Study of a Tricarbide Grooved Ring Fuel Element for Nuclear Thermal Propulsion

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Outline

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

• **Nuclear Thermal Propulsion**
  – NTP uses a reactor to heat propellant prior to expansion through a nozzle
  – Can achieve more than twice the $I_{sp}$ than chemical engines

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

- **New fuel element geometry**
  - 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 can reach higher melting points than other fuel forms
    - Low reactivity with H$_2$ propellant

- **Goal: high propellant temperatures and higher thrust/weight**
  - More efficient engine
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
Neutronics Modeling

- 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

- **Truncated 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
  - Showed fluid/thermal process works as expected
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
Experimental Fabrication Process

• Sift or grind materials to smaller 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
  – Reached up to 98% theoretical density

• Grooves
  – Looking for best way to cut geometry
    • 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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- Direct Current Sintering Variables and the resulting density of sample
Fabrication Experiments – Results to Date

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<th>Nb</th>
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- Early samples used powders as supplied from the manufacturer
- Saw clumping and poor distribution
Fabrication Experiments – Results to Date

Table 2: X-Ray Spectroscopy Analysis of Figure 17

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<th>%</th>
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<th>&lt;</th>
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<th>Nb</th>
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- Sifting materials improved distribution
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](chart)
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**
  - 1\textsuperscript{st} sample maintained structural integrity for 30 minutes at 2000 K
  - 2\textsuperscript{nd} 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
Oxide Formation in Milled Carbides

- Milled Sintered Carbides showed cracks post sintering.
- Milled carbides developed blister formation and experienced crack propagation post CFEET test to 2500 to 2750 K.
Oxide Formation in Milled Carbides

- Oxide formation seen after milling powders
Conclusions and Path Forward

• Fabrication has come a long way in showing a viable means for producing these tricarbide rings
  – High densities reached
  – Appears to be moving toward a solid solution after an extended period in a hot hydrogen environment

• Tricarbide samples have held up in a hot hydrogen environment
  – Future hotter tests are planned

• Path Forward
  – Sift powders / no milling
  – Heat treat in CFEET or Graphite Furnace at ~2500 K for extended period
    • Evaluate for solid solution
  – Water jet test fabrication of geometry