Proliferation-Proof Fusion Power

J.F. Santarius, G.L. Kulcinski, L.A. El-Guebaly

University of Wisconsin
Fusion Technology Institute

Innovative Confinement Concepts Conference
and Fusion Skunkworks

College Park, Maryland
January 22-24, 2002

Outline

- What proliferation risks exist for fusion power plants?
- What fusion fuels might allow sufficiently low neutron production?
- How might we design a proliferation-proof fusion power plant?

What Does Breeding Weapons-Grade Fissile Fuel Require?

- Proliferation-resistant power plant should defeat potential design modifications that could produce fissile fuel (such as ^{239}Pu) in excess of critical rate of ~1 kg/y.
- Fusion designs generating low neutron levels using advanced-fuel cycles probably are necessary.
  - Number of neutrons/year required to convert ^{238}Pu to 1 kg ^{239}Pu corresponds to 0.72 MW of D-T n's or 0.13 MW of D-D n's.
  - For mixed D-T and D-D n's, this implies a neutron wall loading < 0.02 MW/m^2 for an r = 0.5 m, L = 10 m cylinder.
  - For a 100 MWe power plant, this implies a neutron power ~1/200th of the fusion power.
  - Actual neutron power required will depend on conversion efficiency and neutron multiplication in the fissile-fuel breeding module.

Advanced Fuel Designs to Circumvent Proliferation Resistance Would be Very Difficult to Modify and Easy to Monitor

- Key modifications would be:
  - Replacing advanced-fuel cycle with a neutron-rich one
  - Adding a fissile-fuel breeding blanket in place of shielding modules
- Related modifications would probably include:
  - Increasing radial build
  - Replacing magnets with larger ones
  - Inserting more robust breeding/shield modules
    - Advanced structure that handles high power density
  - Using an advanced power cycle for high thermal load
  - Frequently replacing structural components
  - Dealing with much higher radwaste levels

First-Generation Fusion Fuels Produce Copious Neutrons

- **D + T → n (14.07 MeV) + ^{4}He (3.52 MeV)**
  - ***~80% of energy in neutrons.***

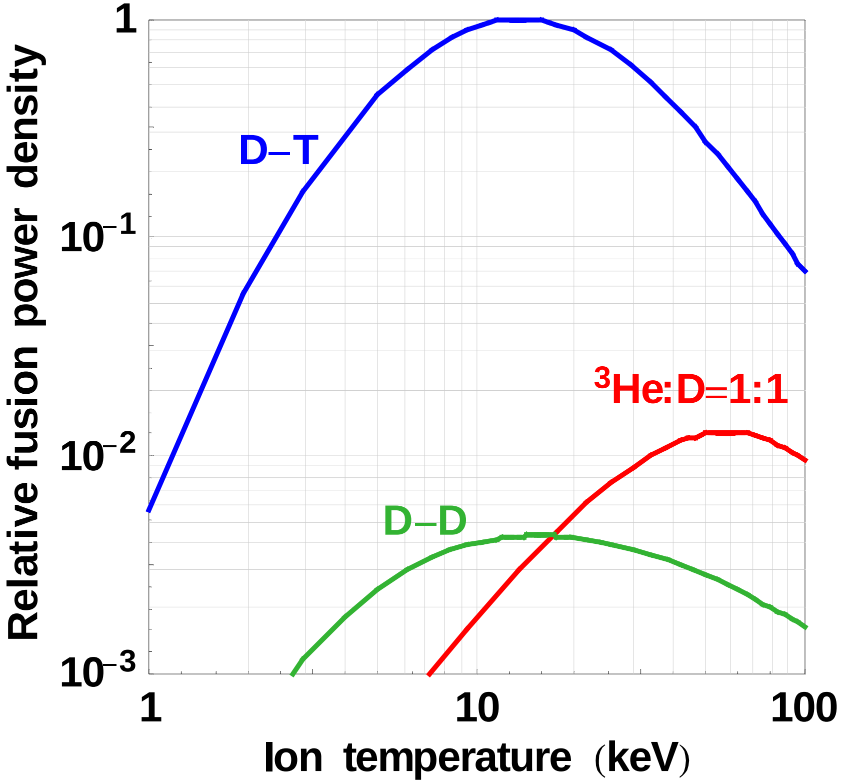
- **D + D → n (2.45 MeV) + ^{3}He (0.82 MeV) {50%}**
  → p (3.02 MeV) + T (1.01 MeV) {50%}
  - ***Typically produces ~40% of energy in neutrons, depending on tritium and helium-3 burnup.***
  - ***Catalyzed-D with T decay to ^{3}He produces D-D neutrons, and it requires T and nτ at second-generation levels to burn ^{3}He with D.***

Advanced Fusion Fuels Might Allow Sufficiently Low Neutron Production to Eliminate Proliferation Risk

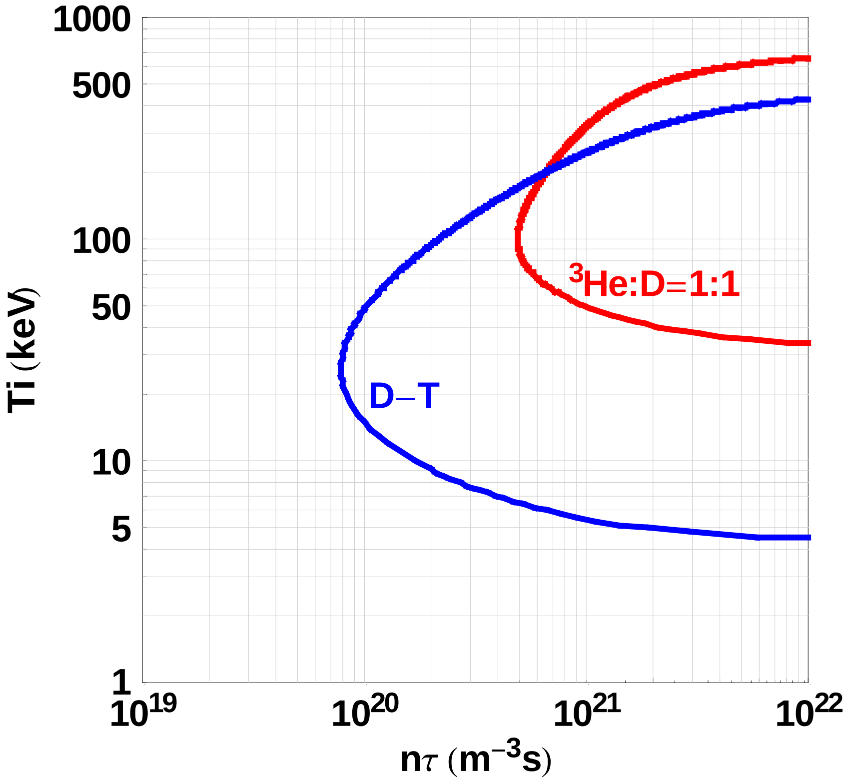
- ***Second Generation Fuel:***
  - **$D + {}^{3}He \rightarrow p\ (14.68\ MeV) + {}^{4}He\ (3.67\ MeV)$**
    - ***Potential for < 1% of energy in neutrons (from D-D)***
- ***Third Generation Fuels:***
  - **$p + {}^{11}B \rightarrow 3\ {}^{4}He\ (8.68\ MeV)$**
    - ***Low levels of n, ^{11}C, and ^{14}C from p-^{11}B and ^{4}He-^{11}B***
  - **$^{3}He + {}^{3}He \rightarrow 2\ p + {}^{4}He\ (12.86\ MeV)$**
    - ***Very low levels of ^{7}Be from ^{3}He-^{4}He***
- ***Today's talk will concentrate on D-^{3}He, because of the difficulty of overcoming bremsstrahlung radiation for third-generation fuels.***

D-^{3}He Fuel Faces
Larger Physics Obstacles than D-T

Power density

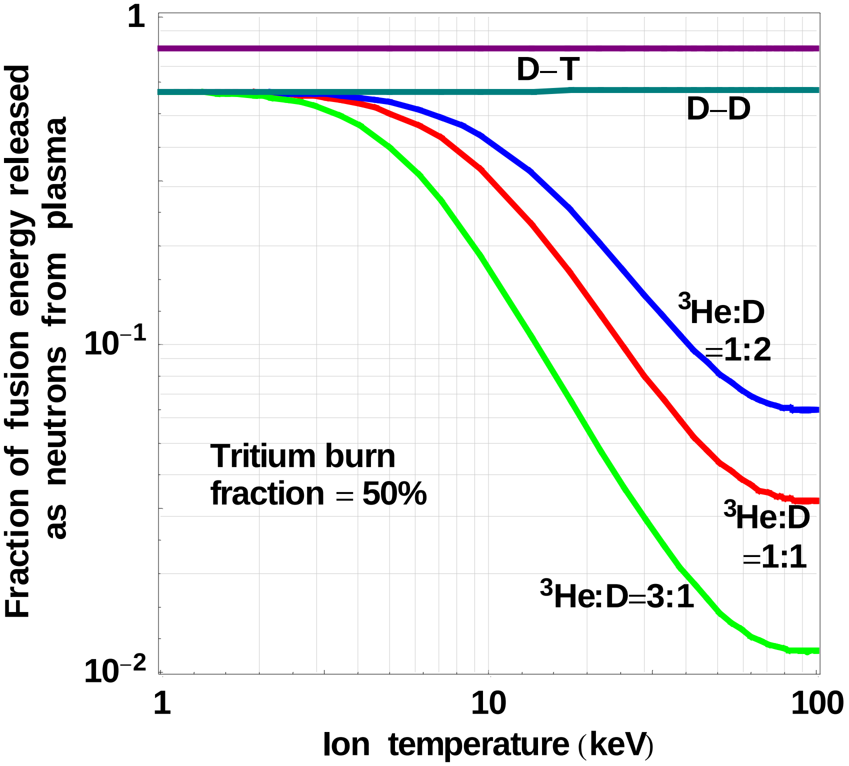


Ignition contours against bremsstrahlung



D-^{3}He Fuel Generally Gives Easier Engineering and Safety

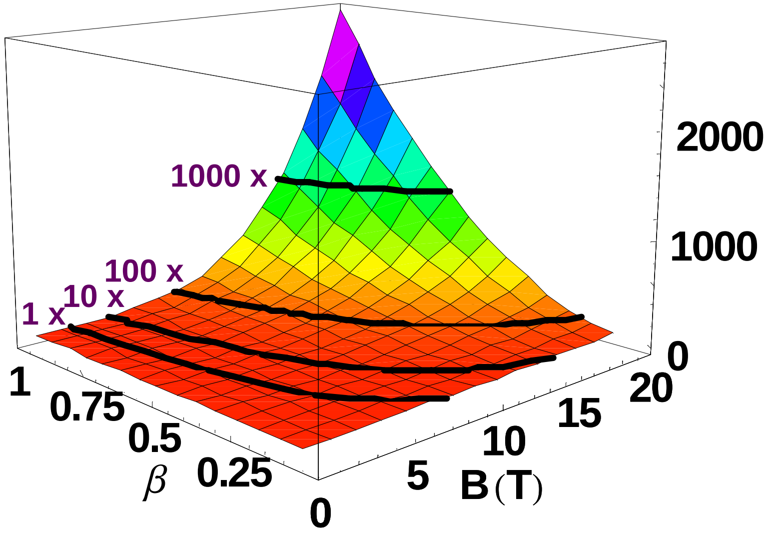
- Must increase fusion core magnetic fields, gaining power density from B^4 scaling.
- Reduced neutron flux allows
  - Smaller radiation shields
  - Smaller magnets
  - Permanent first wall and shield
  - Easier maintenance
- Increased charged-particle flux allows direct energy conversion
- But unburned tritium will be a proliferation and safety issue



D-^{3}He Fuel Could Make Good Use of the High Power Density Capability of Some Innovative Fusion Concepts

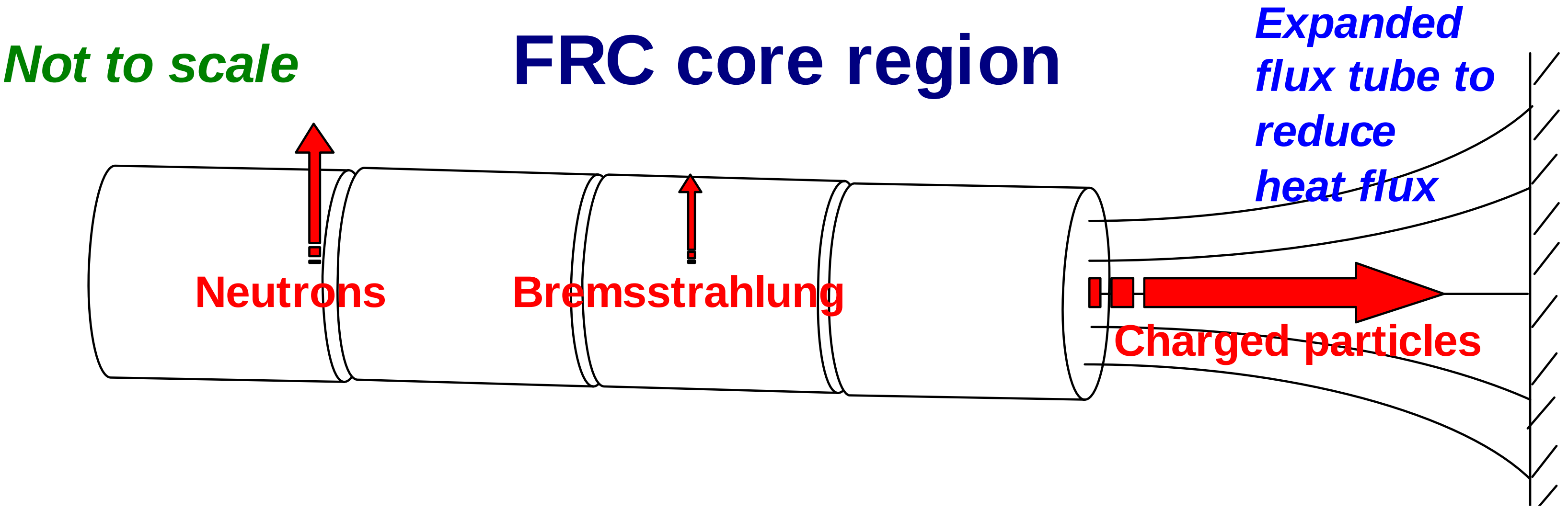
- D-T fueled innovative concepts become limited by neutron wall loads or surface heat loads well before they reach β or B-field limits.
- D-T fueled FRC's (β~85%) optimize at B ≤ 3 T.
- D-^{3}He needs a factor of ~80 above D-T fusion power densities.
  - Superconducting magnets can reach at least 20 T.
  - Fusion power density scales as $\beta^2 B^4$.
  - Potential power-density improvement by increasing β and B-field appears at right.

Power Density Relative to a D–T FRC with β=85% and B=3 T



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, 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.



What Physics Characteristics Can Help Create a Proliferation-Proof Fusion Power Plant?

- Use D-^{3}He or third-generation fuel for low neutron wall loading.
  - Active removal of tritium, if feasible, would reduce neutron production even further.
- Require large gyro-orbits of fusion products for macroscopic stability.
  - For example, D-^{3}He fusion protons have twice the gyroradius of D-T (or D-^{3}He) α particles and carry four times the power.
- Operate at small radius and large aspect ratio.
  - Design so that replacing charged-particle power (flows to ends) with D-T neutron power will overheat superconducting magnets at same power levels.

What Engineering Characteristics Can Help Create a Proliferation-Proof Fusion Power Plant?

- Superconducting magnets
  - Design near quench stability borders.
- Direct conversion
  - Generate most of the electric power by direct conversion of charged particles, so that D-T operation leads to easily monitored drop in electricity production.
- Organic coolant for shield (?)
  - Design so proliferation neutron levels lead to excessive radiolytic and pyrolytic decomposition of coolant.
- Maintenance
  - Sell turn-key units with no provision for first wall, shield, or magnet replacement. (Accommodate routine maintenance, of course.)

Conclusions

- A proliferation-*resistant* fusion power plant certainly would be feasible.
- Design effort would be well worth the attempt.
  - Important non-proliferation objective.
  - Investigates interesting region of fusion design space.
- Whether a proliferation-*proof* fusion power plant could be designed awaits detailed study.
  - Probably requires D-^{3}He fuel and a high-β configuration.

References

- J.F. Santarius, “Advanced-Fuel Heat Flux, Power Density, and Direct Conversion Issues,” *Transactions of Fusion Technology* **27**, 567 (1995).
- J.F. Santarius, G.L. Kulcinski, L.A. El-Guebaly, and H.Y. Khater, “Could Advanced Fusion Fuels Be Used with Today's Technology?”, *Journal of Fusion Energy* **17**, 33 (1998).