Spacecraft Applications for Aneutronic Fusion and Direct Energy Conversion

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Changing the Game in Space Exploration

Human Mars Exploration must change from a 3-year epic event to an annual expedition.

Opposition Class Missions
Nuclear Electric Propulsion
Split Mission; ECCV Return
Piloted Vehicle w/ 40 MT Habitat
30-day Surface Stay
Vehicle disposed upon return

Conjunction Class Missions
(900 day total)

Mars Architecture Study 5.0:
Nuclear Thermal Propulsion
Piloted Vehicle w/ 50 MT Habitat
350 MT IMLEO
Vehicle disposed upon return

Development of direct conversion with ion sources paces availability of low-\(\alpha\) in-space power & propulsion.
Direct energy conversion technology is key to attaining low-$\alpha$ in-space propulsion

A generic multi-MW configuration:
Direct energy conversion technology is key to attaining low-$\alpha$ in-space propulsion.

Multi-MW heat sources (e.g., NEP) can enable moderate $\alpha$.
Direct energy conversion technology is key to attaining low-\(\alpha\) in-space propulsion.

Multi-MW ion sources with direct conversion can enable lower \(\alpha\).
Direct energy conversion technology is key to attaining low-α in-space propulsion. Multi-MW ion sources with TWDEC can enable low α:

- Neutron Shielding
- Energy Source
  - Neutronic sources
    - Nuclear Fission (Thin core)
    - Aneutronic sources
      - Nuclear Fusion (D-^{3}He, p-^{11}B)
  - Direct Conversion
    - Charged particle deceleration in electric fields (TWDEC)
- Energy Conversion
- Electricity
- Radiator
- Heat
- Ions
- PMAD
- Thrust
- l_{sp} = \sim 10^4 \text{ sec}
The Problem

Direct energy conversion technology is key to attaining low-\( \alpha \) in-space propulsion. Multi-MW ion sources with TWDEC and direct propulsion conversion can enable lowest \( \alpha \).

Neutron Shielding

Energy Source

Energy Conversion

Direct Conversion • TWDEC

Electric Propulsion

PMAD

Radiator

Radiator

I_{sp} = \sim 10^4 \text{ sec}
Direct energy conversion technology is key to attaining low-α in-space propulsion.

Direct conversion is the nexus of all the technologies necessary for a truly “game-changing” in-space propulsion and power system.
Options for Low-\(\alpha\) Propulsion and Power Systems for Mars and Beyond  
(For 30 MW\(_e\) class)

**NEP 5 year, 1200 K Fission Reactor with K-Rankine conversion, current PMAD, and Plasma EP**  
\(\alpha = 16\) kg/kW\(_e\)

**NEP 2 year, 1500 K Fission Reactor with K-Rankine conversion, advanced PMAD, and Plasma EP**  
\(\alpha = 10\) kg/kW\(_e\)

**NEP “Massless” Fission or D-T Fusion Reactor at 1500 K with K-Rankine conversion, advanced PMAD, and Plasma EP**  
\(\alpha = 9\) kg/kW\(_e\)

- Requires Nuclear Testing for Fuel Certification and Flight Qualification
- Further High Temperature Fuel Element Certification
- No Nuclear Testing Required

**Aneutronic Fusion with \(T_{\text{top}} = 1500\) K, K-Rankine Conversion, and Plasma EP**  
\(\alpha = 15\) kg/kW\(_e\)

**Aneutronic Fusion with TWDEC and Plasma EP**  
\(\alpha = 3\) kg/kW\(_e\)

**Aneutronic Fusion with TWDEC and Direct Conversion Plasma EP**  
\(\alpha = 1\) kg/kW\(_e\)

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Aneutronic fusion reactors for space applications will require more aggressive $q$ performance than those for civil power generation.
Direct Conversion Options for Ion Energy Output
Literature Survey Results

Charge Collector – TRL 1
• Conceptual design only
• Intended for “Polywell” aneutronic reactor output with MeV energies.
• DC output
  • $\alpha = ?, \eta = ?$
Bussard, Some Physics Considerations of Magnetic Inertial Electrostatic Confinement, Fusion Technology, 1991

Periodic Focusing Direct Energy Converter – TRL 2
• Preliminary design and computer modeling only
• Intended for scavenging energy from D-T “mirror” confinement end leakage (~150 keV energies)
• DC output
  • $\alpha = ?, \eta = 0.6$
Barr, Howard, and Moir (LLNL), Computer Simulation of the Periodic Electrostatic Focusing Converter, IEEE Transactions on Plasma Science, 1977

Traveling Wave Direct Energy Converter – TRL 3
• Preliminary design study and subscale testing (1998 - 2008)
• Originally intended for primary power from of D-3He “pinch confinement” (~15 MeV energies); studied for space applications with IEC fusion.
• RF output
  • $\alpha \approx 0.14 \text{ kg/kW}_\text{in} , \eta \approx 0.7$
Momota (NIFS-Japan), Miley (U. of Illinois), et al, Conceptual Design of the D-3He Reactor ARTEMIS, Fusion Technology, 1992

“Venetian Blind” Convertor – TRL 3
• Preliminary design study and subscale testing
• Intended for scavenging energy from D-T “mirror” confinement end leakage (~150 keV energies)
• DC output
  • $\alpha = ?, \eta = 0.6$
Barr, Moir (LLNL), Test Results On Plasma Direct Converters. Nuclear Technology/Fusion, 1983.
Conceptual design of half of a conversion system for a D-³He reactor with a “venetian blind” DEC for 810 MW of thermal (keV) alpha particles and a TWDEC for 368 MW of 15 MeV protons. Momota, Miley et al, Fusion Technology, 1992.

Schematic of a conversion system for a D-³He reactor for a D-³He reactor with a CUSPDEC for collection of electrons and thermal (keV) alpha particles and a TWDEC for 15 MeV protons. Takeno, Proceedings of 23rd IAEA Fusion Energy Conference. 2010.

**Modulator:** Fusion product ions in a beam are “bunched” as they pass through evenly spaced grids of alternating potential.

**Decelerator:** On each of the grids through which it passes, the ion “bunch” creates an electric potential higher than adjacent grids, which can drive an AC signal. Frequency is set by grid spacing, which decreases as the “bunches” give up energy and slow.

Inefficiencies come from beam thermalization, particle collisions with the grids, and residual, uncollected energy of particles downstream.
TWDEC originally conceived as direct conversion system for “ARTEMIS” D-3He, Maxwellian plasma test reactor for utility grid power.

[Momota 1992].

Estimated performance in ARTEMIS application

- Convert 183 MW from 14.7 MeV protons of $\rho_{\text{beam}} = \sim 10^{10} \text{ m}^{-3}$; Low $\rho_{\text{beam}}$ requires large ($R_{\text{beam}} = 5 \text{ m}$) electrodes
- Predicted $\eta \approx 0.7$; electrode grid collisions rejected as heat
- Estimated $\alpha$ (w/o vacuum structure) = 0.14 kg/kW

Opportunities/issues with $\eta$ and $\alpha$ for spacecraft applications

a) Decreased electrode collisions can minimize losses to be rejected as heat (e.g., replace grids with hollow electrodes)

b) Increased beam density can improve inductive coupling with electrodes and decrease electrode size (e.g., increase of $\rho_{\text{beam}}$ to $\sim 10^{14} \text{ m}^{-3}$ with 3 MeV $p-^{11}\text{B}$ alpha particles would enable 100 MW carried in $R_{\text{beam}}$ of 10 cm)

c) Narrowed relative thermal energy spread can improve inductive coupling with electrodes

d) Limited particle neutralization in ion beam can improve $\eta$

e) Adaptation to possible bimodal or broad spectrum alpha particle beam from $p-^{11}\text{B}$ fusion can improve $\eta$
TWDEC Research to date

a) Electrode Collision Losses

Modeling indicates 20% loss in $\eta$ due to ion collisions with electrode grids
[Shoyama, 1996]

d) Mitigation of Ion Neutralization and Electron Leakage

Experiments with keV beams indicate improvement in $\eta$ due electron deflection
in Cusp-type beam preconditioning and with electrode negative bias
[Takeno 2010a, 2010b, 2011a; Taniguchi 2010]

e) Harnessing Broad Spectrum or Bimodal Beams

Modeling indicates that dual-beam or “fan” TWDECs can efficiently harness
potentially non-mono-energetic ion beams from p-11B reactors.
[Takeno 2010a, 2010b, 2011a; Stave 2011]

b) Beam Densification

Hollow electrode experiments with keV beams indicate $\eta$ maintained with $\rho_{\text{beam}} = 10^{12}$ m$^{-3}$
[Kawana, 2008]

c) Thermal Spread Mitigation

Experiments with keV beams indicate beam acceleration in modulator can
decrease relative thermal energy spread and increase $\eta$
[Takeno, 2011a, 2010a]
Phase 1 NASA test article will enable further model validation of TWDEC $\alpha$ and $\eta$ improvements with keV alpha particles of $\rho_{\text{beam}}$ up to $10^{15}$ m$^{-3}$ and with variable electrode biases and geometries. All major components will be in place by FY12 end.
## DEC Project Cost, Schedule, Deliverables & Key Milestones (Overview)

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<th>FY13</th>
<th>FY14</th>
<th>FY 15-16 option</th>
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<td>Annual US/Japan &amp; NIAC TWDEC Partnership Report</td>
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</tbody>
</table>

- TWDEC keV High Density Hollow Electrode Simulation & Test Report
- TWDEC keV Simulation & Test Final Report
- TWDEC spacecraft TRL 4/5 Assessment
- KDP-MEV test article procurement go ahead
- MeV test article assembly complete
- Initial MeV simulations complete and test matrix baselined
- Final MeV test matrix complete


28 September 2012
Fast ion “bunches” exhausting from a TWDEC may be able to be used to accelerate and heat slow plasma bunches created from inert gas propellant, thus lowering $I_\text{sp}$ from $10^6$ sec to $10^3$ sec and thereby increasing thrust.

**STEP 1.** Injecting the alpha's with a large angle w.r.t. the axis of a solenoidal magnetic field: the longitudinal speed will be reduced and particles follow a spiral orbit.

The gyro radius for a $2.9 \text{ MeV}$ a-particle in a $1 \text{T}$ field is about $0.25 \text{ m}$. Bunching can provide the non-adiabatic injection required to capture the ions.

**STEP 2.** With a collimated pencil-beam the injected bunch turns in to a hollow cylindrical layer with current density $j$.

**STEP 3.** As more particles are collected the current in the layer increases that, in turn, increases the magnetic field.

**STEP 4.** Higher current density produces “magnetic piston effect”.

Fast Electrons (neutralizing, not recombining)
Fission DEC-to-Power
Research to Date

• Concept actively studied 1957-late 1960’s.

• Studies restarted under DOE “Nuclear Energy Research Initiative” in early 2000’s.
  • Energy conversion by means of high voltage DC electrodes.
  • For terrestrial power: Offers higher efficiency conversion and spent fuel burn-up.


| TABLE 47.1 Distribution of the Released Nuclear Fission Energy for Fission of U235 |
|-----------------------------------------------|-----------|--------|
| Component of Energy                          | Energy (MeV) | Fraction (%) |
| Release in Fission                           |            |          |
| • Kinetic Energy of FFs                      | 168        | 81.16   |
| • Kinetic Energy of Fission Neutrons         | 5          | 2.42    |
| • Energy of Prompt γ-Rays                    | 7          | 3.38    |
| • Total Energy of β-Particles                | 8          | 3.86    |
| • Energy of Delayed γ-Rays                   | 7          | 3.38    |
| • Energy of Neutrinos                        | 12         | 5.80    |
| • Total Energy Release per Nuclear Fission Event | 207        | 100.00  |
Fission DEC-to-Power
TWDEC Application

- Solenoidal magnetic field $B_0 = 0.5\, T$:
  - $^{140}\text{Xe}$ fragment gyroradius = $1.71\, m$

- Side injection can reduce drift speed and TWDEC frequency
- **Bunching** can provide the non-adiabatic injection required to capture the ions.
Fusion reactions can occur in both high temperature, thermalized plasmas and low temperature, monoenergetic colliding beams.

**Fusion Fuel Pairs (Product Energy)**

\[
\begin{align*}
D + T &= n^0 (14.07 \text{ MeV}) + ^4\text{He} (3.52 \text{ MeV}) \\
D + D &= n^0 (2.45 \text{ MeV}) + ^3\text{He} (0.82 \text{ MeV}) (50\%) \\
D + D &= p (3.02 \text{ MeV}) + ^3\text{He} (1.01 \text{ MeV}) (50\%) \\
D + ^3\text{He} &= p (14.68 \text{ MeV}) + ^4\text{He} (3.67 \text{ MeV}) \\
p + ^{11}\text{B} &= 3 ^4\text{He} (8.7 \text{ MeV})
\end{align*}
\]
# Fusion Plasma Confinement Trade Space

## Plasma Energy Distribution

<table>
<thead>
<tr>
<th>Maxwellian Thermal Equilibrium</th>
<th>Non-Maxwellian Non-Equilibrium (Monoenergetic)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Maxwellian Distribution" /></td>
<td><img src="image" alt="Non-Maxwellian Distribution" /></td>
</tr>
</tbody>
</table>

### Magnetic Confinement
(e.g., “Tokamak”, Mirror, FRC, Z-Pinch)

- **Magnetic Conf.: Field-Reversed Configuration (FRC)**
  - Betatron orbits: Particles with initial $v > 0$ curve away from null circle
  - Drift orbits: Particles with initial $v > 0$ curve away from null circle

### Magneto/Laser/Mechanical Inertial Confinement
(e.g., National Ignition Facility)

- **Inertial Electrostatic Confinement**
  - + HIGH VOLTS

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Required confinement for maintenance of aneutronic reactions


First Order Heat Balance and Specific Mass @ 30 MW_e:
5-year, 1200 K Fission Reactor with K-Rankine Conversion, Standard PMAD, and Plasma EP

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>MW</th>
<th>MT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200 K Fission Reactor (MW_t,out)</td>
<td>144</td>
<td>78</td>
</tr>
<tr>
<td>Fission Shadow Shield (frac. MW_t,in)</td>
<td>144</td>
<td>145</td>
</tr>
<tr>
<td>K-Rankine Heat Engine Conv. (MW_t,in)</td>
<td>144</td>
<td>73</td>
</tr>
<tr>
<td>800 K, 5.5 kg/m² 1-sided Radiators (MW_t,in)</td>
<td>114</td>
<td>49</td>
</tr>
<tr>
<td>PMAD (MW_e,in)</td>
<td>30</td>
<td>113</td>
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<tr>
<td>600 K, 4.5 g/m² PMAD Radiators (MW_t,in)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Net Power (MW_e,out); Total Mass (MT)</td>
<td>30</td>
<td>457</td>
</tr>
<tr>
<td><strong>Power α (MT/MW_e,out)</strong></td>
<td>15.2</td>
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<tr>
<td>Plamsa EP Thruster (MW_e,in)</td>
<td>0.60</td>
<td>30</td>
</tr>
<tr>
<td>Plamsa EP Thruster (MW_p,out)</td>
<td>18</td>
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</tr>
<tr>
<td><strong>Power &amp; Prop Combined α (MT/MW_e,in)</strong></td>
<td>16.2</td>
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</table>
First Order Heat Balance and Specific Mass @ 30 MW\textsubscript{e}:
2 year, \textbf{1500} K Fission Reactor with K-Rankine conversion, Advanced PMAD, and Plasma EP

\begin{itemize}
  \item \textbf{1500 K Fission Reactor (MW\textsubscript{t,out})} $\alpha$ = 0.15
  \item Fission Shadow Shield (frac. MW\textsubscript{t,in}) $\alpha$ = 1.00
  \item K-Rankine Heat Engine Conv. (MW\textsubscript{t,in}) $\alpha$ = 0.14 $\eta_c$ = 0.18
  \item 1100 K, 5 kg/m\textsuperscript{2} 2-sided Radiators (MW\textsubscript{t,in}) $\alpha$ = 0.12
  \item PMAD (MW\textsubscript{e,in}) $\alpha$ = 1.00 $\eta_p$ = 0.99
  \item 600 K, 4.5 g/m\textsuperscript{2} PMAD Radiators (MW\textsubscript{t,in}) $\alpha$ = 0.98
  \item Net Power (MW\textsubscript{e,out}); Total Mass (MT) 30 265
  \item Power $\alpha$ (MT/MW\textsubscript{e,out}) 8.8
  \item Plamsa EP Thruster (MW\textsubscript{e,in}) $\eta_t$ = 0.60 30 30
  \item Plamsa EP Thruster (MW\textsubscript{p,out}) 18
  \item Power & Prop Combined $\alpha$ (MT/MW\textsubscript{e,in}) 9.8
\end{itemize}
First Order Heat Balance and Specific Mass @ 30 MW\(_e\):
Aneutronic Fusion with T\(_{\text{top}}\) = 1500 K, K-Rankine Conversion,
Advanced PMAD, and Plasma EP

\[ \text{p}^{\text{11}}\text{B Fusion} \rightarrow \text{K-Ra} \rightarrow \text{Q} \]
\[ \text{E-Prop} \rightarrow \text{PMAD} \rightarrow \text{Q} \]

\[ T \]

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>(\alpha)</th>
<th>(\phi_d)</th>
<th>(\phi_{\text{rej}})</th>
<th>(\eta_c)</th>
<th>(\eta_p)</th>
<th>(\alpha)</th>
<th>(\eta_t)</th>
<th>(\text{MWt}_{\text{in}})</th>
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<tr>
<td>Fusion Reactor (MW(_{\text{t, out}}))</td>
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First Order Heat Balance and Specific Mass @ 30 MW_e:
Aneutronic Fusion with TWDEC, Advanced PMAD, and Plasma EP

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<tr>
<td>Driving power (MW_e,in)</td>
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<td>Reactor Heat Radiators 600 K(MW_rej)</td>
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<td>TWDEC (MW_t,in)</td>
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Power α (MT/MW_e,out) 1.7

Plamsa EP Thruster (MW_e,in) - VASIMR
Plamsa EP Thruster (MW_p,out) - VASIMR

Power & Prop Combined α (MT/MW_e,in) 2.7
First Order Heat Balance and Specific Mass @ 30 MW_e:
Aneutronic Fusion with TWDEC, Advanced PMAD, and Direct Conversion Plasma EP

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<td>9</td>
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<td>Driving power (MW_{e,in})</td>
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<td>2</td>
</tr>
<tr>
<td>TWDEC (MW_{t,in} only for driving power)</td>
<td>0.14</td>
<td>16</td>
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<tr>
<td>600 K, 4.5 g/m^2 TWDEC Radiators (MW_{t,in})</td>
<td>0.98</td>
<td>5</td>
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<tr>
<td>PMAD (MW_{e,in})</td>
<td>1.00</td>
<td>11</td>
<td>11</td>
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<tr>
<td>600 K, 4.5 g/m^2 PMAD Radiators (MW_{t,in})</td>
<td>0.98</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Net Power (MW_{t,out}); Total Mass (MT)</td>
<td></td>
<td>30</td>
<td>26</td>
</tr>
<tr>
<td>Power $\alpha$ (MT/MW_{e,out})</td>
<td>0.9</td>
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<td></td>
</tr>
<tr>
<td>Direct Plasma Thruster (MW_{e,in})</td>
<td>0.40</td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td>Direct Plasma Thruster (MW_{p,out})</td>
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</tr>
<tr>
<td>Power &amp; Prop Combined $\alpha$ (MT/MW_{t,in})</td>
<td>1.3</td>
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</tbody>
</table>
First Order Heat Balance and Specific Mass @ 30 MWₑ:

“α = 0” Fission or D-T Fusion Reactor with K-Rankine conversion, Advanced PMAD, and Plasma EP

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>AMT</th>
<th>MT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magic Fission or D-T Fusion Reactor (MWₑₜ,out)</td>
<td>α = 0.00</td>
<td>168</td>
</tr>
<tr>
<td>Fission Shadow Shield (frac. MWₑₜ,in)</td>
<td>α = 1.00</td>
<td>168</td>
</tr>
<tr>
<td>K-Rankine Heat Engine Conv. (MWₑₜ,in)</td>
<td>α = 0.18</td>
<td>ηₑ = 0.18</td>
</tr>
<tr>
<td>1100 K, 5 kg/m² 2-sided Radiators (MWₑₜ,in)</td>
<td>α = 0.12</td>
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</tr>
<tr>
<td>PMAD (MWₑₚ,in)</td>
<td>α = 1.00</td>
<td>ηₑ = 0.99</td>
</tr>
<tr>
<td>600 K, 4.5 g/m² PMAD Radiators (MWₑₜ,in)</td>
<td>α = 0.98</td>
<td>0</td>
</tr>
<tr>
<td>Net Power (MWₑₜ,out); Total Mass (MT)</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td><strong>Power α (MT/MWₑₜ,out)</strong></td>
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<tr>
<td>Plasma EP Thruster (MWₑₚ,in)</td>
<td>α = 1.00</td>
<td>ηₑ = 0.60</td>
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<tr>
<td>Plasma EP Thruster (MWₑₕ,out)</td>
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<td>18</td>
</tr>
<tr>
<td><strong>Power &amp; Prop Combined α (MT/MWₑₚ,in)</strong></td>
<td></td>
<td>9.2</td>
</tr>
</tbody>
</table>