Nuclear Thermal Propulsion Engine: Low-enriched Cermet-based Fuel

Outline

• Motivation for nuclear propulsion systems
• Brief historical programs
• Description of operation
• Engine Requirements
• Neutronic Analysis
• T/H analysis
• Systematic approach to identify nearly optimum designs
• Summary
Why Nuclear Propulsion?

• Similar Thrust levels to chemical rockets
• Double efficiency over chemical rockets
• Faster travel times, reduced exposure/dose to the crew

<table>
<thead>
<tr>
<th></th>
<th>Chemical</th>
<th>Nuclear</th>
<th>Electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust, klbf</td>
<td>100-500 klbf</td>
<td>10-100 klbf</td>
<td>10-100 mlf</td>
</tr>
<tr>
<td>Thrust-to-weight,</td>
<td>30-200</td>
<td>3-5</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Specific impulse, Isp</td>
<td>&lt;455 sec</td>
<td><strong>800-1000 sec</strong></td>
<td>1000-10,000 sec</td>
</tr>
</tbody>
</table>

• Over 20 engines tested under NASA’s Rover Program (1955-1973)
• All designs used HEU based graphite matrix fuel elements
• Demonstrated feasibility of NTP systems
• Most current engine designs build on technology from Rover
Description of Operation

- Engine efficiency (Isp) is dependent primarily on propellant exit temperature
  - $Isp \uparrow M_{propellant} \downarrow$
  - $Isp \uparrow T_{propellant} \uparrow$

- **Hydrogen propellant** is used to cool a nuclear reactor core and its surrounding structural elements

- The hot hydrogen propellant is then **expelled through** a converging-diverging **nozzle**

- Radially distributed **control drums** are used to control reactivity, start, and shutdown the reactor
Engine Requirements

• Several baseline assumptions made by NASA about NTR performance:
  – Thrust: 25 klbf;
  – Isp: 900s;
  – Thrust-to-weight ratio: 3.5

• Material Constraints:
  – Fuel Material Melting Point: 3695 K
  – Moderator Material Melting Point: 1073 K

• Objectives of our design:
  – Previous tested NTPs have been all compact HEU (90% U²³⁵)
  – HEU is no longer acceptable, especially if the private sector is to become involved in the design, fabrication and testing of engines
  – Issues in previous graphite fuel designs caused by hot hydrogen corrosion
Neutronic Analysis

• Analysis performed using Serpent 2
• ENDF/B-VII.0 evaluated cross section library
• **Identified effects of:**
  – Active core height;
  – Axial reflector height;
  – Enrichment studies performed for fuel elements;
  – Investigation of different moderator materials;
  – Effects of moderator-to-fuel element ratio

  – Examined to ensure Isp maximization while still maintaining $k_{eff} > 1$
Fuel Element (FE)

- Ceramic metallic fuel composed of LEU (19.75%) enriched UO₂ particles
- Tungsten (IV refractory metal) is compatible with hot hydrogen
- Tungsten thermal conductivity >100 [W/mK] for all operating T [K]
- Melting point of tungsten and UO₂ in the cermet fuel = 3695 K
- Large parasitic absorption ⇒ Tungsten must be enriched with W\textsuperscript{184}
• Create a thermal spectrum
• $^7\text{LiH}_2 (0.82 \text{ g/cm}^3)$ and $\text{ZrH}_2 (5.56 \text{ g/cm}^3)$ are the most formidable MEs
• Includes the $\text{H}_2$ supply/return channels
• Porous ZrC:
  – Large temperature drop and shields the graphite from any hydrogen contact
Neutronic Results

- Higher ME-to-FE ratio (greater moderation) yields higher reactivity
- Criticality peaks at 80cm height
- Short cores have lower criticality due to leakage
- Thicker axial reflectors reduce need for moderating elements
T/H Methods

- 1.5-dimensional T/H calculator
- Linearly discretized in axial direction
- Single channel radial conduction model
Specific Impulse and Thrust

• T/H analysis \( \implies \) chamber \( T_1 \) and \( P_1 \) at the nozzle inlet
• The nozzle consists of convergent-divergent section
• Specific impulse and thrust, the velocity at the nozzle exit

\[
\frac{v_x}{v_t} = \sqrt{\frac{k + 1}{k - 1}} \left[ 1 - \left( \frac{P_x}{P_1} \right)^{\frac{k-1}{k}} \right]
\]

• Solution:
  – Divide the nozzle into multiple 1D regions
  – \( k \) is a function of \( P_x \) and temperature \( T_x \)
  – An iterative process to update \( k \) in the nozzle

• \( I_{sp} = \frac{v_2}{g_0} + \frac{p_2A_2}{mg_0} \)
• \( F = m\nu_2 + P_2A_2 \)
**Systematic Approach: identify promising design**

**Automated tool:** generates Serpent input files with unique set of parameters:
- H, the ME-to-FE, and total elements
- Multi channel core with multiple axial layers \(\Rightarrow\) power distribution and T/H

**Solution approach**
- Iteration on power to achieve maximum fuel temperature
- Radial power peaking of 1.3 assumed
- Max. fuel temperature of 3100K
- Specific impulse and thrust calculated via discretized nozzle

![Diagram showing different element counts: 835 elements, 1069 elements, 1327 elements.](image)
Results

- Thrust
  - $m \uparrow \Rightarrow F \uparrow$

- Thrust-to-weight
  - $m \uparrow \Rightarrow \frac{F}{M} \uparrow$

- Specific Impulse
  - $- \dot{m} \Rightarrow Isp \uparrow$

- Criticality
  - $- \frac{ME}{FE} \Rightarrow k_{eff} \downarrow$
Near-Optimum Design

- NASA requirements ⇒ confined design space
  - 25,000 lbf of thrust, have a criticality greater or equal to 1, and a thrust-to-weight ratio greater than 4.0

<table>
<thead>
<tr>
<th>Number of elements</th>
<th>835</th>
<th>1069</th>
<th>1327</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME-to-FE ratio</td>
<td>1.47</td>
<td>1.26</td>
<td>1.14</td>
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<tr>
<td>H, cm</td>
<td>102.86</td>
<td>99.2</td>
<td>101</td>
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<tr>
<td>Thrust, klbf</td>
<td>29.74</td>
<td>33.82</td>
<td>39.93</td>
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<tr>
<td>Thrust-to-weight ratio</td>
<td>4.023</td>
<td>4.016</td>
<td>4.032</td>
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<tr>
<td>Isp, sec</td>
<td>890.94</td>
<td>894.06</td>
<td>896.98</td>
</tr>
</tbody>
</table>
Summary

• Most past designs focus on HEU based fuels
• It is feasible to use LEU based fuels with little performance loss
• Near-optimum design meets or surpasses NASA requirements
• Future work
  – Further coupled analysis needs to be performed at all stages of engine operation

THANK YOU
Preliminary Coupled T/H Analysis

- Multi-channels (i.e. each radial ring)
- Converge on mass flow rate distribution (uniform pressure drop)