Exploring the Design Space of CERMET LEU ZrH$_{1.8}$ Moderated Nuclear Thermal Propulsion Systems

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Current Leading LEU Design

**Performance:**
Thrust: 35,000 lbs.
Isp: 893.96 s
System T/W: 3.33
Reactor Mass: 2617.9 kg

**Conservatism:**
Fuel Max: 2850-60=2790K
Flow margin: 1.5 times average
(without violating Mach number limit)
6.9 MPa (~1000 PSI) core inlet
Current Leading LEU Design

MCNP model

SPOC output
Different Colors =
Different Enrichment
Gray is tie tube
Current Leading LEU Design

Fuel Element

Moderator element/tie tube

ZrH1.8
### Current Leading LEU Design

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Channel Radius (mm)</strong></td>
<td>1.40</td>
</tr>
<tr>
<td><strong>Channels per hex</strong></td>
<td>61</td>
</tr>
<tr>
<td><strong>Flat to Flat of Fuel Hex (mm)</strong></td>
<td>31.04</td>
</tr>
<tr>
<td><strong>Fuel elements</strong></td>
<td>151</td>
</tr>
<tr>
<td><strong>Moderator elements</strong></td>
<td>150</td>
</tr>
<tr>
<td><strong>Fuel composition</strong></td>
<td>W-UO$_2$-ThO$_2$</td>
</tr>
<tr>
<td><strong>Volume loading of Oxide</strong></td>
<td>60%</td>
</tr>
<tr>
<td>%a $^{184}$W</td>
<td>98</td>
</tr>
<tr>
<td>%a $^{235}$U</td>
<td>19.75</td>
</tr>
<tr>
<td>% of TD</td>
<td>97</td>
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</tbody>
</table>
Current Leading LEU Design

Radial Peaking Factor: 1.12
How did we get to this?
Motivation

• Full system NTR studies have been done many times
• Many studies fail to recognize:
  1. The large design space available for NTR cores and
  2. The significance of making educated decisions concerning core design in an NTR

• Previous methodology for core design:
  – Select a starting point and change core design until a critical core capable of producing 25k-lbf thrust is reached at peak centerline temperature

• Present methodology for core design:
  – Establish the design space for primary mission requirements (e.g. Thrust or Isp or T/W)
  – Allow communication with other prime actors in the NTR development program to drive final core selection
Workflow - Overview

1. Assemble a large number possible NTR cores
2. Examine the criticality of those cores
3. Conduct a thermal analysis of each core with an acceptable criticality (keff>.99)
4. Arrange relevant performance data in a format which informs the customer of the allowable design space of their core
5. Following discussion, the desired core (or group of reactors) can be objectively chosen for implementation
Workflow - Methods

- SPOC
  - Multifunctional NTP analysis tool
- Nuclear Analysis:
  - MCNP 6.1
- Super computers and Automation:
  - INL High Performance Computing
  - More than 100,000 MCNP 6.1 cases ran
- ISP:
  - Interpolation of desktop calculations from NASA Chemical Equilibrium with Applications (CEA) and Two Dimensional Kinetic (TDK).
  - Expansion ratio of 150
- Hydrogen Properties:

(NASA-TP-3378) COMPUTER PROGRAM FOR THERMAL AND TRANSPORT PROPERTIES OF PARAHYDROGEN FROM 20 TO 10,000 K (NASA) 16 p

Unclas
Workflow - Methods

- **Thermal Analysis**
  - Nodalized compressible flow
  - Correlations used for large channel in a hexagonal geometry

- **Non-reactor mass**
Workflow - Assumptions

- 26,500 lbf (margin for 25k-lbf thrust requirement)
- 300 K hot channel inlet temperature
- 10 MPa hot channel inlet pressure
- 0.3 Mach number limit
- 2850 K max fuel temperature
- 0.99 k_{eff} lower limit with control drums halfway inserted
- 98% W-184 Enrichment for LEU designs, Natural W for HEU designs
- Flow matched to the power of a channel (perfect core orificing)
- Power peaking factor of 1
- Conservative estimates of the mass of the mechanical components
- No heat removal from fuel element to tie-tube
Workflow - Assumptions

• The design space:
  - $\text{uO}_2$ Fuel Loading: 40%, 48%, 54%, 60% (% of total fuel meat composition)
  - Fuel Channel Radius: 1.0287, 1.37935, and 1.73 mm
  - Fuel Webbing thickness: 0.0646 mm and 0.09 mm
  - Channels per Fuel Element: 19, 37, 61, 91, and 169 channels
  - LEU Hexagonal Element Arrangement: 3:1, 2:1, 1:1, 1:2, and 1:3 Fuel to Moderator Element Ratio
  - Reflector thickness: 0.1, 0.15, and 0.2 m
  - Core Height: 0.5, 0.66, 0.75, 1.0, 1.25, and 1.5 m
  - Core Radius: 0.25, 0.30, 0.35, 0.4, and 0.5 m
For every point in the design space we found the maximum ISP that every critical \((k=0.99)\) reactor could produce at 26500 lbs thrust while limiting the max fuel temperature to 2850 K.
LEU vs. HEU
HEU vs. LEU – Ranges of $k_{eff}$

![HEU and LEU Effective Multiplication Factor Ranges](image_url)
HEU vs. LEU – Ranges of L/D
HEU vs. LEU – Ranges of $I_{sp}$ vs. Power Density
LEU Design Space
LEU – Variance in Coolant Channel Radius

All Coolant Radii

All Coolant Radii (Alternative View)
LEU - Variance in Fuel Loading
LEU – Variance in Number of Coolant Channels

All Number of Coolant Channels

All Number of Coolant Channels (Alternative View)
LEU – Variance in Fuel Webbing Thickness
LEU – Variance in Reflector Thickness
LEU - Variance in Hexagonal Element Arrangement
HEU Design Space
HEU - Variance in Coolant Channel Radius

All Coolant Radii

All Coolant Radii (Alternative View)
HEU - Variance in Fuel Loading
HEU – Variance in Number of Coolant Channels

All Number of Coolant Channels

All Number of Coolant Channels (Alternative View)
HEU – Variance in Fuel Webbing Thickness
HEU – Variance in Reflector Thickness

All Reflectors

All Reflectors (Alternative View)
General Observations and Discussion

• General Observations
  – Think of this as a database of core designs
    • We can extract any detail required
  – Further refinement of studies is available
  – Further analysis of chosen core designs is available

• Discussion
  – What are selected core designs and why?
  – What data is desired about selected core designs?
Questions?