D-³He and Pulsed-Power Fusion Approaches Would Shorten Development Times

**Physics Readiness**

- Transport
- Disruptions
- Current Drive
- Fueling
- Impurities
- Profiles

**Engineering Readiness**

- Basic Plasma Science
- D-³He FRC, dipole, spheromak, ST
- Pulsed-power MTF, PHD, fast-ignitor

**Main Development Costs**

Fusion Rocket

JFS 2005  
Fusion Technology Institute
D-^3^He Fusion Will Provide Capabilities Not Available from Other Propulsion Options
Predicted Specific Power of D-³He Magnetic Fusion Rockets Is Attractive (>1 kW/kg)

- Predictions 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>Emrich</td>
<td>2000</td>
<td>Gasdynamic mirror</td>
<td>130</td>
</tr>
<tr>
<td>Thio</td>
<td>2002</td>
<td>Magnetized-target fusion</td>
<td>50</td>
</tr>
<tr>
<td>Williams</td>
<td>2003</td>
<td>Spherical torus</td>
<td>8.7</td>
</tr>
<tr>
<td>Cheung</td>
<td>2004</td>
<td>Colliding-beam FRC</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Fusion Propulsion Would Enable Fast and Efficient Solar-System Travel

- Fusion propulsion would dramatically reduce trip times (shown below) or increase payload fractions.
**Key Fusion Fuels for Space Propulsion**

1\(^{st}\) generation fuels:

\[ \text{D} + \text{T} \rightarrow \text{n} (14.07 \text{ MeV}) + ^4\text{He} (3.52 \text{ MeV}) \]
\[ \text{D} + \text{D} \rightarrow \text{n} (2.45 \text{ MeV}) + ^3\text{He} (0.82 \text{ MeV}) \]
\[ \rightarrow \text{p} (3.02 \text{ MeV}) + \text{T} (1.01 \text{ MeV}) \]
{50% each channel}

2\(^{nd}\) generation fuel:

\[ \text{D} + ^3\text{He} \rightarrow \text{p} (14.68 \text{ MeV}) + ^4\text{He} (3.67 \text{ MeV}) \]

3\(^{rd}\) generation fuels:

\[ ^3\text{He} + ^3\text{He} \rightarrow 2 \text{p} + ^4\text{He} (12.86 \text{ MeV}) \]
\[ \text{p} + ^{11}\text{B} \rightarrow 3 ^4\text{He} (8.68 \text{ MeV}) \]
D-³He Fuel Requires Continuation of the Remarkable Progress of Fusion Physics

• Decades of plasma physics progress created sophisticated tools that will facilitate the development of innovative concepts:

  ➢ Experimental techniques
  ➢ Diagnostics
  ➢ Computational modeling
  ➢ Theory
D-$^3$He Fuel and High $\beta$ Relax Engineering Constraints

- Reduced neutron flux allows
  - Smaller radiation shields,
  - Smaller magnets,
  - Less activation,
  - Easier maintenance, and
  - Potentially, proliferation-proof fusion power plants.

- Increased charged-particle flux allows direct energy conversion to thrust or electricity.
  - Nonlinear gain in useful power / radiator mass
    - $P_{\text{thr}}/M_{\text{rad}} \propto \eta/(1-\eta)$
D-³He 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 ($\beta \sim 85\%$) optimize at $B \leq 3$ T.
- D-³He needs a factor of $\sim 80$ 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.
Plasma Power Flows in Linear Devices Give More Design Flexibility than Flows in Toroidal Devices

- 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.
- Pulsed concepts gain similar advantages by reflecting plasma from a magnetic nozzle.
Low Radiation Damage in D-³He Reactors Allows Permanent First Walls and Shields to be Designed

Maximum Structural Temperature (°C)

Maximum dpa per 30 Full Power Years

“Permanent life regime for steel”

DT Fuel
D³He Fuel

JFS 2005
Fusion Technology Institute
Radioactive Waste Disposal is Much Easier for D-³He Reactors than for D-T Reactors

- **D-³He**
  - 30 full-power years
  - Low-activation Tenelon
  - HT-9 steel
  - Class A

- **D-T**
  - 5 full-power years
  - Low-activation Tenelon
  - HT-9 steel
  - Class C

Deep Geologic Burial
Fusion Rockets Would Provide Electricity Production and Materials Processing Capabilities at Destination

- Direct conversion to electricity could take advantage of the natural vacuum in space.

- Plasmas provide many materials processing capabilities.

A Well Documented Lunar $^3$He Resource Exists

- Lunar $^3$He concentration verified from Apollo 11, 12, 14, 15, 16, & 17 plus USSR Luna 16 & 20 samples.
- Analysis indicates that $\sim 10^9$ kg of $^3$He exists on the lunar surface, or $\sim 1000$ y of world energy supply.
- One-way Earth-Mars trip requires $\sim 100$ kg $^3$He.
- 40 tonnes of $^3$He would supply the entire 2004 US electricity needs.
- $\sim 400$ kg $^3$He (8 GW-y fusion energy) is accessible on Earth for R&D.

Well-Developed Terrestrial Technology
Gives Access to $\sim 10^9$ kg of Lunar $^3$He

- 33 kg $^3$He / year
- $\sim 600$ tonnes volatiles / year
- 556 km$^2$ / year
- $v = 23$ m / h

- Bucket-wheel excavators
- Bulk heating
- Heat pipes
- Conveyor belt
Lunar $^3$He Mining Produces Other Useful Volatiles
D-\(^3\)He Field-Reversed Configuration (FRC) Appears Attractive for Fusion Propulsion

- FRCs possess key desired characteristics for D-\(^3\)He fusion:
  - Very high \(\beta \equiv P_{\text{plasma}} / P_{\text{B-field}}\)
  - Linear external B field
  - Cylindrical geometry

- Recent encouraging results:
  - Emerging understanding of why FRCs appear far more stable than MHD theory predicts.
  - Attractive current drive by rotating magnetic fields (RMF) demonstrated.

From Univ. of Washington web page for the Star Thrust Experiment (STX):
www.aa.washington.edu/AERP/RPPL/STX.html
Spherical Torus Space Propulsion Would Benefit from the Substantial DOE ST Research Effort

- Very low aspect-ratio version of the tokamak.
- High $\beta$, implying high power density.
- Critical issues: recirculating power and providing thrust.

Pegasus ST experiment, Univ. of Wisconsin

- Glenn Research Center design: C.H. Williams, et al., NASA TM 2005-213559.
The Dipole Configuration Offers a Relatively Simple Design That an MIT/Columbia Team Has Begun Testing

Dipole space propulsion design:

Io plasma torus around Jupiter

LDX experiment (MIT)

0.65 m
Magnetized-Target Fusion (MTF)

- Ionized material from the fusion micro-explosion would reflect from a diverging magnetic nozzle to produce thrust.

- Plasma jets would converge, compress, and ignite a magnetized plasmoid.
- Plasma-jet version invented by Francis Thio.

Magnetized-Target Fusion artist’s conception from Marshall Space Flight Center
Pulsed High Density (PHD) Fusion

- Invented by John Slough, Univ. of Washington, who provided this viewgraph.
- Experimental program that takes advantage of a very compact, high energy density FRC to reach fusion conditions.
  - The energy required to achieve fusion conditions is transferred to the FRC via simple, relatively low field acceleration/compression coils.
  - For FRC in smaller, higher density regime, the requirement on the FRC closed poloidal flux is no greater than what has been achieved.
  - The FRC should remain in a stable regime with regard to MHD modes such as the tilt from formation through burn.

1. FRC formed at low energy (~3 kJ) and relatively low density (~10^{21} m^{-3})
2. FRC accelerated by low energy propagating magnetic field (~ 0.4 T) to
3. FRC adiabatically compressed and heated as it decelerates into burn chamber
4. FRC travels several meters during burn time minimizing wall loading
5. If necessary, FRC flux and confinement enhanced by spatial “RMF” field
6. FRC expands and cools converting fusion energy directly into electrical energy
It May be Possible to Efficiently Burn DD or D$^3$He Fuels in Fast-Ignited ICF Targets

Four unique aspects of ICF for advanced fuels:

1. The required high ignition/burn temperatures (~30/150 keV) can be obtained via a precursor DT ignitor region (~10/50 keV).
2. The larger driver energies (required by the larger rho-R’s for efficient advanced fuel burn-up) can be offset through fast ignition.
4. Tritium for the DT ignitor (~1% inventory) is self-bred as the main fuel burns.

• Viewgraph contributed by John Perkins, LLNL.
D-³He Fusion Space Propulsion Can Be Developed Quickly, If the Will Exists

• In parallel, experiment on several concepts with multiple devices.
  - Winnow.
  - Provide substantial power and diagnostic capabilities.
  - Provide sufficient contingency funding and program flexibility to director.

• Incorporate existing terrestrial fusion research program where possible.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Proof-of-Principle Experiments ($240 M)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 experiments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 experiments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 experiments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 experiments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Integrated Test Experiments ($300 M)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Existing Proof-of-Principle Experiments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Burning Plasma Experiments ($2400 M)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Demo ($3500 M)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• Total program cost ~ 6 B$.
Summary and Conclusions

• Attractive fusion space propulsion options exist.
• Development should follow the D-³He and pulsed-power paths of more physics risk and less engineering risk.
  ➢ Pursue “survival of the fittest,” starting with sufficient species.
  ➢ Provided sufficient program flexibility and contingency funds.
  ➢ Estimated cost < $10 B for a demonstration system in two decades.
References

- UW Fusion Technology Institute:  http://fti.neep.wisc.edu/