Design Evolution of Hot Isostatic Press Cans for NTP Cermet Fuel Fabrication

NASA Advanced Exploration System (AES) Project

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NETS
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NTP fuels under development
- W-60vol%UO₂ CERMET
- W coated UO₂ spherical kernels
- W coolant channel, perimeter, face clad
- Inherent stability of W clad in hot H₂ minimize fuel erosion and fission product release during NTP operation

HIP Manufacture Advantages
- Near net-shape
- Full scale
- High density
- Existing industrial base
Problem & Objective

• Fuel Element Constraints
  - Fully encapsulated fuel kernels
  - Long length
  - Numerous coolant channels
  - Integral claddings
  - Limited to refractory alloys (Nb, Ta, Mo)
  - Powder metallurgical constraints

• Develop a sub-scale and full-scale HIP cans that can be used to fabricate NTP fuel elements for process development and fuel element evaluation.
Consolidation

- **Powder Characteristics**
  - Appropriate coarse, medium and fine grain distribution
  - Green packing density drives shrinkage/dimensional tolerance

- **Sinter Temperature**
  - 80% of powder melting temperature

- **Pressure**
  - >15 ksi for consolidation onset

- **Atmosphere**
  - Compatible with can: argon

- **Time**
  - T/P ramp rates and hold times influence microstructure

### Ternary phase diagram

- Initial situation
- Orientation of particles
- Development of contact
- Contact growth
- Grain boundary development
- Pore healing and grain growth

### Consolidation process

- Early Stage
- Middle Stage
- Late Stage

- Grain boundary
- Grain
- Porosity

- Solid
- Liquid
- Porous
**HIP Can Design**

- **Design features**
  - Complex hexagonal can/mandrel geometry
  - 19-61 channels
  - 50-100 cm length
  - Perimeter clad
  - Coolant channel & face clad

- **Design constraints**
  - 10-20% shrinkage
  - Channels must not bow or twist
  - Sufficient flow area for viable powder fill
**HIP Can Manufacture**

- **CNC milling**
  - Specialized techniques for Nb
  - Time consuming
  - Expensive (time and materials)

- **Water jet machining**
  - Iterative development process
  - Non-specialized techniques
  - Significant time reduction
  - Sufficient dimensional tolerance
  - Minimal material waste
  - Minor milling required

- **CNC sheet metal break**
  - Axial tolerance difficult to achieve
  - Tolerance variation proportional to length
Integral Clad

• Coolant channel clad
  – Vacuum plasma spray (VPS)
  – W onto Mo mandrel rods
  – Thickness uniformity and adhesion
  – Completed through a Phase I SBIR by Plasma Processing Inc. (PPI)

• Perimeter Clad
  – Electro (EL)-form
  – W onto a graphite mandrel
  – High density and hermiticity
  – Developed under same PPI effort
Can Assembly

- Can wall welded
- Mandrel rods stacked between spacer grids
- Enclose mandrel in wall
- Can top welded to can
- Vacuum leak check
Fill & Close-Out

- Can surface cleaned
- Can weighed and measured
- Can vibratory filled in a glove box
- Filled can weighed
- Can evacuated
- Fill tube crimped
- Seam weld and fill tube excess cut

61 channel near full scale HIP can: filled and closed out
HIP Operations

- HIP can placed in can jig
- Jig placed in HIP furnace
- HIP schedule initiated
- Remove jig
- Weigh and measure can
Results

• 2013 HIP Trials
  – Circular 7 channel W-ZrO₂
  – Hex 61 channel, near full length W-ZrO₂: Fail
  – Circular slug W-dUO₂ x 2
  – Hex 7 channel W-dUO₂
  – Hex 61 channel, full length W-ZrO₂: Fail

• Failure Analysis
  – Wall cracking observed at can base
  – Significant reduction in ductility of HIP can coupons when compared to control samples
  – SEM/EDS revealed significant C embrittlement
  – Nb can interaction with graphite jig or furnace
Conclusions

- HIP is viable for NTP fuel cermet fabrication
- Fundamental mechanisms are well understood
- Difficulty to meet NTP engine requirements proportional to length
- Design optimization highly iterative
- Significant opportunity for process and design improvement
Recommendations for Future Work

• Develop mitigation strategy to prevent Nb-C interaction
  – Mandrel coating?
  – Sacrificial getter foil?

• 19 channel Rover/NERVA geometry
  – Develop HIP can design
  – Fabricate prototype
  – Fabricate fuel element

• Optimize can designs
  – Finalize can geometry based on nominal green powder packing density
  – Establish fuel dimensional tolerance and NDE requirements

• Investigate methods for W can fabrication
  – Water jet of W sheet
  – VPS?
  – EL-forming?
  – Additive Manufacture?
  – Dip & HIP?
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