D-³He Physics and Fusion Energy Prospects

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Outline: $^3$He Issues

Physics
Engineering
Safety and Environment
$^3$He Resources
Applications
"Advanced" Fusion Fuels
Greatly Reduce Neutron Production

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

2\textsuperscript{nd} generation fuel:
\[ \text{D} + \text{^3}\text{He} \rightarrow \text{p (14.68 MeV)} + \text{^4}\text{He (3.67 MeV)} \]

3\textsuperscript{rd} generation fuels:
\[ \text{^3}\text{He} + \text{^3}\text{He} \rightarrow 2 \text{p} + \text{^4}\text{He (12.86 MeV)} \]
\[ \text{p} + \text{^11}\text{B} \rightarrow 3 \text{^4}\text{He (8.68 MeV)} \]
D-\textsuperscript{3}He Fuel Faces
Larger Physics Obstacles than D-T

• D-\textsuperscript{3}He, compared to D-T, requires:
  ➢ Minimum factor of \( \sim 6 \) increase in ignition temperature,
  ➢ Minimum factor of \( \sim 8 \ n_e \tau_E \) increase,
  ➢ Minimum \( T_n \tau \) increase of \( \sim 50 \) times.

• D-\textsuperscript{3}He fusion relies on significant continued progress in plasma physics.
Burning D-D Fuel without Burning the Tritium Produced by D-D Reactions Would Be Difficult

- D-D reaction-product burnup based on Wildcat D-D tokamak reactor parameters.
- If feasible, would greatly reduce D-\(^3\)He neutron production.

![Graph showing burnup as a function of ion temperature.](image-url)
D-\(^3\)He Could Have a Power Density at Least as High as D-T Power Density

- D-T fueled innovative concepts become limited by neutron wall loads or surface heat loads well before they reach \(\beta\), B-field, or magnet limits.
- D-T fueled FRC’s (\(\beta\sim85\%\)) optimize at \(B \leq 3\) T.
- Fusion power density scales as \(\beta^2 B^4\).
- Superconducting magnets can reach at least 20 T.
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
- Unburned tritium will be a proliferation and safety issue
Linear Geometry Provides Solution to Handling Charged-Particle Surface Heat Flux

- High power density does not necessarily imply unmanageable first-wall 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.
- Mainly bremsstrahlung power contributes to first-wall surface heat.
- Relatively small peaking factor along axis for bremsstrahlung and neutrons.

Not to scale

FRC core region

Expanded flux tube to reduce heat flux

Neutrons
Bremsstrahlung
Charged particles
Direct Conversion to Electricity Can Give 60-80% Efficiency

• Experiment and theory agreed within 2%.

Barr-Moir experiment, LLNL
(Fusion Technology, 1973)
The 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"
Radioactive Waste Disposal is Much Easier for D-\(^3\)He Reactors than for D-T Reactors

\(-D-^3\text{He}-\)
- 30 full-power years
- Low-activation Tenelon
- HT-9 steel
- Class A
- Class C
- Deep Geologic Burial

\(-D-T-\)
- 5 full-power years
- Low-activation Tenelon
- HT-9 steel
The $^3$He Fuel Source is an Issue
—So Think Outside the Box

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

Escher, Other World, 1947
Lunar $^3$He Mining Would Use
Well-Developed Terrestrial Technology

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

$\sim 400 \text{ kg } ^3$He accessible on Earth $\Rightarrow$
$\sim 8 \text{ GW-y fusion energy for R&D}$

$\sim 10^9 \text{ kg } ^3$He on lunar surface $\Rightarrow$
$\sim 1000 \text{ y world energy supply}$
Mining Other Volatiles Would Support a Lunar Initiative, Allowing a Symbiotic Demonstration of Lunar $^{3}$He Acquisition
Proliferation-Resistant
D-³He Power Plant May Be Possible

- D-³He fuel for low neutron wall loading
- High-β for high fusion power density
- Minimal radiation shield to reduce space for D-T shielding
- Direct converter for increased electric power per unit fusion power
- Organic coolant to make high-flux D-T operation difficult.
- Superconducting, high-field magnet for high fusion power density
- Small plasma to reduce space for D-T shielding
- D-³He proton gyroradius contributes to stability
It May be Possible to Efficiently Burn DD or D\textsuperscript{3}He Fuels in Fast-Ignited ICF Targets

Four unique aspects of ICF for advanced fuels:

1. The required high ignition/burn temperatures (~30/150keV) can be obtained via a precursor DT ignitor region (~10/50keV).

2. The larger driver energies (required by the larger rho-R’s for efficient advanced fuel burn-up) can be offset through fast ignition.

3. Bremsstrahlung is self-trapped in the compressed fuel

4. Tritium for the DT ignitor (~1% inventory) is self-bred as the main fuel burns

• Viewgraph contributed by John Perkins, LLNL.
Could D-\(^3\)He Be Used in Magnetized-Target Fusion?

- Investigation in progress.

\[
\begin{align*}
\text{\(m_1=1\,\text{mg}, \Delta_x=5.0\,\text{cm}\)} \\
\text{\(m_j=0.2\,\text{g}, \Delta_j=2.4\,\text{cm}\)} \\
\text{\(m_b=2.0\,\text{g}, \Delta_b=22.1\,\text{cm}\)} \\
\text{\(B_0=2\,\text{T}, v_j=262\,\text{km/s}, v_b=262\,\text{km/s}\)}
\end{align*}
\]
D-\textsuperscript{3}He Fusion Protons Can Produce Useful Radioisotopes

- In inertial-electrostatic confinement (IEC) fusion, high voltages on spherically symmetric, semi-transparent grids radially accelerate and focus ions.
- UW IEC experiments have achieved 180 kV accelerating potentials, steady-state D-\textsuperscript{3}He fusion, and proof-of-principle \textsuperscript{13}N production.
- The glowing cathode shown here is 10 cm in diameter
Conclusions

• Burning D-^3_He fuel requires substantial, continued progress in plasma physics and high-\(\beta\) concepts.

• \(^3\_\text{He}\) fuel for this century must come from the Moon, but long-term \(^3\_\text{He}\) resources are essentially inexhaustible.

• Potential ICF and MTF D-\(^3\_\text{He}\) options should be explored.

• Near-term D-\(^3\_\text{He}\) applications are already being developed.

• The attractiveness of D-\(^3\_\text{He}\) fusion's engineering, safety, and environmental characteristics makes this a potentially important research area.
**D-3He Physics and Fusion Energy Prospects**

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**Abstract**

The path to attractive fusion power contains strongly interrelated physics, engineering, economic, and environmental obstacles. From a purely physics perspective, D-T fuel seems most attractive. From the viewpoint of the broader issues, D-3He fuel compare to the engineering difficulties facing D-T fusion, such as the need for tritium-breeding blankets, neutron damage to structural materials, and frequent large-scale maintenance in a highly radioactive environment.

**Conclusions**

Burning an advanced fusion fuel would require substantial, continued progress in plasma physics, including better plasma energy confinement and development of the FRC or another suitable innovative confinement concept. The attractiveness of D-He fuel's engineering, safety, and environmental characteristics, however, makes this a potentially important research area.

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**D-3He Fuel Lower Neutron Production and Eases Engineering Difficulties**

- Reduced neutron flux allows
  - Smaller radiation shields,
  - Smaller magnets,
  - Permanent first-wall and shield,
  - Easier maintenance.
- Increased charged-particle flux allows direct energy conversion of fusion energy to electricity.
- Smaller neutron flux reduces activation of materials and radiation damage to them.

**Selected fusion fuels**

1st generation fuels:

\[ \text{D} + \text{T} \rightarrow (14.07 \text{ MeV}) + 4\text{He} \]

2nd generation fuels:

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

3rd generation fuels:

\[ 3\text{He} + \text{He} \rightarrow \text{p} + (12.86 \text{ MeV}) + 4\text{He} (0.88 \text{ MeV}) \]

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**D-3He Fuel Leads to Lower Fusion Power Density, but This Can Be Overcome by Higher Magnetic Fields and Beta**

- D-T fueled innovative concepts become limited by neutron wall loads or surface heat loads well before they reach β or B-field limits.
  - \( \beta = \text{plasma pressure/magnetic-field pressure} \)
  - D-T fueled FRC’s (β ~ 85%) optimize at B ≤ 3 T.
- D-3He 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.

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**D-3He Greatly Enhances Safety and Environment**

- Reduced neutron fluxes from internal plasma and edge and then out ends.
- Expanded fusion tube in end chamber reduces heat and particle fluxes.
- Mainly bremsstrahlung power contributes to first-wall surface heat, giving a relatively small peaking factor along the axis.

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**Issues**

***Physics***

- Inertial-electrostatic confinement (IEC) fusion, high voltages on spherically symmetric, semi-transparent grids radially accelerate ions.
- Fusion power density scales as \( \beta^2 B^4 \).
- Potential power-density improvement by increasing \( \beta \) and B-field appears at right.

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**3He Resources**

- Earth Contains 3He Sufficient for an Engineering Test Program.
- Moon Contains ~10^8 kg (~10^14 MW-years) of 3He.

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**3He Resources Are an Issue:**

- Earth Contains ~10^8 kg (~10^14 MW-years) of 3He.

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**Applications**

- **Commercial Fusion Electric Power**
  - Nuclear fusion can produce large amounts of electric power.
  - The energy output is directly proportional to the fusion power density.

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