Proliferation-Proof Fusion Power

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

University of Wisconsin
Fusion Technology Institute

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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 $^{239}\text{Pu}$) in excess of critical rate of $\sim 1 \text{ kg/y}$.

- Fusion designs generating low neutron levels using advanced-fuel cycles probably are necessary.
  - Number of neutrons/year required to convert $^{238}\text{Pu}$ to 1 kg $^{239}\text{Pu}$ 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 $< 0.02 \text{ MW/m}^2$ for an $r = 0.5 \text{ m}$, $L = 10 \text{ m}$ cylinder.
  - For a 100 MWe power plant, this implies a neutron power $\sim 1/200^{th}$ 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) + \(^{4}\text{He} \ (3.52 \text{ MeV})\)
  - \(~80\% \text{ of energy in neutrons.}\)

- D + D → n (2.45 MeV) + \(^{3}\text{He} \ (0.82 \text{ MeV})\) \quad \{50\%\}
  → p (3.02 MeV) + T (1.01 MeV) \quad \{50\%\}
  - \(\text{Typically produces} \sim 40\% \text{ of energy in neutrons, depending on tritium and helium-3 burnup.}\)
  - \(\text{Catalyzed-D with T decay to} \ ^{3}\text{He} \ \text{produces D-D neutrons, and it requires} \ T \ \text{and n} \ \pi \ \text{at second-generation levels to burn} \ ^{3}\text{He} \ \text{with D.}\)
Advanced Fusion Fuels Might Allow Sufficiently Low Neutron Production to Eliminate Proliferation Risk

- **Second Generation Fuel:**
  
  $\text{D} + ^3\text{He} \rightarrow \text{p} (14.68 \text{ MeV}) + ^4\text{He} (3.67 \text{ MeV})$

  - Potential for $< 1\%$ of energy in neutrons (from D-D)

- **Third Generation Fuels:**
  
  $\text{p} + ^{11}\text{B} \rightarrow 3 \times ^4\text{He} (8.68 \text{ MeV})$

  - Low levels of n, $^{11}\text{C}$, and $^{14}\text{C}$ from p-$^{11}\text{B}$ and $^4\text{He}$-$^{11}\text{B}$

  $^3\text{He} + ^3\text{He} \rightarrow 2 \times \text{p} + ^4\text{He} (12.86 \text{ MeV})$

  - Very low levels of $^{7}\text{Be}$ from $^3\text{He}$-$^4\text{He}$

- **Today’s talk will concentrate on D-$^3\text{He}$, 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**

![Graph showing power density vs ion temperature](image)

**Ignition contours against bremsstrahlung**

![Graph showing ignition contours](image)
D-^{3}\text{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-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 neutron wall loads or surface heat loads well before they reach $\beta$ or B-field limits.
- D-T fueled FRC’s ($\beta\sim85\%$) optimize at $B \leq 3$ T.
- D-3He needs a factor of $\sim80$ 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.
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) \(\alpha\) 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-\(\beta\) configuration.
References
