Advanced Manufacturing at GA-EMS and Accelerated Fuel Qualification

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Generation IV International Forum (GIF)

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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

### Requirements

- **ATF Cladding**
- **Channel box/other**
- **Adv. Fission**

<table>
<thead>
<tr>
<th>Requirements</th>
<th>ATF Cladding</th>
<th>Channel box/other</th>
<th>Adv. Fission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-Scale Structures</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SiC Joints &amp; Complex Structures</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>High DPA Irradiation Resistance</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>High-Temp Performance</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Impermeability</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Good Thermal Conductivity</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Corrosion Performance</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pellet-Cladding Interactions</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tbody>
</table>

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)
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

90% furnace x-section

Coating Rate

Inside | Middle | Outside
--- | --- | ---
Coating Rate

Coating Rate

Top | Middle | Bottom
--- | --- | ---
Coating Rate

3' length

Simulated coating rates

~10m tall
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

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>1.25 x 0.15 mm</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>301 GPa</td>
</tr>
<tr>
<td>Tangent Modulus</td>
<td>61 GPa</td>
</tr>
<tr>
<td>PLS Strain</td>
<td>0.16 %</td>
</tr>
<tr>
<td>Failure Strain</td>
<td>0.80 %</td>
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</tbody>
</table>
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
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.
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
  - EM² uses UC fuel, also a fuel of interest for NTP
- Fuel Fab, Modeling, and Irradiation effort
- Key data for phase 1 & 2 AFQ
  - Approach: Small, but mighty
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
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
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

INL
Idaho National Laboratory
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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