The Need for Fusion Propulsion

Presentation Outline

- Presentation Objectives
- Arguments for Fusion Propulsion
- Fusion Enabled Missions and Examples
- Fusion Technology Trade Space
- Proposed Outline for Future Efforts
- Endorsements

Presentation Objectives

- Enable propulsion systems research for
  - crewed exploration beyond Mars
  - routine rapid crewed missions to Mars
  - high-speed robotic missions to the outer solar system and beyond.
- Convince HQ that a NASA-sponsored fusion campaign is needed.
- Allocate research funds to address the scientific and technical feasibility for fusion propulsion.

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Arguments for Investment in Fusion Propulsion

- We need to seed technologies so they are in the maturation pipeline
- Fusion can enable high specific power missions while maintaining high specific impulse
- Lunar and outer planet abundance of He^3 gives further impetus for exploration (see backup slides)
- We must develop an internal fusion science and engineering capability to properly evaluate usefulness of technologies coming from industry, academia, and other government agencies

Arguments for NASA Investment in Fusion Propulsion

- The NASA – DOE relationship[1]
  - DOE's mandate is primarily to develop terrestrial power generation. Premium is on cost effective (i.e. fuel efficient, high containment) power generation, not mass limitation
  - NASA requires a lightweight propulsion system with high exhaust velocities. Electrical power generation is of secondary importance
- DOE pursuing Tokamak research for terrestrial power production
- DOE sponsored investment in fusion terrestrial power generation has generated a substantial database of basic physics and engineering knowledge relating to fusion physics
- NASA should leverage the basic research being developed by DOE to develop fusion propulsion technologies

[1]Schulze, Norman R., Fusion Energy for Space Missions in the 21st Century, NASA TM-4298, August 1991.

Development Times for Previous Propulsion Systems

- A sustained and steady development program is required now to generate usable results in the near future
- A historical perspective indicates advanced propulsion systems require long lead times for development.
  - Flightweight aircraft engine - ~ 15 years
    - Late 1800's it was accepted that a flightweight reciprocating engine was required to enable human flight
    - Wright brothers developed a barely adequate engine (12 hp/140 lb) but combined with adequate aerodynamics and phenomenal propellant efficiencies (70%) was a success
  - Jet engine - ~ 15 years
    - Frank Whittle proposed turbofan engine in 1928 and it received little interest
    - The Messerschmitt Me 262 started mass production in 1942
  - Liquid propellant rocket engine – 30-45 years
    - Theorized by Tsiolkovsky in late 1890's
    - First test flight by Goddard in 1929
    - Used in V-2 rockets in 1944
  - Electric propulsion thrusters - ~ 40 years
    - First proposed in the 1950's by several
    - First flight of Ion thruster for main propulsion was Deep Space 1 in 1990's

[1] Anderson, John, *Introduction to Flight*, McGraw-Hill Companies, Boston, 1999.
[2] Anderson, John, *Fundamentals of Aerodynamics*, McGraw-Hill Companies, Boston, 1995.
[3] Sutton, George and Bilbarz, Oscar, *Rocket Propulsion Elements*, John Wiley and Sons, New York, 2001

Fusion Development Overlap with Prometheus

- Can leverage advancements in fission propulsion and pursue intermediate fission/fusion hybrid
  - Fusion reactions with a gain less than unity to increase specific impulse of magnetically confined electric thruster concepts (i.e. VASIMR)
  - Fission ignited fusion, both steady state (UF4 gas entrained in fusion plasma to increase temperature and pressure) and pulsed (fission explosion to confine fusion plasma to very high densities)
- Common propulsion elements between fission and fusion
  - High voltage and power distribution and management
  - Neutron and gamma shielding

Explanation for Higher Specific Power for Fusion vs. NEP

- Electric power requires *energy conversion* from a reactor or other source
- *Thermal/electric conversion*, required for NEP, is about 30% efficient limited by Carnot cycle (2^{nd} Law) efficiency
  - *Large radiator mass required*
  - *Mass of radiator must be traded against NEP system efficiency to find rejection temperature that yields minimum mass*
- Thermal/electric inefficiencies can be offset in a high gain fusion system
  - *Large propulsion system mass offset by added jet power*
- *Direct conversion* of the plasma exhaust energy, a viable approach for fusion, can approach 70% efficiency of the total fusion reaction
  - *Losses related to Bremmstrahlung and neutron energy*

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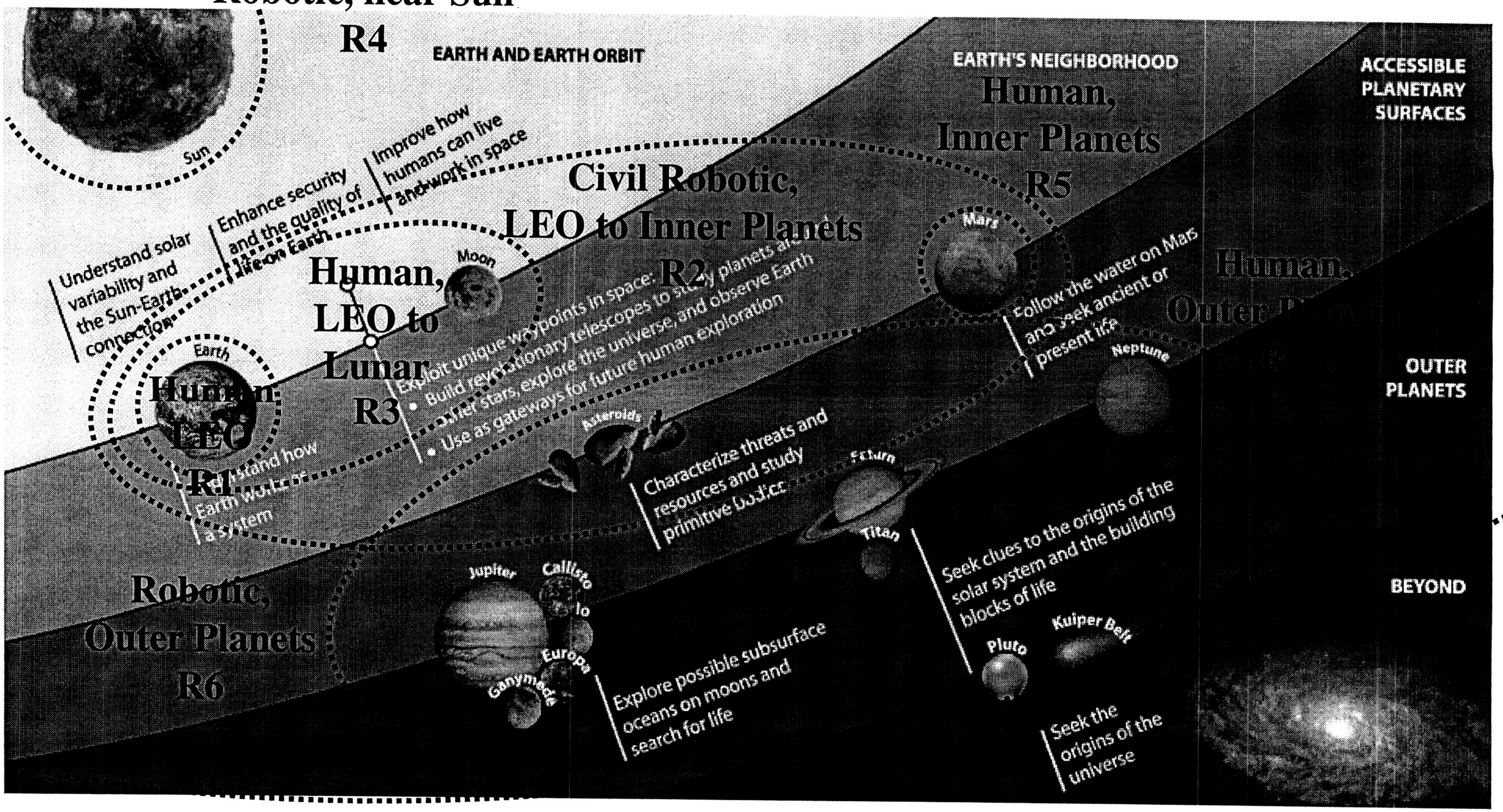
Mission Options

Robotic, near Sun
R4

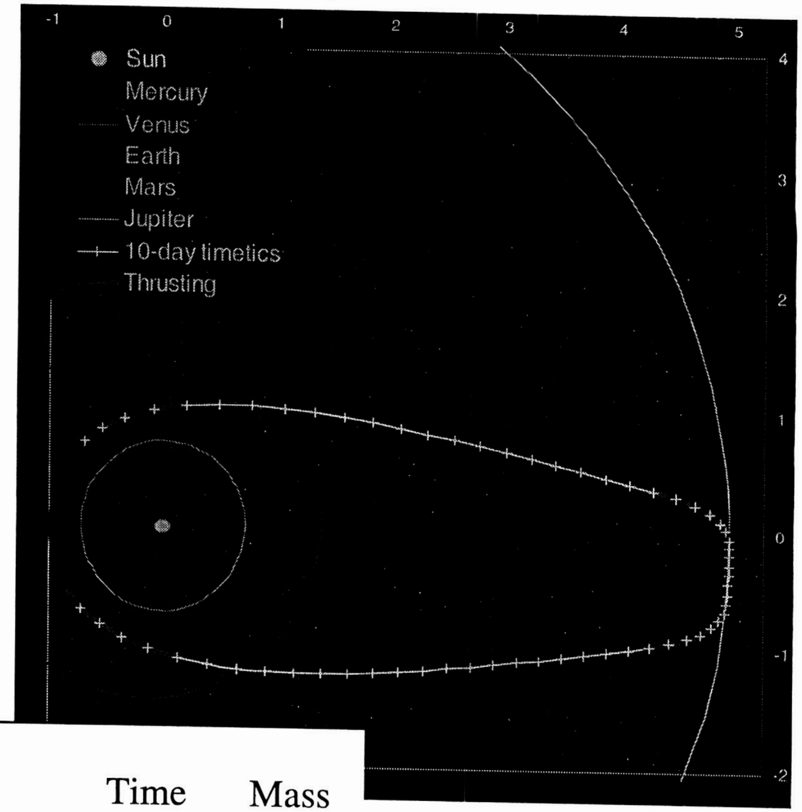


Robotic, Beyond Planets
R8

Fusion propulsion holds the promise of enabling human exploration beyond the inner planets and enhancing all other human/robotic missions outside Lunar orbit

Example Mission – RASC '02 Study

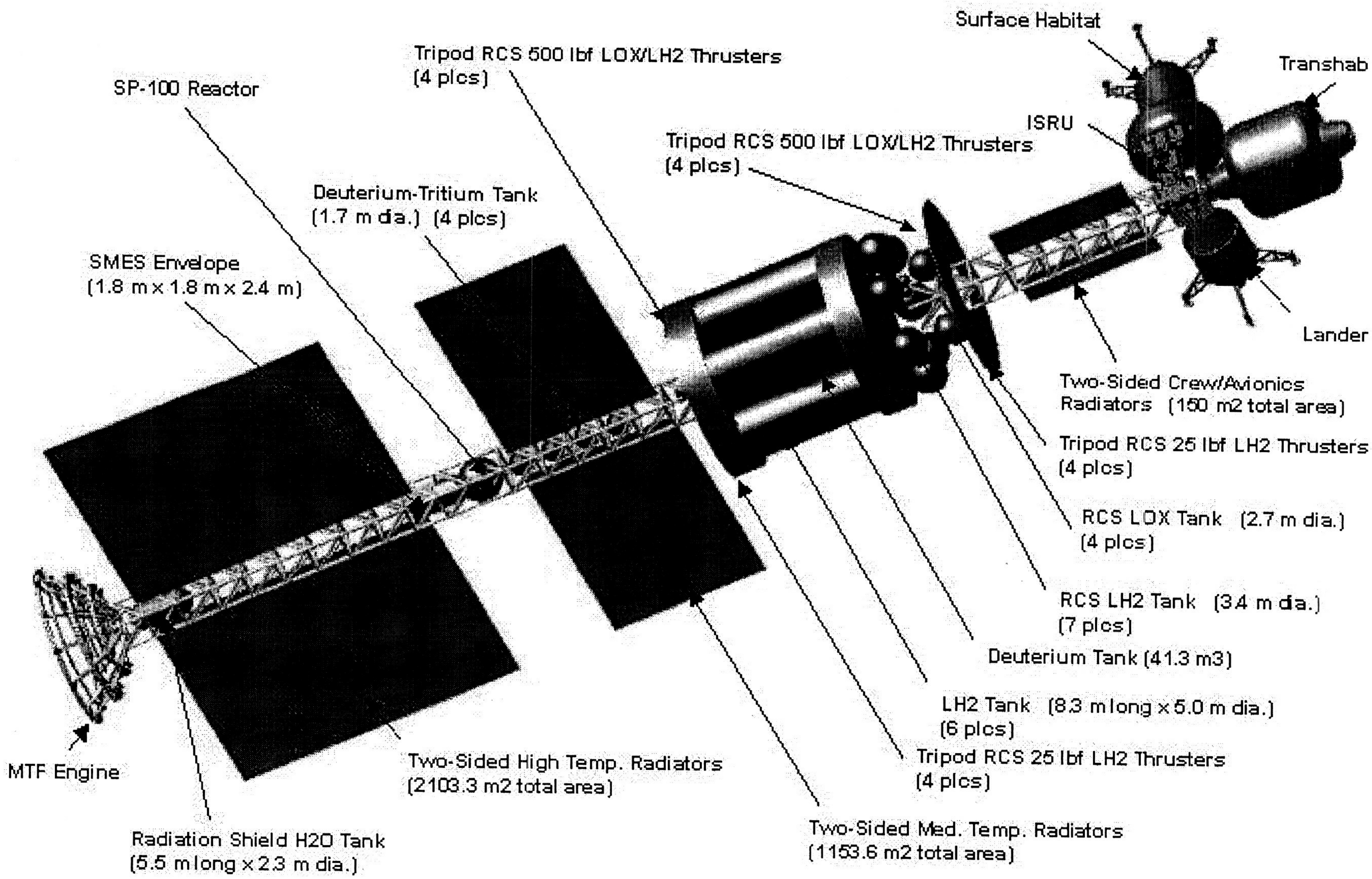
- Start from base at Earth-Moon L1 point
- Assume flight after 2040
- Travel to Callisto and back
- 30 day surface stay minimum
- Carry, Transhab, lander, surface habitat, ISRU



Total Mission Duration ~ 654 days
Outbound Leg Departs 4/22/2045
Flight to Callisto ~ 331 days
Time in Callisto Orbit ~ 33 days
Total time thrusting ~ 258 days
Returns without Surface Habitat, ISRU, and Transport (120 mt total)
Isp = 70,400 sec
Jet Power = 1.072 GW
Propulsion System Specific Mass = 0.122 kg/kW
Initial Acceleration = 0.0005 g's
Final Acceleration = 0.0007 g's

Mission Timeline	Time (days)	Mass (mT)
Depart L1 Station	0	650
Thrust off	51	630
Thrust on	240	630
Arrive Callisto Orbit	331	595
Depart Callisto Orbit	365	475
Thrust off	440	445
Thrust on	614	445
Arrive L1 Station	654	430

Example Mission – RASC '02 Study



R. B. Adams, R. Alexander, J. Chapman, S. Fincher, R. Hopkins, A. Philips, T. Polsgrove, R. Litchford, B. Patton, G. Statham, S. White, Y. C. F. Thio, "Conceptual Design of In-Space Vehicles for Human Exploration of the Outer Planets", NASA TP-2003-212691. Fall 2003.

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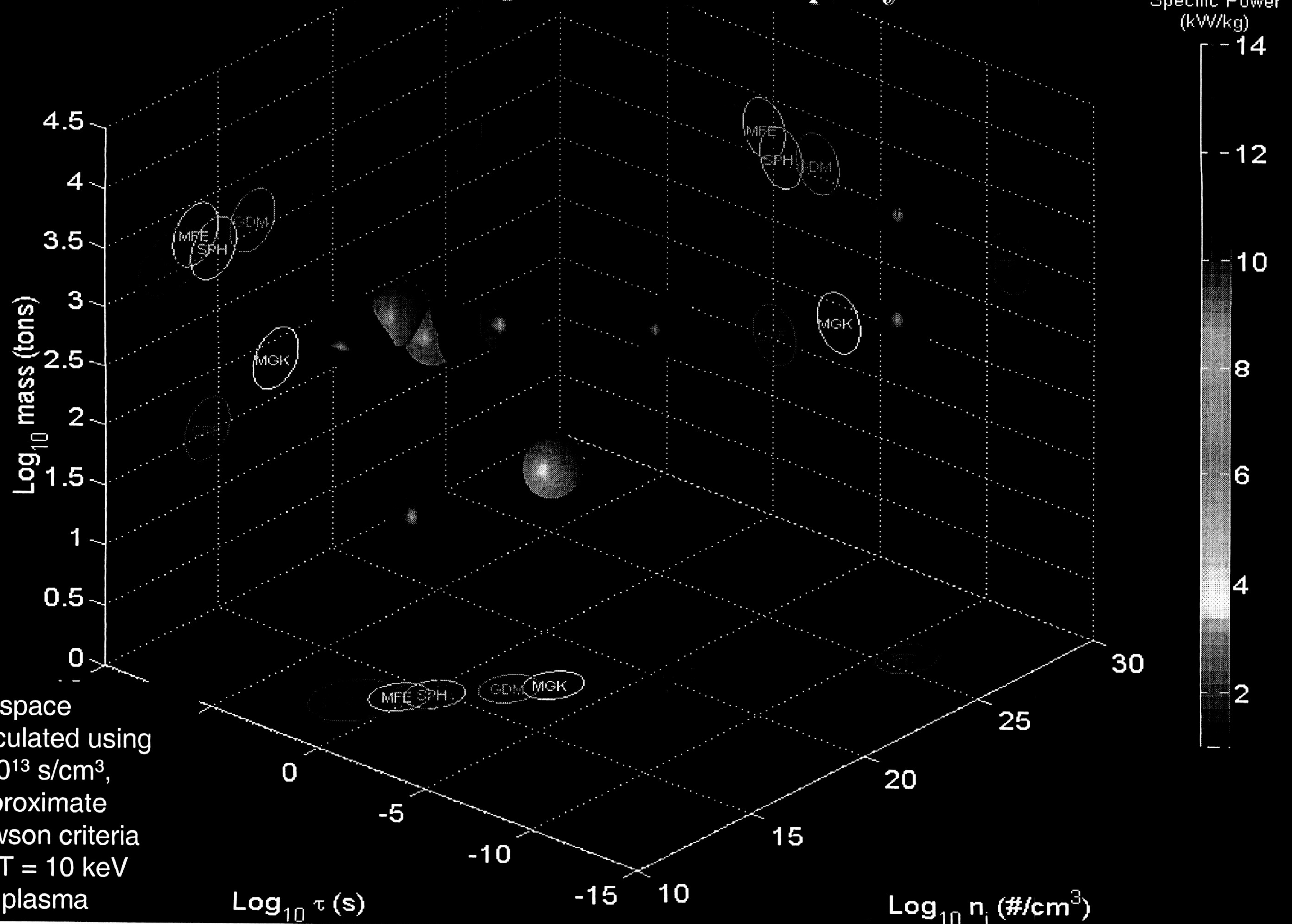
Fusion Technology Trade Space

- Next chart maps technologies of interest to density vs. temperature of confinement plasma
- Charts on each technology are in the appendix
  - Pulsed
    - Magnetized-Target Fusion (MTF)
    - Magnetokinetic-Compression Fusion
    - Fast-Ignitor Inertial Fusion Energy
  - Steady-State
    - Field-Reversed Configuration (FRC)
    - Dipole
    - Spherical Torus (ST)
    - Gas-Dynamic Trap (GDT)
    - IEC (POPS, Polywell®)

Fusion Technology Trade Space

Concept	Alpha (kW/kg)	n (1/m3)	Freq (Hz)	Mass (mT)	Source
Steady State					
Quiet Electric Discharge (QED)	12	n/a	n/a	500	Fusion Energy in Space Propulsion, AIAA 1995
Inertial Electrostatic Confinement (IEC)	0.02	n/a	n/a	300	Fusion Energy in Space Propulsion, AIAA 1995
Gas Dynamic Mirror (GDM)	10	$1.0 \cdot 10^{22}$	n/a	1225	STAIF 2000 p1420-1424
Tandem Mirror (SOAR)	1.2	$5.0 \cdot 10^{19}$	n/a	1220	UWFDM-753
Spheromak	5.75	$8.0 \cdot 10^{20}$	n/a	1050	AIAA 87-1814
Field Reversed Configuration (FRC)	1	$1.0 \cdot 10^{21}$	n/a	1100	Proc. 11th Symp. Space nuclear Power and Space Prop. Sys. 1994.
Colliding Beam FRC	1.5	$5.0 \cdot 10^{20}$	n/a	33	STAIF 2004, p354-361
Dipole	1	$1.0 \cdot 10^{19}$	n/a	1300	Fus. Tech. 22, 82, 1982
Spherical Torus	8.7	$5.0 \cdot 10^{20}$	n/a	1630	Fusion S&T 43(1) p99-109, Jan 03
Pulsed					
Inertial Fusion Rocket (IFR)	70	$1.0 \cdot 10^{25}$	100	760	AIF 83-896
Inertial Confinement Fusion (ICF)	3.4	$1.0 \cdot 10^{25}$	30	5800	URCL-96676
Magnetized Target Fusion (MTF)	1.12	$1.0 \cdot 10^{26}$	20	890	NASA TP-2003-212691
Magneto-Kinetic Expansion (MKE)	2.2	$1.0 \cdot 10^{24}$	10	67	AIAA 2000-3364

Fusion Propulsion Regimes in Density, Confinement Time, Engine Mass, and Specific Power



$n\tau$ space calculated using $3{\cdot}10^{13}$ s/cm^3, approximate Lawson criteria for T = 10 keV DT plasma

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Proposed Outline for Future Efforts

- Definition of actual funding levels were discussed but were considered premature at this time
- However, to sustain a research program funding levels for the next few years are expected to be in the 2-10 million dollar range
- Initial objectives should include
  - Deeper research into DOE efforts and how they can be adapted for NASA's purposes
  - Research announcements soliciting ideas for developing benchmark experiments
  - Periodic workshops with fusion community to create fusion propulsion system development roadmap, review of research developments
  - Development/enhancement of analytical codes to further system design and development
  - Emphasis on coordinating code and experimental work to be broadly applicable to the wide range of fusion propulsion concepts
  - Coordinate efforts with common technology requirements for other propulsion systems (NTP, NEP, etc.)

Backup Slides

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Fusion Propellant Options

- There are several propellant options available
- Each require different confinement conditions
- Each offer advantages in confinement requirements, neutron by-products, availability of propellants, etc.

IS THIS IN THE LITERATURE

$$D+D \xrightarrow{50\%} T(1.01)+p(3.02)$$
$$\xrightarrow{50\%} He^3(0.82)+n(2.45)$$
$$D+T \xrightarrow{100\%} He^4(3.5)+n(14.1)$$
$$D+He^3 \xrightarrow{100\%} He^4(3.6)+p(14.7)$$
$$T+T \xrightarrow{100\%} He^4+2n+11.3$$
$$He^3+T \xrightarrow{51\%} He^4+p+n+12.1$$
$$\xrightarrow{43\%} He^4(4.8)+D(9.5)$$
$$\xrightarrow{6\%} He^3(2.4)+D(11.9)$$
$$p+Li^6 \xrightarrow{100\%} He^4(1.7)+He^3(2.3)$$
$$p+Li^7 \xrightarrow{\sim 20\%} 2He^4+17.3$$
$$\xrightarrow{\sim 80\%} Be^3+n-1.6$$
$$D+Li^6 \xrightarrow{100\%} 3He^4+22.4$$
$$p+B^{11} \xrightarrow{100\%} 3He^4+8.7$$
$$n+Li^6 \xrightarrow{100\%} T+He^4+4.8$$
$$n+Li^7 \xrightarrow{100\%} T+He^4-2.5$$

Explanation for Higher Specific Impulse for Fusion vs. NEP

- *Higher energy release per unit mass enables higher internal propellant energies which corresponds to higher exhaust velocities*
- *Apart from mass annihilation, some fusion reactions of the light elements give highest energy release per unit mass*

Fuels	Energy Release *J/kg*	Converted mass fraction $\alpha=\Delta m/m_i$
LO_2+LH_2	$1.35\cdot10^{7}$	$1.5\cdot10^{-10}$
U^{233},U^{235},Pu^{239}	$8.2\cdot10^{13}$	$9.1\cdot10^{-4}$
D+T	$3.4\cdot10^{14}$	$3.8\cdot10^{-3}$
$D+He^3$	$3.5\cdot10^{14}$	$3.9\cdot10^{-3}$
p^++B^{11}	$7.3\cdot10^{13}$	$8.1\cdot10^{-4}$
p^++p^-	$9.0\cdot10^{16}$	1.0

[1] Kammash, Terry, "Principles of Fusion Energy Utilization in Space Propulsion", in *Fusion Energy in Space Propulsion*, edited by Terry Kammash, AIAA, Washington DC, 1995.

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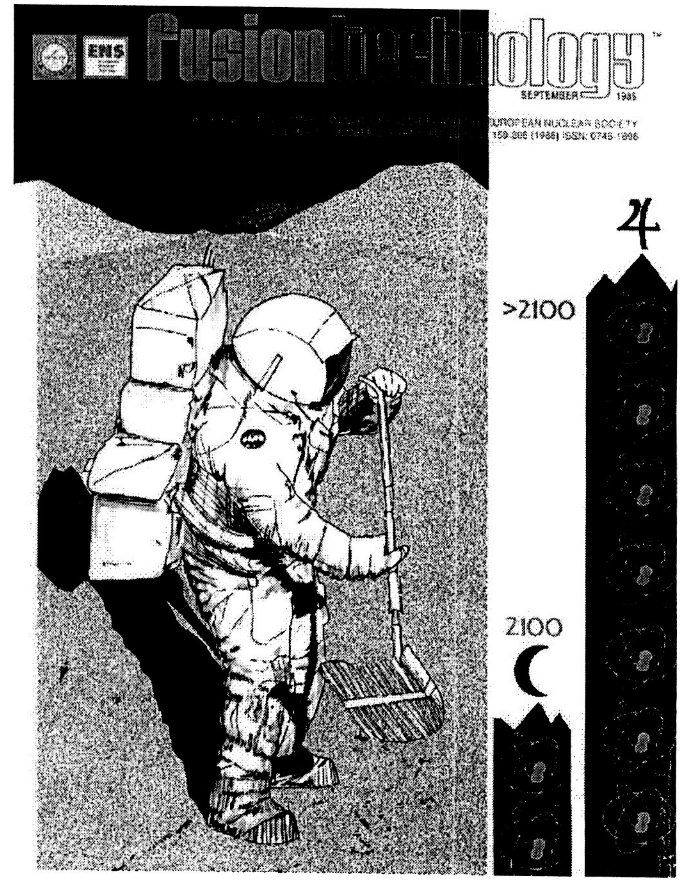
Appendix A – Justification for Mining Lunar Regolith

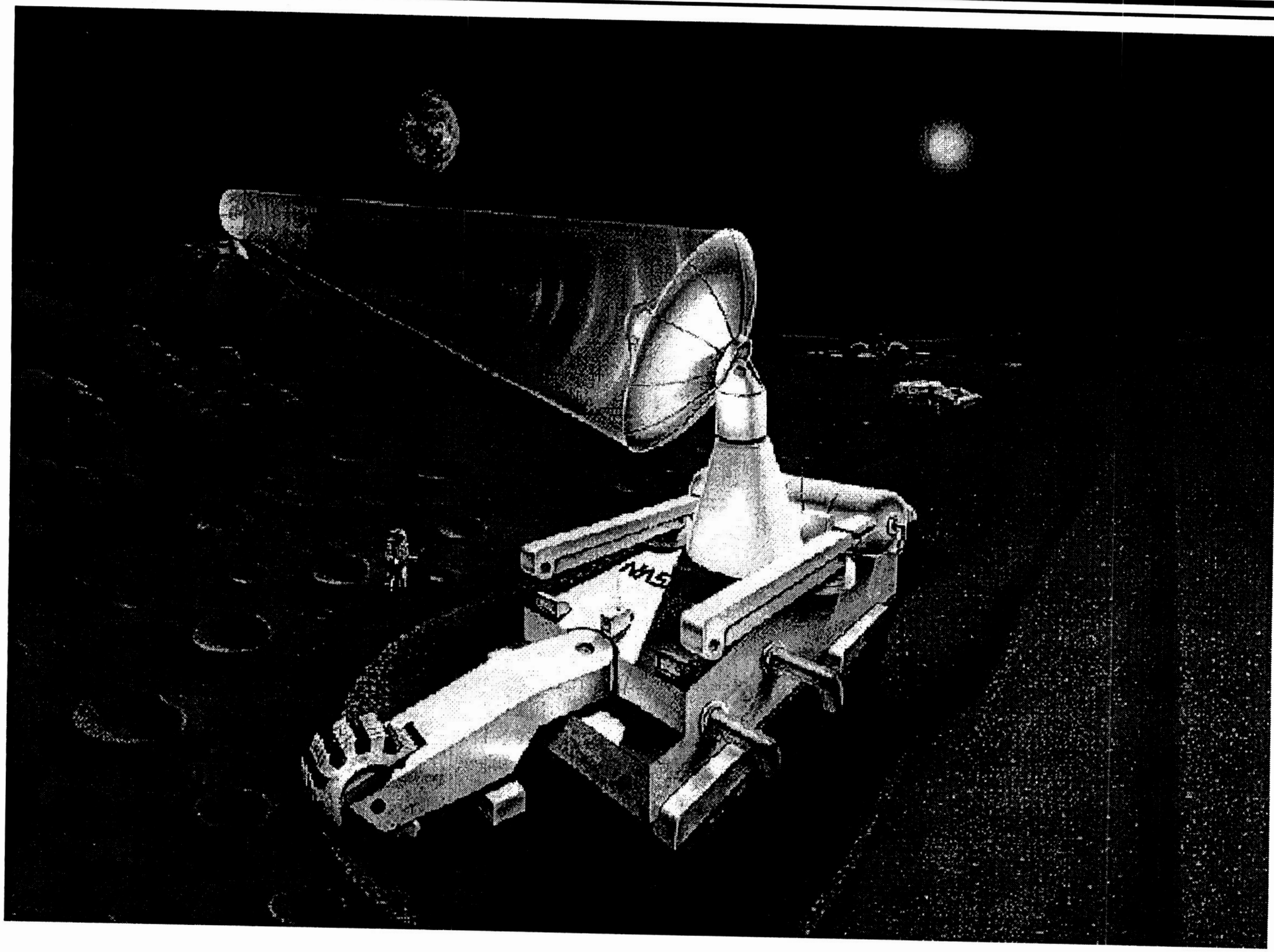
A Well Documented Lunar ^3He Resource Exists

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

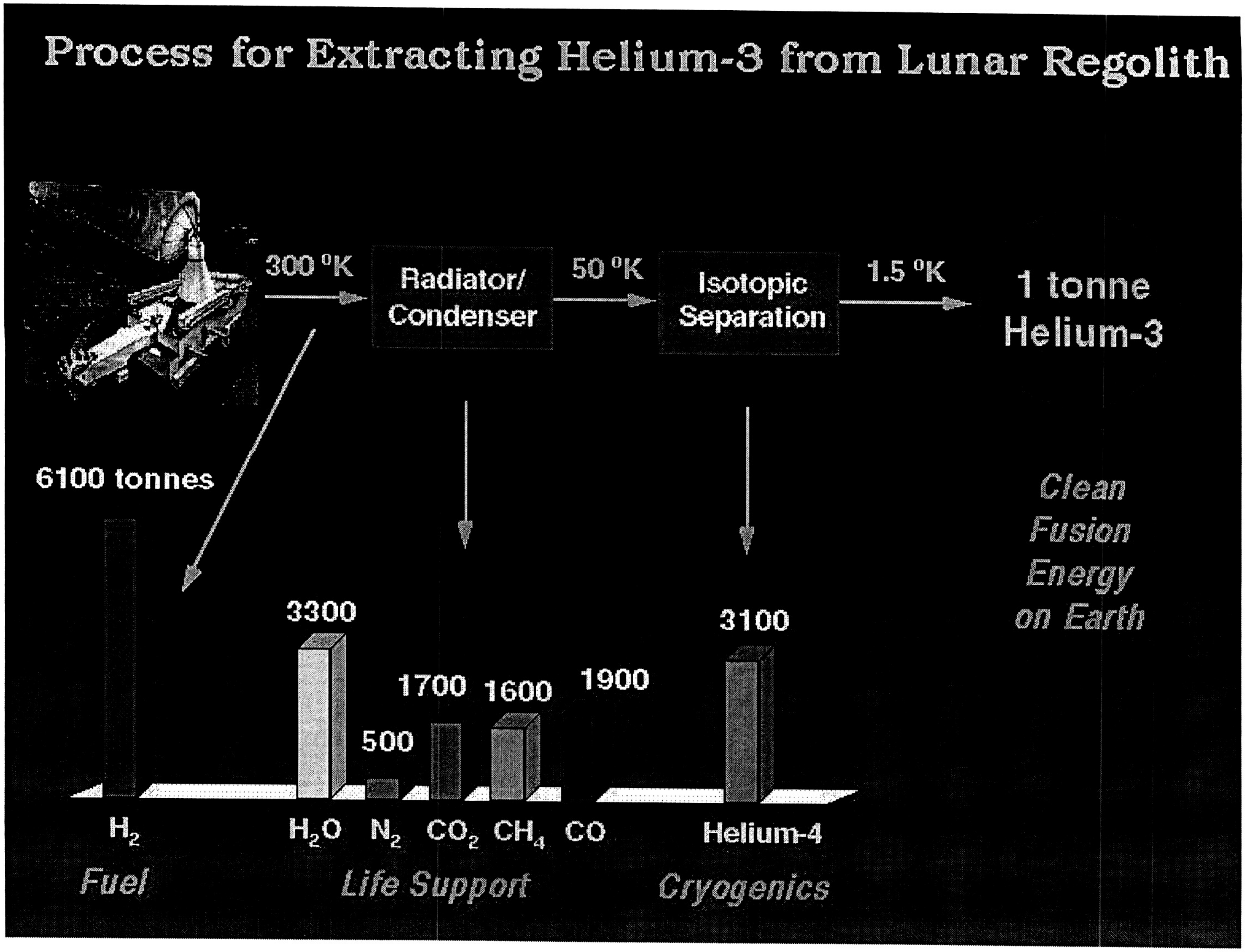


L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^3He for Commercial Fusion Power," *Fusion Technology* **10**, 167 (1986).

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

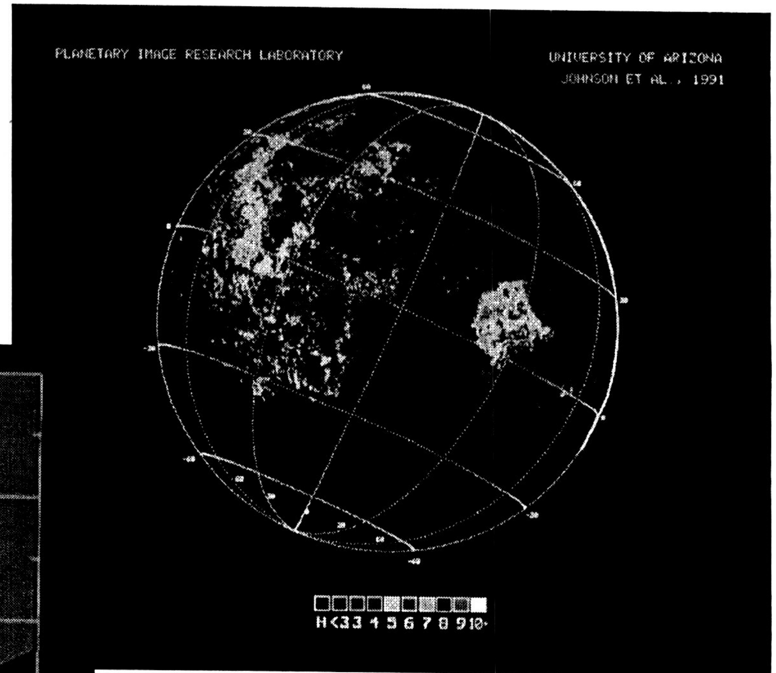


Lunar ^3He Mining Produces Other Useful Volatiles

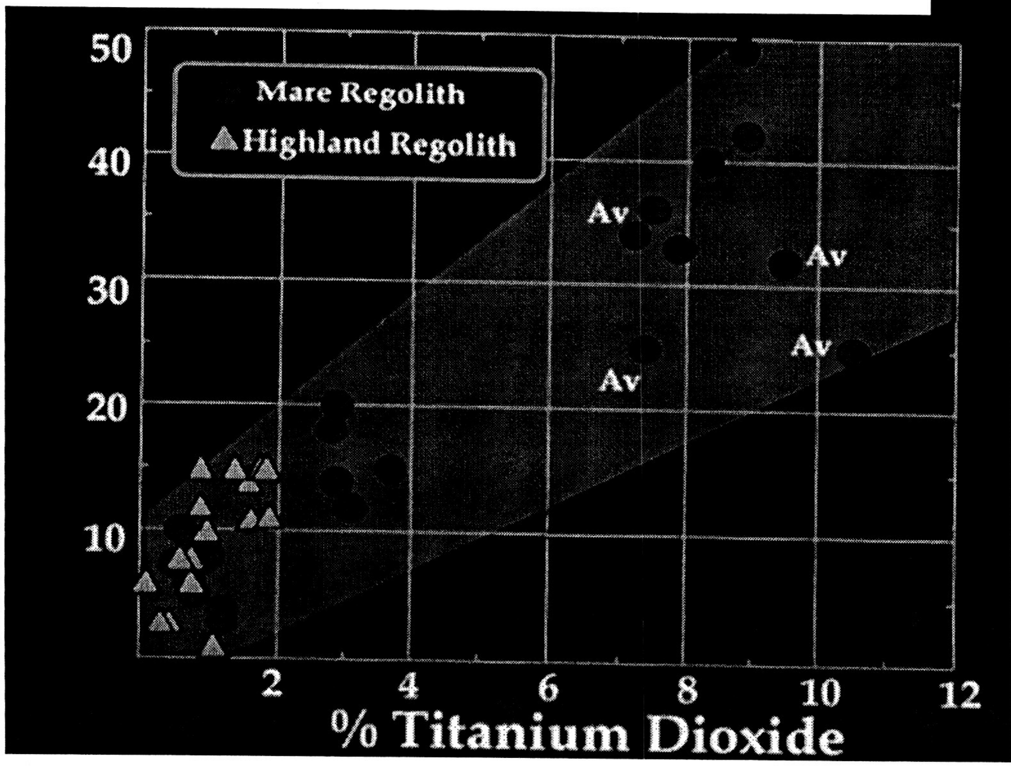


Helium Content Correlates Well with Ti Content, Indicating Locations of Lunar He Concentrations

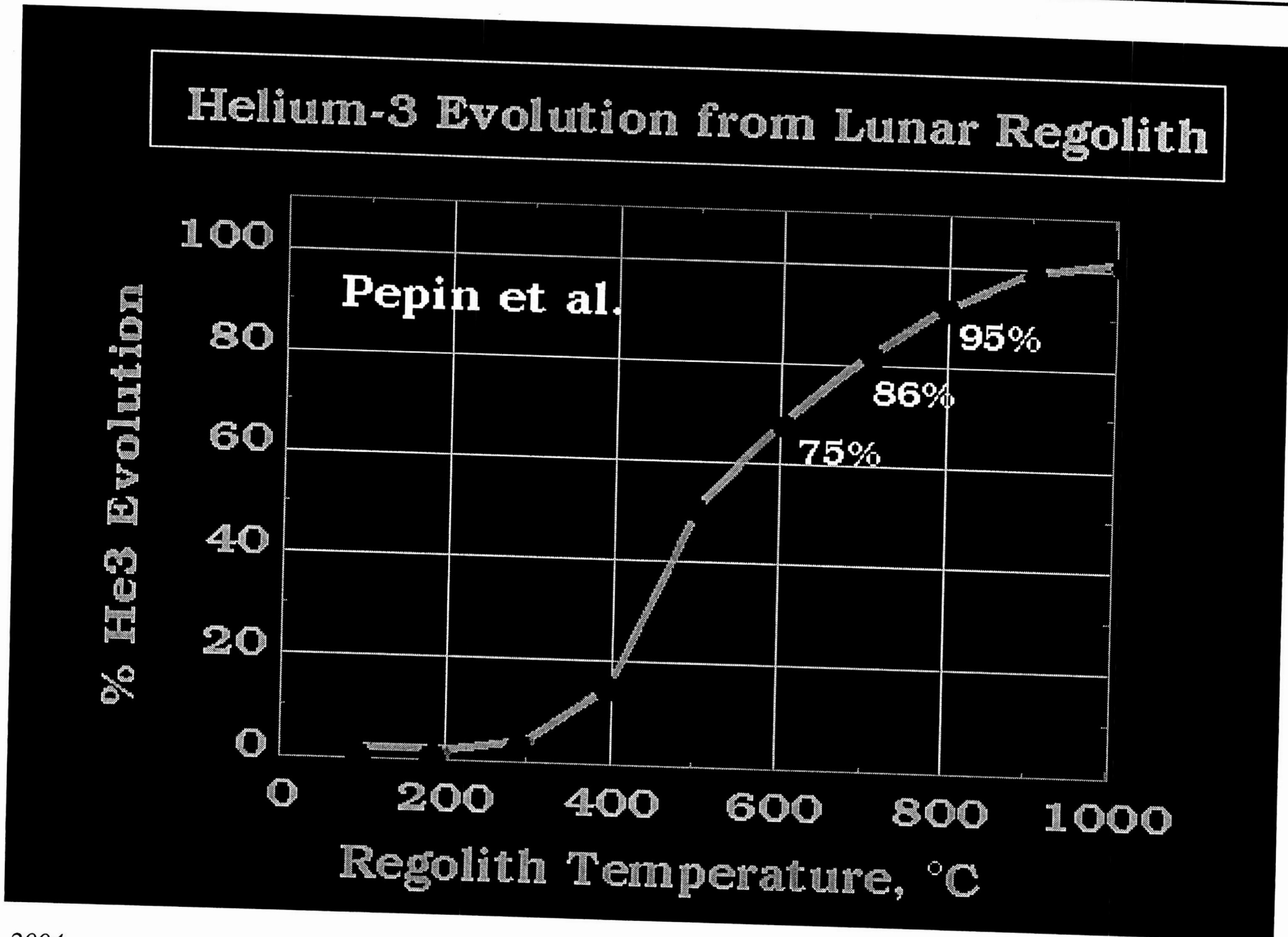
Spectral reflectance map of lunar Ti content



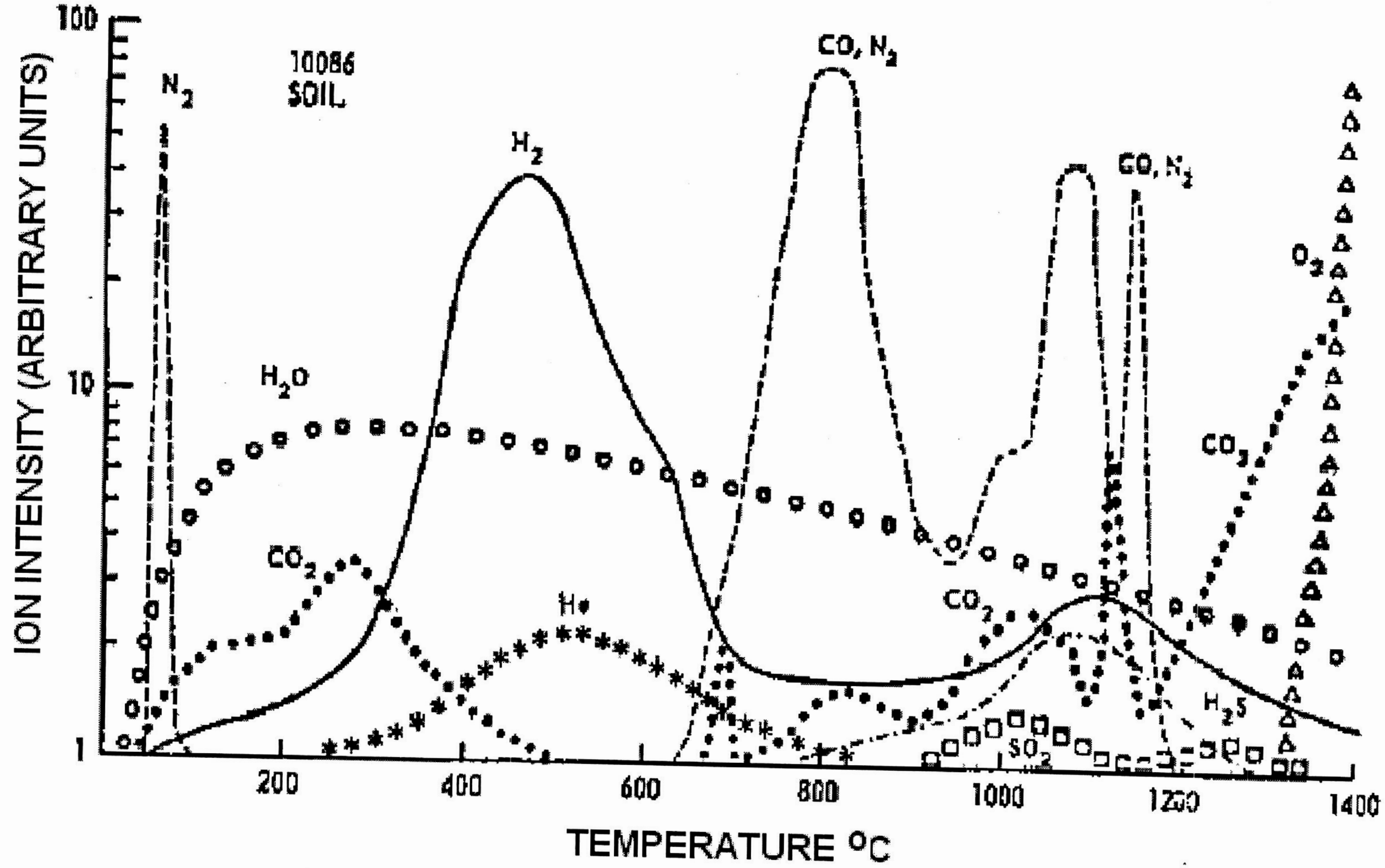
Measured correlation of He and Ti contents



^3He Evolves When Heating Lunar Regolith



Useful Volatiles Evolve When Heating Lunar Regolith

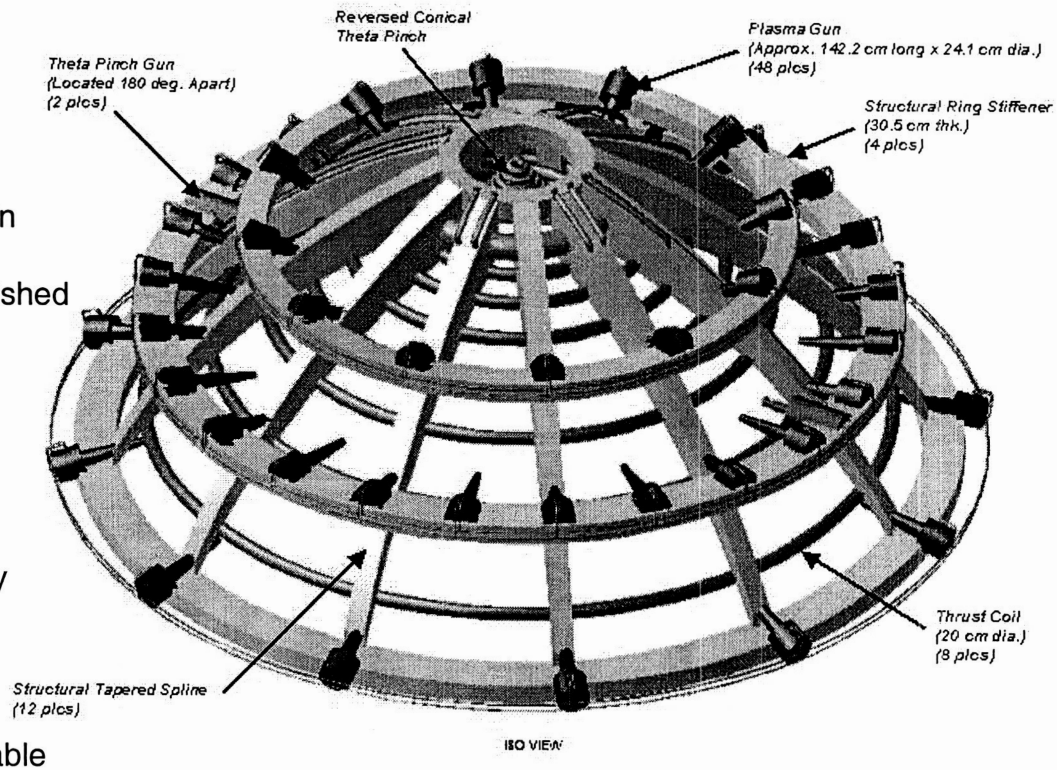


Gibson and Johnson, *Proc. 2nd Lunar Science Conf.* **2**, 1351 (1971)

Backup Charts on Various Fusion Concepts

Magnetized Target Fusion (MTF)

- **Projected performance**
  - Specific power: 10 kW/kg to 100 kW/kg
  - Specific impulse: 50,000 s to 100,000 s
- **Maturity/Feasibility**
  - TRL: 1-2 (Physics principles demonstrated in Sandia ϕ-θ experiment; target formation demonstrated, theoretical foundation established by Kirkpatrick, Thio, etc.)
  - Experiments in progress: (1) LANL MTF experiment funded by DOE at Concept Exploration level. (2) MTF plasma liner experiment at MSFC.
  - Planned experiments: (1) Demonstration of fusion Q > 1 for electrical power by LANL by 2010.
- **Operability**
  - Fuel: D (1st-gen). D + He3 (2nd-gen)
  - Ability to Throttle: Power: continuously variable from 0 to max by varying pulse rate
  - Isp: continuously variable from 5000 s to max by mixing inert propellant (e.g. H, Li) with fusion plasma
  - By-products: He4; neutrons
  - Radiation: electromagnetic waves; neutrons (may be moderated by fusion plasma and shielded)

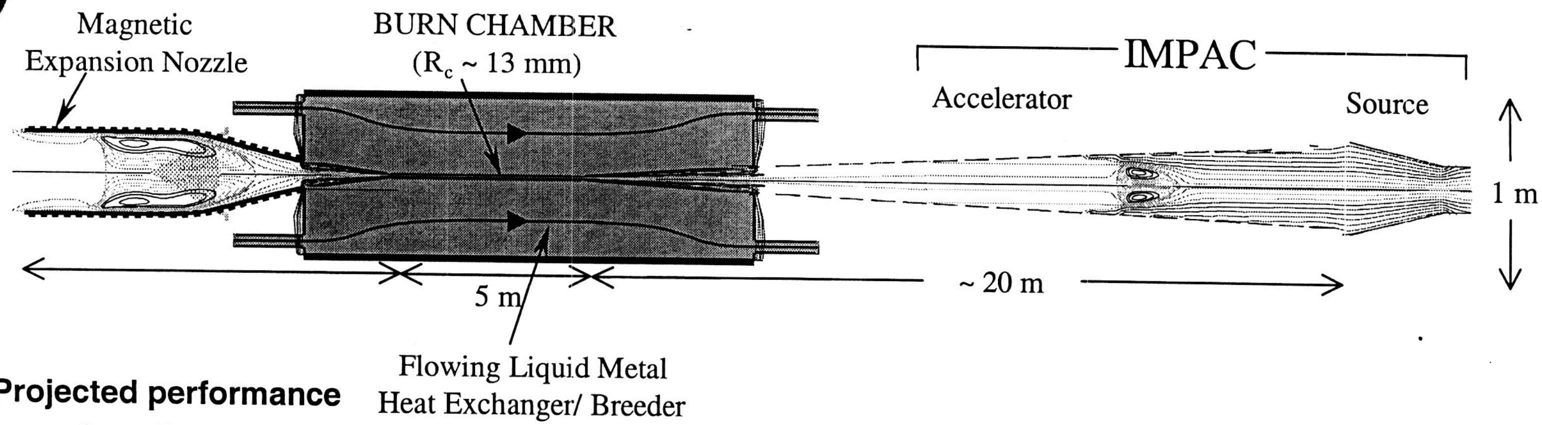


[1] Siemon, R. E., Lindemuth, I. R., Schoenberg, K. F., "Why Magnetized Target Fusion Offers a Low-Cost Development Path for Fusion Energy," *Comments on Plasma Physics and Controlled Fusion,* 18, p. 363, 1999.

[2] Thio, Y. C. F., et al. "Magnetized Target Fusion in a Spheroidal Geometry with Standoff Drivers," *Current Trends in Fusion Research, Proc. of the 2nd Symposium,* Canada NRC, Ottawa, Canada, 1999.

[3] Y. C. F. Thio, et. al., *"High-Energy Space Propulsion based upon Magnetized Target Fusion," AIAA 99-2703, 35th AIAA Joint Propulsion Conference, Los Angeles, CA, 20-24 June 1999.*

Magnetokinetic Compression of FRC Fusion Rocket



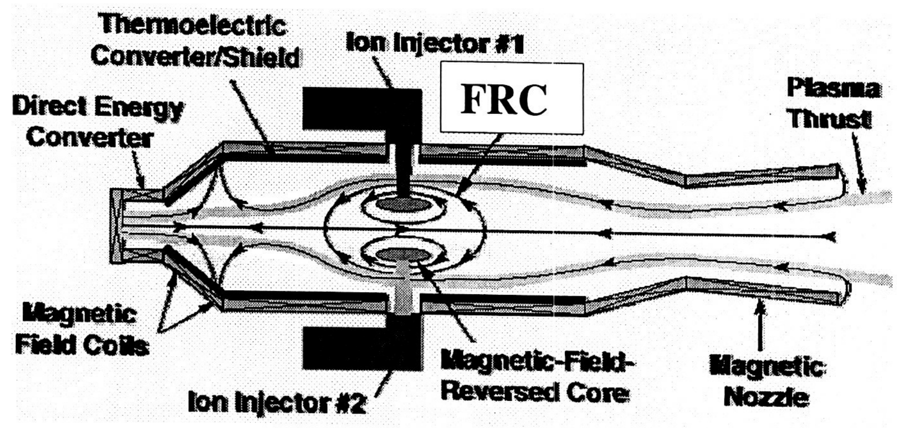
- **Projected performance**
  - Specific power: 5 kW/kg to 15 kW/kg
  - Specific impulse: 50,000 s to 100,000 s
- **Maturity/Feasibility**
  - TRL: 1 (Scaling laws for FRC stability established; Acceleration of FRC demonstrated to 250 km/s.)
  - Critical mass of propulsion vehicle: 20 Tonnes
  - Experiments in progress: (1) FRC acceleration at MSFC. (2) RMF experiment at UW, Seattle.
  - Planned experiments: Demonstration of fusion Q > 1 for propulsion by MSFC by 2012.
- **Operability**
  - Fuel: D + T (1^{st}-gen). D + He^3 (2^{nd}-gen)
  - Throttability:
  - Power: continuously variable from 0 to max.
  - Isp: continuously variable from 10,000 s to max.
  - By-products: He^4; neutrons
  - Radiation: electromagnetic waves; neutrons (may be shielded)

[1] J. T. Slough, "Propulsion based on a pulsed high density plasmoid fusion," AIAA 2000-3364, Joint Propulsion Conference, Huntsville, AL, July 2000.

[2] A.L. Hoffman, J.T. Slough, "*FRC Lifetime Scaling Based on Measurements from the Large s Experiment (LSX)*", Nuclear Fusion 33, 23 (1993).

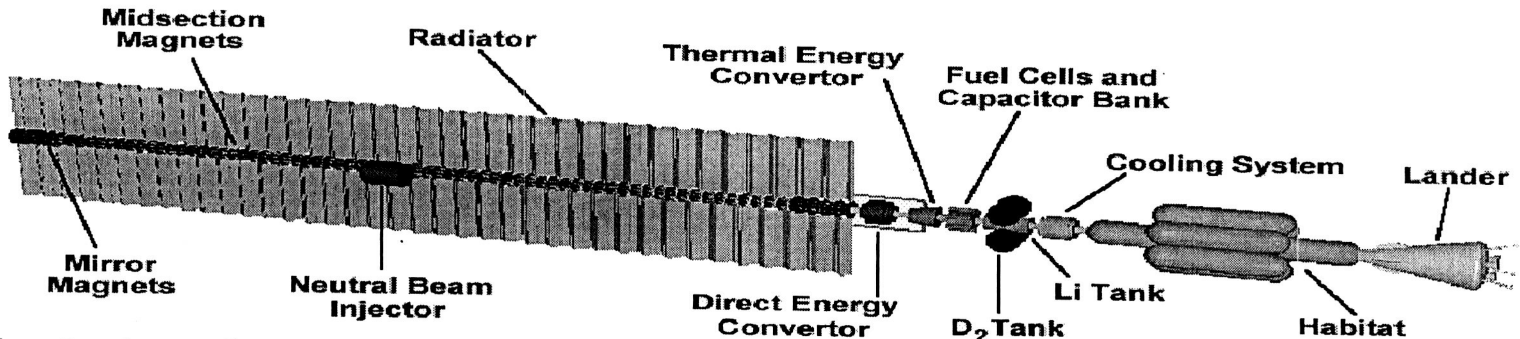
Steady-State or Quasi-Steady-State FRC Fusion Rocket

- **Projected performance**
  - Specific power: 2 kW/kg to 15 kW/kg
  - Specific impulse: 50,000 s to 200,000 s
- **Maturity/Feasibility**
  - TRL: 1-2 (Plasma temperature in excess of 300 eV for more than 10 ms demonstrated experimentally. Extensive physics database of FRC established.)
  - Critical mass of propulsion vehicle: 1000 Tonnes
  - Experiments in progress: DOE OFES funded at the level of Concept Exploration (CE) at U. Washington-Seattle and U. Wisconsin-Madison.
  - Planned experiments: Proof-of-Principle (Q ~ 0.1) experiment to follow upon successful completion of present CE experiment by DOE.
- **Operability**
  - Fuel: D + T in 1:1 mixture.
  - Throttability:
  - Power: fixed.
  - Isp: continuously variable from 50,000 s to max.
  - By-products: He^4; neutrons
  - Radiation: electromagnetic waves; neutrons (may be shielded).

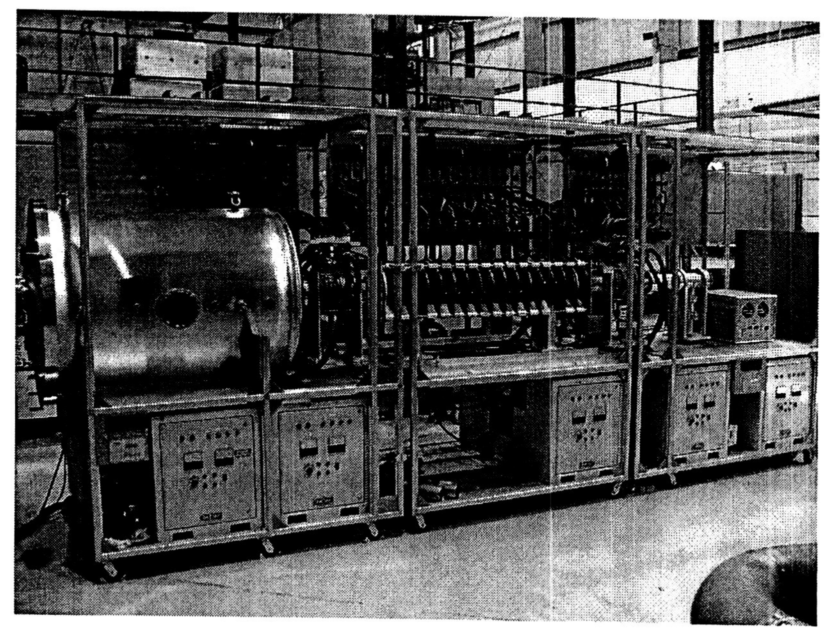


[1] A.L. Hoffman, J.T. Slough, "*FRC Lifetime Scaling Based on Measurements from the Large s Experiment (LSX)*", Nuclear Fusion 33, 23 (1993).

Gasdynamic Trap (GDT) Fusion Rocket



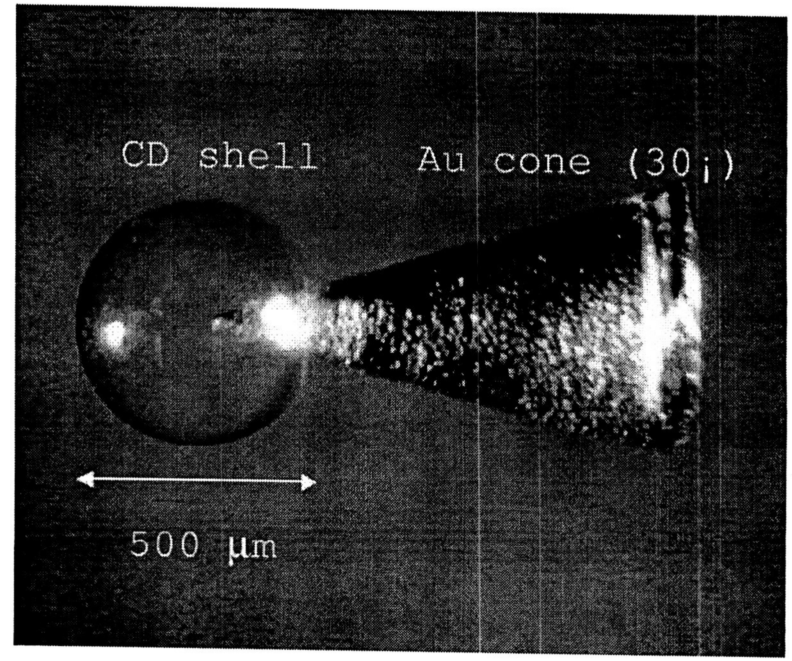
- **Projected performance**
  - Specific power: 5 kW/kg to 14 kW/kg
  - Specific impulse: 50,000 s to 200,000 s
- **Maturity/Feasibility**
  - TRL: 2 (Gasdynamic trapping of plasmas demonstrated in Novosibirst; Plasma temperature > 100 eV.)
  - Critical mass of propulsion vehicle: 1225 Tonnes
  - Experiments in progress: (1) Plasma stability exploration in low-temperature range (10 eV). (2) Plasma injection experiment. Both at MSFC.
  - Planned experiments: no continuation of the above experiments planned.
- **Operability**
  - Fuel: D + T in 1:1 mixture.
  - Throttability:
  - Power: fixed.
  - Isp: continuously variable from 50,000 s to max.
  - By-products: He^4; neutrons
  - Radiation: electromagnetic waves; neutrons (may be shielded)



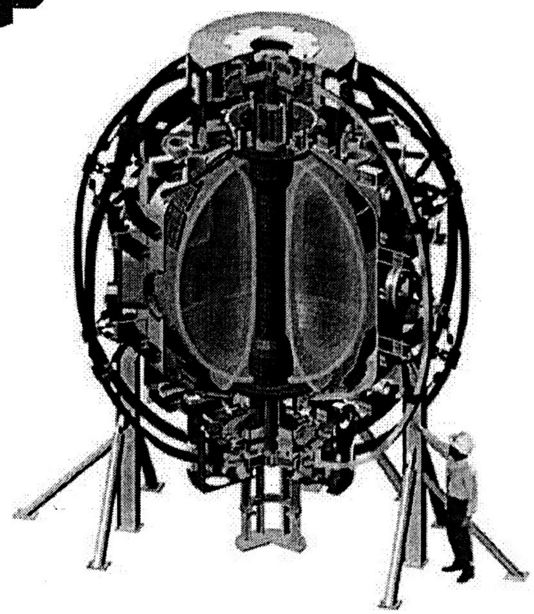
[1] Kammash, T. and Emrich, W., "Interplanetary Missions with the GDM Propulsion System," *STAIF-98*, pages 1145-1150, (1998).
[2] Emrich, W. and Kammash, T., "Performance Optimization of the Gasdynamic Mirror Propulsion System," *STAIF-00*, pages 1420-1424, (2000).
[3] Bagryanskij, P. A., Ivanov, A. A., Klesov, V. V., *et al.*, "First Experiments on the Gasdynamic Trap," Nuclear Fusion Supplement, Vol. 3, pages 467-476, (1987).

Fast Ignition Inertial Confinement Fusion

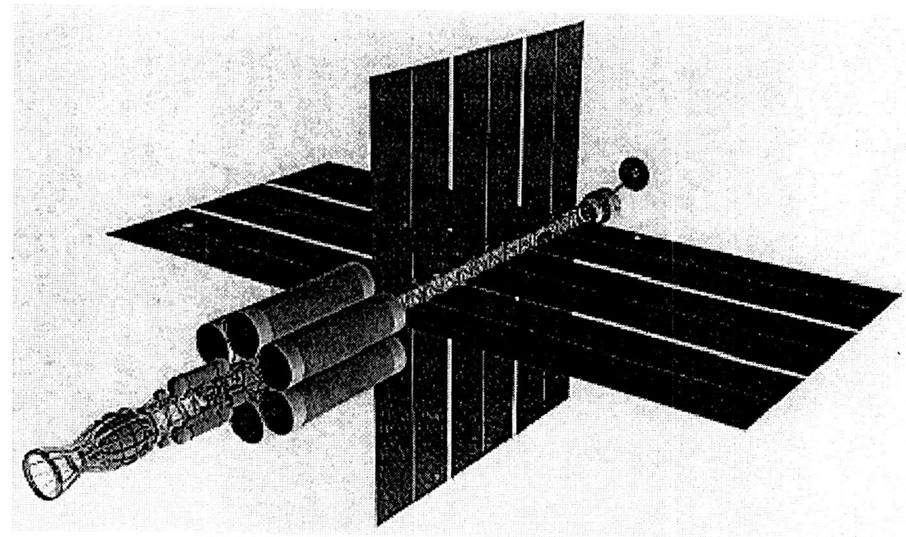
- **Summary**
  - 3 Laser pulses
    1. High energy compression
    2. Hole boring 2nd prepulse
    3. Fast ignitor pulse
  - Au cone used to guide pulse
  - Ignitor intensity 10^{18} to 10^{20} W/cm^2
  - Last pulse raises electron temperature to several MeV to ignite the core
  - 800 eV ion temperatures have been measured
- **Projected performance**
  - Gain: 100



Spherical Torus



NSTX Experiment



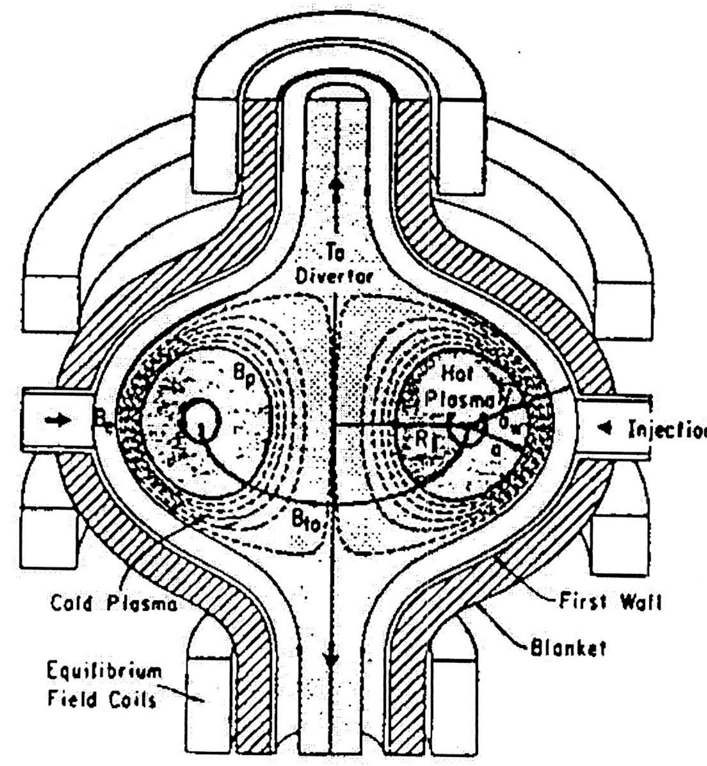
Conceptual Space Vehicle Using a Spherical Torus

- Experiment currently underway at Princeton (NSTX Experiment)
- Spherical torus produces a plasma that is shaped like a sphere with a hole through its center
- High betas possible with spherical torus could allow the development of smaller and lighter systems (relative to the tokamak)
- Use in a propulsion system would require a fairly complex divertor system

The Spheromak Was Chosen for an Early Fusion Rocket Design

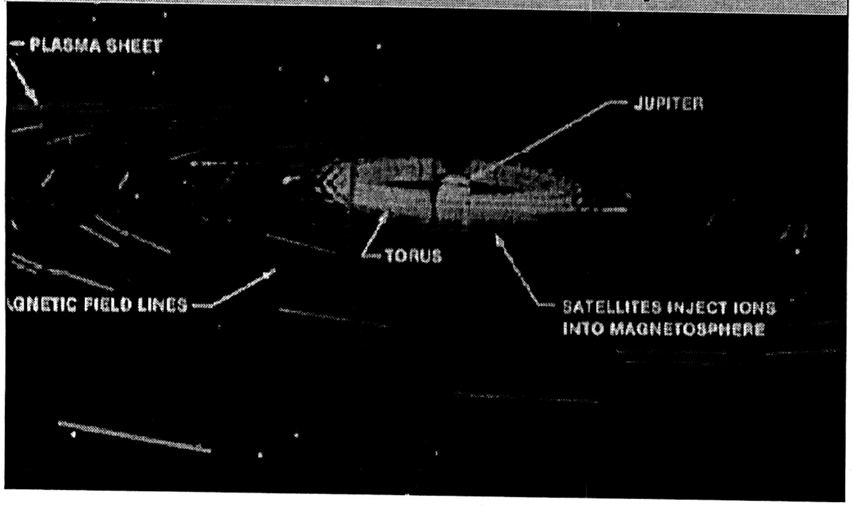
- Key design by Borowski, 1987.
- High $\beta \equiv P_{plasma}/P_{B\text{-field}}$
- Linear external B field.
- Cylindrical geometry.
- Plasma confinement is a critical issue.

Spheromak main elements

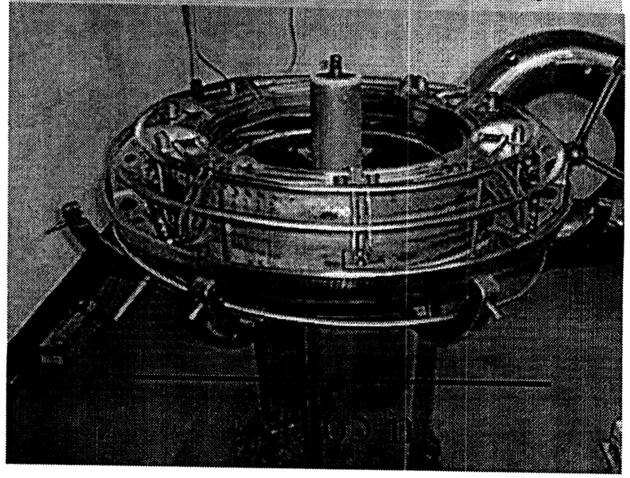


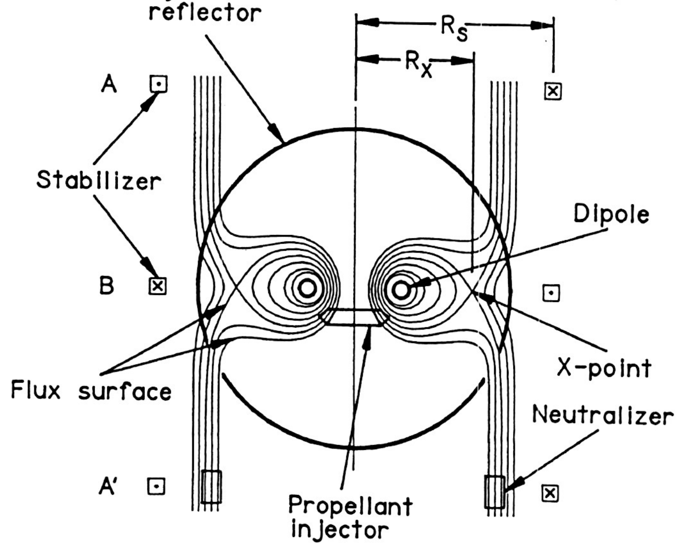
The Dipole Configuration Offers a Relatively Simple Design That an MIT/Columbia Team Has Begun Testing

Io plasma torus around Jupiter



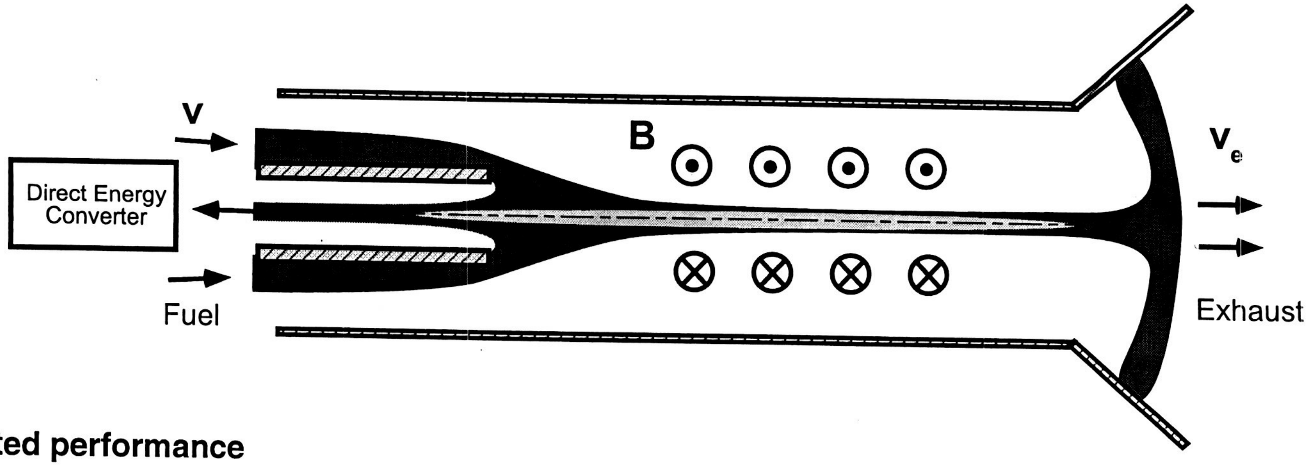
LDX experiment (MIT)





Dipole space propulsion design:
E. Teller, et al., *Fusion Technology* **22**, 82 (1992).

Flow Z-Pinch Fusion Rocket



- **Projected performance**
  - Specific power: 10 kW/kg (short-pulsed); 100 kW/kg (long-pulsed) [No external field coils]
  - Specific impulse: 130,000 s to 350,000 s
- **Maturity/Feasibility**
  - TRL: 1 (Stable Z-pinch observed for over 2000 exponential growth times; Mechanism for long-pulsed operation. High plasma density, 10^{23} m^{-3}, and plasma temperature, 200 eV)
  - Critical mass of propulsion vehicle: ~10 Tonnes
  - Experiments in progress: DOE OFES funded at level of Concept Exploration, ZaP Flow Z-Pinch experiment at Univ Washington, Seattle.
  - Planned experiments: Demonstration of increased plasma compression and long-pulsed operation.
- **Operability**
  - Fuel: D + T (1^{st}-gen); D + He^3 (2^{nd}-gen); p + B^{11} (3^{rd}-gen)
  - Throttability: variable duty cycle
  - Power: continuously variable from 0 to max.
  - Isp: continuously variable from 10,000 s to max.
  - By-products: He^4; neutrons (1^{st}-gen)
  - Radiation: electromagnetic waves; neutrons (may be shielded or radiated since no coils around plasma)

[1] U. Shumlak, *et al.*, "A Flow-Stabilized Z-Pinch Fusion Space Thruster," AIAA 2003-4826, Joint Propulsion Conference, Huntsville, AL, July 2003.
[2] U. Shumlak, *et al.*, "Sheared flow stabilization experiments in the ZaP flow Z pinch," Physics of Plasmas **10**, 1683 (2003).

The Need for Fusion Propulsion

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Fusion propulsion is inevitable if the human race remains dedicated to exploration of the solar system. There are fundamental reasons why fusion surpasses more traditional approaches to routine crewed missions to Mars, crewed missions to the outer planets, and deep space high speed robotic missions, assuming that reduced trip times, increased payloads, and higher available power are desired. A recent series of informal discussions were held among members from government, academia, and industry concerning fusion propulsion. We compiled a sufficient set of arguments for utilizing fusion in space. If the U.S. is to lead the effort and produce a working system in a reasonable amount of time, NASA must take the initiative, relying on, but not waiting for, DOE guidance. In this talk those arguments for fusion propulsion are presented, along with fusion enabled mission examples, fusion technology trade space, and a proposed outline for future efforts.

*Significant contributions to the material in the presentation have been provided by Rob Adams, Robert Chiroux, John Cole, Bill Emrich, Tom Jarboe, Ron Kirkpatrick, Irv Lindemuth, Adam Martin, Uri Shumlak, John Slough, Geoffrey Statham, Vince Teofilo, and Y. C. Francis Thio.