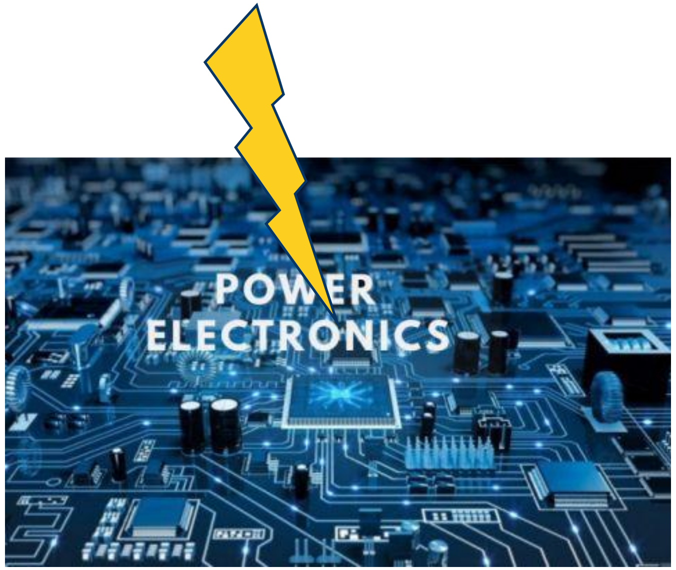
AFRL/CoolCAD/Cornell

- In-situ device testing under combined radiation and/or thermal+radiation almost impossible with current test facilities
- Quantifying secondary effects of ionizing radiation requires in-situ characterization beyond IV curves. No current capabilities in in-situ microscopy or tomography under radiation (not space)
- Lack of mesoscale modeling able to connect in-situ characterization to predictive performance/failure in real-world environments.



Josh Kennedy
Todd Turner
Adam Neal

Semiconductor Devices (Inorganic/Organic)



- How to measure and predict heavy ion radiation causing transient error or catastrophic failure (Single Event Effect, Single Event Burnout). Wide bandgap materials for RF and Power electronics application (e.g. at BNL)
- Other radiation sources (photon (x-ray, gamma ray), proton, neutron, and pulsed-laser) useful for fundamental material study of wide bandgap semiconductors.
- Need structural characterization (i.e. TEM) under strategic radiation environment

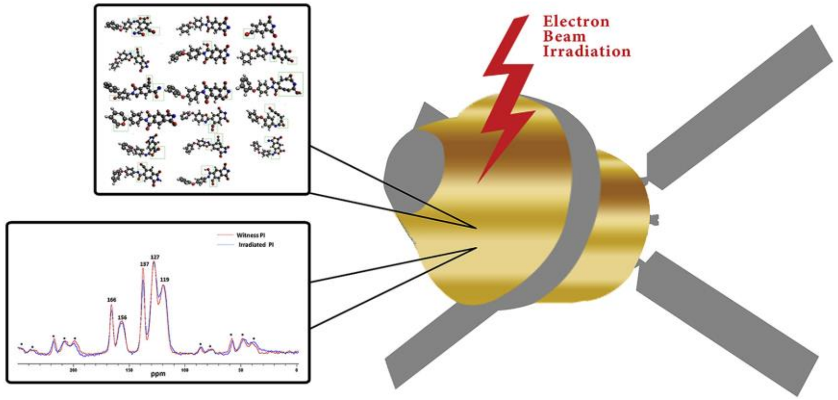
No one type of radiation is appropriate for the entire space environment (Si logic, solar cells, and wide bandgap power and RF transistors)

Josh Kennedy
Todd Turner
Adam Neal

Satellites (Polymers)

Space environment (GEO), commonly used by military and communication satellites

- Vacuum and drastic temperature swings
- Space radiation and unusual corrosive chemistry (atomic oxygen)
- Broad-spectrum electron, proton, and photon fluxes that all interact to:
  - degrade materials performance
  - cause subtle effects* (e.g. spacecraft charging, single event upsets and reaction wheel failure)



*subtle effects are most challenging, cause ~ 50% of spacecraft anomalies, difficult to diagnose.

Ryan Hoffman

Summary

- Measurement science in EE – equipment, sensors and facilities
- Combined environmental effects – stress and temperature, austere environment, radiation testing and characterization
- Capture multiphysics behavior (structural and functional) across length scales, dependent on testing environment and looking at effects and performance
- Modeling combinations of EE and predicting performance – effective use of ML/AI tools

QUESTIONS?