High Temperature Moderator - ANL

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Milestones

• **Title:** Develop advanced coating solutions for high-temperature moderator applications with optimization and demonstration
  - **Level:** M3  **Due:** 3/31/2023
  - **Description:** Develop advanced functional coatings to enhance the performance of microreactor moderators at elevated temperatures where the coatings will be applied to a TZM substrate which is the enclosure solution material for hydride moderators. The coating parameters will be optimized based on the substrate and designed operating conditions.

• **Title:** Develop advanced design for yttrium hydride moderator encapsulation
  - **Level:** M3  **Due:** 9/30/2023
  - **Description:** Fabricate and test miniature advanced moderation modules (AMMs) with all essential components (i.e., hydride pellet, refractory metal liner, advanced coating, and SiC/SiC cladding) and endcaps appropriately joined.
**Milestones Status:**

**Current Moderator**
- Design of H$_2$ permeation barrier for TZM
  - Selection of compatible materials (optimized)
  - Permeation barrier architecture (optimized)
  - Resistant to H.T. thermal cycling
  - Resistant to radiation damages

**Advanced Moderator Design**
- Design & Development of tube coating technologies (*Primarily Internal tube surface*)
  - Identification of parameters to implement metal coating internally with plasma sputtering technique.
  - Verification of developed film quality

**Containment:** TZM alloy

**Based on our previous Barrier Design**
- Significant reduction in H$_2$ Permeation

**Containment:** Nb liner + SiC

**PVD/ALD technique**

**Graphite**

**SiC/SiC Metal Liner**

**YH2**

**H$_2$ Permeation Barrier**

**TZM Diffusion Barrier**

**YH2**

**Nb-SiC Diffusion Barrier**
Functional Coating Implementation Infrastructure at ANL

PVD: Physical Vapor Deposition
ALD: Atomic layer Deposition

PVD System 1
PVD system 2
ALD system

External surface coating facility (metal/alloy layer)
Internal surface coating facility (metal/alloy layer)
Internal/External surface coating facility (Ceramic layer)

Capabilities
- Can deposit both metal & ceramic materials.
- Minimum Tube diameter ~5 mm, and max length ~ 12 feet.
Material Selection for H₂ Permeation Barrier & Thermal Performance

Barrier coating considerations:
- Low H₂ permeability,
- Stable at High temperature,
- Low neutron penalty.

Selected materials:
- H₂ permeation Barrier: Al₂O₃
- Intermediate layer with TZM: Cr
- Alternate metal layer: BCC phase CrAl

Observations:
- No surface cracks
- No separation at the interfaces.
- No interaction between the metal/ceramic layers.
- Small pore formation in the metal layers (expected).

Conclusion:
CrAl-Al₂O₃ multilayer design performance is satisfactory

Carried out under 2.5% H₂ (Ar gas)
Coating designs survived 750 C heavy ion irradiation with 80 MeV Xe ions. (No spalling or cracking observed)

- Coulomb effect (Type H) most likely due to use of high beam current and energy
Radiation Tolerance of Developed Permeation Barrier (Low Energy Ions)

- While undergoing irradiated with 1 MeV Kr ions.
- Total dose reached $4E15$ ions/cm$^2$ to achieve $\sim 5$ dpa damage.

**Observations:**
- Negligible change in the microstructure.
- No observable diffusion between multilayers.
- No bubble formation observed within/interfaces.
- BCC CrAl and Al$_2$O$_3$ phases remain intact.
IMPLEMENTING THE COATING WITHIN A TUBULAR STRUCTURE

Summary of Processes

- As-Received Nb Tubes (50 cm × Φ1 cm)
- ALD Al₂O₃ (inside & outside)
- PVD CrAl (inside & outside)
- ALD Al₂O₃ (inside & outside)
- PVD CrAl (inside & outside)

Processed Tube

Inside surface

As-Deposited
After 5 Thermal cycles (850°C)

<table>
<thead>
<tr>
<th></th>
<th>Inside surface</th>
<th>Outside surface</th>
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</thead>
<tbody>
<tr>
<td>Pt layer</td>
<td>Al₂O₃ CrAl Nb</td>
<td>Al₂O₃ CrAl Nb</td>
</tr>
<tr>
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<td>Carried out under 2.5% H₂ (Ar gas)</td>
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Conclusions

- Uniform & Conformal
- Dense
- No spallation, cracks
- Interfaces intact
Next Steps and Ongoing work

**H₂ permeation barrier development**
- Perform H₂ permeation study with the identified coating designs (H, I, G) implemented over TZM discs. Using 2.5 to 3.5% diluted H₂ gas at 700 – 750 °C.
  - Use current H₂ permeation setup at ANL
  - Coated TZM discs prepared for LANL/INL for further testing
- Upgrade the H₂ permeation measurement capability, to allow long term 800 °C +, operation with almost pure H₂ gas.

**TZM-Graphite barrier development**
- Diffusion studies with graphite in contact with TZM (with and without barrier coating) at 900 °C.
  - We want to implement similar coating designs to reduce complicacies.

**Continue to implementation of the final coating design over tubes.**
**Manufacturing of ANL Advanced Moderator Module sample.**