General Atomics Electromagnetic Systems

Advanced Manufacturing at GA-EMS and Accelerated Fuel Qualification

08 November, 2021

Presented To: AMME Virtual Workshop on Advanced Manufacturing
Generation IV International Forum (GIF)

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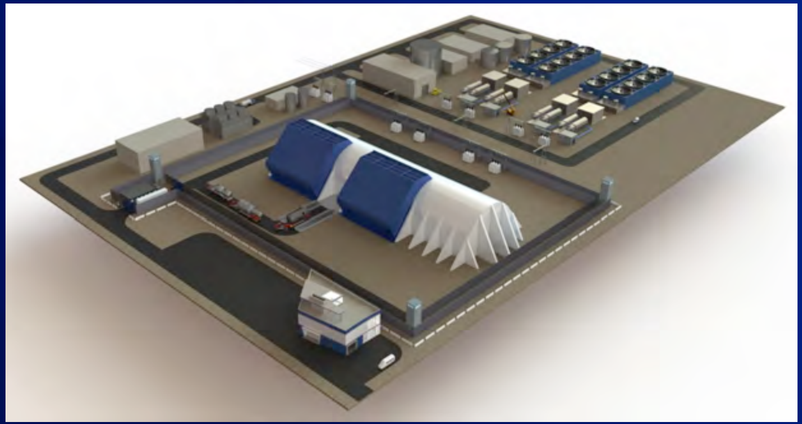
Scientist
Nuclear Technologies and Materials



250 MWe Energy Multiplier Module

50 MWe Fast Modular Reactor

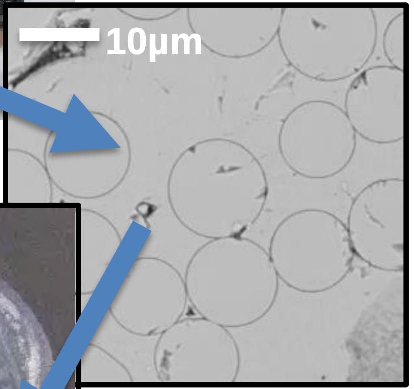
Nuclear Thermal Propulsion

Powering Innovation

SiGA® Technology
Silicon Carbide – General Atomics

Material Fabrication and Performance Requirements For Current and Advanced Reactors Are Cross-Cutting

SiC Fiber



Composite

Requirements	ATF Cladding	Channel box/other	Adv. Fission
Large-Scale Structures	✓	✓	✓
SiC Joints & Complex Structures	✓	✓	✓
High DPA Irradiation Resistance			✓
High-Temp Performance	✓	✓	✓
Impermeability	✓		✓
Good Thermal Conductivity	✓	✓	✓
Corrosion Performance	✓	✓	✓
Pellet-Cladding Interactions	✓		✓

SiGA® combines: Composite SiC (strength, toughness)
Monolithic SiC (hermeticity, corrosion)

Current Capabilities Supports Production of SiGA® Prototype Components

- **Chemical Vapor Infiltration/Deposition manufacturing at GA-EMS:**
  - Tubes up to 15” (hundreds/batch)
  - Tubes up to 36” (tens/batch)
  - Tubes to 144” (demonstration basis)
  - Planar/test coupons (hundreds/batch)
  - Complex structure demos (small batch)
  - Ceramic to Ceramic joints (tens/batch)

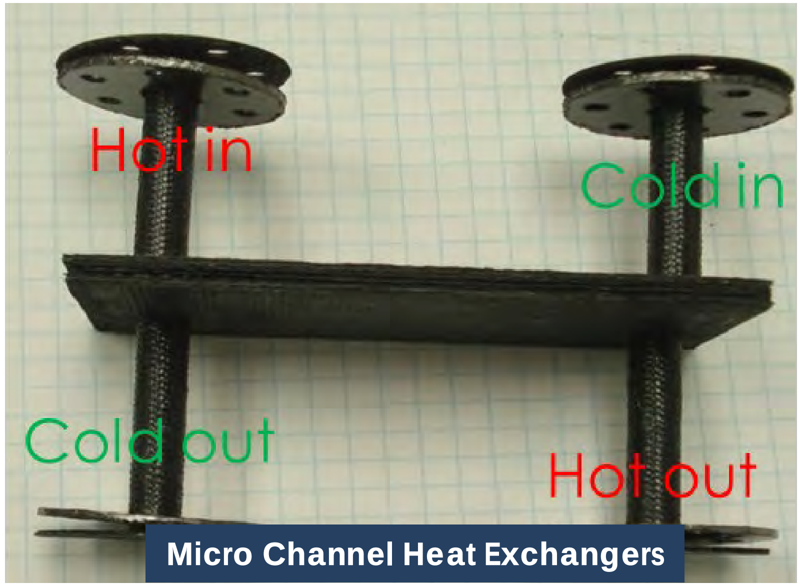

Sealed Cladding Via Local Joining


Flared Tubes for ASTM Round Robin


Honeycomb Insulation


Planar for Thermo-mechanical Testing

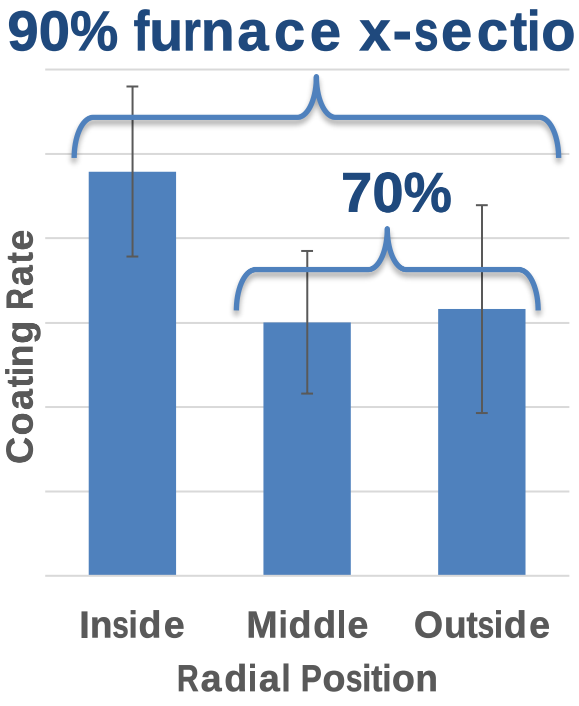
Cladding

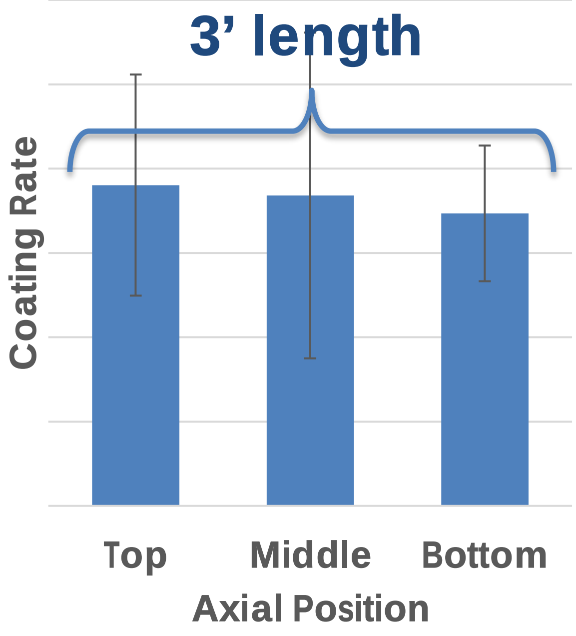


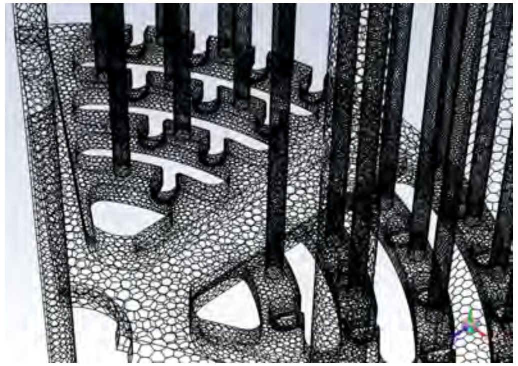
Micro Channel Heat Exchangers

SiC Coating Process Simulation Implemented to Support Full-Length Scaling

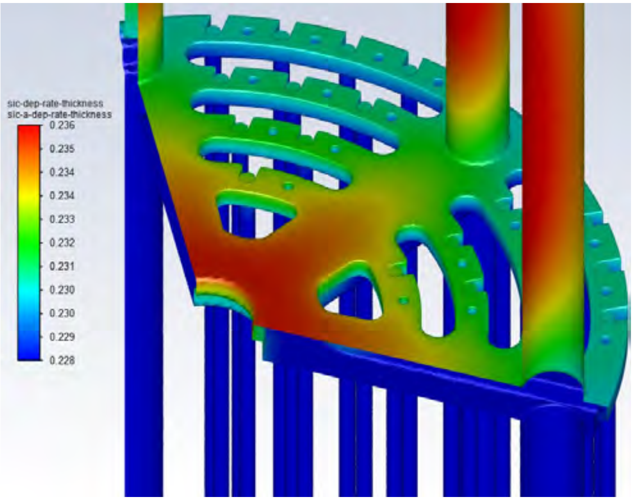
- **Implemented CFD modeling of CVD process**
  - Supports densification improvement
  - Process, fixture design refinements
- **Radial, Axial uniformity improvement**



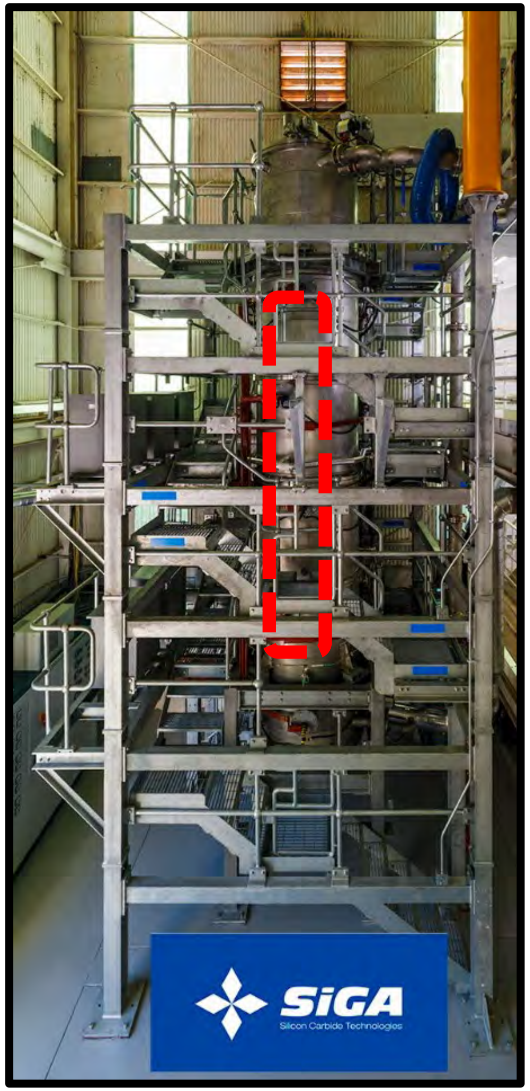




Simulated coating rates



~10m tall

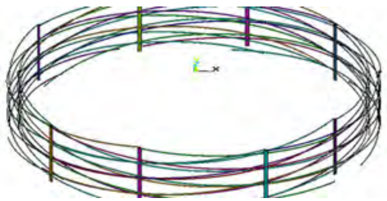


Composite FEM Used to Predict Performance For a Given Fiber Architecture

- **Finite element model gives stress-strain of SiC-SiC**
  - 3D model capable of utilizing a wide variety of complex fiber architectures
- **Model inputs include:**
  - Fiber Preform
  - Fiber Tow Properties
  - Matrix Properties
  - Dimensions

Example Input Data for Fiber Tow

Property	Value
Dimensions	1.25 x 0.15 mm
Elastic Modulus	301 GPa
Tangent Modulus	61 GPa
PLS Strain	0.16 %
Failure Strain	0.80 %



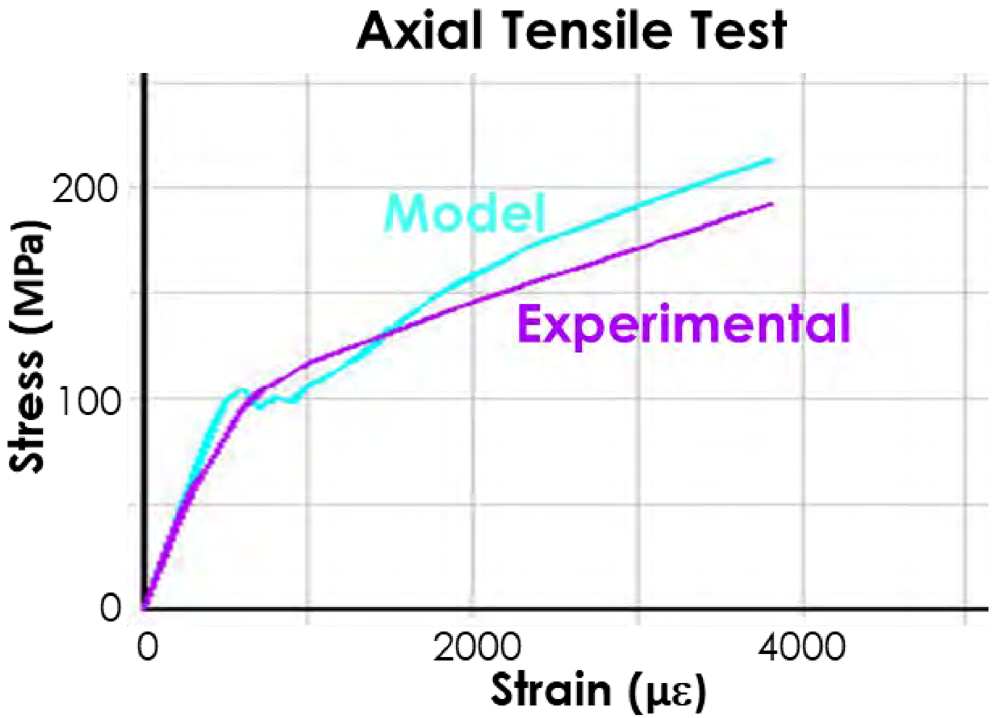
Initial Architecture

Meshed fiber preform

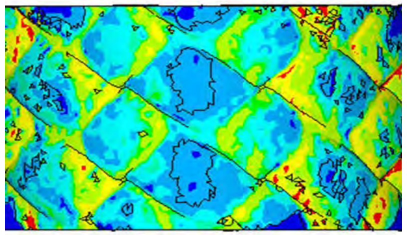
Same preform with matrix added

Mechanical Response is Predicted on Both Micro and Macro Level

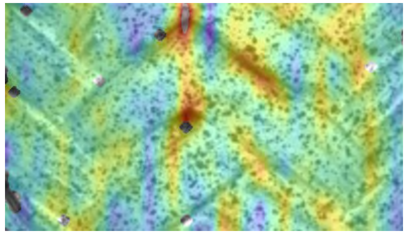
- **Non-linear composite response is captured in model**
  - Matches closely to experimental stress-strain
- **Model used to predict localized stress and strain**
- **Ultimately need is to simplify for incorporation into other models**
  - Unit Area Approach
  - Super-elements
  - Direct Coupling



Localized Strain Hoop Testing

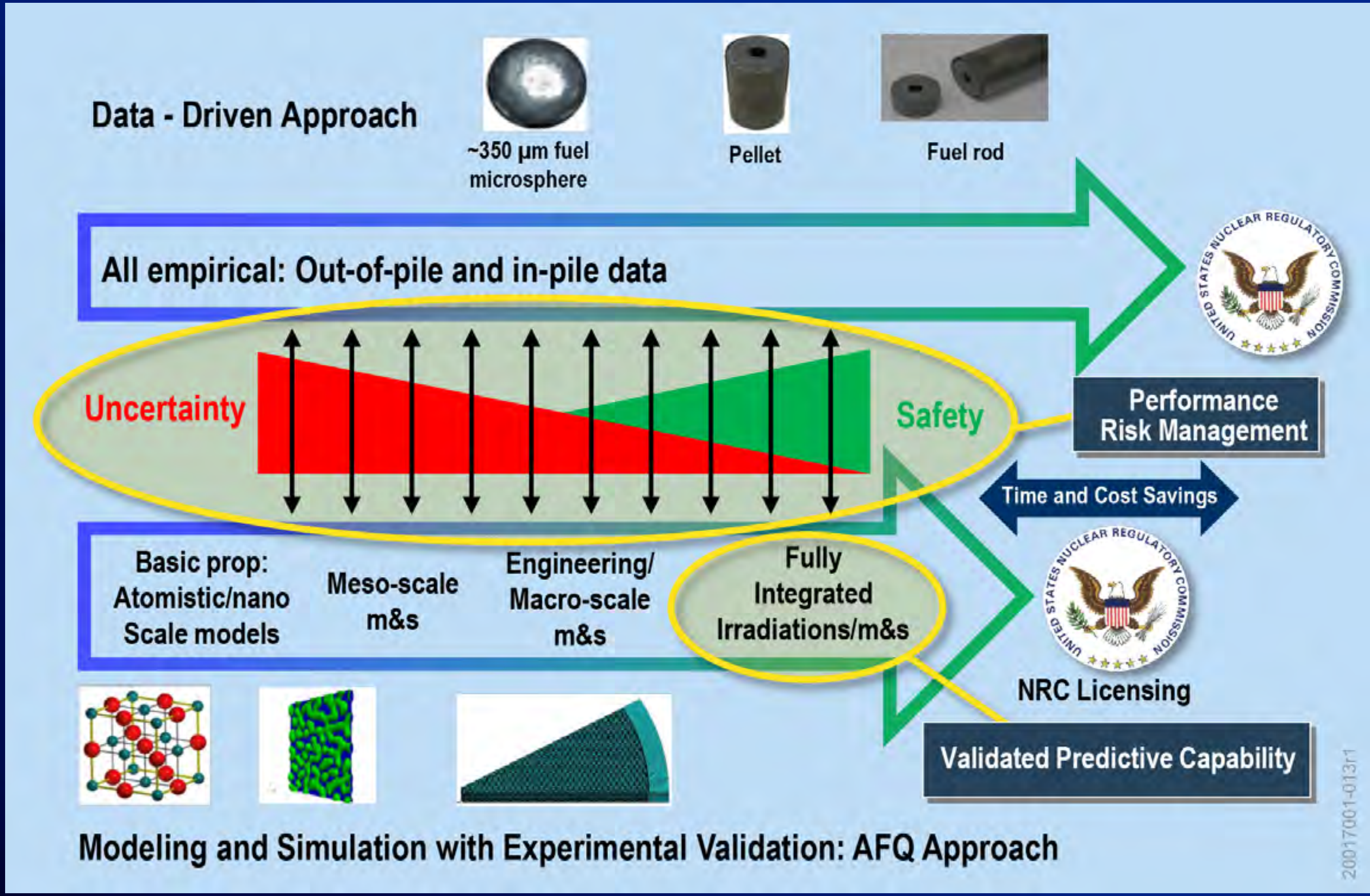


Model



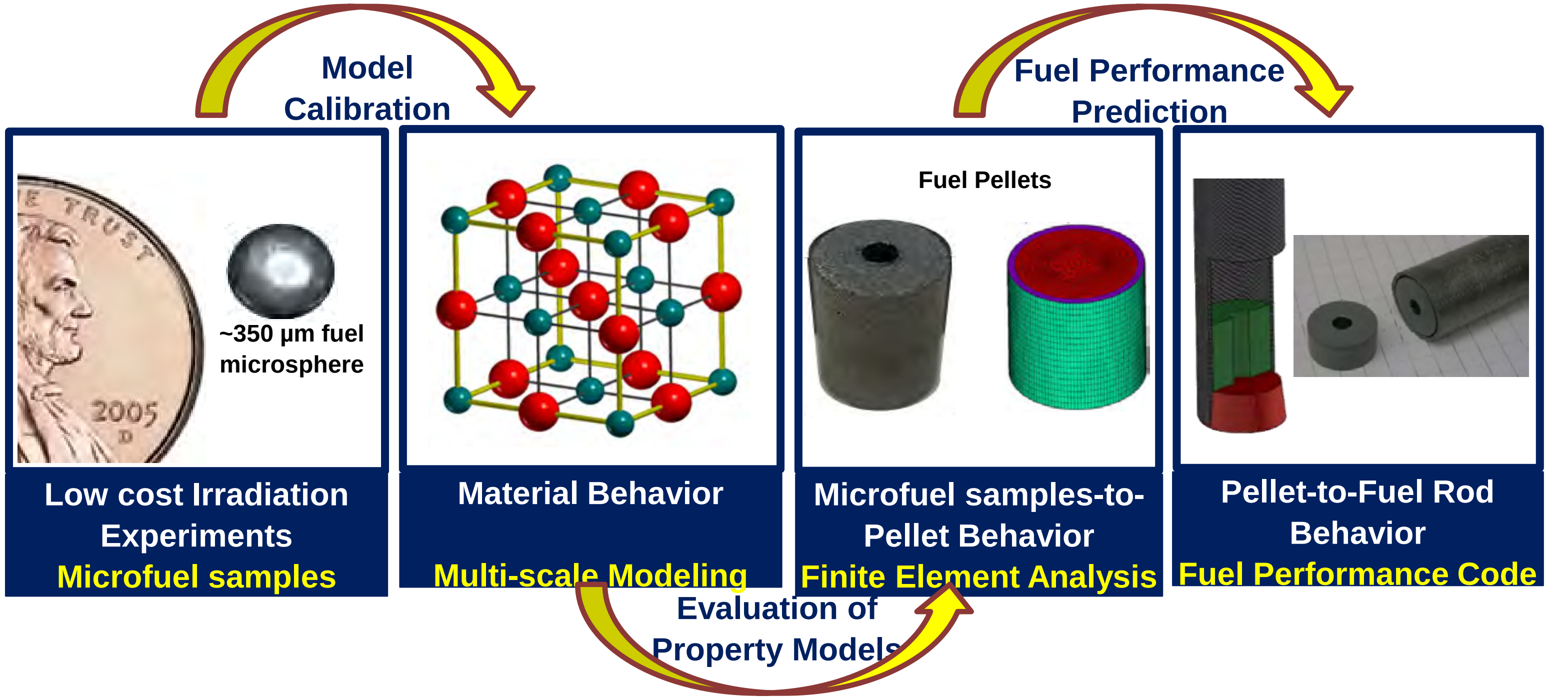
Experimental (DIC)

Accelerated Licensing - The Proposition



Modeling and experiments must be simultaneously exploited to markedly reduce the years of data that would otherwise be required for deployment of new harsh environment nuclear fuels and materials

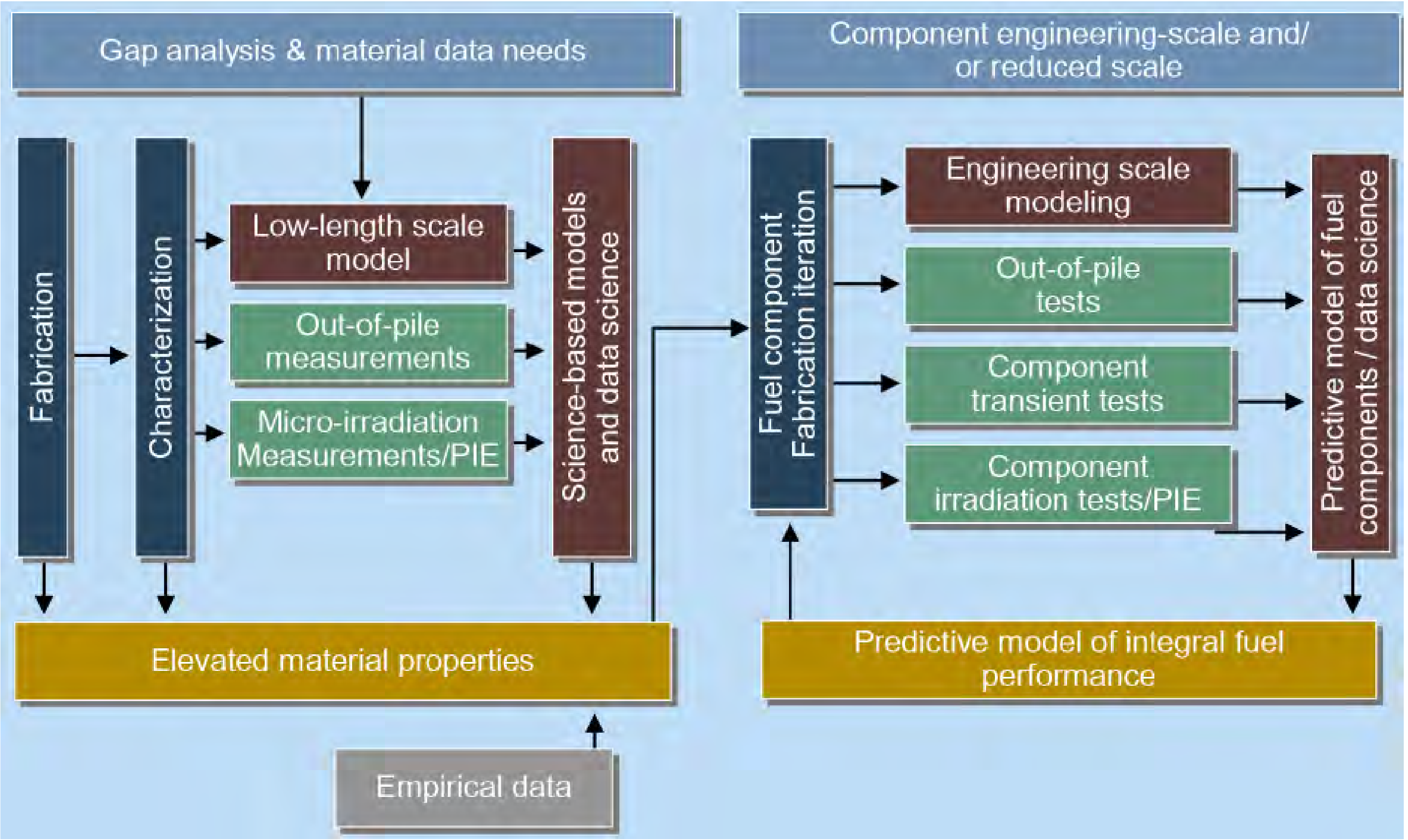
Accelerated Fuel Qualification (AFQ)



The combination of microstructurally-informed advanced nuclear fuel performance modeling and simulation (M&S) tools with targeted irradiation and other select experimental data that can significantly reduce the cost and number of irradiation experiments, and, ultimately the cost and time associated with new fuel qualification.

Three Phase Approach to AFQ

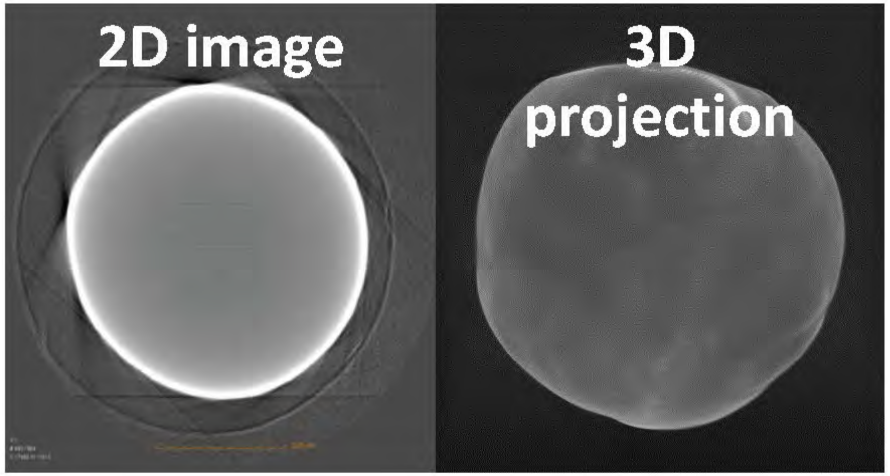
- **PHASE 1: Expedited materials testing and screening of fuels systems**
- **PHASE 2: Separate effects testing coupled with integral fuel analyses**
- **PHASE 3: Integral fuel testing and validation**

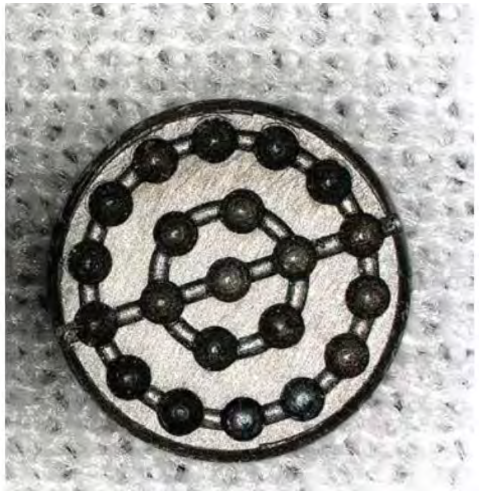


Phase 2 Workflow for iterative analyses and testing

UC Fuel Form is Being Used as a Demonstration of AFQ

- **US DOE-NE funded demonstration using UC**
  - EM^2 uses UC fuel, also a fuel of interest for NTP
- **Fuel Fab, Modeling, and Irradiation effort**
- **Key data for phase I & 2 AFQ**
  - Approach: Small, but mighty

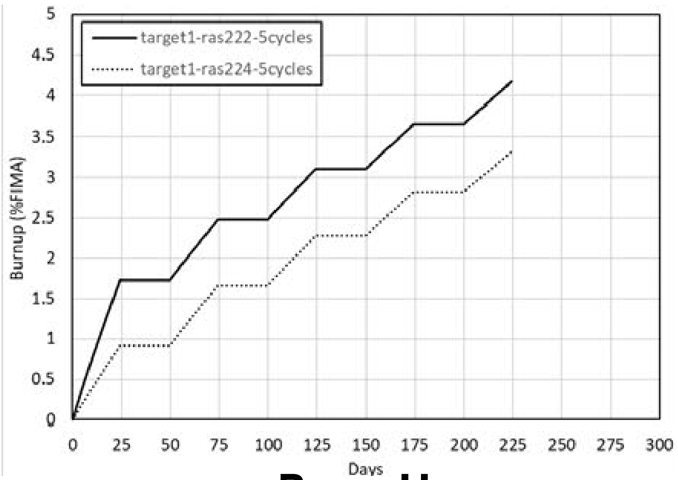




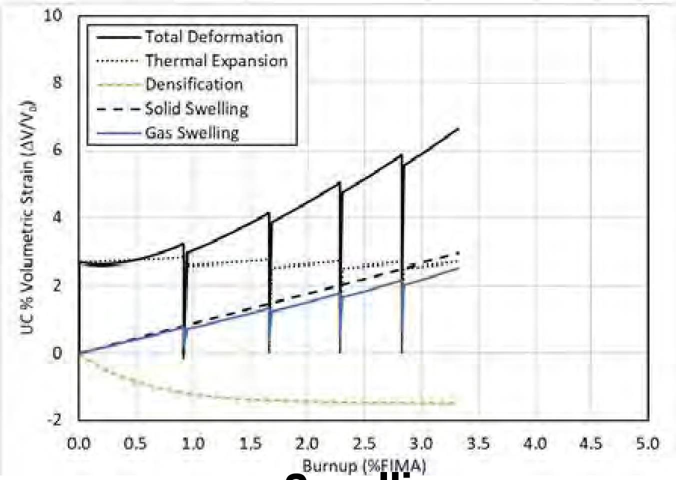
OAK RIDGE National Laboratory

Specimens Are Currently Being Irradiated at HFIR

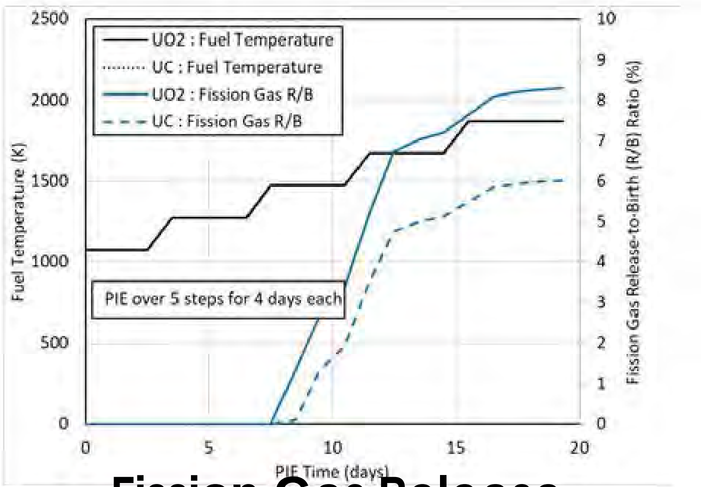
- **Irradiation over multiple cycles in HFIR**
- **Fundamental properties for model validation**
  - swelling, fission gas release, microstructure
- **Post-irradiation heating tests to measure fission gas release at elevated temperature**
- **BISON being used to capture preliminary fuel performance**



Burn-Up



Swelling



Fission Gas Release

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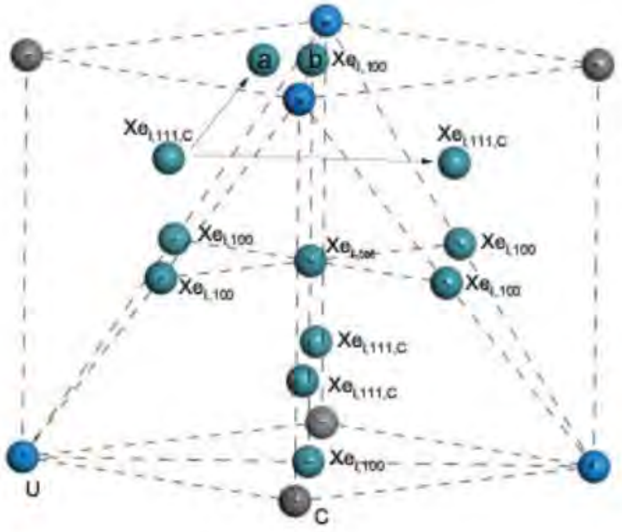
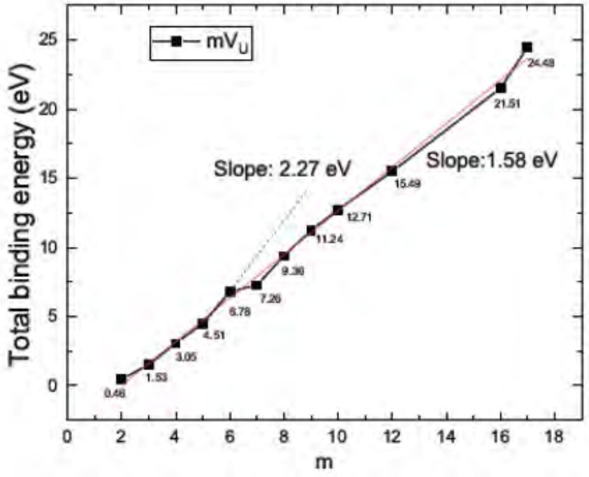
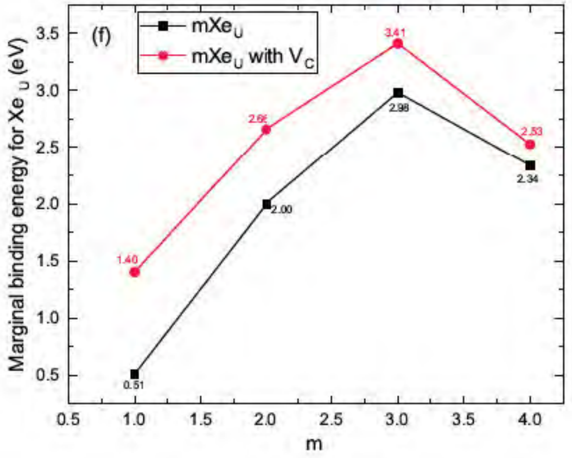
ELECTROMAGNETICS

Simultaneous Effort to Model UC Mechanisms and Behaviors

- Ab-initio electronic structure modeling of Xe behavior, diffusion, and clustering in UC
- Density Functional theory calculation of vacancy and Xe clustering
- Parameterization of bubble populations using Xolotl calculations







THE UNIVERSITY OF TENNESSEE KNOXVILLE

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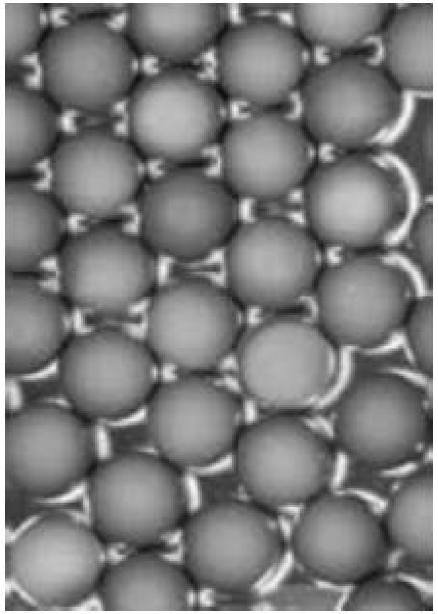
Next Step is Accelerated Irradiation at Advanced Test Reactor

- **Accelerated irradiation of UC pellets using Idaho National Laboratory Fission Accelerated Steady-State (FAST) capsule design and approach**
- **Reduced size pellets key objectives:**
  - Fission gas release
  - Fuel Swelling
  - Creep
  - Microstructural Evolution
  - Validate science-based models

Idaho National Laboratory



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AFQ is Gaining Traction

ACCELERATED FUEL QUALIFICATION WHITE PAPER

PRE-APPLICATION LICENSE REVIEW OF SILICON CARBIDE COMPOSITE CLAD URANIUM CARBIDE FUEL FOR LONG-LIFE GAS-COOLED FAST REACTOR CORES

ENERGY MULTIPLIER MODULE ACCELERATED FUEL QUALIFICATION STRATEGY

Prepared

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JOURNAL OF NUCLEAR MATERIALS

Accelerating nuclear fuel development and qualification: Modeling and simulation integrated with separate-effects testing☆

Check for updates

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Accelerated Fuel Qualification Workshop 2
16 January 2020

Final Agenda

The Second Accelerated Fuel Qualification (AFQ) Workshop will build on the First AFQ Workshop and address the clear need for a new methodology to qualify nuclear fuel. In particular, this workshop will explore how various technology elements can be implemented to reduce the time and cost to qualify nuclear fuel for use in commercial nuclear reactor applications.

Through workshops, white papers, journal articles, and NRC pre-application reviews the AFQ Working Group and GA-EMS are pushing forward with both community and NRC buy-in

Challenges to AFQ

- **Nuclear fuel performance spans an enormous spatial and temporal range with multiple coupled physical processes**
  - Use all of the above approaches – mechanistic models, look up tables, empirical formula, inline models, exc.
- **Connecting atomic properties with macroscopic properties with manufacturing modeling**
  - Statistical mechanics models can help
- **Uncertainty quantification and propagation**
  - Independent validation and multiscale measurements
- **Regulator Buy-In**
  - Early Communication is key

Thank You!

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