Investigation of a Tricarbide Grooved Ring Fuel Element for a Nuclear Thermal Rocket

Brian Taylor  
Dr. Bill Emrich  
Dr. Dennis Tucker  
Marvin Barnes  
NASA MSFC

Nicolas Donders  
Kettering University

Kelsa Benensky  
University of Tennessee

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Outline

• Background
• Introduction
• Modeling
  – Neutronics
  – Fluid/Thermal
• Fabrication Experiments
  – material selection
  – Process
• Material Characterization
• Path Forward
Background

• Nuclear Propulsion
  – Nuclear Thermal is far more efficient than chemical engines
    • Nuclear power allows for high Isp while maintaining high thrust
    • Propulsion system efficiency, mass, and thrust have a large impact upon mission logistics and cost

• Traditional Reactor Elements
  – Hexagonal rods with straight axial flow passages
    • Cermet or graphite based
  – Particle Beds attempted
    • Much larger surface area
    • thermal instabilities/hot spots
Grooved Ring Fuel Element

- New fuel element concept
  - Stacked grooved disks designed to increase surface area and heat transfer to propellant
    - Leading to higher thrust/weight engines
    - Propellant flows from outer to inner diameter of disks which heat the propellant
    - Stack of disks makes an element
    - Cluster of elements in a reactor

- Carbide materials (e.g. UC, NbC, ZrC)
  - Mixture has higher melting point than traditional fuel forms
    - Result: hotter propellant and greater thrust/efficiency
NEUTRONICS MODELING
Neutronics Modeling

• **Purpose**
  – Develop a concept reactor layout for a set thrust goal
    • Power and distribution
  – Analyze impact of material selection upon nuclear reactions
  – Study relative material quantities
  – Determine uranium enrichment and quantities required
    • Relate to theoretical density
NTR Reactor Configuration Using (U-Zr-Nb)C Fuel
25K Thrust -- 8 kW/cm³ -- Optimal Fuel to Moderator Ratio = 0.261
NTR Reactor Configuration Using (U-Zr-Ta)C Fuel
25K Thrust -- 8 kW/cm³ -- Optimal Fuel to Moderator Ratio = 2.95
Uranium Carbide Material Neutron Absorption Cross-Sections
• Grooves and porosity decrease overall density requiring additional UC for reactivity
Neutronics Modeling

• Power peaking profile of a grooved ring fuel element
  – Modest power peaking seen so far
THERMAL FLUID MODEL
Thermal Fluid Model

- Shortened element modeled (2 rings)
  - Comsol

- Beryllium structure with zirconium carbide rings
  - Properties of mixtures not yet developed for model

- Boundary conditions varied to determine appropriate pressure delta to heat the flow for a given power/volume of 8 kW/cm³
• 4 psi seems to drive the flow at the right flow rate to heat it to near 3000 K for 8 kW/cm³
• Cold spots exist due to cooling from the top cover of the rings, but would be reduced in a full stack with mixing and additional heated propellant
• Velocity of H₂ through the element is fairly slow along the outer radius and through the grooves but increases in the central cavity while mixing but remaining laminar
FABRICATION EXPERIMENTS
Selection of Materials

- **Material Selection**
  - Need high melting temperature and low neutron cross section (except uranium)
  - NbC and ZrC chosen
    - Lower neutron cross section than HC or TC
  - Uranium Carbide Surrogate
    - Substitute for uranium
      - Avoid regulatory hurdles
    - Vanadium Carbide chosen
      - Similar crystal structure
Process

• Grind materials to uniform particle size

• Spark Plasma Sintering
  – Powder compressed at high pressure in die
  – High current passed through die
    • Control dwell, rise and cooling times as well as temperatures
  – Trying to reach high theoretical density
    • Porosity reduces reactivity and could lead to hydrogen reactions with the uranium

• Goal
  – Achieve a uniform distribution in a solid solution, ultimately with low porosity
  – Best to date: 98% theoretical density

• Grooves
  – Test grooves cut with saw
  – Looking for best way to cut grooves
    • Attempting to try to use a water jet
### DCS Variables Chart

**Screening Runs of “As Received”** $[V_{0.120} Zr_{0.587} Nb_{0.293}] \cdot C$

<table>
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<th>Date</th>
<th>Sintering Temperature [°C]</th>
<th>Dwell Time [min]</th>
<th>Cooling Rate [°C/min]</th>
<th>Pressure [Mpa]</th>
<th>Density [g/cc]</th>
<th>% Theoretical Density</th>
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<td>97.92%</td>
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- Direct Current Sintering Variables and the resulting density of sample.
% Theoretical Density Plots

% THEORETICAL DENSITY vs. SINTERING TEMPERATURE [°C]

% THEORETICAL DENSITY vs. COOLING RATE [°C/MIN]

% THEORETICAL DENSITY vs. DWELL TIME [MIN]

% THEORETICAL DENSITY vs. PRESSURE [MPA]
Fabrication Experiments – Results to Date

- Early samples showed less than optimal distribution
  - Clumps of elements in different regions

Table 1: X-Ray Spectroscopy Analysis of Figure 16

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<th>Material %</th>
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Fabrication Experiments – Results to Date

- Sifting materials has improved distribution
- Micro milling has only recently begun but is expected to improve distribution
  - Visual inspection seems to show improved distribution, but samples have fractured for unknown reasons

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<th>Zr</th>
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CARBIDE MATERIAL CHARACTERIZATION
Thermal Diffusivity Measurements

• The team is attempting to measure thermal diffusivity to fill in gaps in the literature
  – Disintegration of the first samples occurred for unknown reasons
    • Reasons are unknown, but it should be noted that samples survived much higher temperatures in CFEET
    • Future measurement attempts are planned
Hot Hydrogen Environment Testing

• Samples tested in Compact Fuel Element Environmental Test (CFEET) system at MSFC
  – 50 kW induction power supply and two-color pyrometers for temperature measurements up to 3000 °C
  – Designed to flow hydrogen across subscale fuel materials for testing at high temperatures for up to ten hours.
Hot Hydrogen Environment Testing

• CFEET Results
  – 1st sample maintained structural integrity for 30 minutes at 2000 K
  – 2nd set of three samples were run at 2250 K for 30 minutes
  • X-ray diffraction (XRD) analysis appears to show the tricarbides moving toward a solid solution
  • Unidentified peaks need further analysis to verify if they are due to the formation of free carbon, ZrC2, or other lower melting temperature compounds
Conclusions

- Results of this work are promising
- Fabrication has come a long way in showing a viable means for producing these tricarbide rings
  - High densities reached
  - Micro milling expected to lead to better distribution
  - Appears to be moving toward a solid solution after an extended period in a hot hydrogen environment
- Thermal diffusivity measurements are expected from future samples
- Tricarbide samples have held up in a hot hydrogen environment
  - Future hotter tests are planned
- The use of tricarbide fuels and this geometry have potential and warrant further investigation