D-³He Physics and Fusion Energy Prospects

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Outline: $D-^3He$ Issues

Physics

Engineering

Safety and Environment

$^3He$ Resources

Applications
“Advanced” Fusion Fuels
Greatly Reduce Neutron Production

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

\{50% each channel\}

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

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

- D-\(^3\)He, compared to D-T, requires:
  - Minimum factor of \(~6\) increase in ignition temperature,
  - Minimum factor of \(~8\) \(n_e\tau_E\) increase,
  - Minimum \(T_n\tau\) increase of \(~50\) times.

- D-\(^3\)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-³He neutron production.
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 (\(\beta \sim 85\%\)) 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.
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
Radioactive Waste Disposal is Much Easier for D-\(^{3}\)He Reactors than for D-T Reactors

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

- **D-T**
  - 5 full-power years
  - Class A
  - Class C
  - 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

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

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

D-\textsuperscript{3}He Power Plant May Be Possible

- D-\textsuperscript{3}He fuel for low neutron wall loading
- High-\(\beta\) for high fusion power density
- D-\textsuperscript{3}He 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
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 (~30/150keV) 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.


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

*Viewgraph contributed by John Perkins, LLNL.*
Could D-³He Be Used in Magnetized-Target Fusion?

- Investigation in progress.

\[ m_t = 1 \text{ mg}, \Delta_t = 5.0 \text{ cm} \]
\[ m_j = 0.2 \text{ g}, \Delta_j = 2.4 \text{ cm} \]
\[ m_b = 2.0 \text{ g}, \Delta_b = 22.1 \text{ cm} \]
\[ B_0 = 2 \text{ T}, v_j = 262 \text{ km/s}, v_b = 262 \text{ km/s} \]
D-\(^3\)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-\(^3\)He fusion, and proof-of-principle \(^{13}\)N production.
- The glowing cathode shown here is 10 cm in diameter

Cross sections for producing the PET-scan isotope \(^{13}\)N
Conclusions

- Burning D-$^3$He fuel requires substantial, continued progress in plasma physics and high-β concepts.

- $^3$He fuel for this century must come from the Moon, but long-term $^3$He resources are essentially inexhaustible.

- Potential ICF and MTF D-$^3$He options should be explored.

- Near-term D-$^3$He applications are already being developed.

- The attractiveness of D-$^3$He fusion's engineering, safety, and environmental characteristics makes this a potentially important research area.