Lunar $^3$He and Fusion Power

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The Rate of Fusion Related PhD's Graduated From the University of Wisconsin is 1/3 of that in the 1980's

- Fusion Technology-98
- Plasma Theory-76
- Plasma Experimental-155
UW Investigates Several Fusion Configurations

MST – Physics

HSX - Electrical & Computer Engineering

Pegasus - Engineering Physics

IEC - Engineering Physics
Fusion Technology Institute Research Activities

- High Average Power Laser ICF Chamber (NRL)
- IEC (Greatbatch, Grainger, DOE)
- D-³He Fusion
- Resources from Space (Berndt, Grainger)
- Greenhouse Gas Emissions (ECOW)
- Liquid-Metal Safety (DOE)
- Coupling of Neutronics & 3-D CAD (DOE)
- Materials for Pulsed Power (NRL)
- Z-Pinch Reactor Design (SNL)
- ICF Radiation Hydrodynamics (U. Rochester)
- High Energy Density Opacity and EOS (DOE)
- ARIES Reactor Studies (DOE)
- ITER Nuclear Technology (DOE)
- Magnetized-Target Fusion (DOE)
- Resources from Space (Berndt, Grainger)
- Greenhouse Gas Emissions (ECOW)
- Liquid-Metal Safety (DOE)
- Coupling of Neutronics & 3-D CAD (DOE)
Fusion Combines Light Isotopes to Create Other Particles

- Deuterons
- Tritons or helium-3
- Energetic Neutron or proton
- Helium-4
Fusion Converts Mass into Energy
“Advanced” Fusion Fuels Face a More Difficult Physics Development Path than D-T Fuel

1\textsuperscript{st} generation fuels:
\begin{align*}
\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}) \\
& \quad \rightarrow \text{p} (3.02 \text{ MeV}) + \text{T} (1.01 \text{ MeV}) \\
& \{50\% \text{ each channel}\}
\end{align*}

2\textsuperscript{nd} generation fuel:
\begin{align*}
\text{D} + ^3\text{He} & \rightarrow \text{p} (14.68 \text{ MeV}) + ^4\text{He} (3.67 \text{ MeV})
\end{align*}

3\textsuperscript{rd} generation fuels:
\begin{align*}
^3\text{He} + ^3\text{He} & \rightarrow 2 \text{p} + ^4\text{He} (12.86 \text{ MeV}) \\
p + ^{11}\text{B} & \rightarrow 3 \ ^4\text{He} (8.68 \text{ MeV})
\end{align*}

![Graph showing reaction rates vs. ion temperature](image-url)
D-\(^3\)He Fuel Faces
Larger Physics Obstacles than D-T

Ignition contours against bremsstrahlung

Power density

\( D-\text{He}: D=1:1 \)

\( D-T \)

\( D-D \)

Ion temperature (keV)

Relative fusion power density

\( 10^{-3} \) to \( 1 \)

\( 10^{-2} \) to \( 10^{-1} \)

\( 1 \) to \( 10 \)

\( 10 \) to \( 100 \)

\( 10^{19} \) to \( 10^{22} \)

\( 10^{20} \) to \( 10^{21} \)

\( n_T (m^{-3}s) \)

\( 1 \) to \( 1000 \)

\( 100 \) to \( 500 \)

\( 50 \) to \( 100 \)

\( 10 \) to \( 5 \)

\( 5 \) to \( 1 \)
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 first-wall neutron or surface heat loads well before they reach $\beta (=\text{plasma pressure}/\text{B-field pressure})$ or B-field limits.
- D-T fueled tokamaks ($\beta \sim 5\%$) optimize at $B \sim 15$ 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.
Inertial-Electrostatic Fusion Depends on
Creation of a Radial Electrostatic Well and
Spherically (or Cylindrically) Convergent Ion Flow

1. Inner grid (cathode) is biased to a high negative potential.
2. Fuel gas flows into the chamber and pressure is maintained.
3. Positive ions are created around the outer grid (anode).
4. Ions accelerate toward inner grid, gaining fusion-relevant energies.
5. Ions and electrons ionize neutral gas.
6. Ions charge-exchange with neutrals, fuse with other ions or neutrals, or hit grids.
7. Charge-exchange neutrals fuse with background gas.
8. Particle detectors monitor reaction rates.
Low-Voltage, High-Pressure Conditions Produce Visible Electron Jets

D-D
30kV, 45mA, 6 mtorr
R.L. Hirsch and G.A. Meeks: Mid-60’s Ion-Gun-Driven IEC Experiment

- Operated with D-T fuel
- Generated \( \sim 10^{10} \) neutrons/s
Present UW Aluminum Chamber Provides a Large Volume Reaction Region
Significant Progress Has Been Made in Achieving High-Voltage Operation
Fabrication System for Standardized Grid

1. Mold produced from rapid prototype model
2. Wax poured into mold
3. Wires wound around wax form
4. Wires spot welded at junctions
5. Wax form melted away at ~80 °C
6. Finished grid cathode
Maximum UW IEC D-D Neutron Production So Far is $1.8 \times 10^8$ per Second

![Graph showing neutron production from Jan-98 to Jan-04.](image)
Fast He Ions Can Produce Significant Damage in Materials

Wire grid cathode was replaced by a sample target.

Deuterium bombardment did little damage.
TaC irradiated at 830 °C with >6x10^{17} D/cm².

Helium bombardment did significant damage.
HfC irradiated at 775 °C with >6x10^{17} He/cm².

- Presently part of Ross Radel’s thesis research.
D-\(^3\)He Fusion Protons Can Produce Useful Radioisotopes for Nuclear Medicine

- The glowing cathode shown here is 10 cm in diameter

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

Cross sections for producing the PET-scan isotope \(^{13}\)N
# Examples of Positron Emitting Isotopes

<table>
<thead>
<tr>
<th>Parent Isotope</th>
<th>Production Reaction</th>
<th>PET Isotope</th>
<th>Half Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{O}$</td>
<td>$(p, n)$</td>
<td>$^{18}\text{F}$</td>
<td>110 min</td>
</tr>
<tr>
<td>$^{14}\text{N}$</td>
<td>$(p, \alpha)$</td>
<td>$^{11}\text{C}$</td>
<td>20 min</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>$(p, \alpha)$</td>
<td>$^{13}\text{N}$</td>
<td>10 min</td>
</tr>
<tr>
<td>$^{13}\text{C}$</td>
<td>$(p, n)$</td>
<td>$^{13}\text{N}$</td>
<td>10 min</td>
</tr>
<tr>
<td>$^{15}\text{N}$</td>
<td>$(p, n)$</td>
<td>$^{15}\text{O}$</td>
<td>2 min</td>
</tr>
</tbody>
</table>
UW IEC Experiments Produced $^{13}$N, a Valuable PET-scan Radioisotope

John Weidner
Helicon Ion Source Operating with UW’s Spherical IEC Chamber

• Thesis research by Greg Piefer
Fusion Can Be Accomplished in Several Ways

- Magnetic Confinement
- Gravitational Confinement in the Sun and Stars
- Inertial Confinement Using Lasers
D-$^3$He Fuel Will Lower Development Costs

![Diagram showing the relationship between engineering readiness, physics readiness, and development costs.]

- **Engineering Readiness**
  - Materials, magnets, power, radioactivity, maintenance

- **Physics Readiness**
  - Transport, disruptions, current drive, fueling, impurities, profiles

- **D-$^3$He FRC, Spheromak, ST**

- **Conventional D-T Tokamak**

- **β-driven**

- **nτ-driven**

- **Main Development Costs**
D-\(^3\)He Fuel Generally Gives Easier Engineering and Safety

- Reduced neutron flux allows
  - Smaller radiation shields
  - Smaller magnets
  - Permanent first wall and shield
  - Easier maintenance
- Increased charged-particle flux allows direct energy conversion
- But unburned tritium will be a proliferation and safety issue
Linear Geometry Provides Solution to Handling Charged-Particle Surface Heat Flux

- Charged-particle power transports from internal plasmoid (in an FRC or spheromak) to edge region and then out ends of fusion core.
- Expanded flux tube in end chamber reduces heat and particle fluxes, so charged-particle transport power only slightly impacts the first wall.
- Mainly bremsstrahlung power contributes to first-wall surface heat.
  - Relatively small peaking factor along axis for bremsstrahlung and neutrons.
- High power density does not necessarily imply unmanageable first-wall heat flux.
Field-Reversed Configuration (FRC) Would Be Attractive for Fusion Power

- Very high $\beta = P_{\text{plasma}} / P_{\text{B-field}}$
- Linear external B field
- Cylindrical geometry
- Requires efficient current drive

FRC as Power Source and Ion Engine for High Energy Space Missions

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)
The Low Radiation Damage in D-³He Reactors Allows Permanent First Walls and Shields to be Designed
Radioactive Waste Disposal is Much Easier for D-3He Reactors than for D-T Reactors
Proliferation-Resistant D-³He Power Plant May Be Possible

- D-³He fuel for low neutron wall loading
- High-β for high fusion power density
- D-³He proton gyroradius contributes to stability
- Minimal radiation shield to reduce space for D-T shielding
- Organic coolant to make high-flux D-T operation difficult.
- Small plasma to reduce space for D-T shielding
- Direct converter for increased electric power per unit fusion power
- Superconducting, high-field magnet for high fusion power density
The $^3$He Fuel Source is an Issue
—So Think Outside the Box

- ~400 kg $^3$He accessible on Earth
  (~8 GW-a fusion energy for R&D)
- ~$10^9$ kg $^3$He on lunar surface for
  21st century
- ~$10^{23}$ kg $^3$He in gas-giant planets
  for indefinite future

- L.J. Wittenberg, J.F. Santarius, and
  G.L. Kulcinski,
  “Lunar Source of
  $^3$He for Commercial
  Fusion Power,”
  *Fusion Technology* 10, 167 (1986).

Escher, *Other World*, 1947
Significance of Lunar Helium-3

- 1 tonne of He-3 can produce 10,000 MWe-y of electrical energy.

- 40 tonnes of He-3 could provide for the entire U.S. electricity consumption in 2004.
Lunar Helium-3 Is Well Documented

- Helium-3 concentration verified from Apollo 11, 12, 14, 15, 16, 17 and U.S.S.R. Luna 16, 20 samples.

- Current analyses indicate that there are at least 1,000,000 tonnes of helium-3 embedded in the lunar surface.
$^3$He Evolution from Lunar Regolith

![Graph showing Helium-3 Evolution from Lunar Regolith]

- Pepin et al.
- % He3 Evolution
- Regolith Temperature, °C
- 95% 86% 75%

*JFS 2004* Fusion Technology Institute
He Content Correlates Well with Ti Content

Spectral reflectance map of lunar Ti content

Measured correlation of He and Ti contents
Lunar $^3$He Mining Produces Other Volatiles Useful for Sustaining a Lunar Base

Process for Extracting Helium-3 from Lunar Regolith

- **6100 tonnes**
- **3300 tonnes**
- **1700 tonnes**
- **1600 tonnes**
- **1900 tonnes**
- **3100 tonnes**

- **H$_2$**
- **H$_2$O**
- **N$_2$**
- **CO$_2$**
- **CH$_4$**
- **CO**

**Fuel**

- **Radiator/Condenser**
- **Isotopic Separation**

- **300 K**
- **50 K**
- **1.5 K**

**1 tonne Helium-3**

Clean Fusion Energy on Earth
Lunar $^3$He Mining Would Use Well-Developed Terrestrial Technology

- Bucket-wheel excavators
- Bulk heating
- Heat pipes
- Conveyor belt

$\sim 10^9$ kg $^3$He on lunar surface ==> $\sim 1000$ y world energy supply
Earliest D-\(^3\)He 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 High Mass

Cutaway of the ARIES-RS Power Core

PF Coils
Central Solenoid
TF Coil
Cryostat
Vacuum Vessel
Maintenance Port
First Wall & Blanket
Low Temperature Shield
High Temperature Shield
Divertor Region
Hardback Structure
D-\(^3\)He Space-Propulsion Tandem Mirror

Tandem mirror rocket design by UW EMA 569 students

Specific power 1.2 kW/kg
Thrust power 1500 MW
Length 113 m
Ave. outer radius 1 m
Core B field 6.4 T
The Dipole Configuration Offers a Relatively Simple Design That an MIT/Columbia Team Is Testing

Io plasma torus around Jupiter

LDX experiment (MIT)

0.65 m
D-$^3$He Fusion Propulsion
Could Provide Flexible Thrust Modes

Fuel plasma exhaust

Mass-augmented exhaust

Thermal exhaust

Pellet injection
Pulsed Fusion Also Holds Promise

- MTF: magnetized-target fusion would use a conducting liner to implode a magnetized plasmoid.
- ICF: inertial-confinement fusion would use lasers or ion beams to implode a material target.

In both cases, ionized material from the fusion micro-explosion would reflect from a magnetic field to produce thrust.

Magnetized-Target Fusion Artist’s Conception from Marshall Space Flight Center
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

D-³He Fusion Will Provide Capabilities Not Available from Other Propulsion Options
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**

![Bar chart showing trip times and payload fractions for chemical and fusion rockets between Earth-Mars and Earth-Jupiter.](chart.png)
Final Thought:
Where Do We Go from Here?