The Need for Fusion Propulsion
Presentation Outline

• Presentation Objectives
• Arguments for Fusion Propulsion
• Fusion Enabled Missions and Examples
• Fusion Technology Trade Space
• Proposed Outline for Future Efforts
• Endorsements
Presentation Objectives

- Enable propulsion systems research for
  - crewed exploration beyond Mars
  - routine rapid crewed missions to Mars
  - high-speed robotic missions to the outer solar system and beyond.

- Convince HQ that a NASA-sponsored fusion campaign is needed.

- Allocate research funds to address the scientific and technical feasibility for fusion propulsion.
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Arguments for Investment in Fusion Propulsion

- We need to seed technologies so they are in the maturation pipeline
- Fusion can enable high specific power missions while maintaining high specific impulse
- Lunar and outer planet abundance of He$^3$ gives further impetus for exploration (see backup slides)
- We must develop an internal fusion science and engineering capability to properly evaluate usefulness of technologies coming from industry, academia, and other government agencies
Arguments for NASA Investment in Fusion Propulsion

- The NASA – DOE relationship\textsuperscript{1}
  - DOE’s mandate is primarily to develop terrestrial power generation. Premium is on cost effective (i.e. fuel efficient, high containment) power generation, not mass limitation
  - NASA requires a lightweight propulsion system with high exhaust velocities. Electrical power generation is of secondary importance

- DOE pursuing Tokamak research for terrestrial power production

- DOE sponsored investment in fusion terrestrial power generation has generated a substantial database of basic physics and engineering knowledge relating to fusion physics

- NASA should leverage the basic research being developed by DOE to develop fusion propulsion technologies

\textsuperscript{1}Schulze, Norman R., Fusion Energy for Space Missions in the 21\textsuperscript{st} Century, NASA TM-4298, August 1991.
Development Times for Previous Propulsion Systems

- A sustained and steady development program is required now to generate usable results in the near future.
- A historical perspective indicates advanced propulsion systems require long lead times for development.
  - Flightweight aircraft engine - ~ 15 years
    - Late 1800's it was accepted that a flightweight reciprocating engine was required to enable human flight.
    - Wright brothers developed a barely adequate engine (12 hp/140 lb) but combined with adequate aerodynamics and phenomenal propellant efficiencies (70%) was a success.
  - Jet engine - ~ 15 years
    - Frank Whittle proposed turbofan engine in 1928 and it received little interest.
    - The Messerschmitt Me 262 started mass production in 1942.
  - Liquid propellant rocket engine – 30-45 years
    - Theorized by Tsiolkovsky in late 1890's.
    - First test flight by Goddard in 1929.
    - Used in V-2 rockets in 1944.
  - Electric propulsion thrusters - ~ 40 years
    - First proposed in the 1950's by several.
    - First flight of Ion thruster for main propulsion was Deep Space 1 in 1990's.

Fusion Development Overlap with Prometeus

- Can leverage advancements in fission propulsion and pursue intermediate fission/fusion hybrid
  - Fusion reactions with a gain less than unity to increase specific impulse of magnetically confined electric thruster concepts (i.e. VASIMR)
  - Fission ignited fusion, both steady state (UF4 gas entrained in fusion plasma to increase temperature and pressure) and pulsed (fission explosion to confine fusion plasma to very high densities)

- Common propulsion elements between fission and fusion
  - High voltage and power distribution and management
  - Neutron and gamma shielding
Explanation for Higher Specific Power for
Fusion vs. NEP

• Electric power requires energy conversion from a reactor or other source

• Thermal/electric conversion, required for NEP, is about 30% efficient limited by Carnot cycle (2nd Law) efficiency
  – Large radiator mass required
  – Mass of radiator must be traded against NEP system efficiency to find rejection temperature that yields minimum mass

• Thermal/electric inefficiencies can be offset in a high gain fusion system
  – Large propulsion system mass offset by added jet power

• Direct conversion of the plasma exhaust energy, a viable approach for fusion, can approach 70% efficiency of the total fusion reaction
  – Losses related to Bremmstrahlung and neutron energy
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Mission Options

Robotic, near Sun
R4

EARTH AND EARTH ORBIT

Human, LEO to Lunar
R2

Understand solar variability and the Sun-Earth connection
Enhance security and the quality of life on Earth
Improve how humans can live and work in space

Civil Robotic, LEO to Inner Planets
R5

Earth

Human, Inner Planets
R3

Build revolutionary telescopes to study planets
Explore unique viewpoints in space

Robotic, Outer Planets
R6

Characterize threats and resources and study primitive life forms
Explore possible subsurface oceans on moons and search for life

Human, Outer Planets
R5

Follow the water on Mars and seek ancient or present life
Use as gateway for future human exploration

Robotic, Beyond Planets
R8

Fusion propulsion holds the promise of enabling human exploration beyond the inner planets and enhancing all other human/robotic missions outside Lunar orbit
Example Mission – RASC ’02 Study

- Start from base at Earth-Moon L1 point
- Assume flight after 2040
- Travel to Callisto and back
- 30 day surface stay minimum
- Carry, Transhab, lander, surface habitat, ISRU

<table>
<thead>
<tr>
<th>Mission Timeline</th>
<th>Time (days)</th>
<th>Mass (mT)</th>
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</thead>
<tbody>
<tr>
<td>Depart L1 Station</td>
<td>0</td>
<td>650</td>
</tr>
<tr>
<td>Thrust off</td>
<td>51</td>
<td>630</td>
</tr>
<tr>
<td>Thrust on</td>
<td>240</td>
<td>630</td>
</tr>
<tr>
<td>Arrive Callisto Orbit</td>
<td>331</td>
<td>595</td>
</tr>
<tr>
<td>Depart Callisto Orbit</td>
<td>365</td>
<td>475</td>
</tr>
<tr>
<td>Thrust off</td>
<td>440</td>
<td>445</td>
</tr>
<tr>
<td>Thrust on</td>
<td>614</td>
<td>445</td>
</tr>
<tr>
<td>Arrive L1 Station</td>
<td>654</td>
<td>430</td>
</tr>
</tbody>
</table>

Total Mission Duration ~ 654 days
Outbound Leg Departs 4/22/2045
Flight to Callisto ~ 331 days
Time in Callisto Orbit ~ 33 days
Total time thrusting ~ 258 days
Returns without Surface Habitat, ISRU, and Transport (120 mt total)
Isp = 70,400 sec
Jet Power = 1.072 GW
Propulsion System Specific Mass = 0.122 kg/kW
Initial Acceleration = 0.0005 g’s
Final Acceleration = 0.0007 g’s
Example Mission – RASC ’02 Study

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Fusion Technology Trade Space

• Next chart maps technologies of interest to density vs. temperature of confinement plasma
• Charts on each technology are in the appendix
  – Pulsed
    • Magnetized-Target Fusion (MTF)
    • Magnetokinetic-Compression Fusion
    • Fast-Ignitor Inertial Fusion Energy
  – Steady-State
    • Field-Reversed Configuration (FRC)
    • Dipole
    • Spherical Torus (ST)
    • Gas-Dynamic Trap (GDT)
    • IEC (POPS, Polywell®)
## Fusion Technology Trade Space

<table>
<thead>
<tr>
<th>Concept</th>
<th>Alpha (kW/kg)</th>
<th>n (1/m³)</th>
<th>Freq (Hz)</th>
<th>Mass (mT)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steady State</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Quiet Electric Discharge (QED)</td>
<td>12</td>
<td>n/a</td>
<td>n/a</td>
<td>500</td>
<td>Fusion Energy in Space Propulsion, AIAA 1995</td>
</tr>
<tr>
<td>Inertial Electrostatic Confinement (IEC)</td>
<td>0.02</td>
<td>n/a</td>
<td>n/a</td>
<td>300</td>
<td>Fusion Energy in Space Propulsion, AIAA 1995</td>
</tr>
<tr>
<td>Gas Dynamic Mirror (GDM)</td>
<td>10</td>
<td>1.0 · 10^{22}</td>
<td>n/a</td>
<td>1225</td>
<td>STAIF 2000 p1420-1424</td>
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<tr>
<td>Tandem Mirror (SOAR)</td>
<td>1.2</td>
<td>5.0 · 10^{19}</td>
<td>n/a</td>
<td>1220</td>
<td>UWFDM-753</td>
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<tr>
<td>Spheromak</td>
<td>5.75</td>
<td>8.0 · 10^{20}</td>
<td>n/a</td>
<td>1050</td>
<td>AIAA 87-1814</td>
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<tr>
<td>Field Reversed Configuration (FRC)</td>
<td>1</td>
<td>1.0 · 10^{21}</td>
<td>n/a</td>
<td>1100</td>
<td>Proc. 11th Symp. Space nuclear Power and Space Prop. Sys. 1994.</td>
</tr>
<tr>
<td>Colliding Beam FRC</td>
<td>1.5</td>
<td>5.0 · 10^{20}</td>
<td>n/a</td>
<td>33</td>
<td>STAIF 2004, p354-361</td>
</tr>
<tr>
<td>Dipole</td>
<td>1</td>
<td>1.0 · 10^{19}</td>
<td>n/a</td>
<td>1300</td>
<td>Fus. Tech. 22, 82, 1982</td>
</tr>
<tr>
<td>Spherical Torus</td>
<td>8.7</td>
<td>5.0 · 10^{20}</td>
<td>n/a</td>
<td>1630</td>
<td>Fusion S&amp;T 43(1) p99-109, Jan 03</td>
</tr>
<tr>
<td><strong>Pulsed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inertial Fusion Rocket (IFR)</td>
<td>70</td>
<td>1.0 · 10^{25}</td>
<td>100</td>
<td>760</td>
<td>AIF 83-896</td>
</tr>
<tr>
<td>Inertial Confinement Fusion (ICF)</td>
<td>3.4</td>
<td>1.0 · 10^{25}</td>
<td>30</td>
<td>5800</td>
<td>URCL-96676</td>
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<tr>
<td>Magnetized Target Fusion (MTF)</td>
<td>1.12</td>
<td>1.0 · 10^{26}</td>
<td>20</td>
<td>890</td>
<td>NASA TP-2003-212691</td>
</tr>
<tr>
<td>Magneto-Kinetic Expansion (MKE)</td>
<td>2.2</td>
<td>1.0 · 10^{24}</td>
<td>10</td>
<td>67</td>
<td>AIAA 2000-3364</td>
</tr>
</tbody>
</table>
Fusion Propulsion Regimes in Density, Confinement Time, Engine Mass, and Specific Power

\[ n \tau \text{ space} \]
\[ \text{calculated using } 3 \cdot 10^{13} \text{ s/cm}^3, \]
\[ \text{approximate} \]
\[ \text{Lawson criteria} \]
\[ \text{for } T = 10 \text{ keV} \]
\[ \text{DT plasma} \]
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Proposed Outline for Future Efforts

- Definition of actual funding levels were discussed but were considered premature at this time
- However, to sustain a research program funding levels for the next few years are expected to be in the 2-10 million dollar range
- Initial objectives should include
  - Deeper research into DOE efforts and how they can be adapted for NASA’s purposes
  - Research announcements soliciting ideas for developing benchmark experiments
  - Periodic workshops with fusion community to create fusion propulsion system development roadmap, review of research developments
  - Development/enhancement of analytical codes to further system design and development
  - Emphasis on coordinating code and experimental work to be broadly applicable to the wide range of fusion propulsion concepts
  - Coordinate efforts with common technology requirements for other propulsion systems (NTP, NEP, etc.)
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Fusion Propellant Options

- There are several propellant options available
- Each require different confinement conditions
- Each offer advantages in confinement requirements, neutron by-products, availability of propellants, etc.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D + D)</td>
<td>50%</td>
</tr>
<tr>
<td>(D + T)</td>
<td>100%</td>
</tr>
<tr>
<td>(D + \text{He}^3)</td>
<td>100%</td>
</tr>
<tr>
<td>(T + T)</td>
<td>100%</td>
</tr>
<tr>
<td>(\text{He}^3 + T)</td>
<td>51%</td>
</tr>
<tr>
<td>(p + \text{Li}^6)</td>
<td>100%</td>
</tr>
<tr>
<td>(p + \text{Li}^7)</td>
<td>~20%</td>
</tr>
<tr>
<td>(D + \text{Li}^6)</td>
<td>100%</td>
</tr>
<tr>
<td>(p + B^{11})</td>
<td>100%</td>
</tr>
<tr>
<td>(n + \text{Li}^6)</td>
<td>100%</td>
</tr>
<tr>
<td>(n + \text{Li}^7)</td>
<td>100%</td>
</tr>
</tbody>
</table>

IS THIS IN THE LITERATUR

\(T(1.01) + p(3.02)\)
\(\text{He}^3(0.82) + n(2.45)\)
\(\text{He}^4(3.5) + n(14.1)\)
\(\text{He}^4(3.6) + p(14.7)\)
\(\text{He}^4 + 2n + 11.3\)
\(\text{He}^4 + p + n + 12.1\)
\(\text{He}^4(4.8) + D(9.5)\)
\(\text{He}^3(2.4) + D(11.9)\)
\(\text{He}^4(1.7) + \text{He}^3(2.3)\)
\(2\text{He}^4 + 17.3\)
\(\text{Be}^3 + n - 1.6\)
\(3\text{He}^4 + 22.4\)
\(3\text{He}^4 + 8.7\)
\(T + \text{He}^4 + 4.8\)
\(T + \text{He}^4 - 2.5\)
Explanation for Higher Specific Impulse for Fusion vs. NEP

- *Higher energy release per unit mass enables higher internal propellant energies which corresponds to higher exhaust velocities*

- *Apart from mass annihilation, some fusion reactions of the light elements give highest energy release per unit mass*

<table>
<thead>
<tr>
<th>Fuels</th>
<th>Energy Release J/kg</th>
<th>Converted mass fraction $\alpha=\Delta m/m_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{LO}_2+\text{LH}_2$</td>
<td>$1.35 \cdot 10^7$</td>
<td>$1.5 \cdot 10^{-10}$</td>
</tr>
<tr>
<td>$\text{U}^{233},\text{U}^{235},\text{Pu}^{239}$</td>
<td>$8.2 \cdot 10^{13}$</td>
<td>$9.1 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\text{D}+\text{T}$</td>
<td>$3.4 \cdot 10^{14}$</td>
<td>$3.8 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\text{D}+\text{He}^3$</td>
<td>$3.5 \cdot 10^{14}$</td>
<td>$3.9 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\text{p}^+\text{B}^{11}$</td>
<td>$7.3 \cdot 10^{13}$</td>
<td>$8.1 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\text{p}^+\text{p}^-$</td>
<td>$9.0 \cdot 10^{16}$</td>
<td>$1.0$</td>
</tr>
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</table>

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Signatories

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Appendix A – Justification for Mining Lunar Regolith
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.

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
Lunar $^3$He Mining Produces Other Useful Volatiles

Process for Extracting Helium-3 from Lunar Regolith

6100 tonnes

$\begin{align*}
\text{Fuel} & : \text{H}_2, \text{H}_2\text{O}, \text{N}_2 \\
\text{Life Support} & : \text{CO}_2, \text{CH}_4, \text{CO} \\
\text{Cryogenics} & : \text{Helium-4}
\end{align*}$

300 °K Radiator/Condenser 50 °K Isotopic Separation 1.5 °K 1 tonne Helium-3

Clean Fusion Energy on Earth

JFS 2004
Fusion Technology Institute, University of Wisconsin
Helium Content Correlates Well with Ti Content, Indicating Locations of Lunar He Concentrations

Spectral reflectance map of lunar Ti content

Measured correlation of He and Ti contents
$^3$He Evolves When Heating Lunar Regolith

**Helium-3 Evolution from Lunar Regolith**

<table>
<thead>
<tr>
<th>% He3 Evolution</th>
<th>0</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>95%</td>
<td>86%</td>
<td>75%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regolith Temperature, °C

*JFS 2004  Fusion Technology Institute, University of Wisconsin*
Useful Volatiles Evolve When Heating Lunar Regolith

Gibson and Johnson, *Proc. 2nd Lunar Science Conf. 2*, 1351 (1971)
Backup Charts on Various Fusion Concepts
Magnetized Target Fusion (MTF)

- **Projected performance**
  - Specific power: 10 kW/kg to 100 kW/kg
  - Specific impulse: 50,000 s to 100,000 s

- **Maturity/Feasibility**
  - TRL: 1-2 (Physics principles demonstrated in Sandia δ-θ experiment; target formation demonstrated, theoretical foundation established by Kirkpatrick, Thio, etc.)
  - Experiments in progress: (1) LANL MTF experiment funded by DOE at Concept Exploration level. (2) MTF plasma liner experiment at MSFC.
  - Planned experiments: (1) Demonstration of fusion Q > 1 for electrical power by LANL by 2010.

- **Operability**
  - Fuel: D (1st-gen), D + He3 (2nd-gen)
  - Ability to Throttle: Power: continuously variable from 0 to max by varying pulse rate
  - Isp: continuously variable from 5000 s to max by mixing inert propellant (e.g. H, Li) with fusion plasma
  - By-products: He4; neutrons
  - Radiation: electromagnetic waves; neutrons (may be moderated by fusion plasma and shielded)


Magnetokinetic Compression of FRC Fusion Rocket

- **Projected performance**
  - Specific power: 5 kW/kg to 15 kW/kg
  - Specific impulse: 50,000 s to 100,000 s

- **Maturity/Feasibility**
  - TRL: 1 (Scaling laws for FRC stability established; Acceleration of FRC demonstrated to 250 km/s.)
  - Critical mass of propulsion vehicle: 20 Tonnes
  - Experiments in progress: (1) FRC acceleration at MSFC. (2) RMF experiment at UW, Seattle.
  - Planned experiments: Demonstration of fusion Q > 1 for propulsion by MSFC by 2012.

- **Operability**
  - Fuel: D + T (1st-gen). D + He³ (2nd-gen)
  - Throttability:
  - Power: continuously variable from 0 to max.
  - Isp: continuously variable from 10,000 s to max.
  - By-products: He⁴; neutrons
  - Radiation: electromagnetic waves; neutrons (may be shielded)


Steady-State or Quasi-Steady-State FRC Fusion Rocket

- **Projected performance**
  - Specific power: 2 kW/kg to 15 kW/kg
  - Specific impulse: 50,000 s to 200,000 s

- **Maturity/Feasibility**
  - TRL: 1-2 (Plasma temperature in excess of 300 eV for more than 10 ms demonstrated experimentally. Extensive physics database of FRC established.)
  - Critical mass of propulsion vehicle: 100 Tonnes
  - Planned experiments: Proof-of-Principle (Q ~ 0.1) experiment to follow upon successful completion of present CE experiment by DOE.

- **Operability**
  - Fuel: D + T in 1:1 mixture.
  - Throttability:
  - Power: fixed.
  - Isp: continuously variable from 50,000 s to max.
  - By-products: He⁴; neutrons
  - Radiation: electromagnetic waves; neutrons (may be shielded).

**Projected performance**
- Specific power: 5 kW/kg to 14 kW/kg
- Specific impulse: 50,000 s to 200,000 s

**Maturity/Feasibility**
- TRL: 2 (Gasdynamic trapping of plasmas demonstrated in Novosibirst; Plasma temperature > 100 eV.)
- Critical mass of propulsion vehicle: 1225 Tonnes
- Experiments in progress: (1) Plasma stability exploration in low-temperature range (10 eV). (2) Plasma injection experiment. Both at MSFC.
- Planned experiments: no continuation of the above experiments planned.

**Operability**
- Fuel: D + T in 1:1 mixture.
- Throttability:
- Power: fixed.
- Isp: continuously variable from 50,000 s to max.
- By-products: He⁴; neutrons
- Radiation: electromagnetic waves; neutrons (may be shielded)

Fast Ignition Inertial Confinement Fusion

Summary
- 3 Laser pulses
  1. High energy compression
  2. Hole boring 2nd prepulse
  3. Fast ignitor pulse
- Au cone used to guide pulse
- Ignitor intensity $10^{18}$ to $10^{20}$ W/cm$^2$
- Last pulse raises electron temperature to several MeV to ignite the core
- 800 eV ion temperatures have been measured

Projected performance
- Gain: 100
Spherical Torus

- Experiment currently underway at Princeton (NSTX Experiment)
- Spherical torus produces a plasma that is shaped like a sphere with a hole through its center
- High betas possible with spherical torus could allow the development of smaller and lighter systems (relative to the tokamak)
- Use in a propulsion system would require a fairly complex divertor system
The Spheromak Was Chosen for an Early Fusion Rocket Design

- Key design by Borowski, 1987.
- High $\beta = \frac{P_{\text{plasma}}}{P_{B\text{-field}}}$
- Linear external B field.
- Cylindrical geometry.
- Plasma confinement is a critical issue.
The Dipole Configuration Offers a Relatively Simple Design

That an MIT/Columbia Team Has Begun Testing

Io plasma torus around Jupiter

LDX experiment (MIT)

Dipole space propulsion design:
Flow Z-Pinch Fusion Rocket

- **Projected performance**
  - Specific power: 10 kW/kg (short-pulsed); 100 kW/kg (long-pulsed) [No external field coils]
  - Specific impulse: 130,000 s to 350,000 s

- **Maturity/Feasibility**
  - TRL: 1 (Stable Z-pinch observed for over 2000 exponential growth times; Mechanism for long-pulsed operation. High plasma density, $10^{23}$ m$^{-3}$, and plasma temperature, 200 eV)
  - Critical mass of propulsion vehicle: $\sim$10 Tonnes
  - Experiments in progress: DOE OFES funded at level of Concept Exploration, ZaP Flow Z-Pinch experiment at Univ Washington, Seattle.
  - Planned experiments: Demonstration of increased plasma compression and long-pulsed operation.

- **Operability**
  - Fuel: $D + T$ (1st-gen); $D + He^3$ (2nd-gen); $p + B^{11}$ (3rd-gen)
  - Throttability: variable duty cycle
  - Power: continuously variable from 0 to max.
  - Isp: continuously variable from 10,000 s to max.
  - By-products: $He^4$; neutrons (1st-gen)
  - Radiation: electromagnetic waves; neutrons (may be shielded or radiated since no coils around plasma)

The Need for Fusion Propulsion

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Fusion propulsion is inevitable if the human race remains dedicated to exploration of the solar system. There are fundamental reasons why fusion surpasses more traditional approaches to routine crewed missions to Mars, crewed missions to the outer planets, and deep space high speed robotic missions, assuming that reduced trip times, increased payloads, and higher available power are desired. A recent series of informal discussions were held among members from government, academia, and industry concerning fusion propulsion. We compiled a sufficient set of arguments for utilizing fusion in space. If the U.S. is to lead the effort and produce a working system in a reasonable amount of time, NASA must take the initiative, relying on, but not waiting for, DOE guidance. In this talk those arguments for fusion propulsion are presented, along with fusion enabled mission examples, fusion technology trade space, and a proposed outline for future efforts.

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