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

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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
Reactor Design

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
Neutronics Modeling

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
Temperature

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

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<th>Date</th>
<th>Sintering Temperature [°C]</th>
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- Direct Current Sintering Variables and the resulting density of sample
% Theoretical Density Plots

1. % Theoretical Density vs. Sintering Temperature
   - Sintering Temperature [°C]
   - % Theoretical Density
   - Data points show an increase in % Theoretical Density with temperature.

2. % Theoretical Density vs. Cooling Rate
   - Cooling Rate [°C/Min]
   - % Theoretical Density
   - A positive correlation is observed between cooling rate and % Theoretical Density.

3. % Theoretical Density vs. Dwell Time
   - Dwell Time [Min]
   - % Theoretical Density
   - % Theoretical Density increases with increasing dwell time.

4. % Theoretical Density vs. Pressure
   - Pressure [MPa]
   - % Theoretical Density
   - Pressure has a notable impact on % Theoretical Density, showing a steady rise as pressure increases.
Fabrication Experiments – Results to Date

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

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Fabrication Experiments – Results to Date

Table 2: X-Ray Spectroscopy Analysis of Figure 17

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- 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
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

![THERMAL DIFFUSIVITY Curve](image-url)
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