Fusion Propulsion

Opening the Solar System Frontier

John F Santarius

Lecture 28

Resources from Space

NEEP 533/ Geology 533 / Astronomy 533 / EMA 601

University of Wisconsin

March 31, 2004
Key Points

• D-\(^3\)He appears to be the fusion fuel of choice for space applications.
• D-\(^3\)He fusion will provide capabilities not available from other propulsion options.
• Several configurations appear promising for space propulsion, particularly the field-reversed configuration (FRC), magnetized-target fusion (MTF), spheromak, and spherical torus.
• Successful development of D-\(^3\)He fusion would provide attractive propulsion, power, and materials processing capabilities.
“A Prophecy Whose Time Will Come

“The short-lived Uranium Age will see the dawn of space flight; the succeeding era of fusion power will witness its fulfillment.”

From the essay “The Planets Are Not Enough” (1961).
D-³He Fusion Will Provide Capabilities Not Available from Other Propulsion Options
At the Predicted Specific Power, $\alpha=1-10$ kW/kg, Fusion Propulsion Would Enable Attractive Solar-System Travel

- Comparison of trip times and payload fractions for chemical and fusion rockets:

**Fast human transport**

**Efficient cargo transport**
Key Fusion Fuel Cycles for Space Applications

- $D + ^3\text{He} \rightarrow p (14.68 \text{ MeV}) + ^4\text{He} (3.67 \text{ MeV})$
- $D + T \rightarrow n (14.07 \text{ MeV}) + ^4\text{He} (3.52 \text{ MeV})$
- $D + D \rightarrow n (2.45 \text{ MeV}) + ^3\text{He} (0.82 \text{ MeV})\{50\%\}$
  \[\rightarrow p (3.02 \text{ MeV}) + T (1.01 \text{ MeV}) \{50\%\}\]
Physics Viewpoint:
D-$^3$He Fuel Requires High $\beta \cdot n\tau$, and $T^+$

Confinement

Power density

$\beta = \text{plasma pressure/magnetic field pressure}$
$\tau = \text{energy confinement time}$
D-\(^3\)He Fuel Could Make Good Use of the High Power Density Capability of Some Innovative Fusion Concepts

- D-T fueled innovative concepts become limited by neutron wall loads or surface heat loads well before they reach \(\beta\) or B-field limits.
- D-T fueled FRC’s (\(\beta\sim85\%\)) optimize at \(B \leq 3\) T.
- D-\(^3\)He needs a factor of \(~80\) above D-T fusion power densities.

- Superconducting magnets can reach at least 20 T.
- Fusion power density scales as \(\beta^2 B^4\).
- Potential power-density improvement by increasing \(\beta\) and B-field appears at right.
Engineering Viewpoint: 
D-³He Fuel and High β Relax Constraints

- Reduced neutron flux allows
  - Smaller radiation shields
  - Smaller magnets
  - Less activation
  - Easier maintenance

- Increased charged-particle flux allows direct energy conversion to thrust or electricity
• High efficiency increases thrust power and reduces radiator mass.

• Doubling efficiency from a thermal cycle’s ~1/3 to direct conversion’s ~2/3 gives 4 times better power per unit waste heat.
Predicted Specific Power of D-\(^{3}\)He Magnetic Fusion Rockets is 1-10 kW/kg

- Prediction based on reasonably detailed magnetic fusion rocket studies.

<table>
<thead>
<tr>
<th>First Author</th>
<th>Year</th>
<th>Configuration</th>
<th>Specific Power (kW/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borowski</td>
<td>1987</td>
<td>Spheromak</td>
<td>10.5</td>
</tr>
<tr>
<td>Borowski</td>
<td>1987</td>
<td>Spherical torus</td>
<td>5.8</td>
</tr>
<tr>
<td>Santarius</td>
<td>1988</td>
<td>Tandem mirror</td>
<td>1.2</td>
</tr>
<tr>
<td>Bussard</td>
<td>1990</td>
<td>Riggatron</td>
<td>3.9</td>
</tr>
<tr>
<td>Teller</td>
<td>1991</td>
<td>Dipole</td>
<td>1.0</td>
</tr>
<tr>
<td>Nakashima</td>
<td>1994</td>
<td>Field-reversed configuration</td>
<td>1.0</td>
</tr>
<tr>
<td>Williams</td>
<td>2003</td>
<td>Spherical torus</td>
<td>8.7</td>
</tr>
<tr>
<td>Thio</td>
<td>2002</td>
<td>Magnetized-target fusion</td>
<td>50</td>
</tr>
<tr>
<td>Emrich</td>
<td>2000</td>
<td>Gasdynamic mirror</td>
<td>130</td>
</tr>
<tr>
<td>Wessel</td>
<td>2000</td>
<td>Colliding-beam FRC</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Generic Fusion Rocket Model Supports 1-10 kW/kg

  - Cylindrical geometry
  - Main mass contributors: radiation shields, magnets, refrigerators, and radiators
  - Heat flux limit of 5-10 MW/m²
  - Neutron wall load limit of 20 MW/m²
  - Radiators reject 5 kW/kg
  - Low temperature superconducting magnet He refrigerators require 1000 kg/kW\text{rejected}
  - Low-mass radiation shield (LiH with 10% Al structure)
  - Magnet mass calculated by virial theorem and by winding-pack current density limit (50 MA/m²); larger value used
  - Development of high-temperature superconductors should reduce the power-plant mass.
    - Reduced refrigerator mass for magnet coolant
    - Reduced shielding, because more magnet heating can potentially be tolerated before quenching
Earliest D-³He Reactor Design
Was a Fusion Rocket

G.W. Englert,
NASA Glenn Research Center
New Scientist (1962)

“If controlled thermonuclear fusion can be used to power spacecraft for interplanetary flight it will give important advantages over chemical or nuclear fission rockets. The application of superconducting magnets and a mixture of deuterium and helium-3 as fuel appears to be the most promising arrangement.”
Conventional Tokamaks Have Large Mass
EFBT Toroidal Fusion Rocket
J. Reece Roth, NASA Lewis, 1972
Spherical Torus Space Propulsion

• ST’s give high $\beta$, implying high power density.

• Crucial problems are recirculating power and providing thrust from a toroidal configuration.

• Martin Peng has suggested helicity *ejection*, and the concept will be tried on NSTX.
Plasma-Jet Magnetized-Target Fusion
Allows Liner Standoff from Target

- An approximately spherical distribution of jets is launched towards the compact toroid at the center of a spherical vessel.
- The jets merge to form a spherical shell (liner), imploding towards the center.
The MTF Explosion/Implosion Process Involves a Complicated Mixture of Shock Waves

- Red=target; Purple=plasma jet; Green=buffer plasma

Case 030313_02
- $m_t = 4.38$ mg; $\Delta t = 5.0$ cm
- $m_j = 0.2$ g; $\Delta j = 2.4$ cm
- $m_b = 2.0$ g; $\Delta b = 22.1$ cm
- $v_j = 125$ km/s; $v_b = 125$ km/s
Conversion of Fusion Energy into Thrust

- Fusion produces a high-temperature plasma, which can be used to push against a magnetic field to produce thrust directly.
- Direct conversion of the fusion energy into thrust is important in realizing the benefits of fusion for propulsion.
Theta Pinch Gun
(Located 180 deg. Apart)
(2 plcs)

Reversed Conical
Theta Pinch

Plasma Gun
(Approx. 56 in. long x 9.5 in. dia.)
(48 plcs)

Structural Ring Stiffener
(12 in. thk.)
(4 plcs)

Structural Tapered Spline
(12 plcs)

Thrust Coil
(7.87 in. dia.)
(8 plcs)

RASC/HOPE MTF Engine Configuration

NASA MSFC
NASA Produced a Conceptual MTF Rocket Design

- Fusion power = 4 GW
- Total power-system mass = 80 Mg
- \(\alpha = 50 \text{ kW/kg}\)

- Power density can be very high due to $\beta^2 B^4$ scaling, but first-wall heat fluxes would remain manageable.
  - Charged-particle power transports from internal plasmoid to edge region and then out ends of fusion core.
  - Magnetic flux tube can be “pinched” on one end by increasing the magnetic field on that side, giving primarily single-ended flow.

Not to scale

FRC core region

Neutrons Bremsstrahlung

Expanded flux tube to reduce heat flux

Charged particles

Thrust
Linear Geometry
Greatly Facilitates Engineering

• Steady-state heat flux is broadly spread and due almost exclusively to bremsstrahlung radiation power.
  ➢ Relatively small peaking factor along axis for bremsstrahlung and neutrons.

• Maintenance of single-unit modules containing blanket, shield, and magnet should be relatively easy, improving reliability and availability.

• Considerable flexibility and space exist for placement of pipes, manifolds, etc.

• Direct conversion of transport power to thrust by a magnetic nozzle can increase efficiency.
Radioactivity Will Most Likely Lead to a Requirement for Remote Maintenance

Maintenance Scheme for a Terrestrial-Electric FRC Using a Telescopic Vacuum Vessel

- Design by E.A. Mogahed
Several Concepts with Linear External Magnetic Fields Have Been Investigated for Space Propulsion

- **FRC**
- **Spheromak**
- **Tandem mirror**
D-³He Space-Propulsion Tandem Mirror

Specific power  1.2 kW/kg
Thrust power    1500 MW
Length          113 m
Ave. outer radius  1 m
Core B field    6.4 T
Field-Reversed Configurations (FRC) Would Be Attractive for Space Applications

- High $\beta = \frac{P_{\text{plasma}}}{P_{\text{B-field}}}$
- Linear external B field
- Cylindrical geometry
- Rotating B field current drive

From Univ. of Washington web page for the Star Thrust Experiment (STX):
www.aa.washington.edu/AERP/RPPL/STX.html
ARTEMIS Field-Reversed Configuration
(D-³He, Momota, et al., NIFS, 1992)
Colliding-Beam FRC
Conceptual Design Exists for Space Propulsion

• Variant of “classic” FRC.
• Invokes p-\textsuperscript{11}B fusion fuel.
• 51 MW\textsubscript{thrust}, 33 Mg mass \Rightarrow \alpha = 1.5 \text{ kW/kg}
The Dipole Configuration Offers a Relatively Simple Design That an MIT/Columbia Team Is Testing

Io plasma torus around Jupiter

LDX experiment
(under construction at MIT)

Dipole space propulsion design
(Teller, et al., 1992)
Inertial-Electrostatic Confinement (IEC) May Be Attractive for Space Propulsion

• Key principle: spherical or cylindrical electrostatic focussing.
Other IEC Concepts
Potentially Attractive for Space Propulsion

Barnes-Nebel-Turner, Penning Trap

Bussard, Polywell

1 cm

1 m
D-³He Fusion Propulsion
Could Provide Flexible Thrust Modes

- Fuel plasma exhaust
- Mass-augmented exhaust
- Thermal exhaust
Direct Conversion to Electricity Could Take Advantage of the Natural Vacuum in Space

Barr-Moir experiment, LLNL
*(Fusion Technology, 1973)*
Plasmas Provide Many Materials Processing Capabilities

Summary

- D-³He fusion requires continued physics progress.
- D-³He engineering appears manageable.
- Several configurations appear promising for space propulsion, particularly the field-reversed configuration (FRC), magnetized-target fusion (MTF), spheromak, and spherical torus.
- Successful development of D-³He fusion would provide attractive propulsion, power, and materials processing capabilities.