Fusion Space Propulsion--

A Shorter Time Frame than You Think

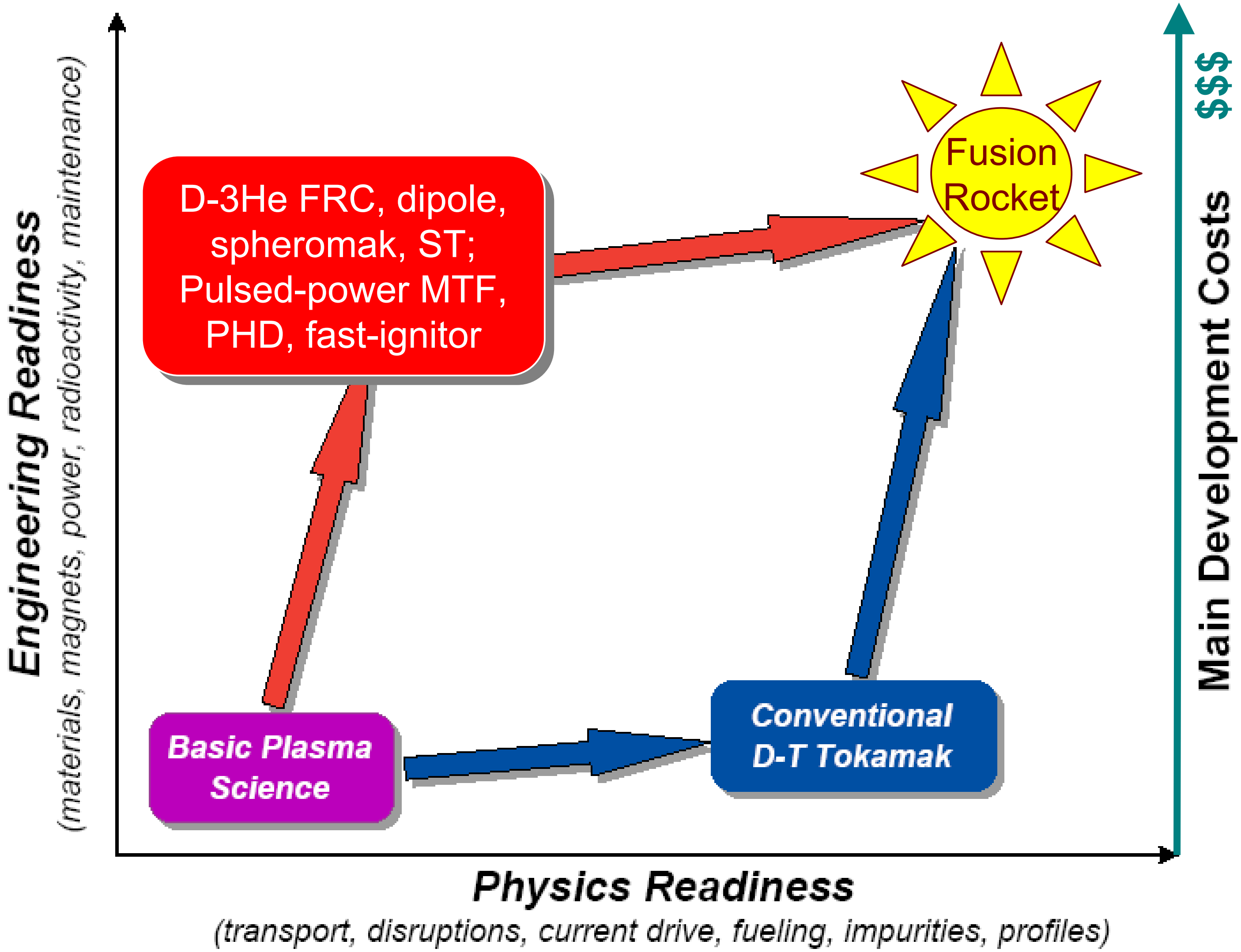
John F. Santarius

Fusion Technology Institute
University of Wisconsin

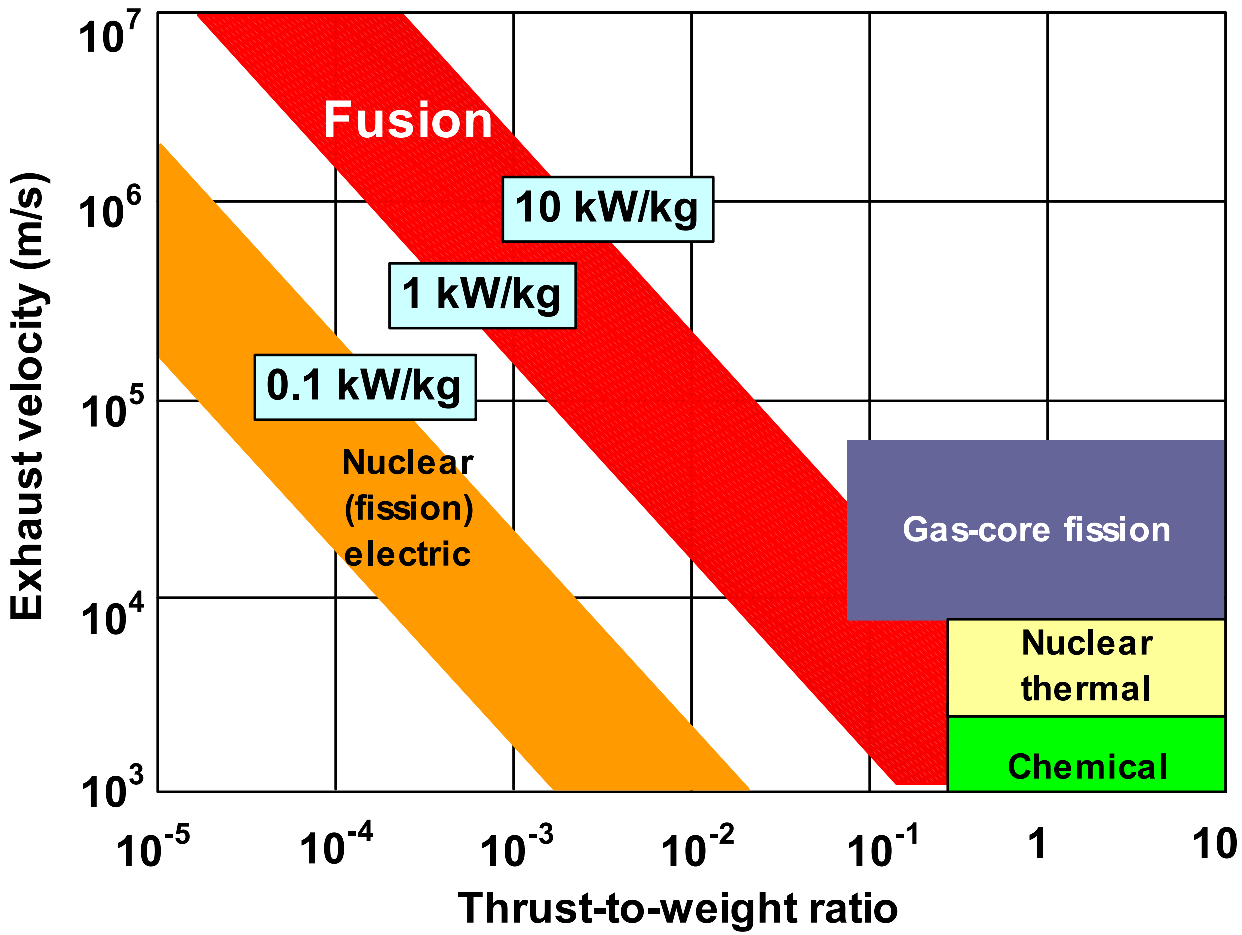
JANNAF

Monterey, 5-8 December 2005

D-^{3}He and Pulsed-Power Fusion Approaches Would Shorten Development Times



D-^{3}He Fusion Will Provide Capabilities Not Available from Other Propulsion Options



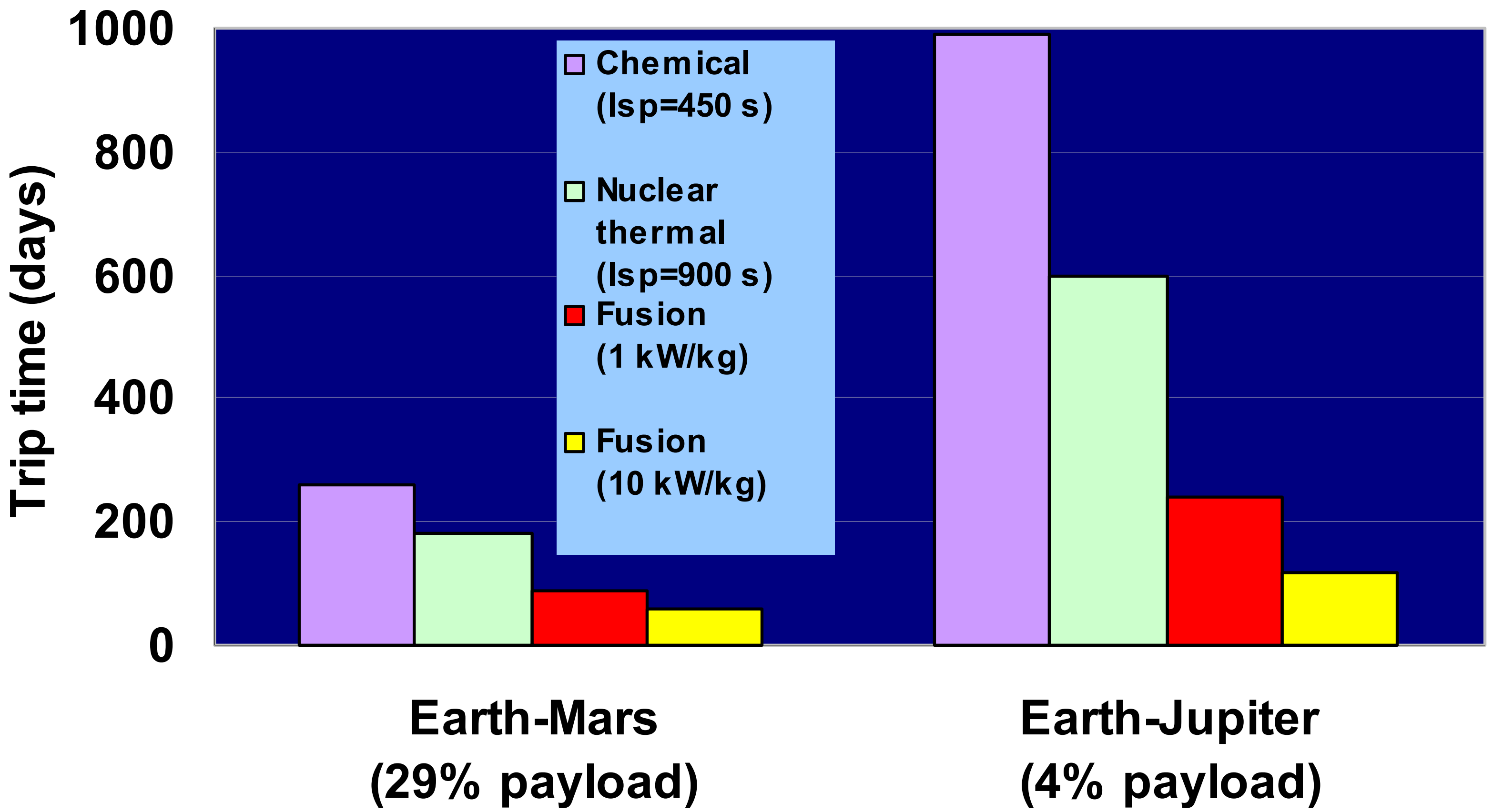
Predicted Specific Power of D-^{3}He Magnetic Fusion Rockets Is Attractive (>1 kW/kg)

- Predictions based on reasonably detailed magnetic fusion rocket studies.

First Author	Year	Configuration	Specific Power (kW/kg)
Borowski	1987	Spheromak	10.5
Borowski	1987	Spherical torus	5.8
Santarius	1988	Tandem mirror	1.2
Bussard	1990	Riggatron	3.9
Teller	1991	Dipole	1.0
Nakashima	1994	Field-reversed configuration	1.0
Emrich	2000	Gasdynamic mirror	130
Thio	2002	Magnetized-target fusion	50
Williams	2003	Spherical torus	8.7
Cheung	2004	Colliding-beam FRC	1.5

Fusion Propulsion Would Enable Fast and Efficient Solar-System Travel

- Fusion propulsion would dramatically reduce trip times (shown below) or increase payload fractions.



Key Fusion Fuels for Space Propulsion

1st generation fuels:

D + T → n (14.07 MeV) + ^{4}He (3.52 MeV)

D + D → n (2.45 MeV) + ^{3}He (0.82 MeV)

→ p (3.02 MeV) + T (1.01 MeV)

{50% each channel}

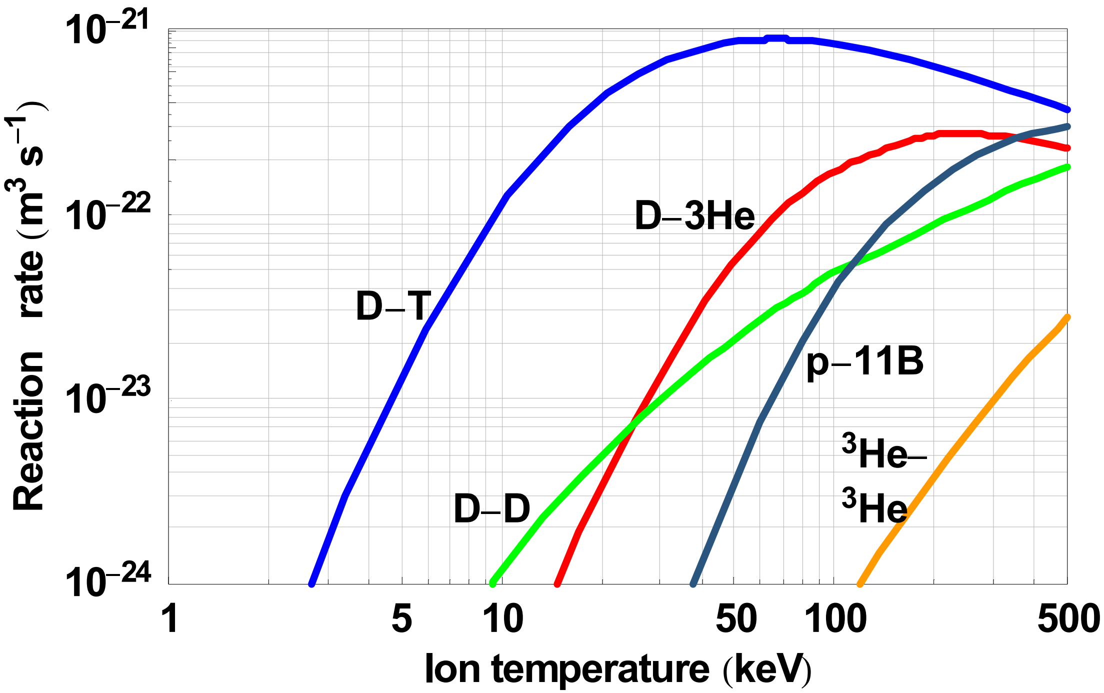
2nd generation fuel:

D + ^{3}He → p (14.68 MeV) + ^{4}He (3.67 MeV)

3rd generation fuels:

^{3}He + ^{3}He → 2 p + ^{4}He (12.86 MeV)

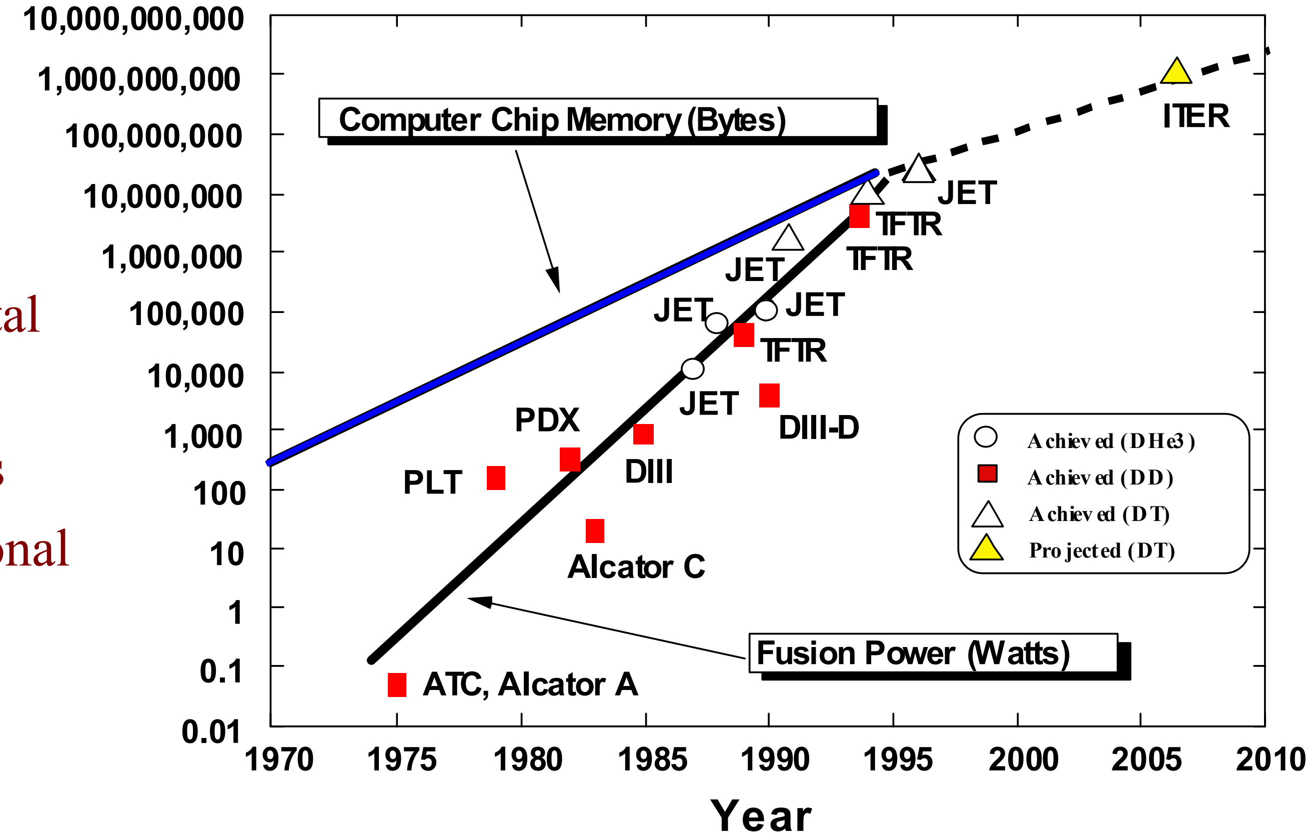
p + ^{11}B → 3 ^{4}He (8.68 MeV)



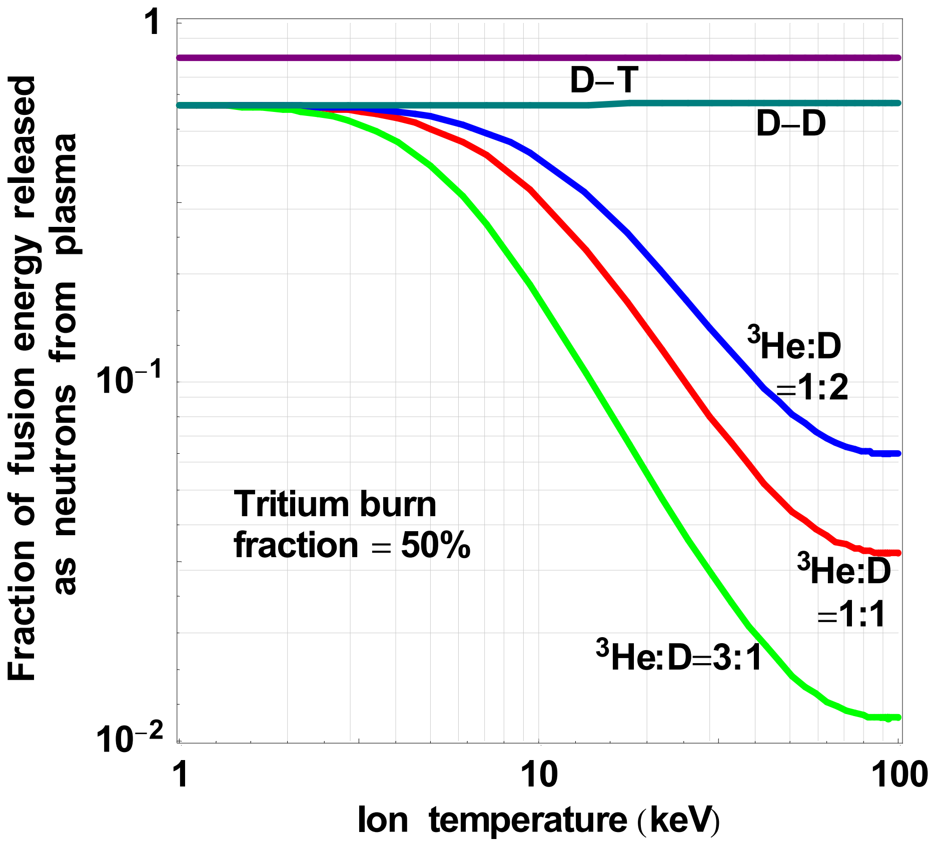
D-^{3}He Fuel Requires Continuation of the Remarkable Progress of Fusion Physics

- Decades of plasma physics progress created sophisticated tools that will facilitate the development of innovative concepts:

  - Experimental techniques
  - Diagnostics
  - Computational modeling
  - Theory



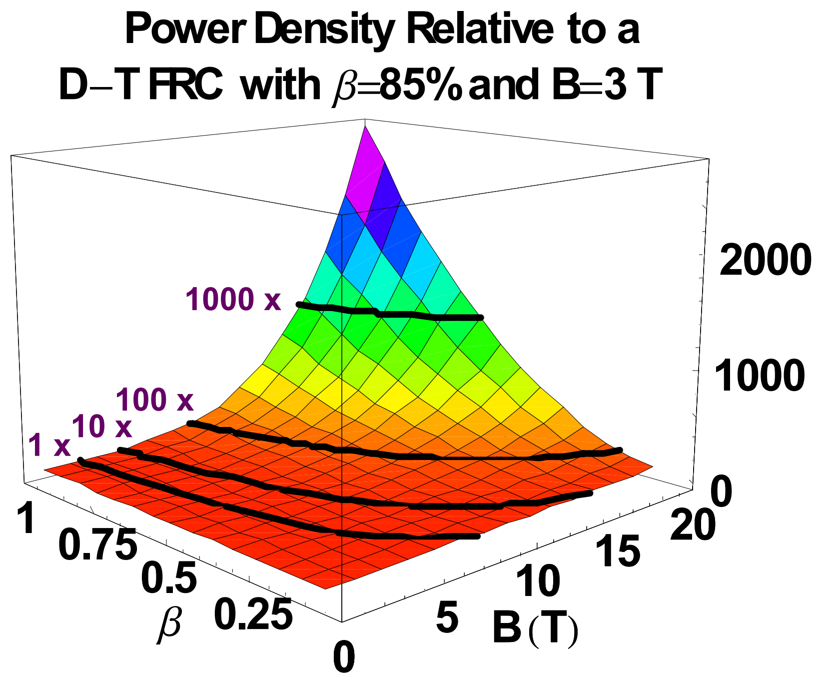
D-^{3}He Fuel and High β Relax Engineering Constraints



- Reduced neutron flux allows
  - Smaller radiation shields,
  - Smaller magnets,
  - Less activation,
  - Easier maintenance, and
  - Potentially, proliferation-proof fusion power plants.
- Increased charged-particle flux allows direct energy conversion to thrust or electricity.
  - Nonlinear gain in useful power / radiator mass
    - P_{thr}/M_{rad} α $\eta/(1-\eta)$

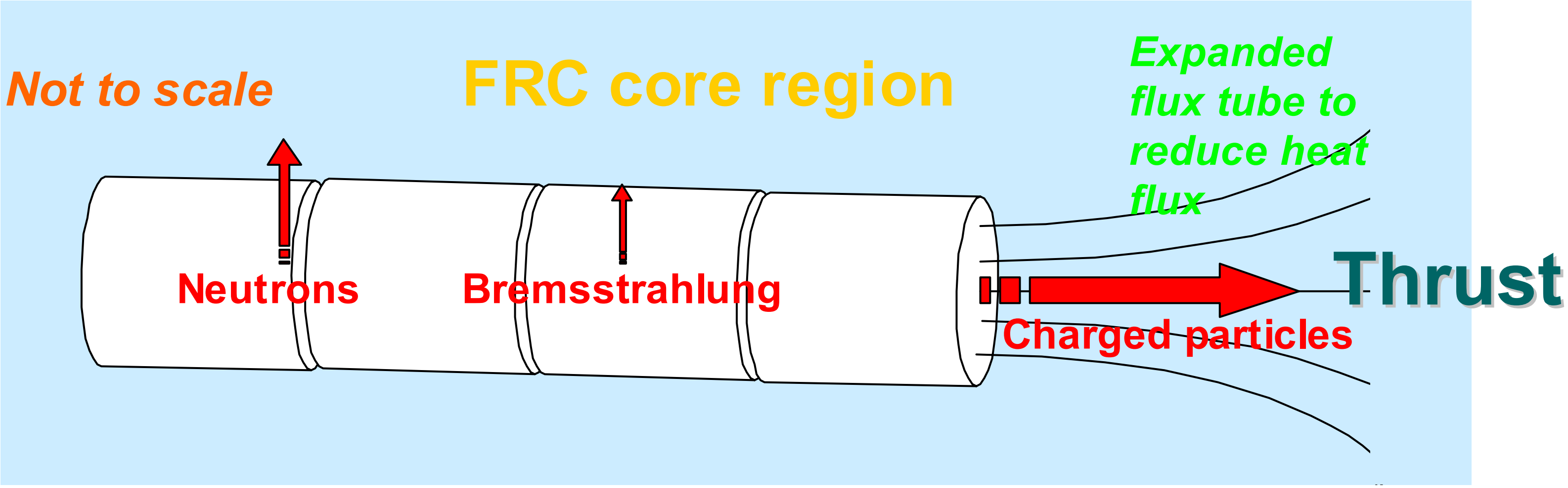
D-^{3}He Fuel Could Make Good Use of the High Power Density Capability of Some Innovative Fusion Concepts

- 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.

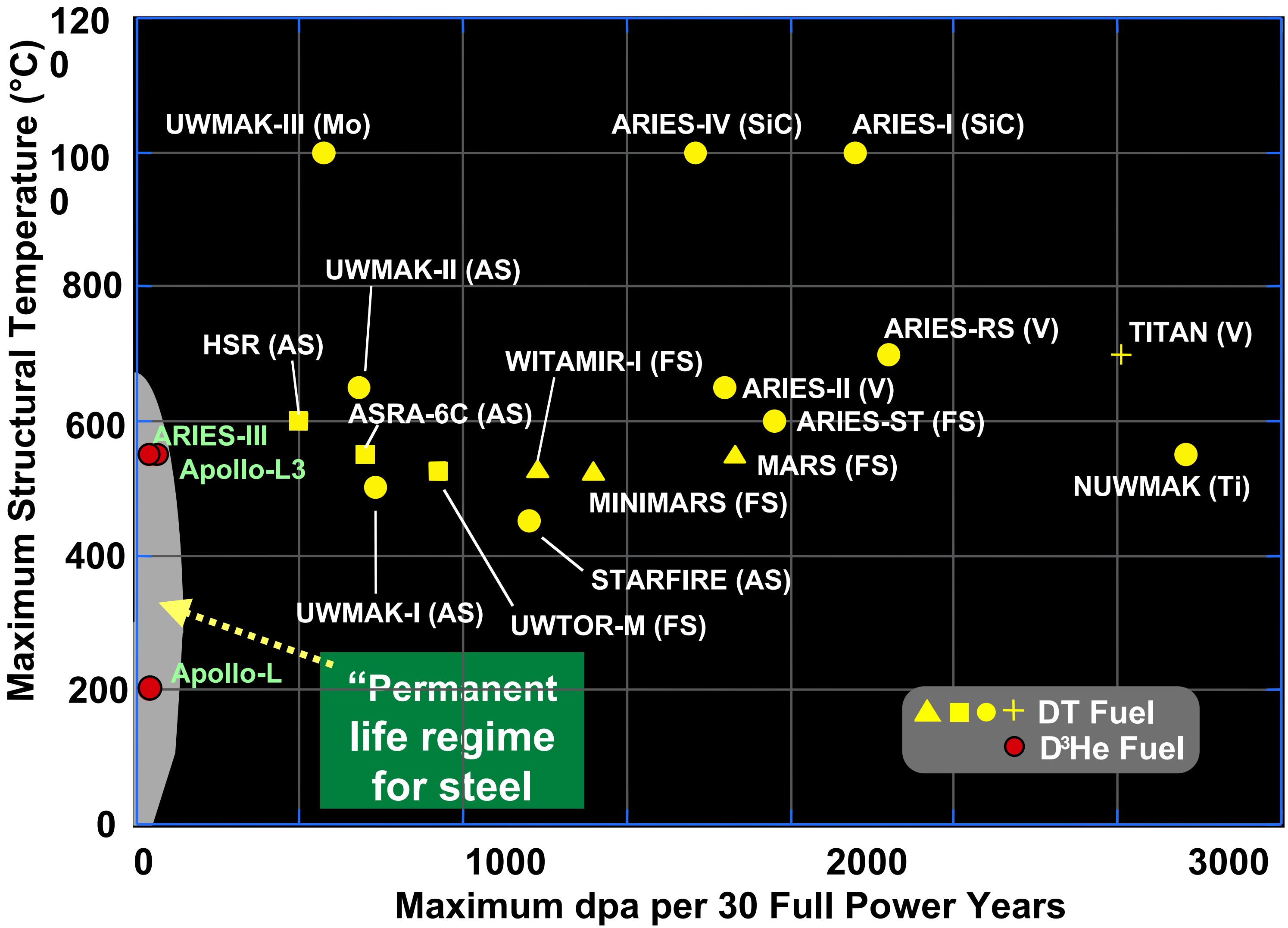


Plasma Power Flows in Linear Devices Give More Design Flexibility than Flows in Toroidal Devices

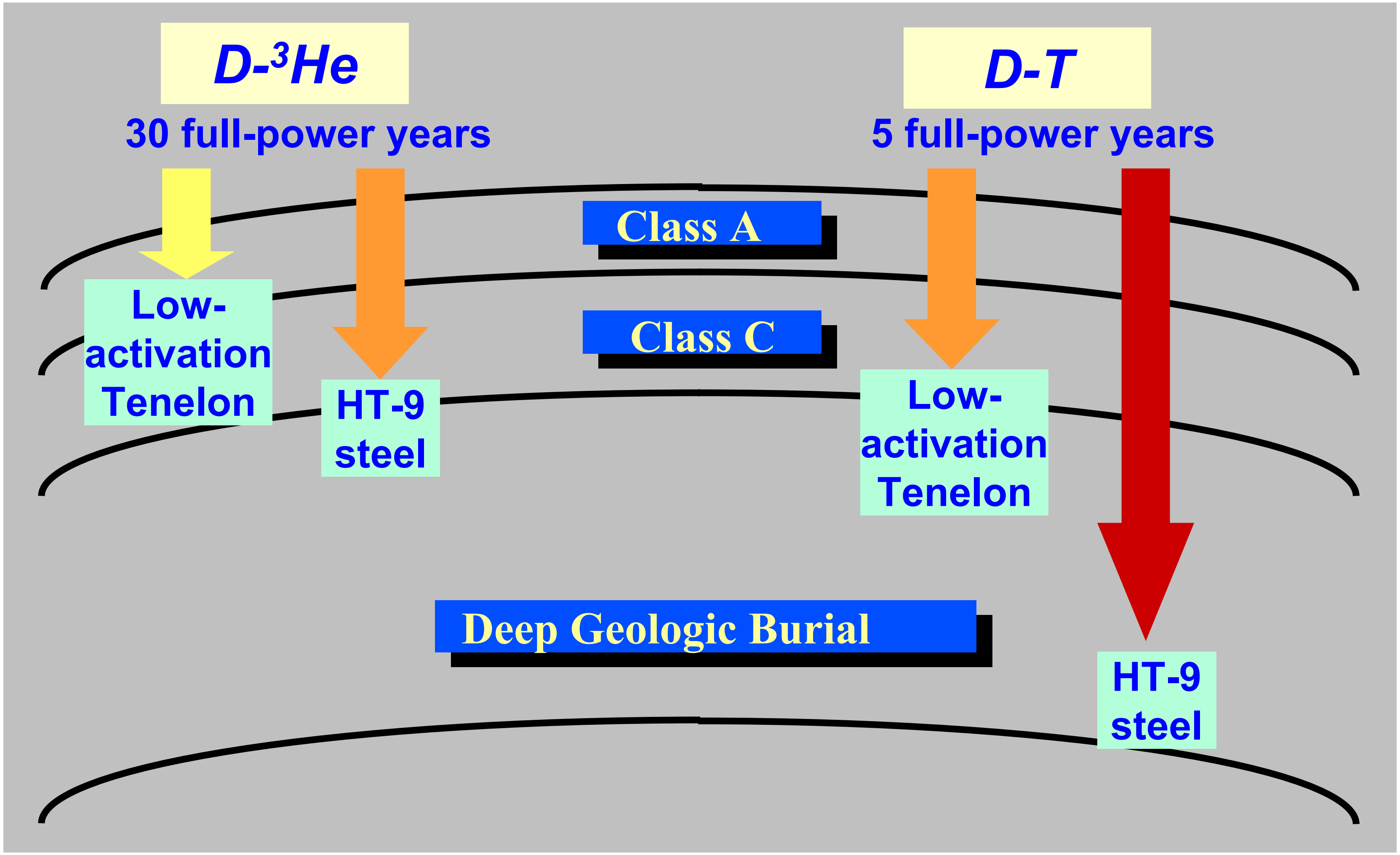
- Power density can be very high due to $\beta^2 B^4$ scaling, but first-wall heat fluxes would remain manageable.
  - Charged-particle power transports from internal plasmoid to edge region and then out ends of fusion core.
  - Magnetic flux tube can be “pinched” on one end by increasing the magnetic field on that side, giving primarily single-ended flow.
- Pulsed concepts gain similar advantages by reflecting plasma from a magnetic nozzle.



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



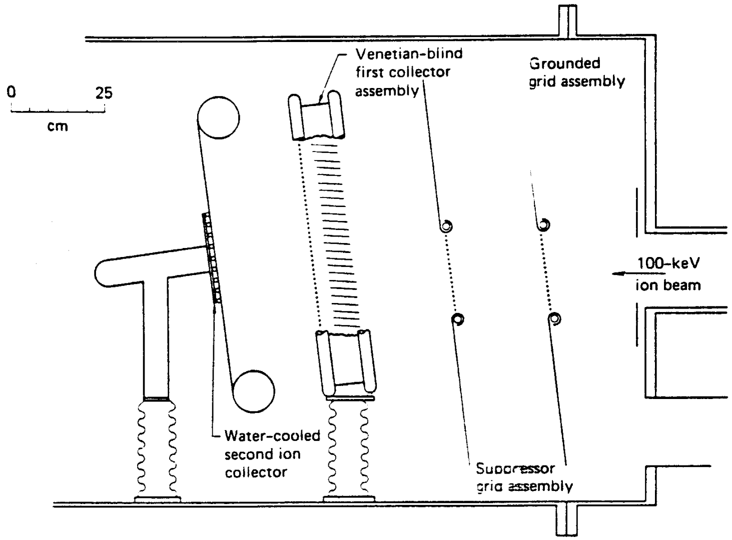
Radioactive Waste Disposal is Much Easier for D-^{3}He Reactors than for D-T Reactors



Fusion Rockets Would Provide Electricity Production and Materials Processing Capabilities at Destination

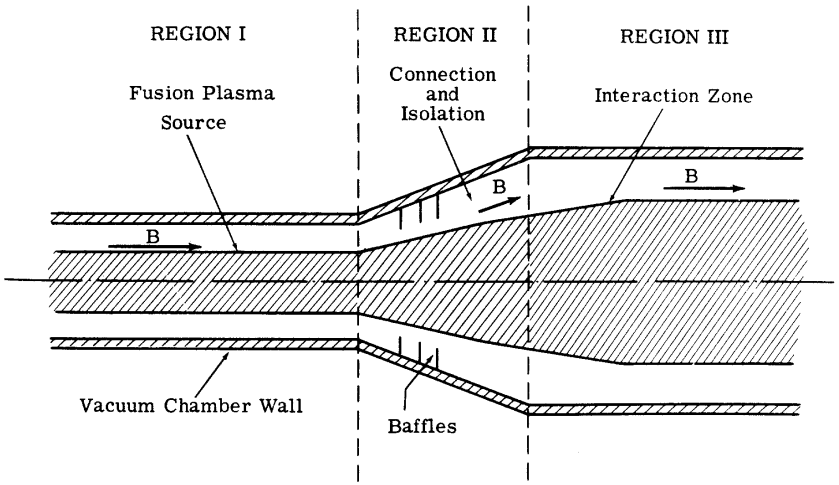
- Direct conversion to electricity could take advantage of the natural vacuum in space.

Barr & Moir experiment, LLNL
(*Fusion Technology*, 1973)



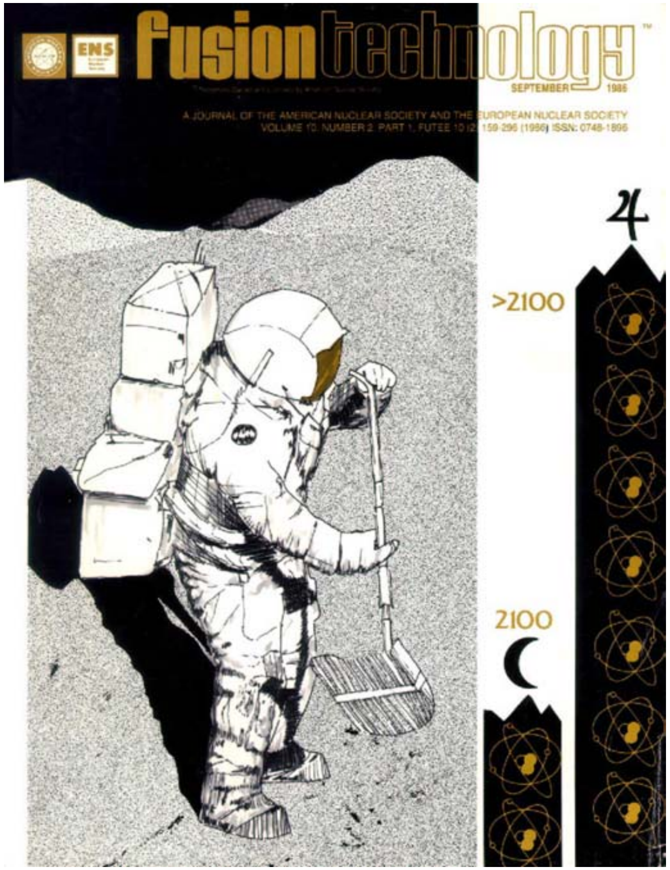
- Plasmas provide many materials processing capabilities.

B.J. Eastlund and W.C. Gough, "The Fusion Torch--Closing the Cycle from Use to Reuse," WASH-1132 (US AEC, 1969).



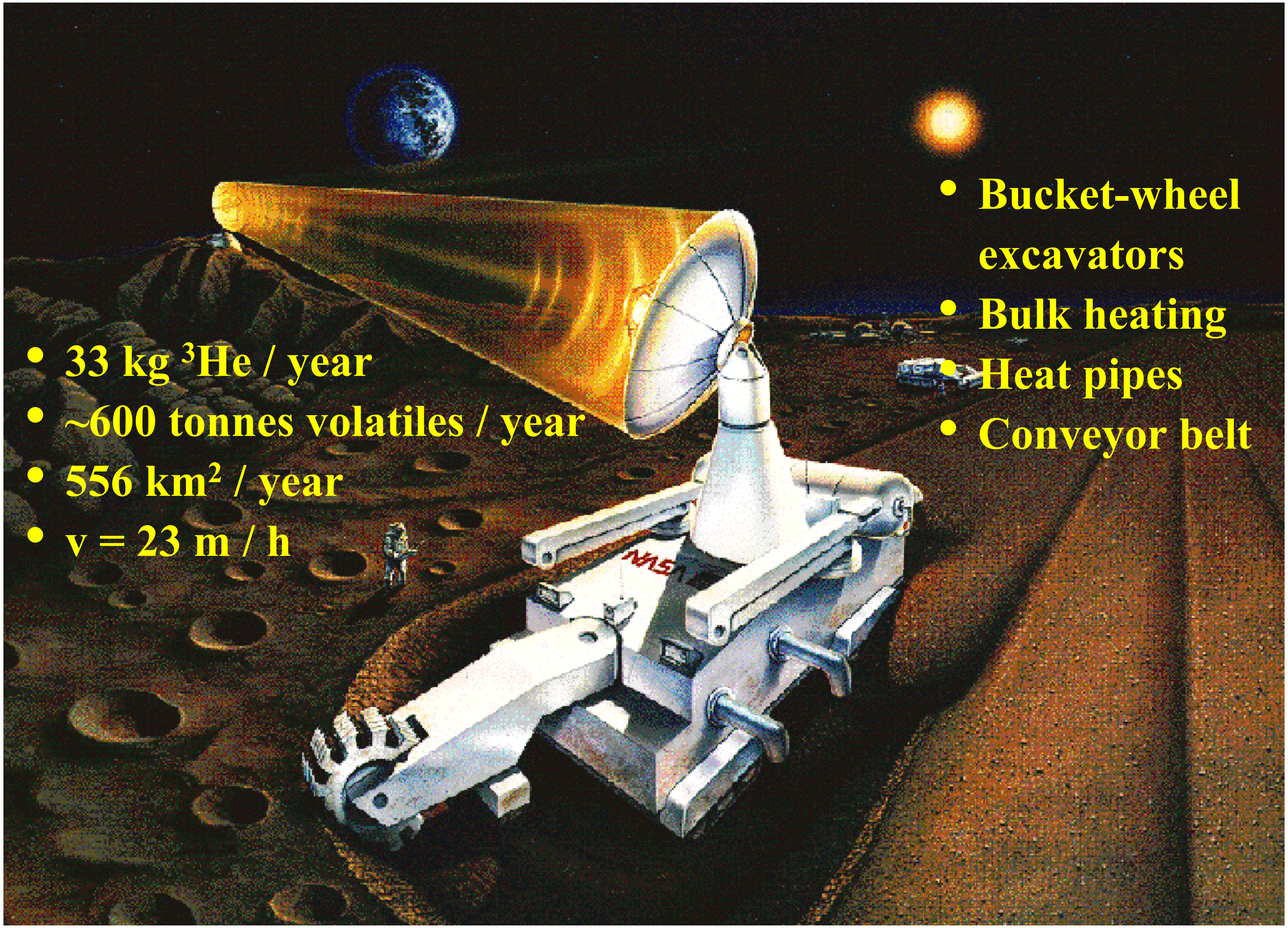
A Well Documented
Lunar ^{3}He Resource Exists

- Lunar ^{3}He concentration verified from Apollo 11, 12, 14, 15, 16, & 17 plus USSR Luna 16 & 20 samples.
- Analysis indicates that ~10^9 kg of ^{3}He exists on the lunar surface, or ~1000 y of world energy supply.
- One-way Earth-Mars trip requires ~100 kg ^{3}He.
- 40 tonnes of ^{3}He would supply the entire 2004 US electricity needs.
- ~400 kg ^{3}He (8 GW-y fusion energy) is accessible on Earth for R&D.



L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technology* **10**, 167 (1986).

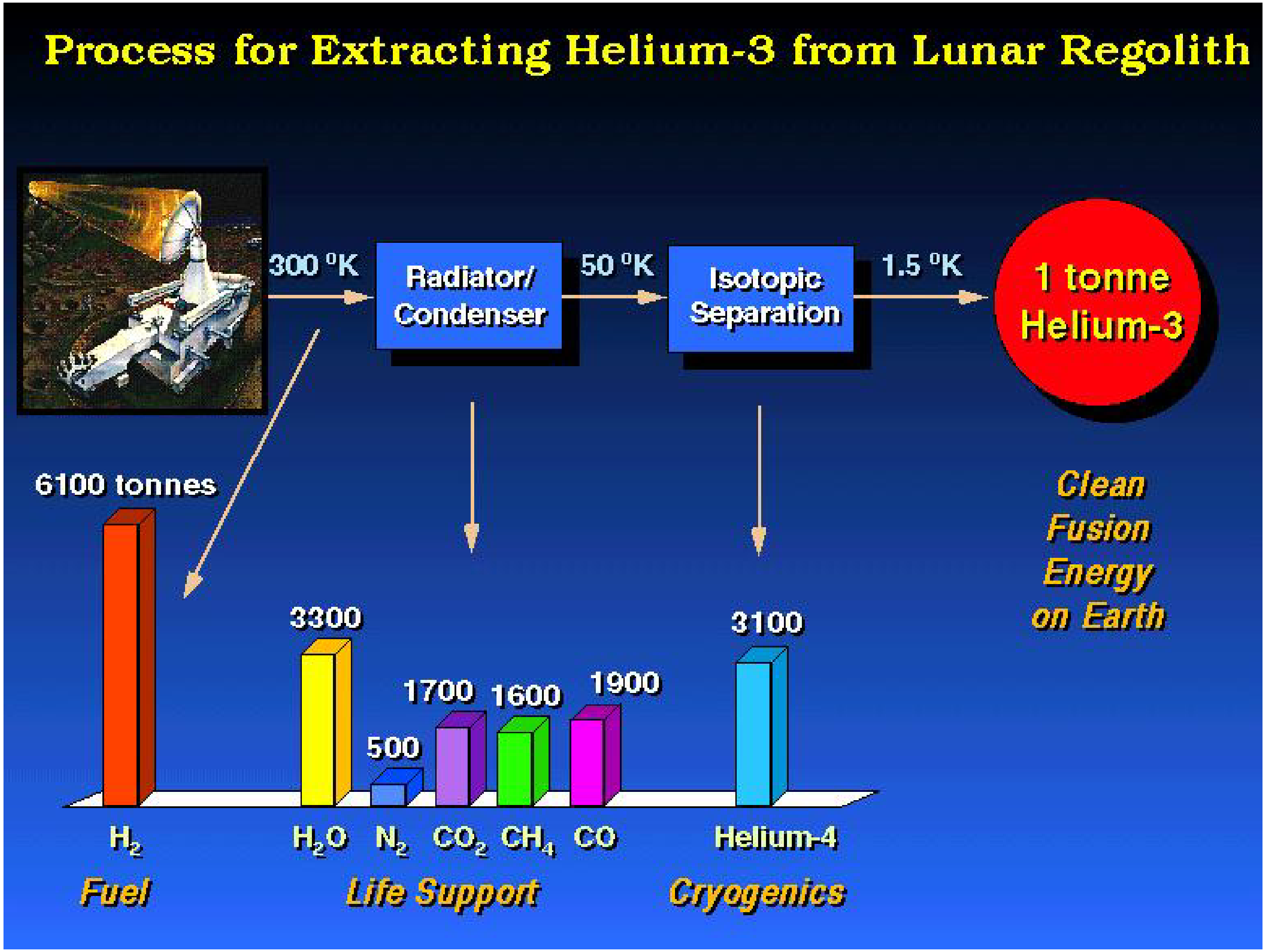
Well-Developed Terrestrial Technology Gives Access to ~10^9 kg of Lunar ^3He



- 33 kg ^3He / year
- ~600 tonnes volatiles / year
- 556 km^2 / year
- v = 23 m / h

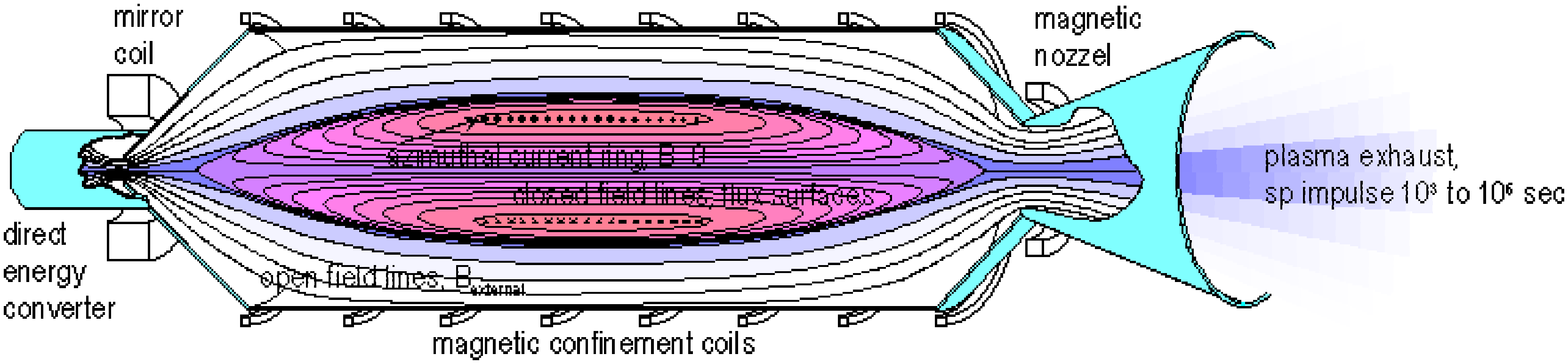
- Bucket-wheel excavators
- Bulk heating
- Heat pipes
- Conveyor belt

Lunar ^3He Mining Produces Other Useful Volatiles



D-^{3}He Field-Reversed Configuration (FRC) Appears Attractive for Fusion Propulsion

- FRCs possess key desired characteristics for D-^{3}He fusion:
  - Very high $\beta \equiv P_{plasma}/P_{B\text{-}field}$
  - Linear external B field
  - Cylindrical geometry
- Recent encouraging results:
  - Emerging understanding of why FRCs appear far more stable than MHD theory predicts.
  - Attractive current drive by rotating magnetic fields (RMF) demonstrated.

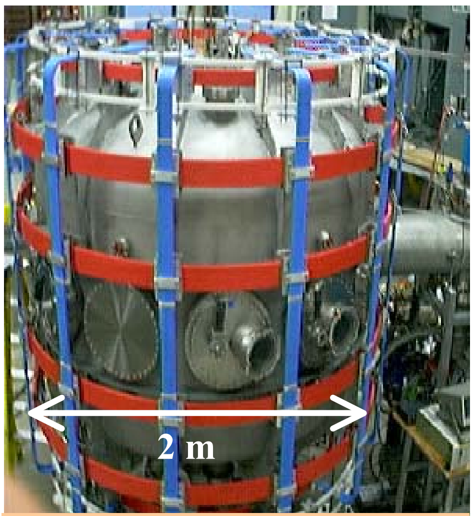


FRC as Power Source and Ion Engine for High Energy Space Missions

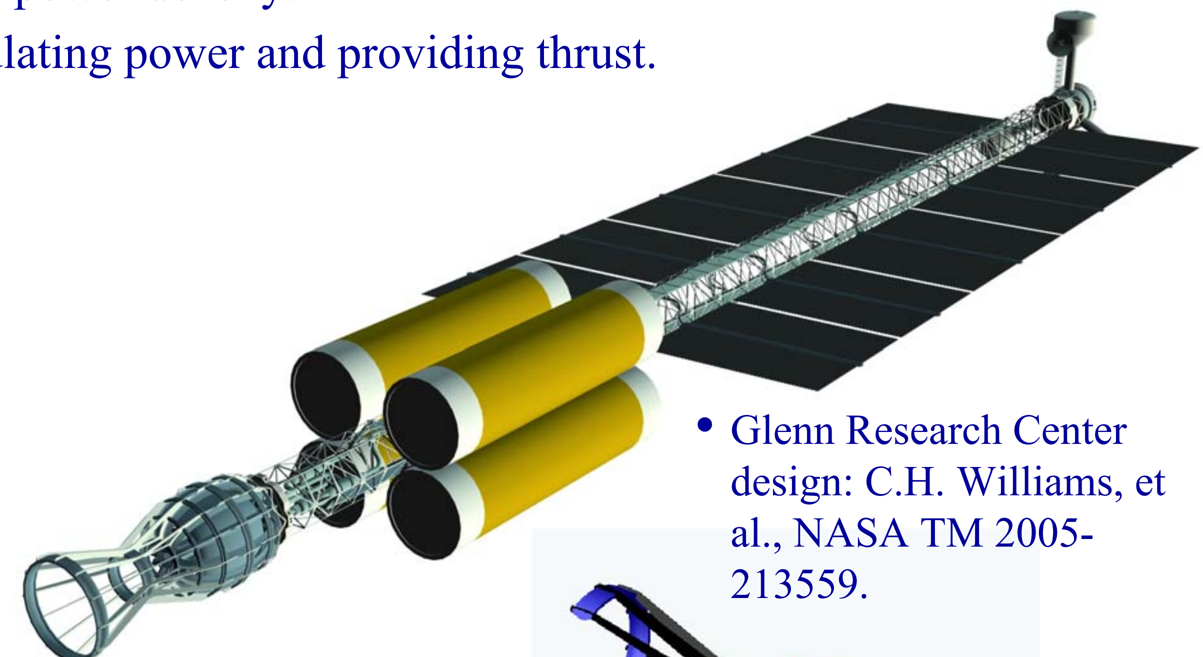
From Univ. of Washington web page for the Star Thrust Experiment (STX):
www.aa.washington.edu/AERP/RPPL/STX.html

Spherical Torus Space Propulsion Would Benefit from the Substantial DOE ST Research Effort

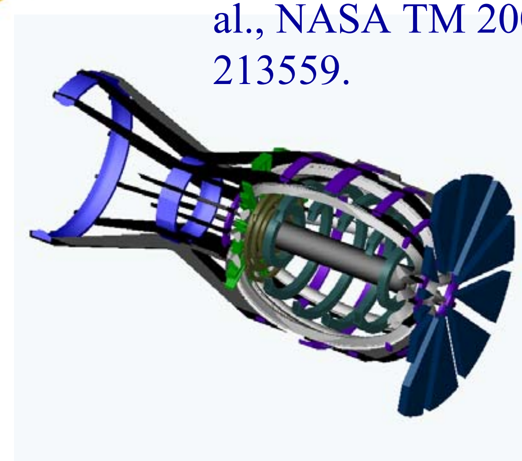
- Very low aspect-ratio version of the tokamak.
- High β, implying high power density.
- Critical issues: recirculating power and providing thrust.



Pegasus ST experiment,
Univ. of Wisconsin

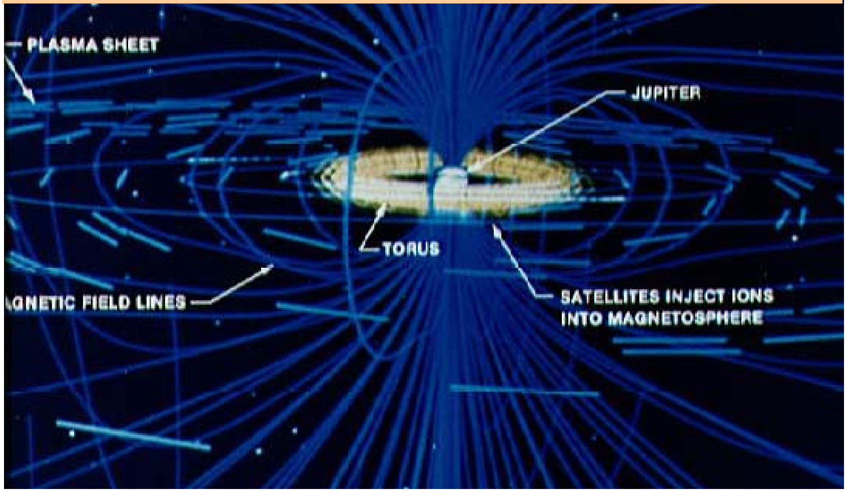


- Glenn Research Center design: C.H. Williams, et al., NASA TM 2005-213559.

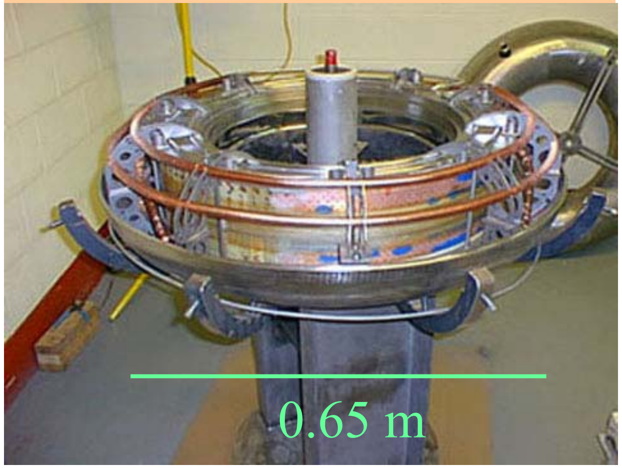


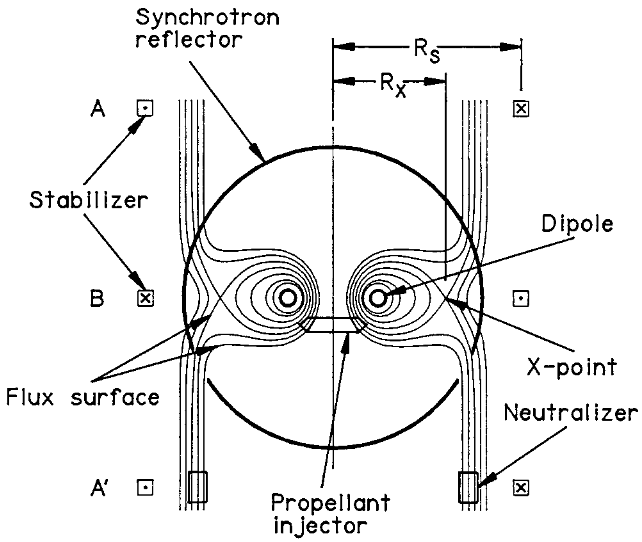
The Dipole Configuration Offers a Relatively Simple Design That an MIT/Columbia Team Has Begun Testing

Io plasma torus around Jupiter



LDX experiment (MIT)





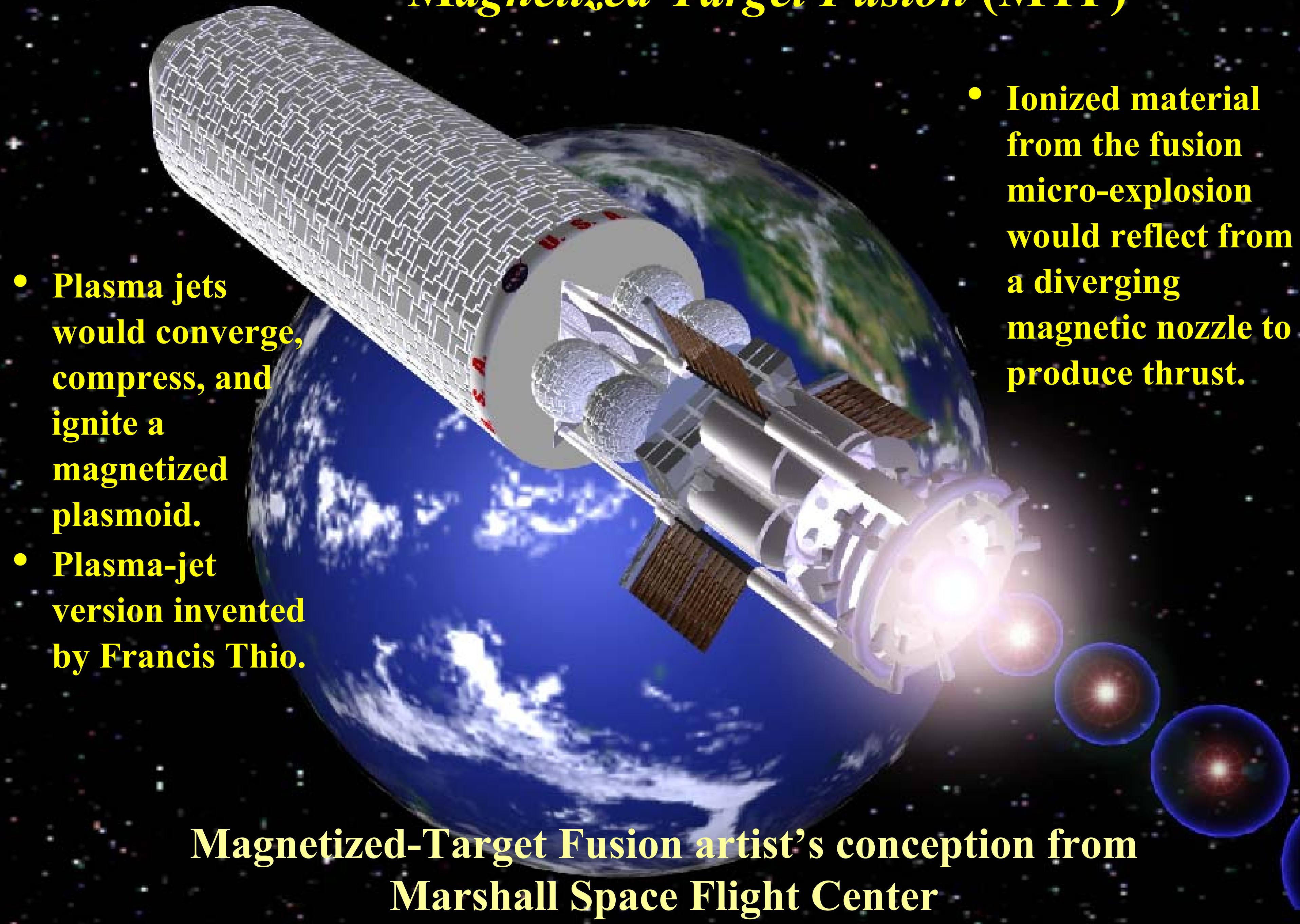
Dipole space propulsion design:

E. Teller, A.J. Glass, T.K. Fowler, A. Hasegawa, and J.F. Santarius, "Space Propulsion by Fusion in a Magnetic Dipole," *Fusion Technology* **22**, 82 (1992).

Magnetized-Target Fusion (MTF)

- Plasma jets would converge, compress, and ignite a magnetized plasmoid.
- Plasma-jet version invented by Francis Thio.

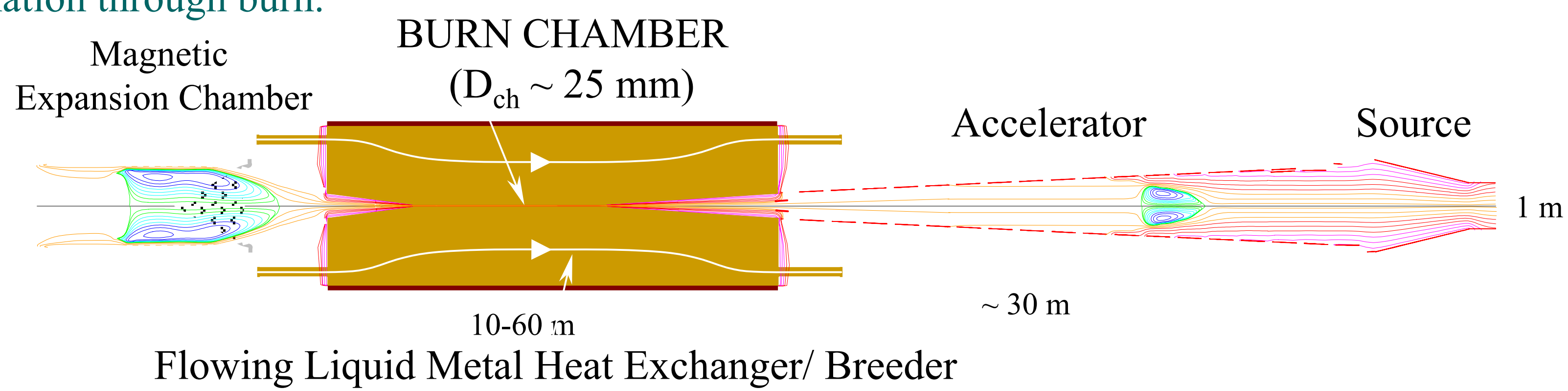
- Ionized material from the fusion micro-explosion would reflect from a diverging magnetic nozzle to produce thrust.

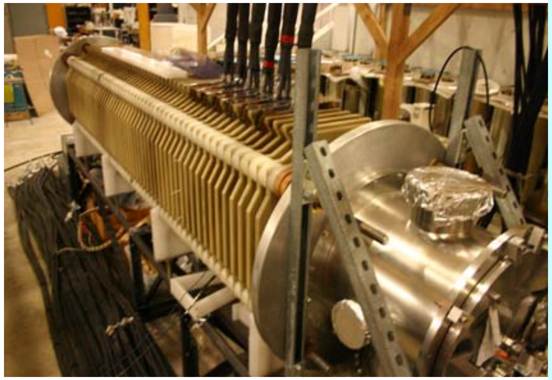


Magnetized-Target Fusion artist's conception from Marshall Space Flight Center

Pulsed High Density (PHD) Fusion

- Invented by John Slough, Univ. of Washington, who provided this viewgraph.
- Experimental program that takes advantage of a very compact, high energy density FRC to reach fusion conditions.
  - The energy required to achieve fusion conditions is transferred to the FRC via simple, relatively low field acceleration/compression coils.
  - For FRC in smaller, higher density regime, the requirement on the FRC closed poloidal flux is no greater than what has been achieved
  - The FRC should remain in a stable regime with regard to MHD modes such as the tilt from formation through burn.





1 - FRC formed at low energy (~3 kJ) and relatively low density (~10^{21} m^{-3})

2 - FRC accelerated by low energy propagating magnetic field (~ 0.4 T) to

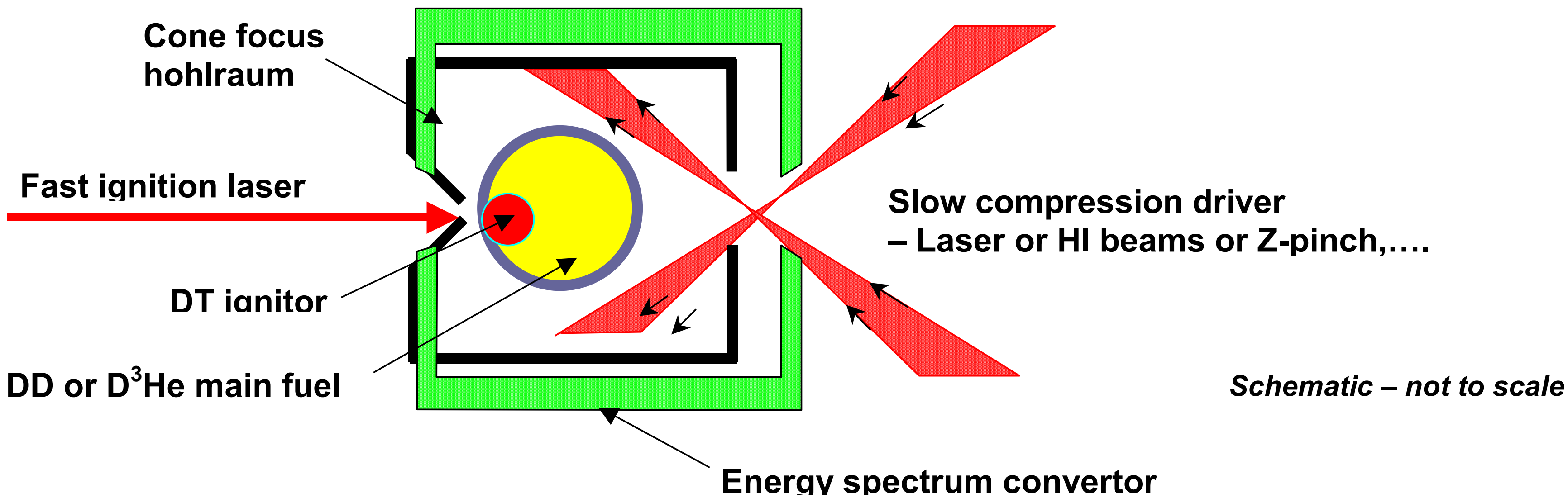
3 - FRC adiabatically compressed and heated as it decelerates into burn chamber

4 - FRC travels several meters during burn time minimizing wall loading

5 - If necessary, FRC flux and confinement enhanced by spatial "RMF" field

6 - FRC expands and cools converting fusion energy directly into electrical energy

It May be Possible to Efficiently Burn DD or D^3He 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.

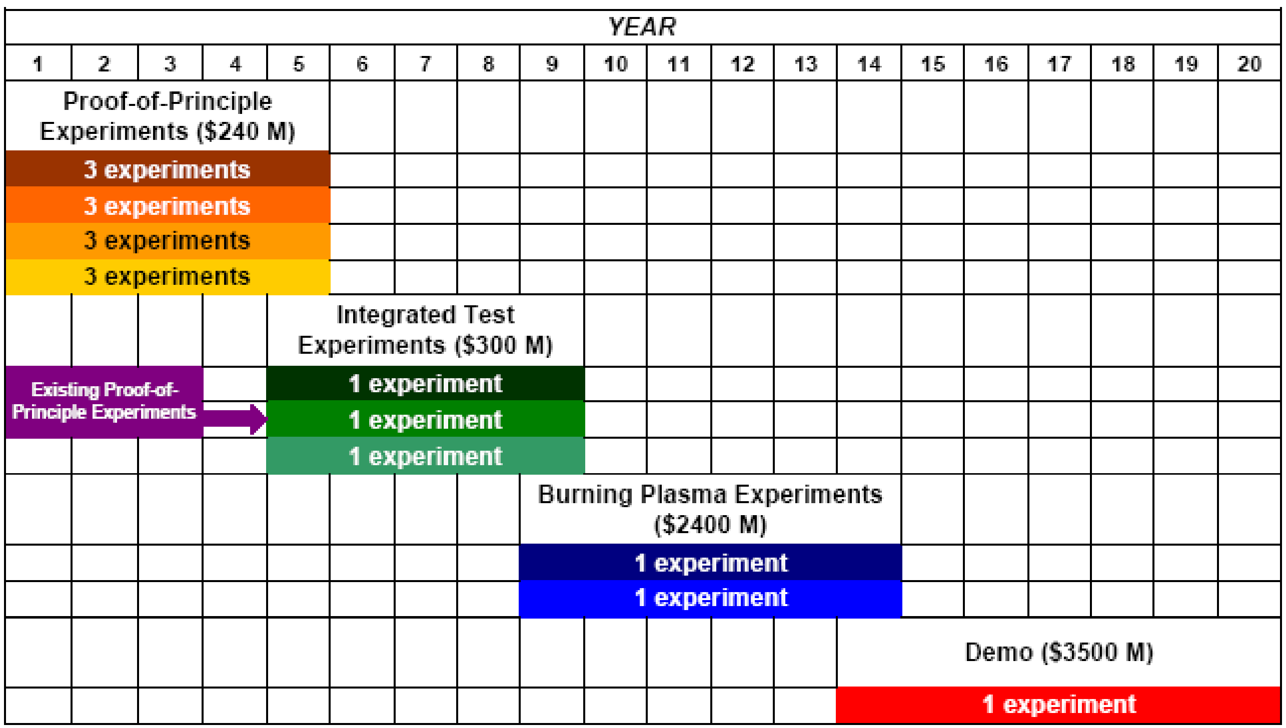
(3) Bremsstrahlung is self-trapped in the compressed fuel

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

- Viewgraph contributed by John Perkins, LLNL.

D-^{3}He Fusion Space Propulsion Can Be Developed Quickly, *If the Will Exists*

- In parallel, experiment on several concepts with multiple devices.
  - Winnow.
  - Provide substantial power and diagnostic capabilities.
  - Provide sufficient contingency funding and program flexibility to director.
- Incorporate existing terrestrial fusion research program where possible.



- Total program cost ~ 6 B$.

Summary and Conclusions

- Attractive fusion space propulsion options exist.
- Development should follow the D-^{3}He and pulsed-power paths of more physics risk and less engineering risk.
  - Pursue "survival of the fittest," starting with sufficient species.
  - Provided sufficient program flexibility and contingency funds.
  - Estimated cost < $10 B for a demonstration system in two decades.

References

- UW Fusion Technology Institute: http://fti.neep.wisc.edu/
- 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).
- J.F. Santarius and B.G. Logan, "Generic Magnetic Fusion Rocket Model," *Journal of Propulsion and Power* **14**, 519 (1998).
- J.F. Santarius, G.L. Kulcinski, and L.A. El-Guebaly, "A Passively Proliferation-Proof Fusion Power Plant," *Fusion Science and Technology* **44**, 289 (2003).
- L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technology* **10**, 167 (1986).
- L.J. Wittenberg, E.N. Cameron, G.L. Kulcinski, S.H. Ott, J.F. Santarius, G.I. Sviatoslavsky, I.N. Sviatoslavsky, and H.E. Thompson, "A Review of Helium-3 Resources and Acquisition for Use as Fusion Fuel," *Fusion Technology* **21**, 2230 (1992).