A Passively Proliferation-Proof Fusion Power Plant

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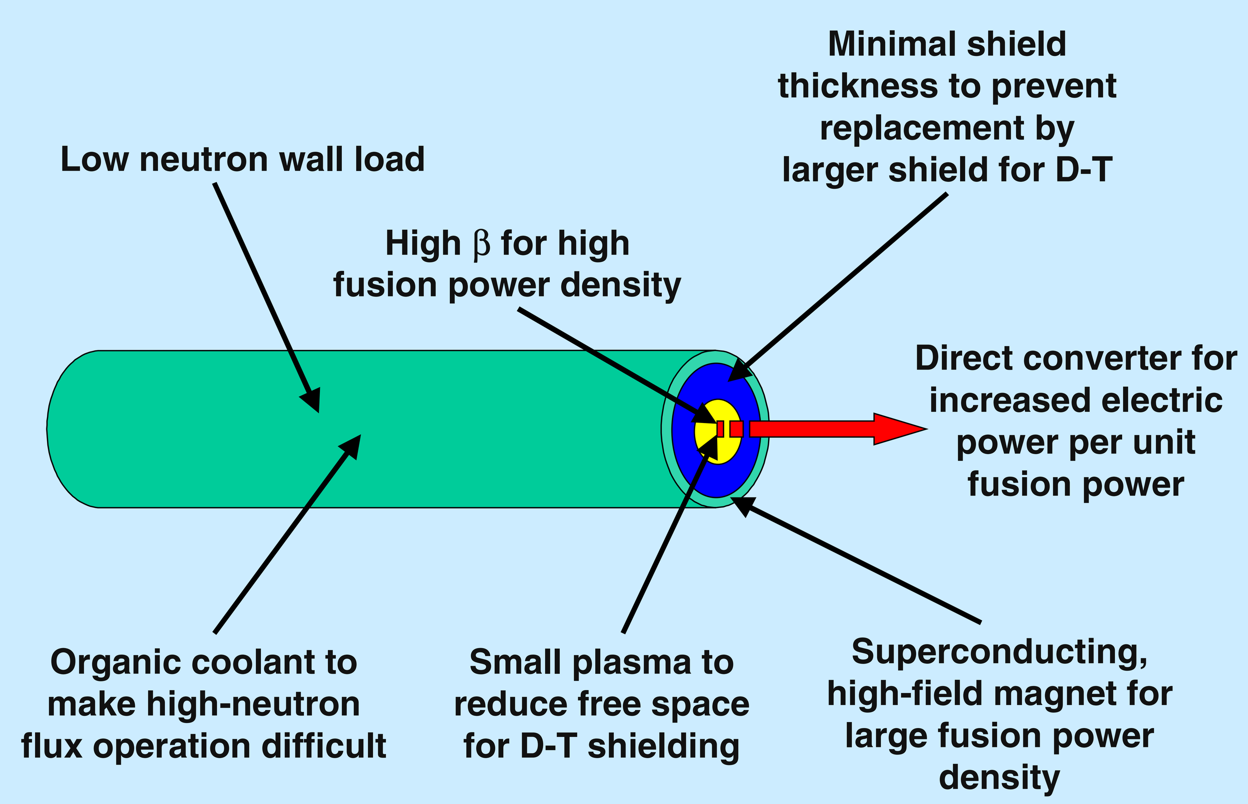
Objective:

Show that a fusion power plant could be made passively proliferation-proof.

- *Some contributors to proliferation resistance:*



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 or ^{233}U) in excess of a critical rate of ~1 kg/y.
- Fusion designs generating low neutron levels using advanced-fuel cycles are necessary.
  - Number of neutrons/year required to convert ^{238}U 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 a cylinder with r = 0.5 m, L = 10 m.
  - 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.
- Key modifications to breed fissile fuel would include:
  - Replacing advanced-fuel cycle with a neutron-rich one
  - Adding a fissile-fuel breeding blanket in place of shielding modules

Advanced Fusion Fuels

1st generation fuels:

$D + T \rightarrow n\ (14.07\ MeV) + {}^4He\ (3.52\ MeV)$

$D + D \rightarrow n\ (2.45\ MeV) + {}^3He\ (0.82\ MeV)$ {50%}

$\rightarrow p\ (3.02\ MeV) + T\ (1.01\ MeV)$ {50%}

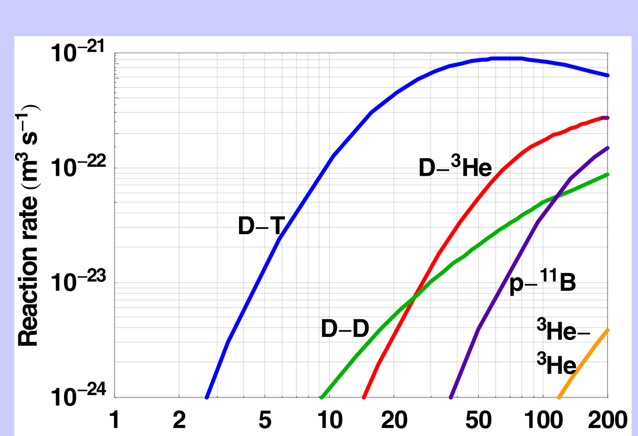
2nd generation fuel:

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

3rd generation fuels:

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

$p + {}^{11}B \rightarrow 3\ {}^4He\ (8.68\ MeV)$

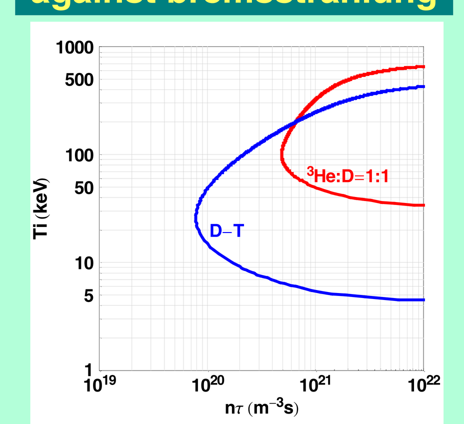


What Physics Characteristics Can Help Create a Proliferation-Proof Fusion Power Plant?

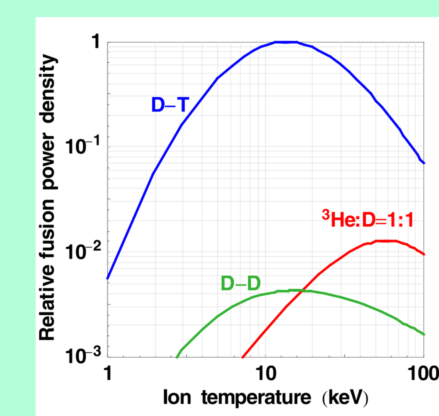
- Use D-^{3}He or third-generation fuel for low neutron wall loading.
  - Active removal of tritium, if feasible, would reduce neutron production even further.
- Design so that the large gyro-orbits of fusion products are necessary for macroscopic stability.
  - For example, D-^{3}He fusion protons have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

Advanced Fusion Fuels Must Overcome Larger Physics Obstacles than D-T

Ignition contours against bremsstrahlung

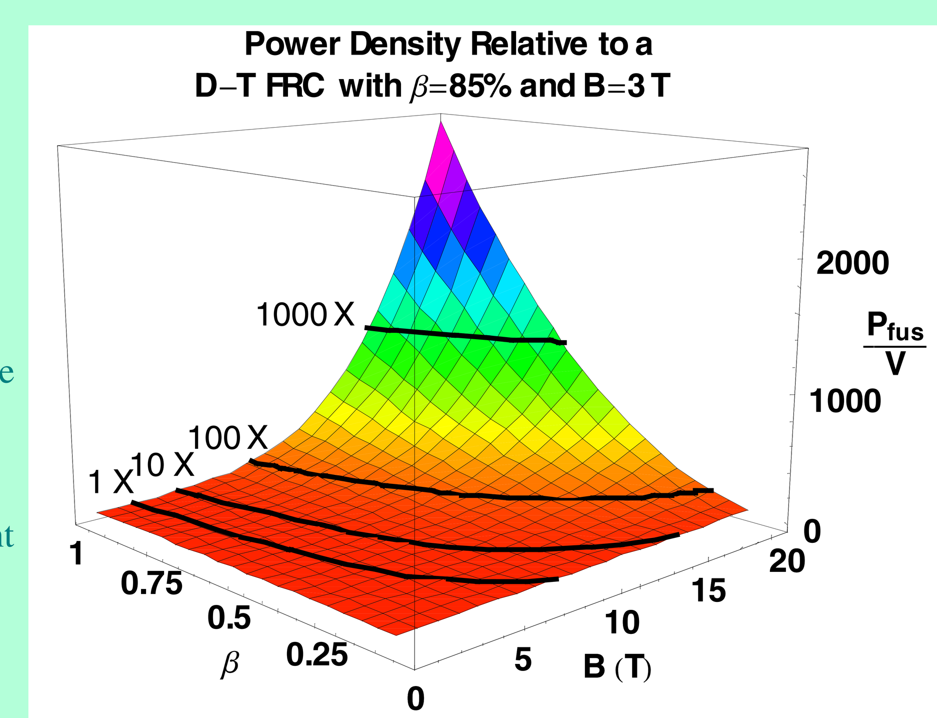


Power density

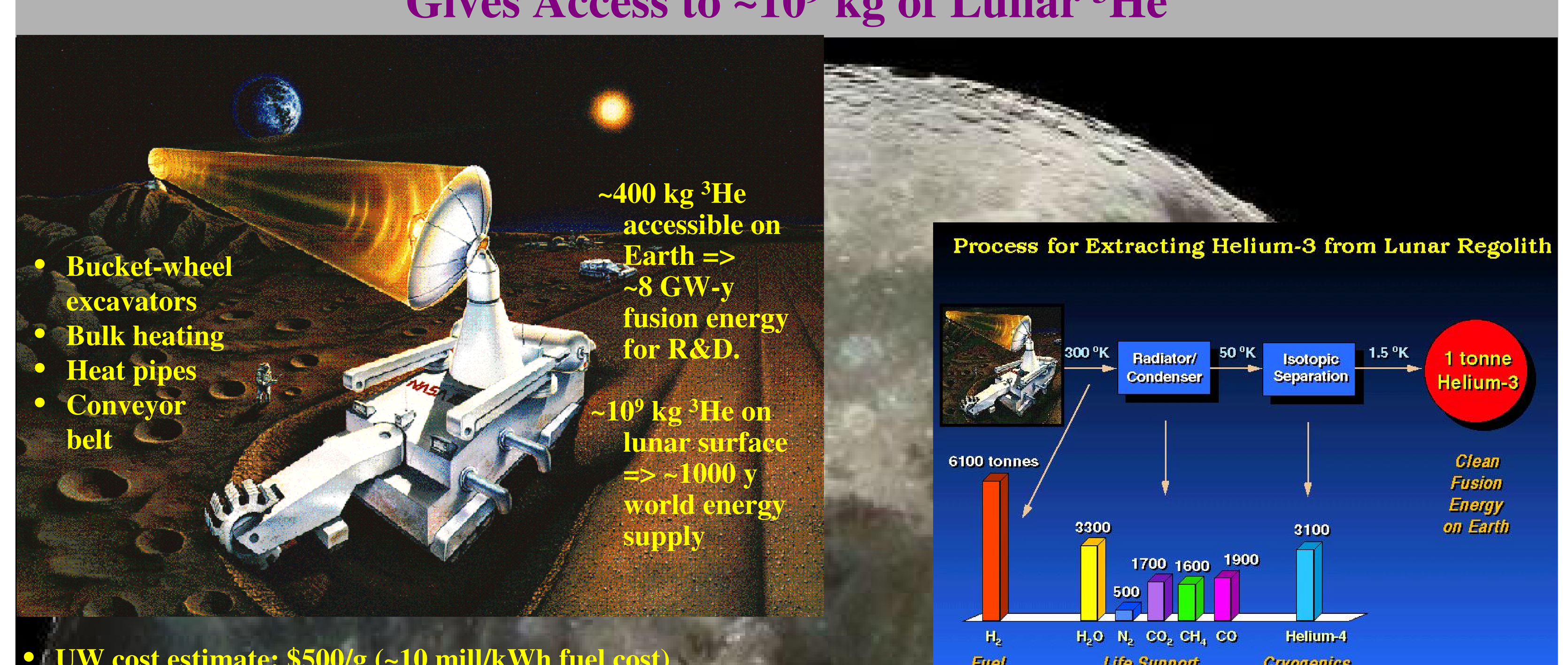


D-^{3}He Fuel Gives Lower Fusion Power Density, but This Can Be Overcome by Moderately Higher Magnetic Fields

- 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-^{3}He needs a factor of ~80 above D-T fusion power densities.
  - D-T fueled FRC's (β ~85%) optimize at B ≤ 3 T.
  - Fusion power density scales as $\beta^2 B^4$.
  - Potential power-density improvement by increasing β and B-field appears at right.



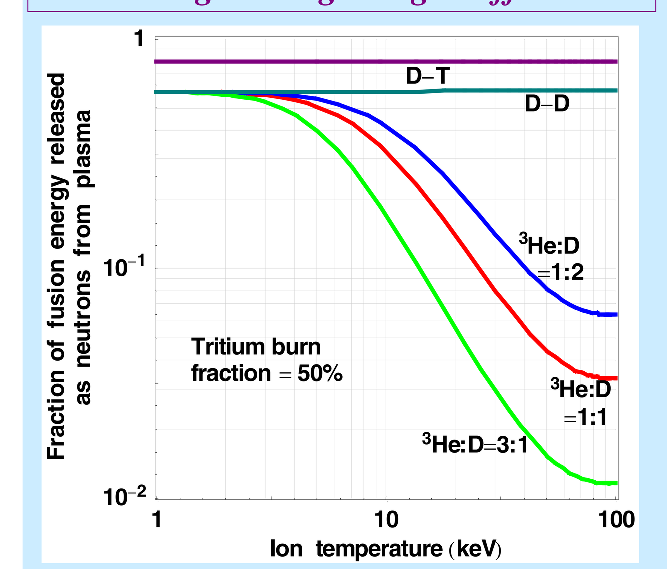
^{3}He Resources Are an Issue: Earth Contains ^{3}He Sufficient Only for an Engineering Test Program, but Well-Developed Terrestrial Technology Gives Access to ~10^9 kg of Lunar ^{3}He



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

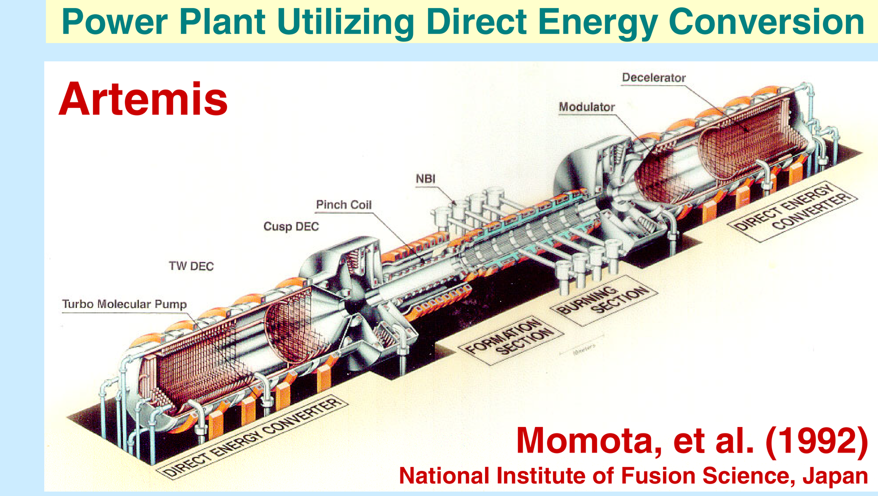
- Shield
  - Minimize thickness, so increased D-T neutron fluence would exceed magnet radiation damage limits.
- Superconducting magnets
  - Design near quench stability boundaries.
- Direct conversion
  - Generate most of the electric power by direct conversion of charged particles, so that D-T operation leads to easily monitored drop in electricity production.
- Organic coolant for shield (needs verification)
  - Design so proliferation neutron levels lead to excessive radiolytic and pyrolytic decomposition.
- Maintenance
  - Sell turn-key units with no provision for shield or magnet replacement. (Allow routine maintenance.)

D-^{3}He Fuel Reduces Neutron Power Fraction and Eases Engineering Design Difficulties



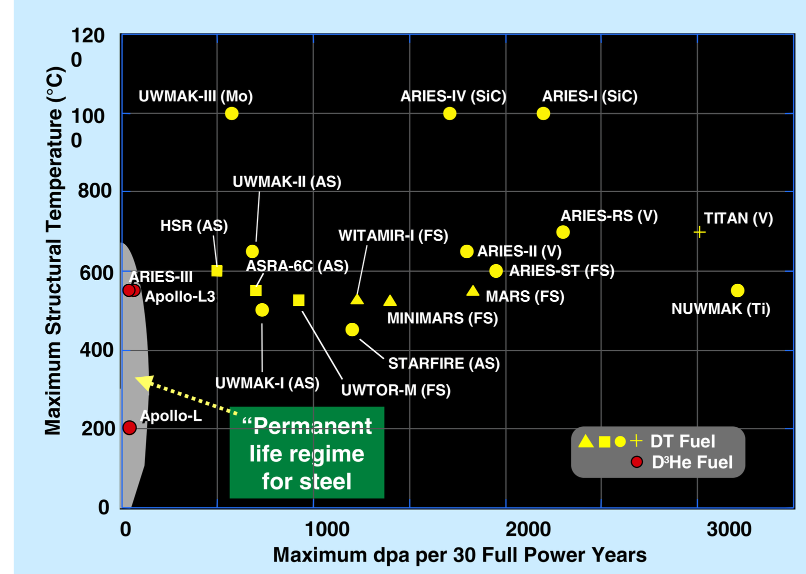
D-^{3}He Fuel Can Utilize Direct Energy Conversion Effectively because of Its Large Charged-Particle Power Fraction; D-T Fuel, with 80% Neutron Power, Cannot

Conceptual Commercial D-^{3}He Fusion Electric Power Plant Utilizing Direct Energy Conversion



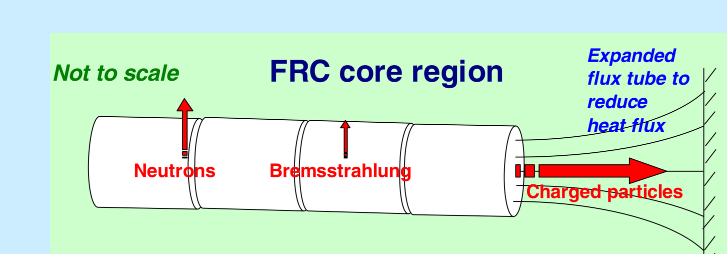
Momota, et al. (1992)
National Institute of Fusion Science, Japan

The Low Radiation Damage in D-^{3}He Reactors Allows Permanent First Walls and Shields to be Designed



High Heat Fluxes in D-^{3}He Reactors Stem from High Power Density, but Are Manageable

- 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, giving a relatively small peaking factor along the axis.



Summary

- **A proliferation-resistant fusion power plant is feasible.**
- **Whether a completely proliferation-proof fusion power plant could be designed awaits detailed study.**
- **Probably requires D-^{3}He fuel and development of an attractive high-power-density configuration, such as the FRC.**
- **Engineering features could make replacement of D-^{3}He by D-T fuel difficult.**
  - **Single-module reactors, full-lifetime shields and magnets, minimal shield thickness, magnets near damage and stability limits, direct conversion, organic coolant.**