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

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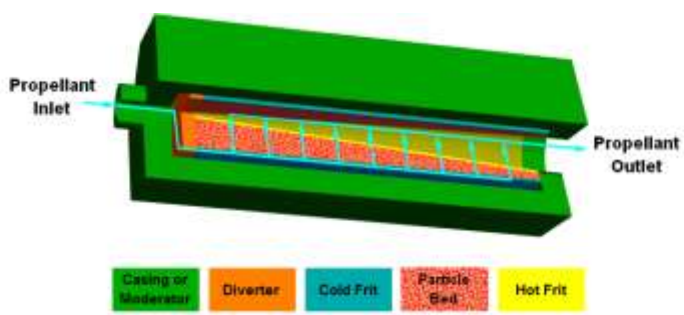
2/26/2018

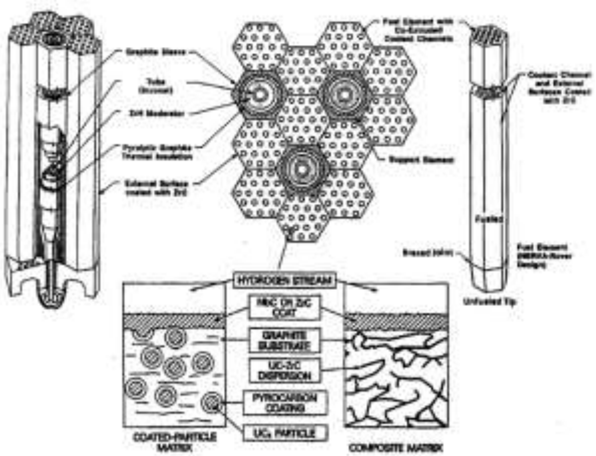
Outline

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

Background

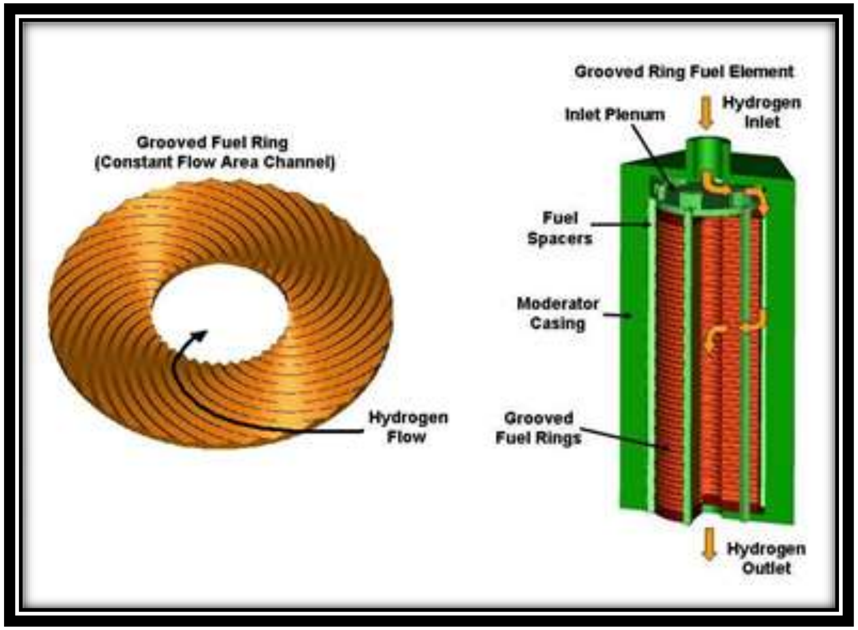
- **Nuclear Thermal Propulsion**
  - NTP uses a reactor to heat propellant prior to expansion through a nozzle
  - Can achieve more than twice the I_{sp} than chemical engines
- **Traditional Reactor Elements**
  - Hexagonal rods with straight axial flow passages
  - Particle Beds attempted
    - Much larger surface area
    - thermal instabilities/hot spots





Groved 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



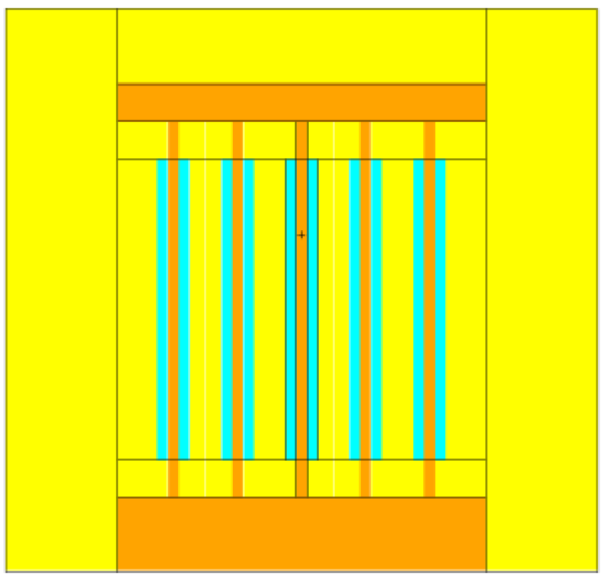
NEUTRONICS MODELING

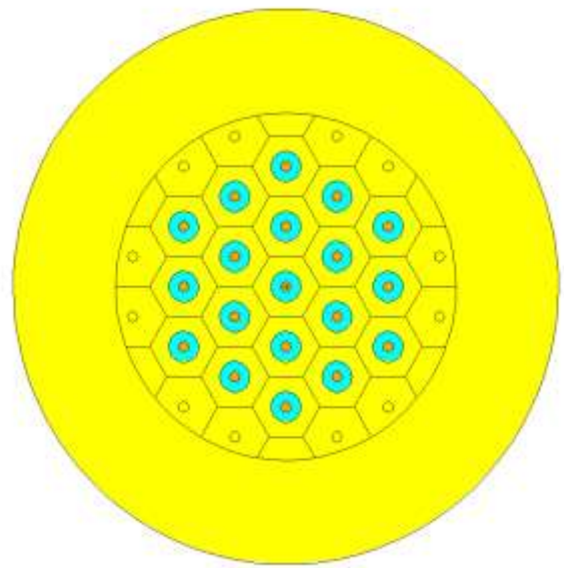
Neutronics Modeling

- **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

NTR Reactor Configuration Using (U-Zr-Nb)C Fuel

25K Thrust -- 8 kW/cm³ -- Optimal Fuel to Moderator Ratio = 0.261





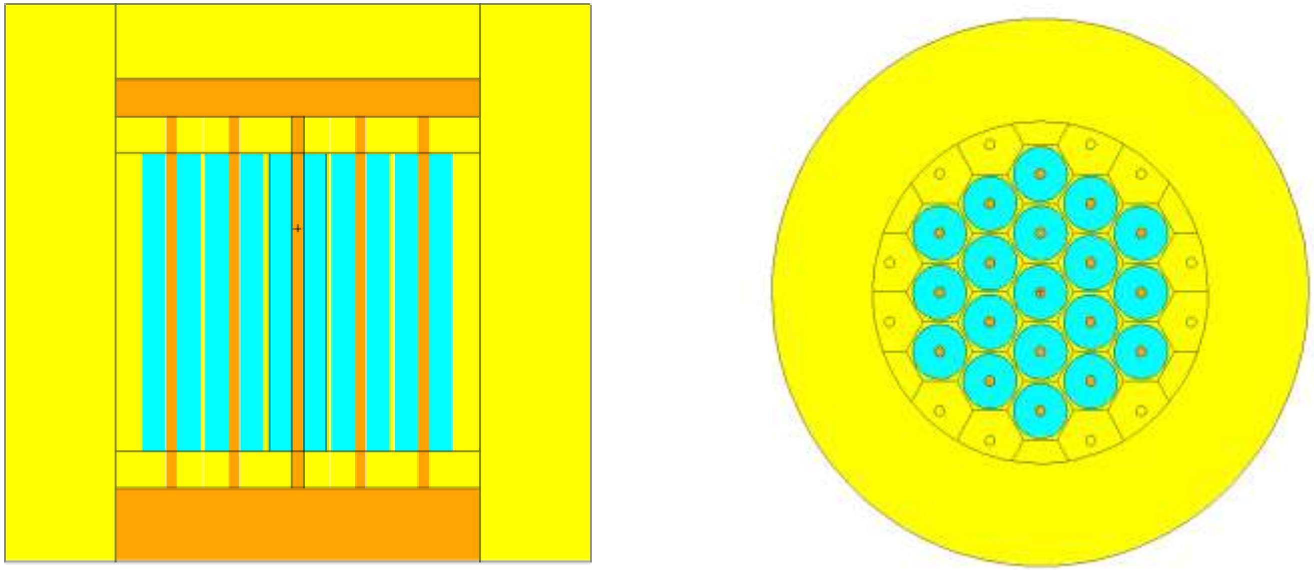
Beryllium

Hydrogen

Fuel

NTR Reactor Configuration Using (U-Zr-Ta)C Fuel

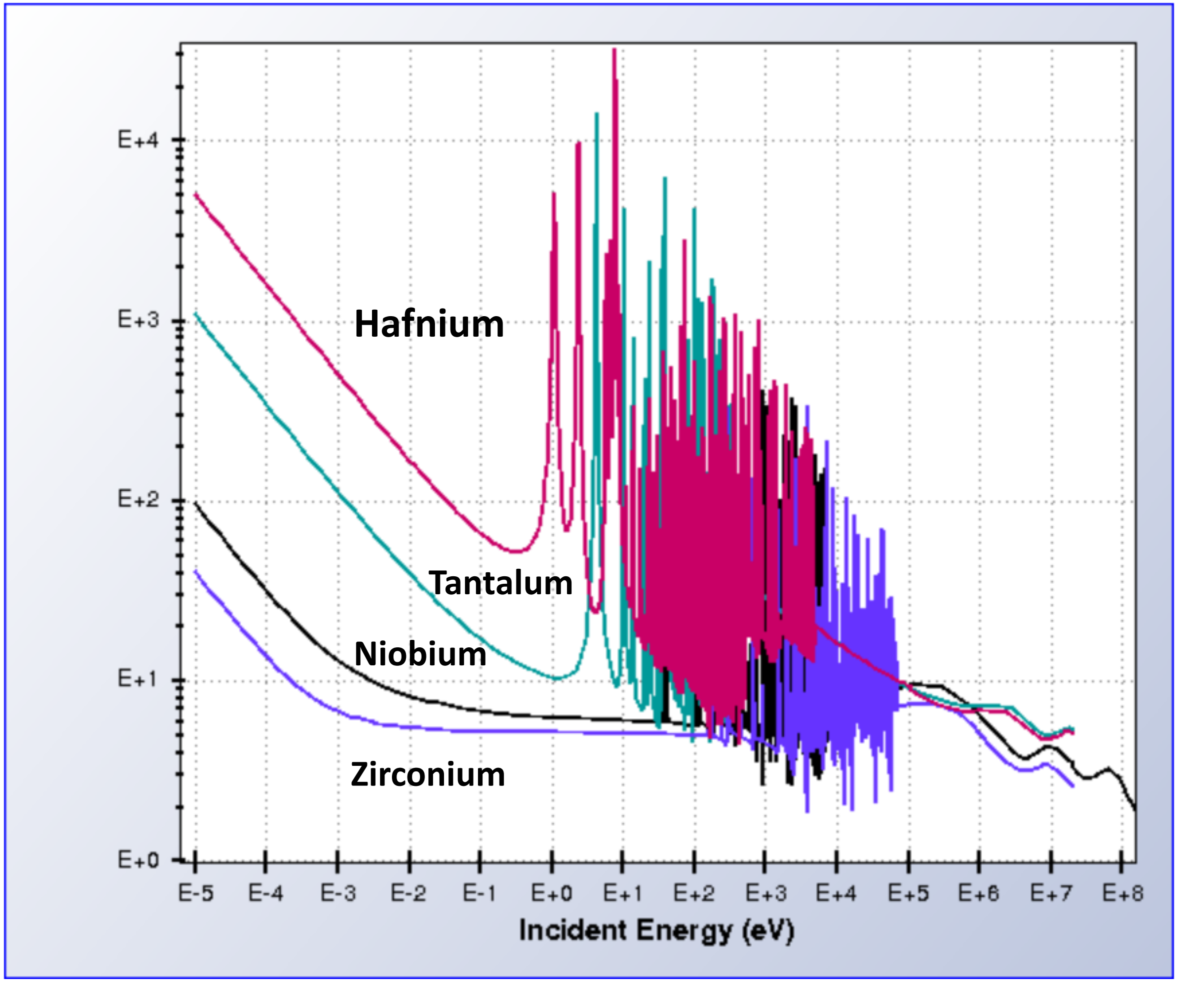
25K Thrust -- 8 kW/cm3 -- Optimal Fuel to Moderator Ratio = 2.95



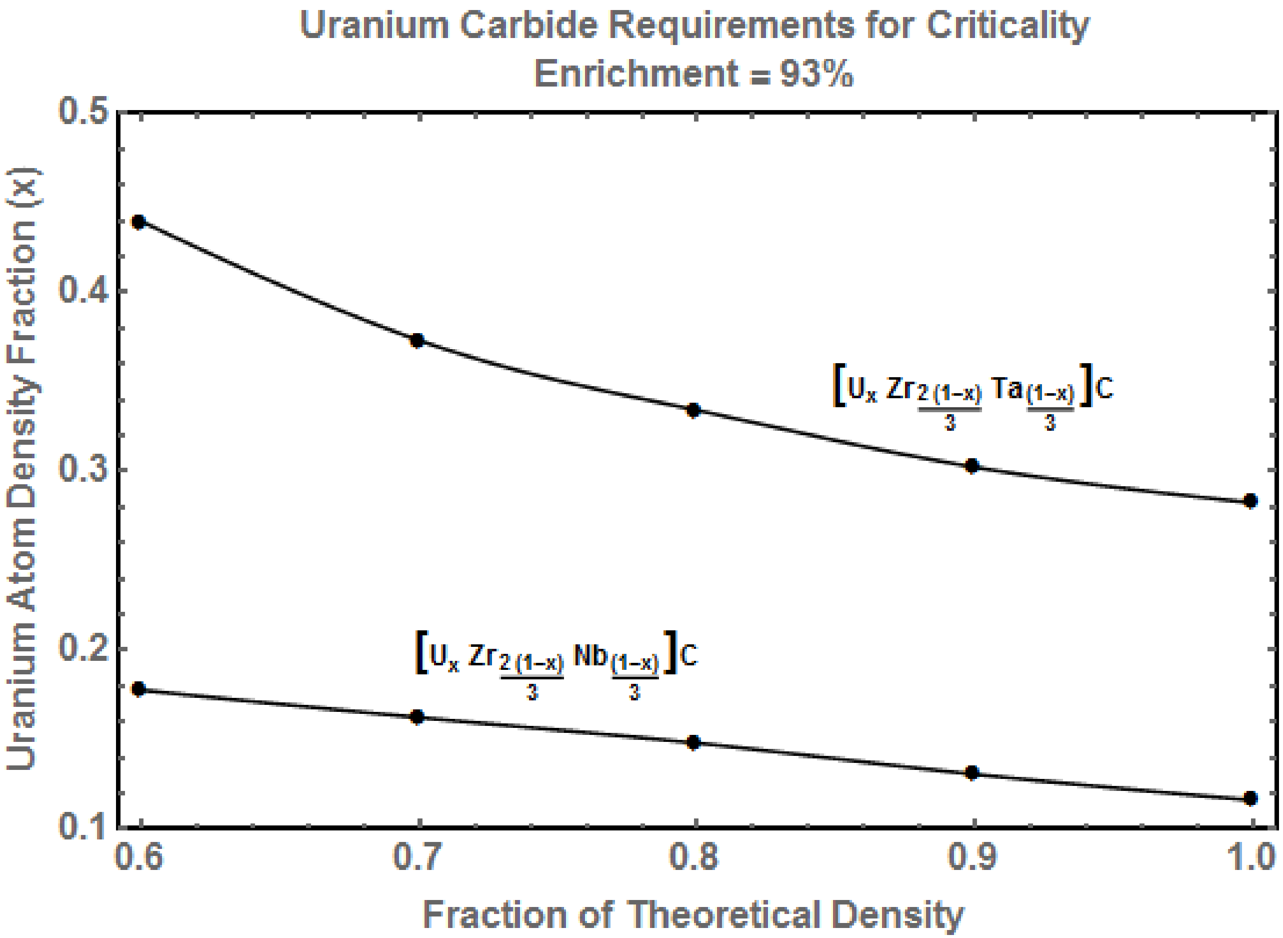
Beryllium | **Hydrogen** | **Fuel**

Neutronics Modeling

Uranium Carbide Material Neutron Absorption Cross-Sections

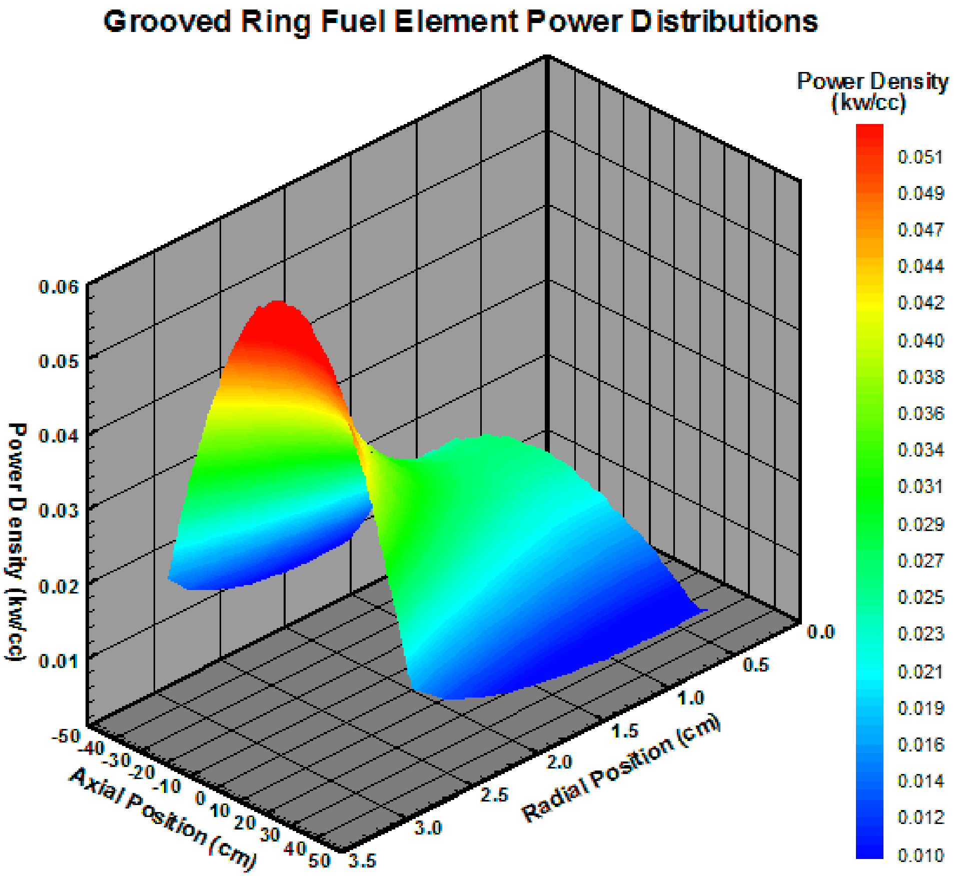


Neutronics Modeling



- Grooves and porosity decrease overall density requiring additional UC for reactivity

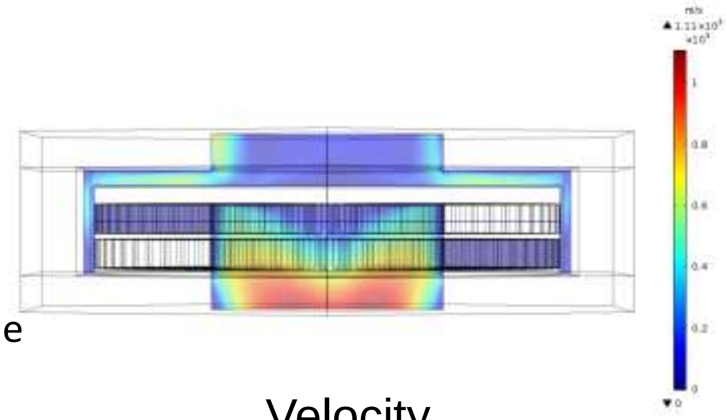
Neutronics Modeling



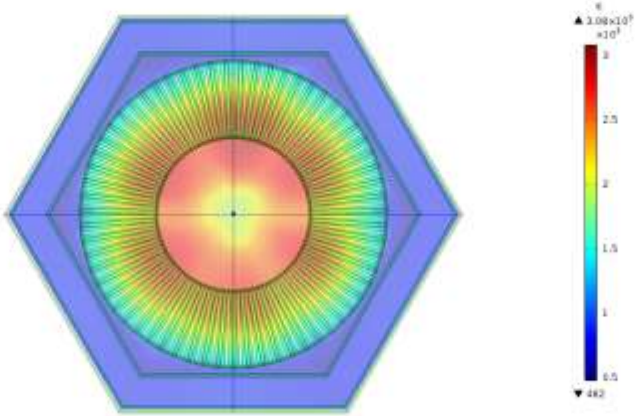
- **Power peaking profile of a grooved ring fuel element**
  - Modest power peaking seen so far

THERMAL FLUID MODEL

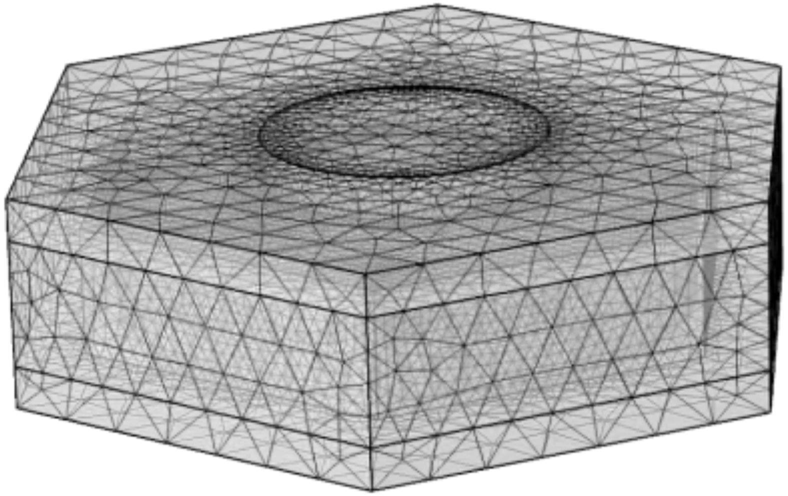
- **Truncated element modeled (2 rings)**
  - Comsol
  - Beryllium structure with zirconium carbide rings
  - Properties of mixtures not yet developed for model
  - Boundary conditions varied to determine appropriate pressure delta to heat the flow for a given power/volume of 8 kW/cm^3
  - Showed fluid/thermal process works as expected



Velocity



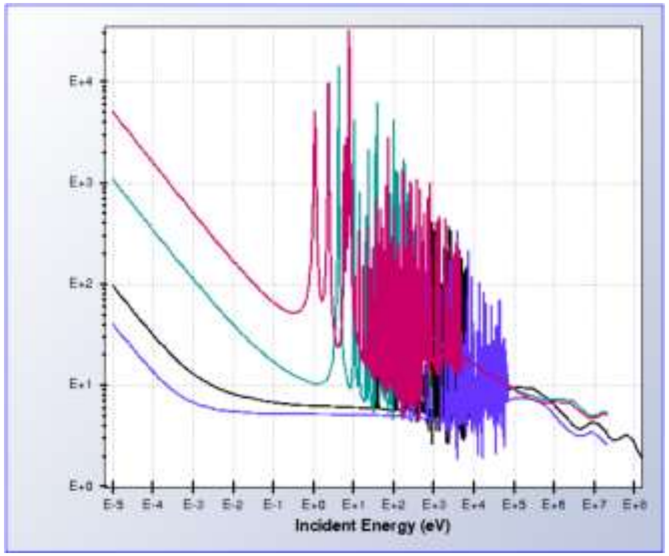
Temperature



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

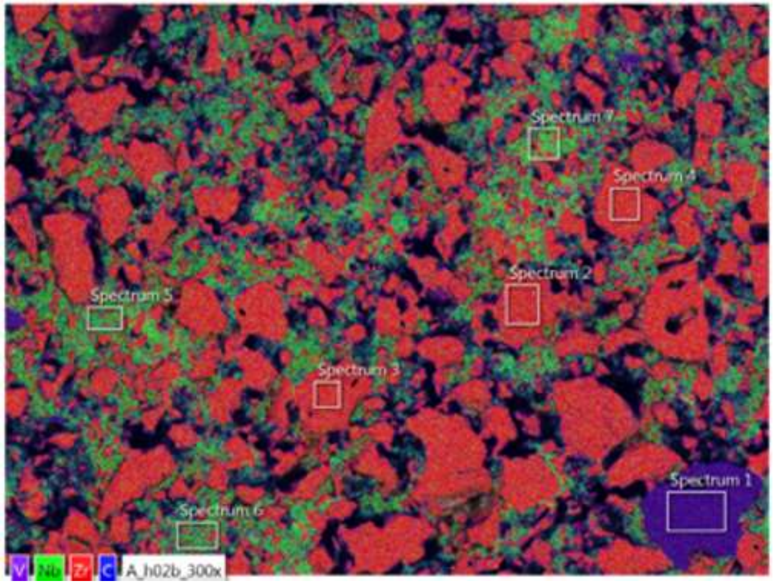
Screening Runs of “As Received” $[V_{0.120}Zr_{0.587}Nb_{0.293}] \cdot C$

Date	Sintering Temperature [*C]	Dwell Time [min]	Cooling Rate [*C/min]	Pressure [Mpa]	Density [g/cc]	% Theoretical Density
1/27/2017	1500	10	100	50	5.65	80.77%
1/31/2017	1500	10	100	50	5.75	82.20%
2/1/2017	1600	10	100	50	5.86	83.77%
2/2/2017	1600	20	100	50	6.05	86.48%
2/2/2017	1600	20	200	50	6.52	93.20%
2/3/2017	1500	20	50	50	6.46	92.34%
2/13/2017	1600	20	20	50	6.20	88.62%
2/24/2017	1600	20	200	50	6.65	95.06%
3/17/2017	1600	20	200	50	6.60	94.35%
3/20/2017	1700	20	200	50	6.80	97.21%
3/21/2017	1550	30	200	50	6.83	97.64%
3/22/2017	1600	20	200	50	6.87	98.21%
3/27/2017	1600	20	200	60	6.85	97.92%

- Direct Current Sintering Variables and the resulting density of sample

Fabrication Experiments – Results to Date

Table 1: X-Ray Spectroscopy Analysis of Figure 16					
Material %	C	O	V	Zr	Nb
Spectrum 1	23.47		66.41	6.71	3.41
Spectrum 2	26.59	1.32	0.24	67.92	3.94
Spectrum 3	25.62	0.92	0.31	68.95	4.20
Spectrum 4	25.48	1.21	0.38	68.81	4.12
Spectrum 5	34.74	1.85		22.79	40.63
Spectrum 6	35.56	1.93	0.25	22.75	39.51
Spectrum 7	31.71	2.62	0.39	26.76	38.52

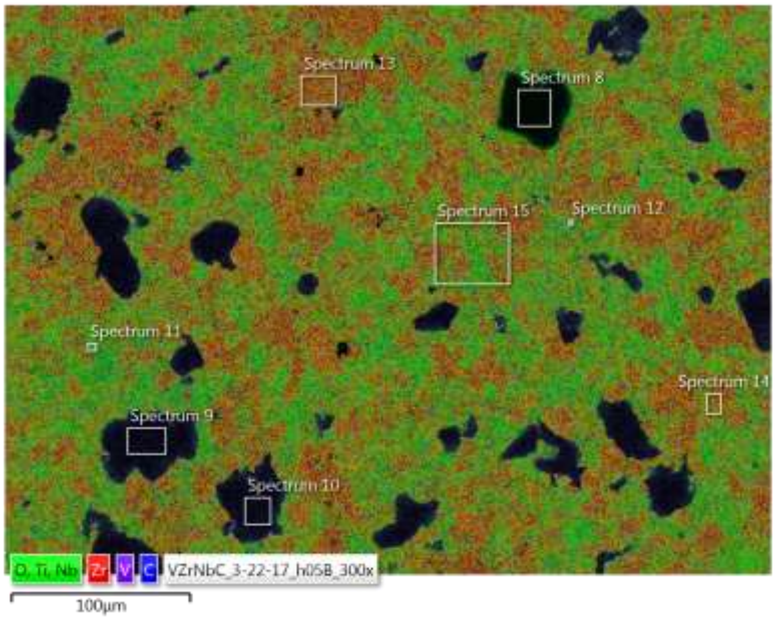


- Early samples used powders as supplied from the manufacturer
- Saw clumping and poor distribution

Fabrication Experiments – Results to Date

Table 2: X-Ray Spectroscopy Analysis of Figure 17							
%	C	Ti	V	Zr	Nb	Hf	Ta
8	18.1	80.8	0	0.31			
9	18.24	1.15	78.26	0.36	0.99		
10	18.56	0.49	78.29	0.65	1.32		
11	18.94		2.1	31.08	29.87		15.91
12	16.06		3.04	25.52	33.76	21.61	
13	18.77		0.19	77.83	3.21		
14	17.67		0.44	73.07	8.81		
15	19.32		1.69	47.06	30.15		

EDS Layered Image 2

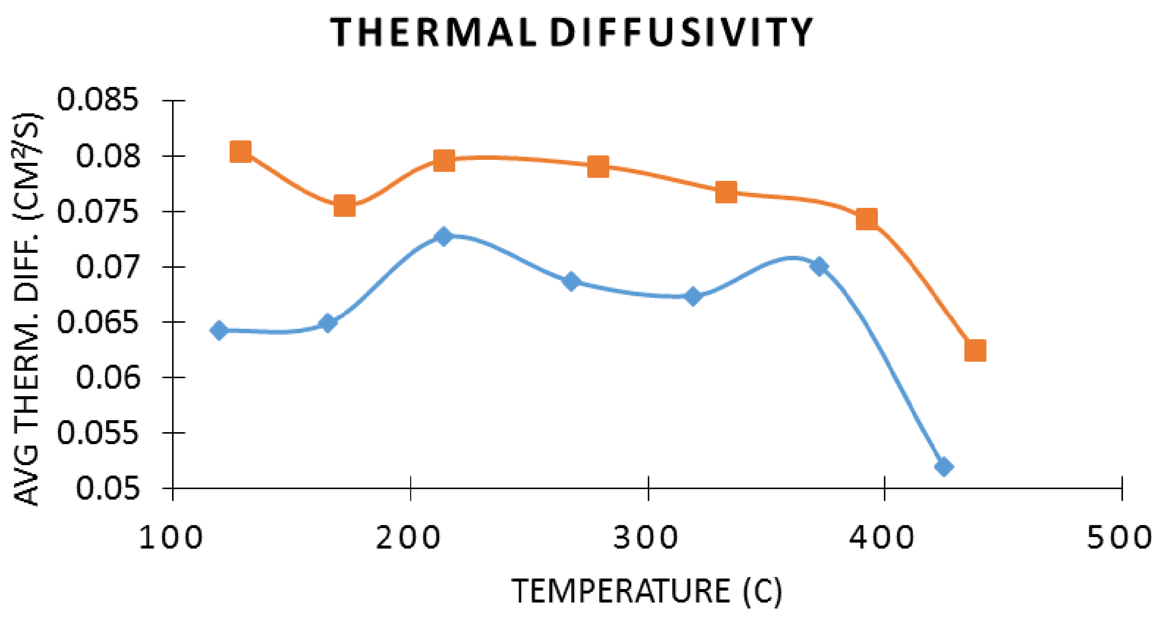


- Sifting materials improved distribution

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

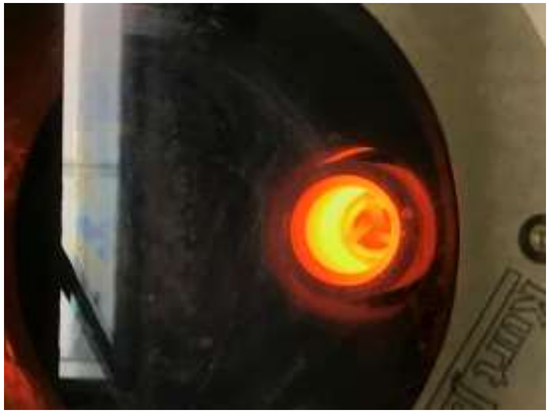


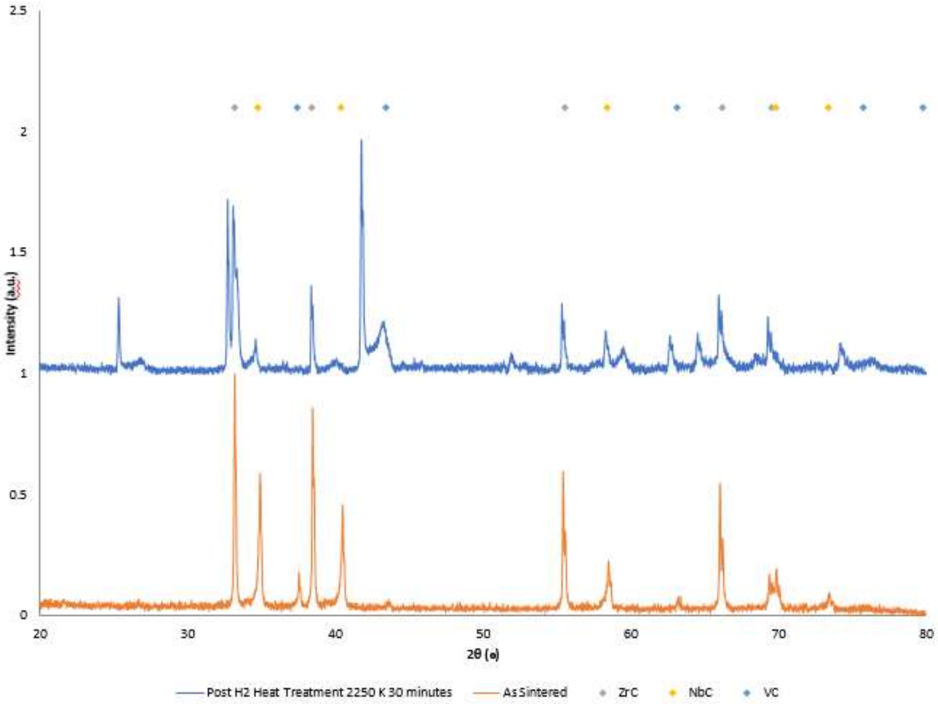
Hot Hydrogen Environment Testing

- **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

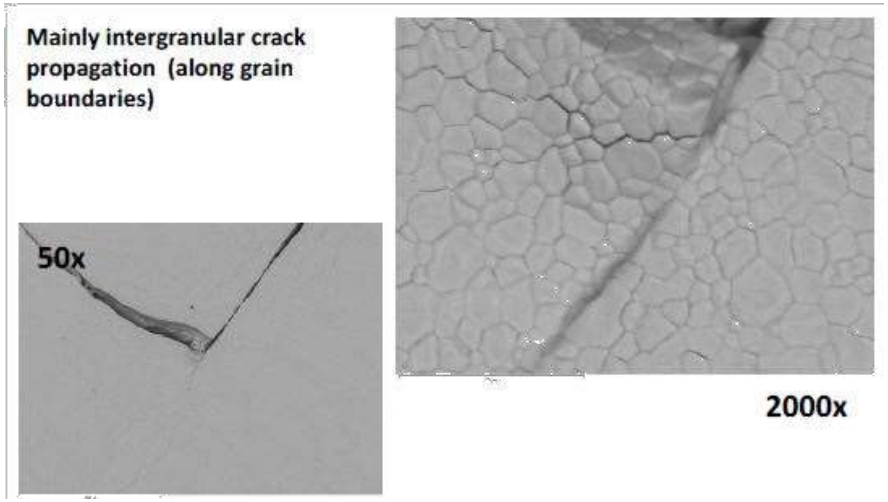
- **CFEET Results**
  - 1st sample maintained structural integrity for 30 minutes at 2000 K
  - 2nd set of three samples were run at 2250 K for 30 minutes
    - X-ray diffraction (XRD) analysis appears to show the tricarbides moving toward a solid solution
    - Unidentified peaks need further analysis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

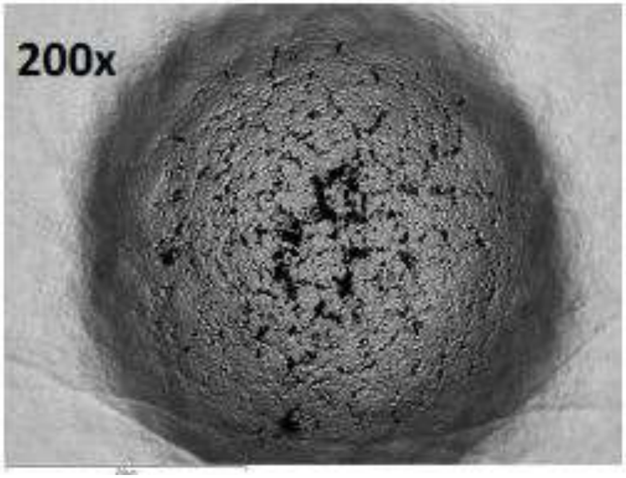




Oxide Formation in Milled Carbides

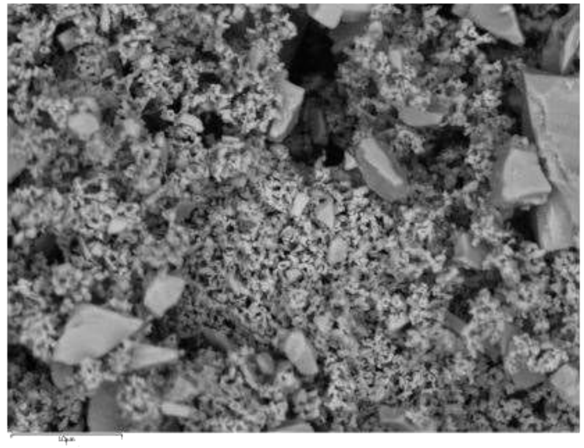
- Milled Sintered Carbides showed cracks post sintering
- Milled carbides developed blister formation and experienced crack propagation post CFEET test to 2500 to 2750 K

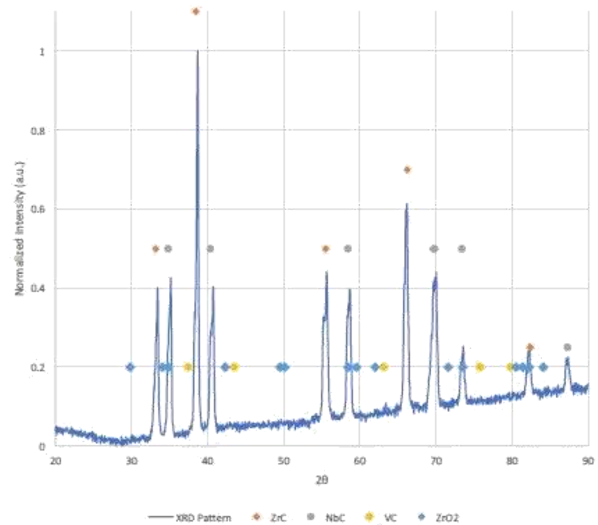




Oxide Formation in Milled Carbides

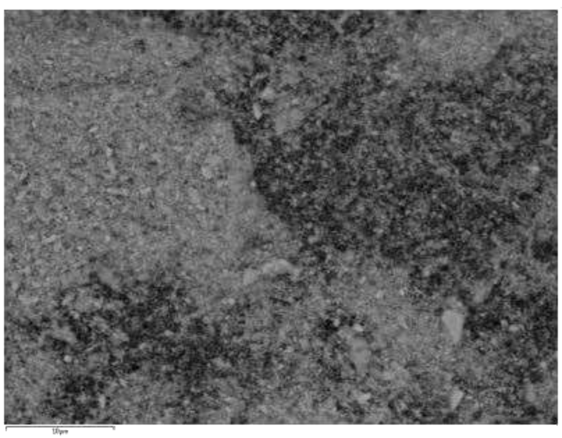
Tricarbide Powders, no milling: XRD

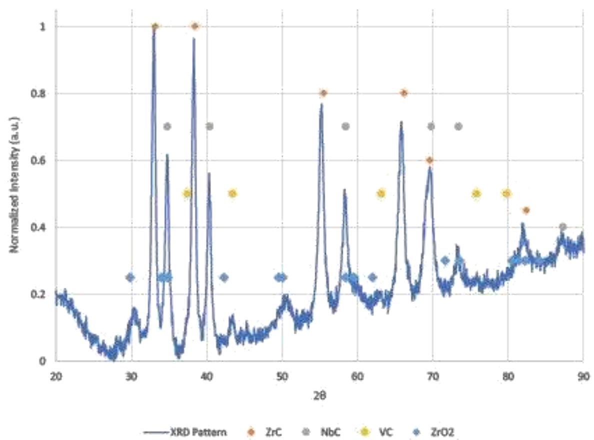




No oxide formation

Tricarbide Powders, milled: XRD





Zirconium Oxide Formation

- ZrO2 peaks
- Reduced ZrC intensity

- 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