Manned Spacecraft Propulsion through Direct Conversion of Nuclear Energy

John Slough

MSNW LLC

16436 SE 39th Place

Bellevue, WA 98008



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Why We Are Not on Mars Yet?

Takes too long

Safety

- Radiation exposure
- Cancer risk
- Bone & muscle loss
- Mental fatigue
- Increased risk of critical failure

Political

- Governmental support
- Public interest

Costs too much

Mission

Operational costs:

- Complexity
- Asset Pre-deployment
- Space assembly

Launch

- Large space structures
- Huge fuel Mass

New method of propulsion is needed

Short trip time → High $\frac{\text{Engine Power}}{\text{Spacecraft Mass}}$ (α)

Reduced IMLEO → High Exit Velocity (I_{sp})

Trip Time for Direct Mission to Mars

Accelerating the space ship mass M_{ss} over a time τ implies a power P where:

$$P_j \approx \frac{M_{ss} v_c^2}{2\tau}$$

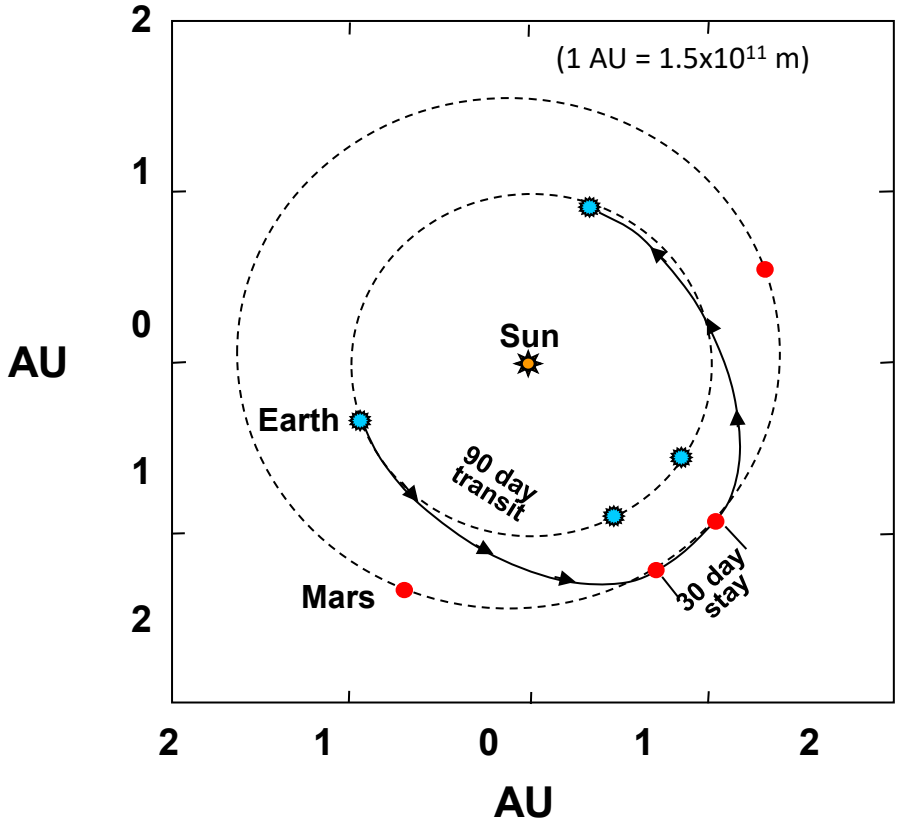
One defines a characteristic velocity v_c: $v_c = (2\alpha\tau)^{1/2}$

where α_P is the specific power: $\alpha_P = \frac{P_j}{M_{ss}} = \alpha_M^{-1}$

with α_M the specific mass.

The the trip time, τ_{trip}, to go a distance L is

$$\tau_{trip} \approx 2\frac{L}{v_c} \quad \text{or} \quad \tau_{trip}\,(\text{days}) \cong 51.6\left[\alpha_M\,(\text{kg/kW})L^2(\text{AU})\right]^{1/3}$$



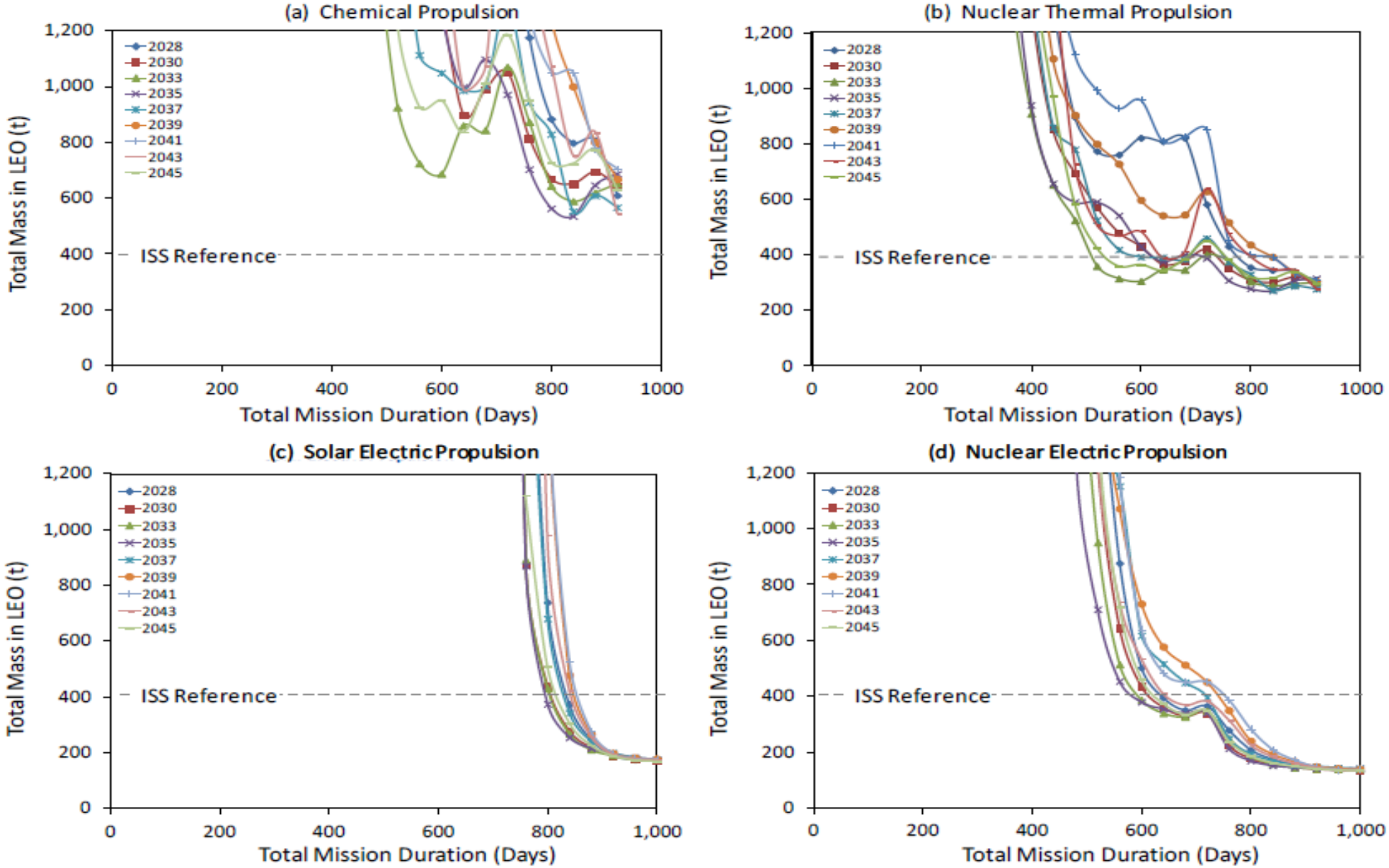
For the 90 day Mars transit (L ~ 1.5 AU) $\Rightarrow \alpha_P >\sim 0.4$ kW/kg

For the 30 day Mars transit (L ~ 0.7 AU) $\Rightarrow \alpha_P >\sim 2.5$ kW/kg

FP4: $.25 < \alpha_P < 3$

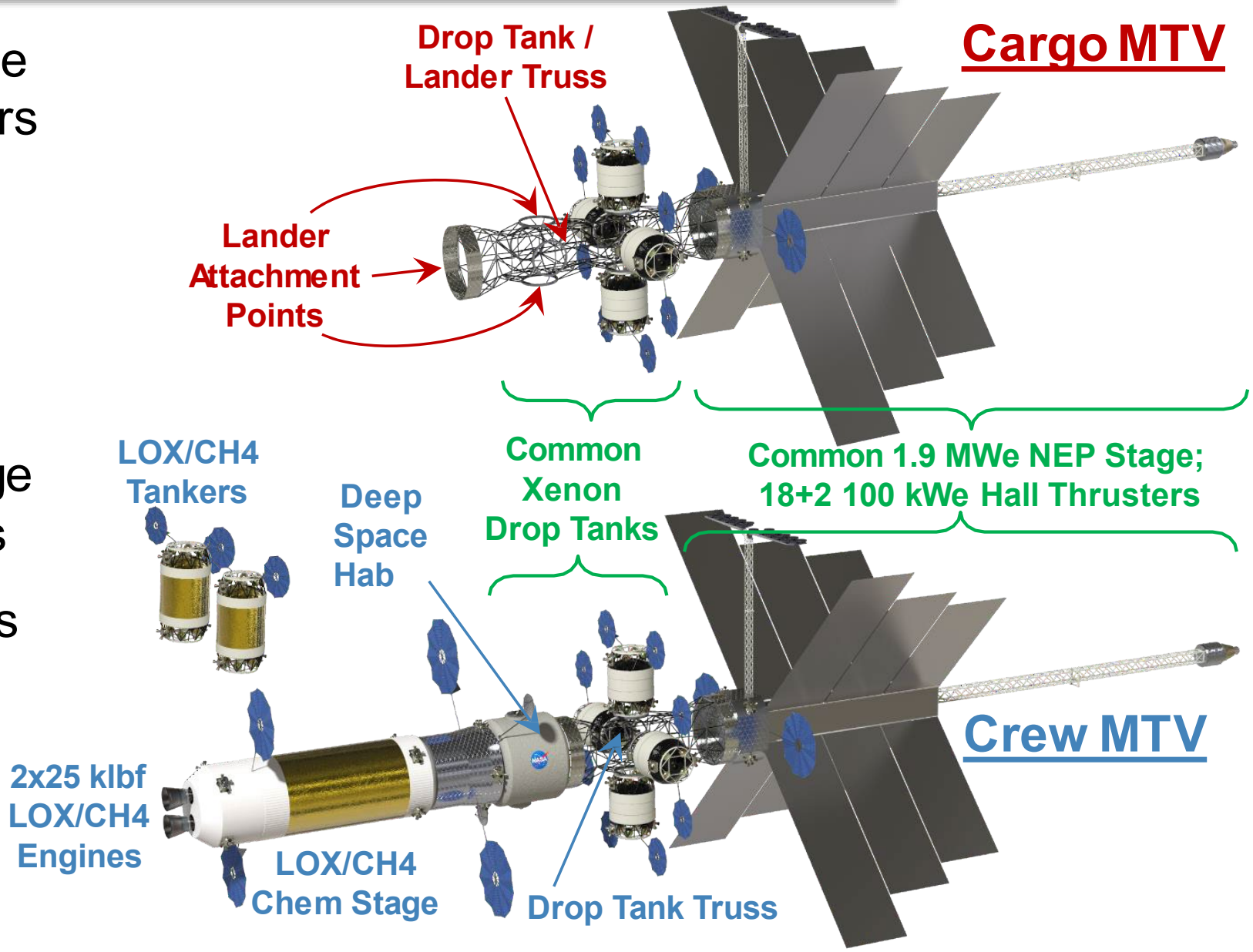
Crew Vehicle Mass as a Function of Round-trip Mission Duration

Short-stay, 60 days at Mars, Opposition-class Missions



Cargo and Crew NEP/Chem Mars Transport Vehicles

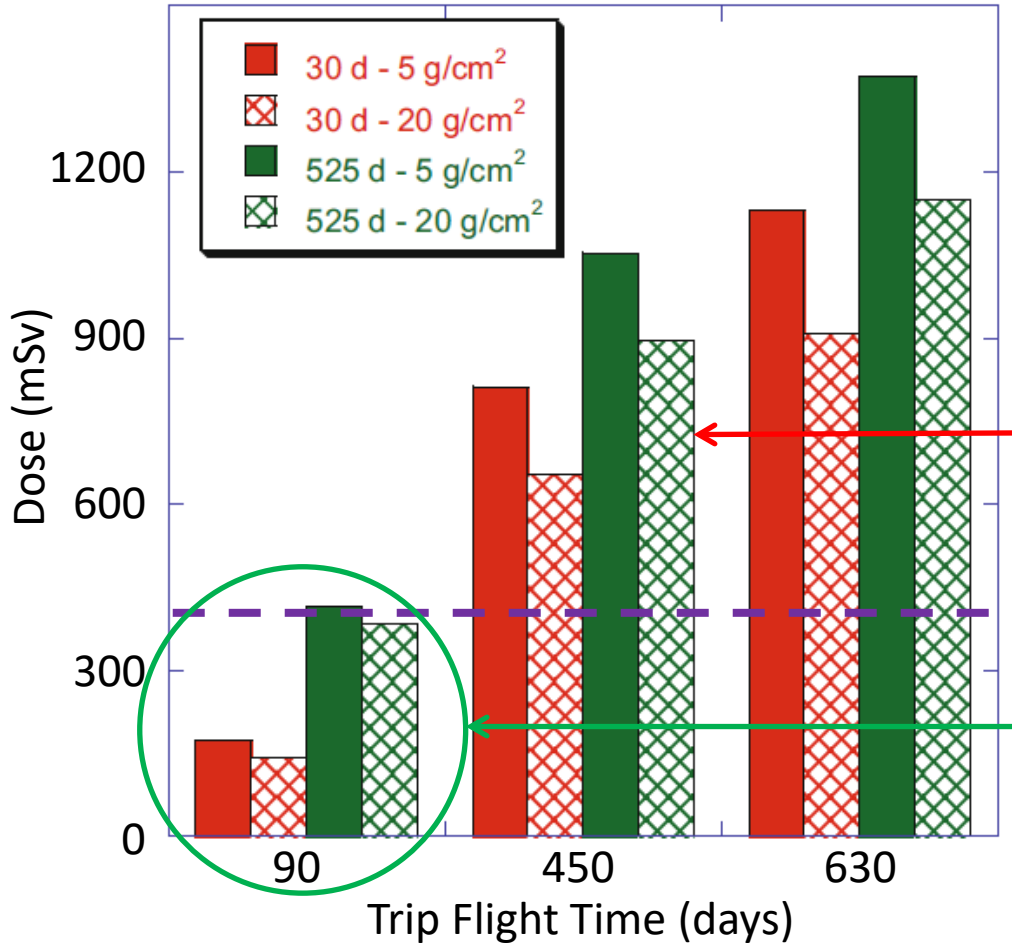
- Cargo and Crew MTV's provide in-space transportation for Mars landers and Crew in Deep Space Hab
- MTV's are reusable for up to three missions
- MTV's use common NEP Stage design with Xenon Drop Tanks
- Modular design enables MTV's to support a wide variety of missions throughout the campaign



Estimated Total Equivalent Doses for Mars Mission

Mars sortie mission (30 days stay)

Long stay at Mars base (525 days)



Current technology (420 days)

NTP/NEP

Fission-Powered Pulsed Plasma Propulsion (F4P)

- The career limit is 400 mSv for a 25 year old for a 3% risk of fatal cancer
- There is uncertainty as to what is the actual risk of long-term, low-level exposure

Determining the Optimal Mars Mission

Opposition-class

- short surface stay at Mars typically 30 to 90 days
- relatively short total round-trip mission times
  - 500 to 650 days

Conjunction-class

- long-duration surface stay times - 500 days or more
- long total round-trip times approximately 900 days
- minimum-energy solutions for a given launch

Both options are well outside the current permissible exposure limit of radiation

Attributes that would comprise the ideal nuclear propulsion system.

(1) all nuclear energy is released into the propellant, no need for conversion to electricity.

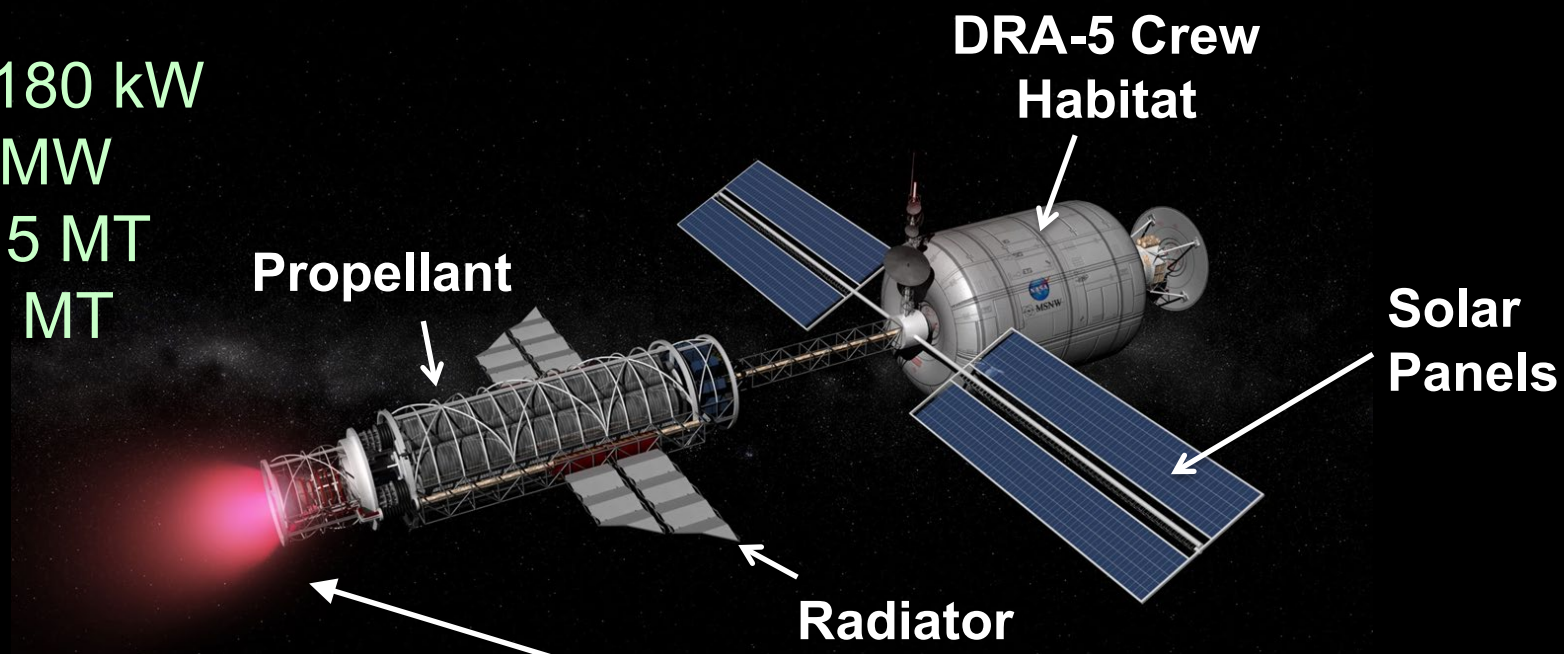
(2) The propellant requires no significant tankage mass by being a solid

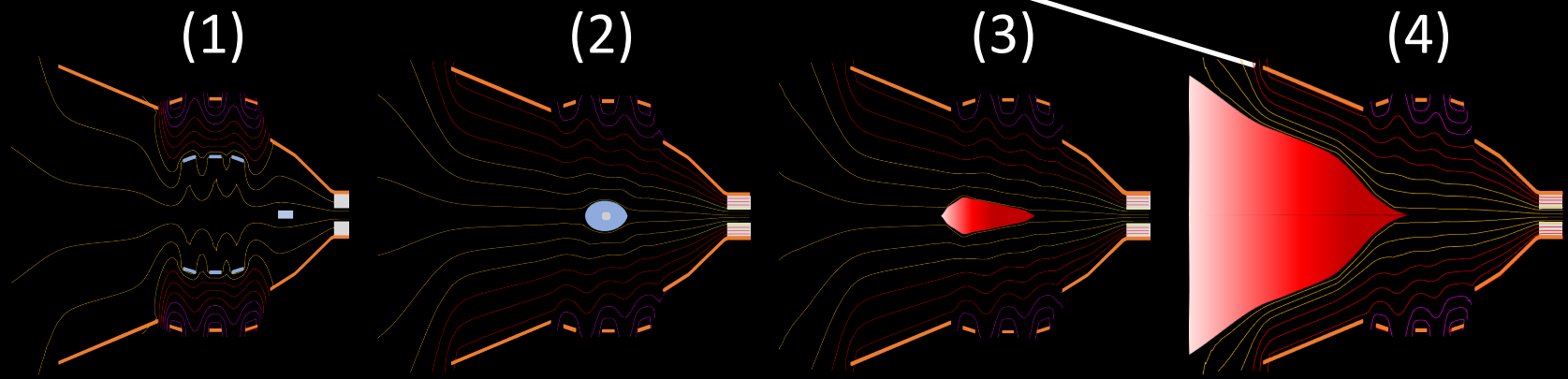
(3) the propellant is rapidly heated and accelerated to optimal exhaust velocity > 20 km/s

(4) no significant physical interaction with the spacecraft thereby limiting thermal heat load, spacecraft damage, and radiator mass.

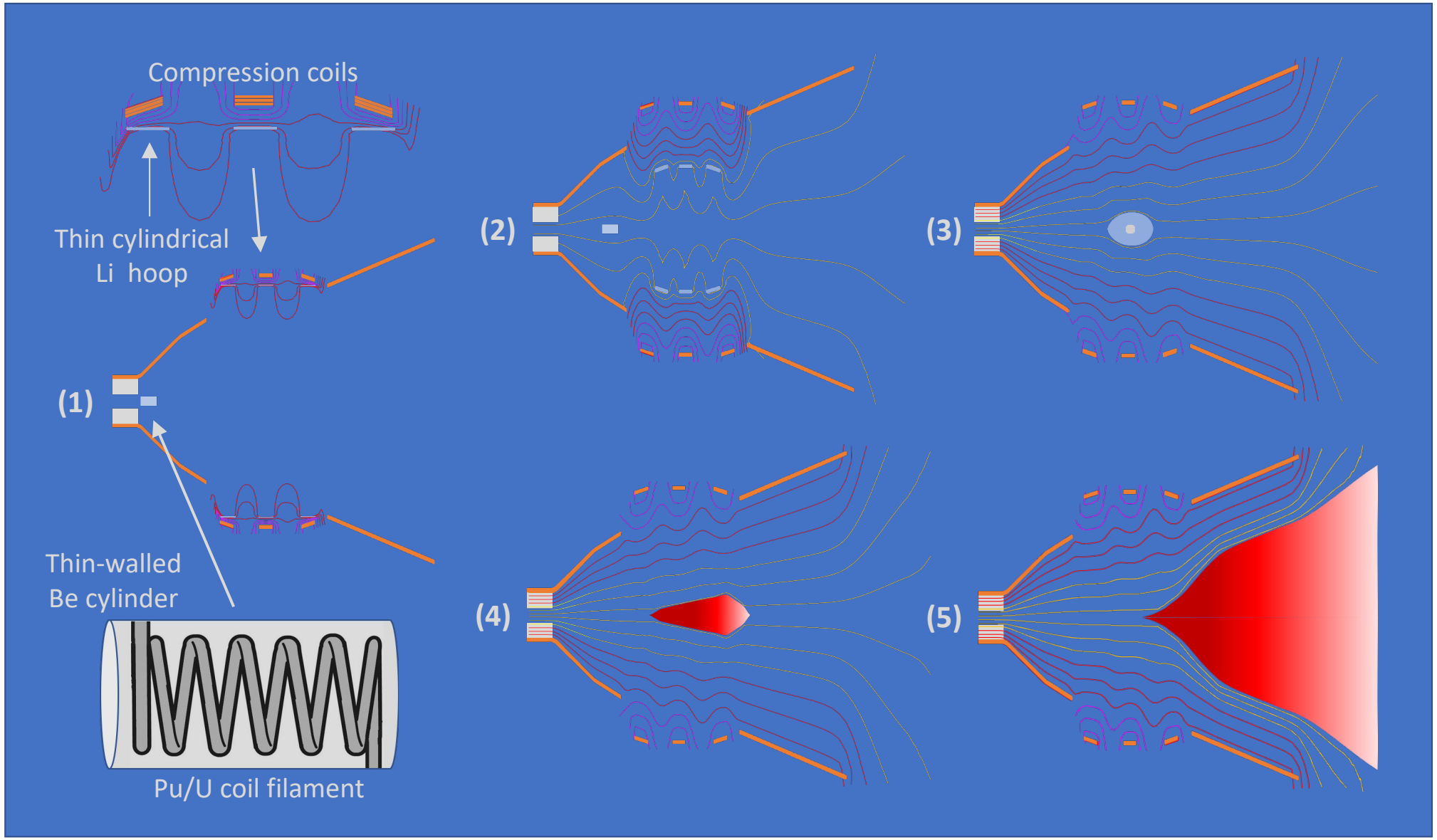
Fission-Powered Pulsed Plasma Propulsion (F4P)

Isp = 3-5 ksec
Solar Power Input= 0-180 kW
Jet Power = 10-36 MW
Spacecraft Mass = 15 MT
Payload Mass = 61 MT



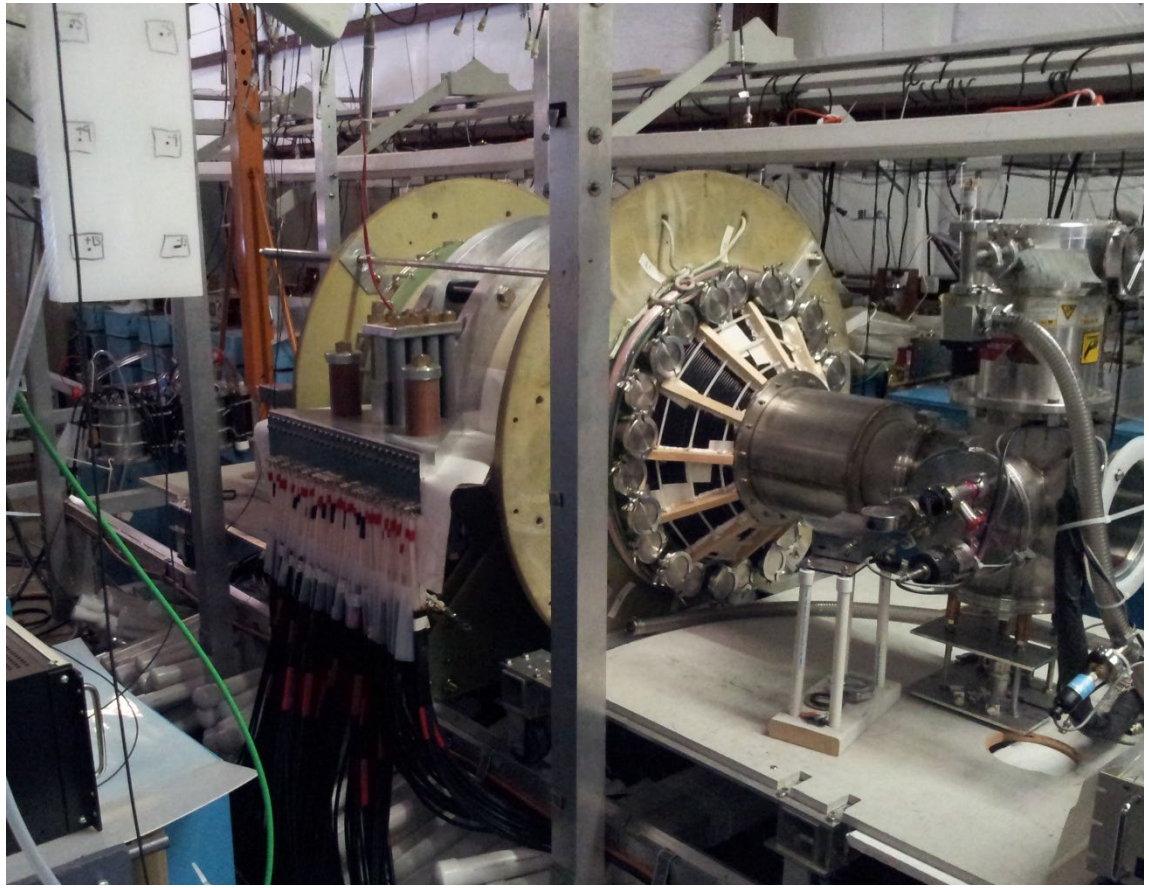


Schematic of the Key Operational Steps for Fission-Powered Pulsed Plasma Propulsion (F4P) Thruster

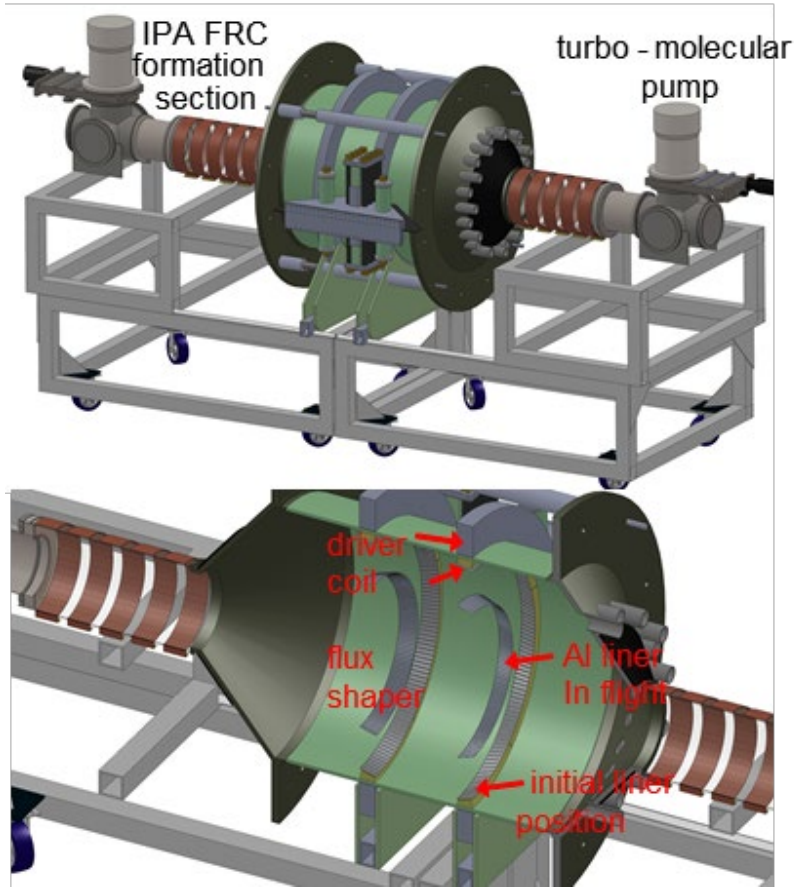


Experimental Research

Inductively Driven Liner Validation Experiment at MSNW

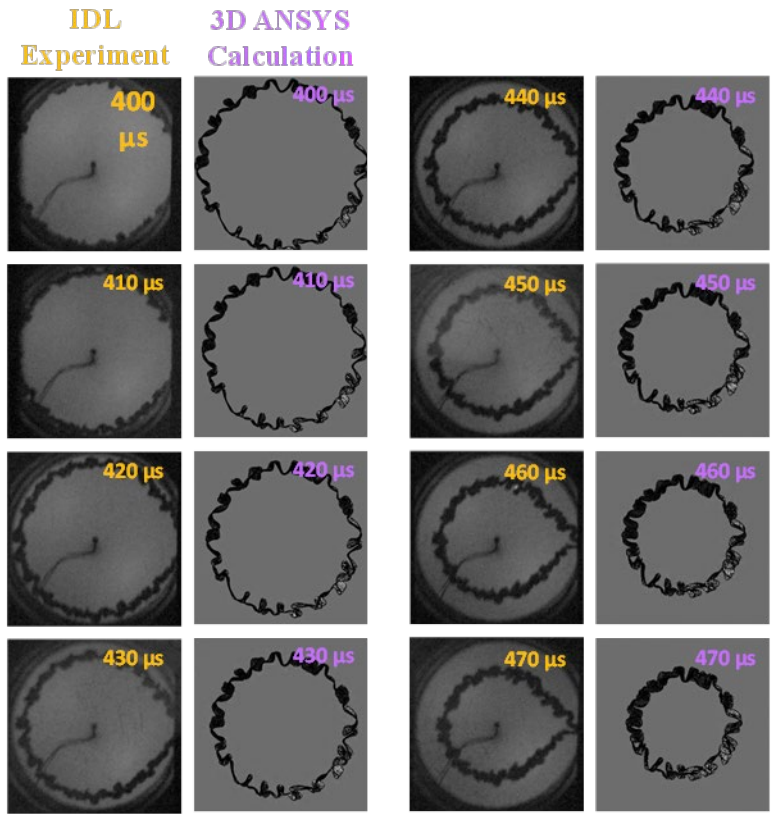


Picture of the IDL validation experiment
Used in the testing at U. of Wash..

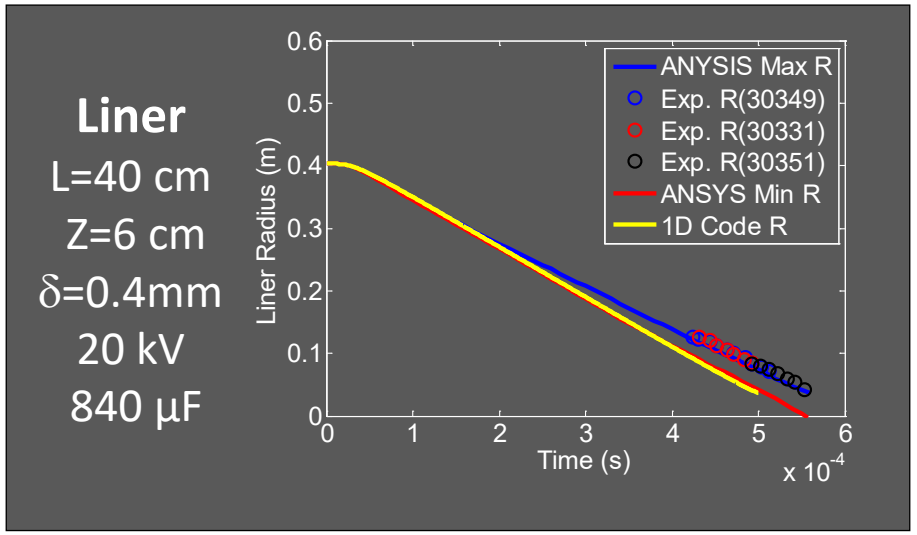


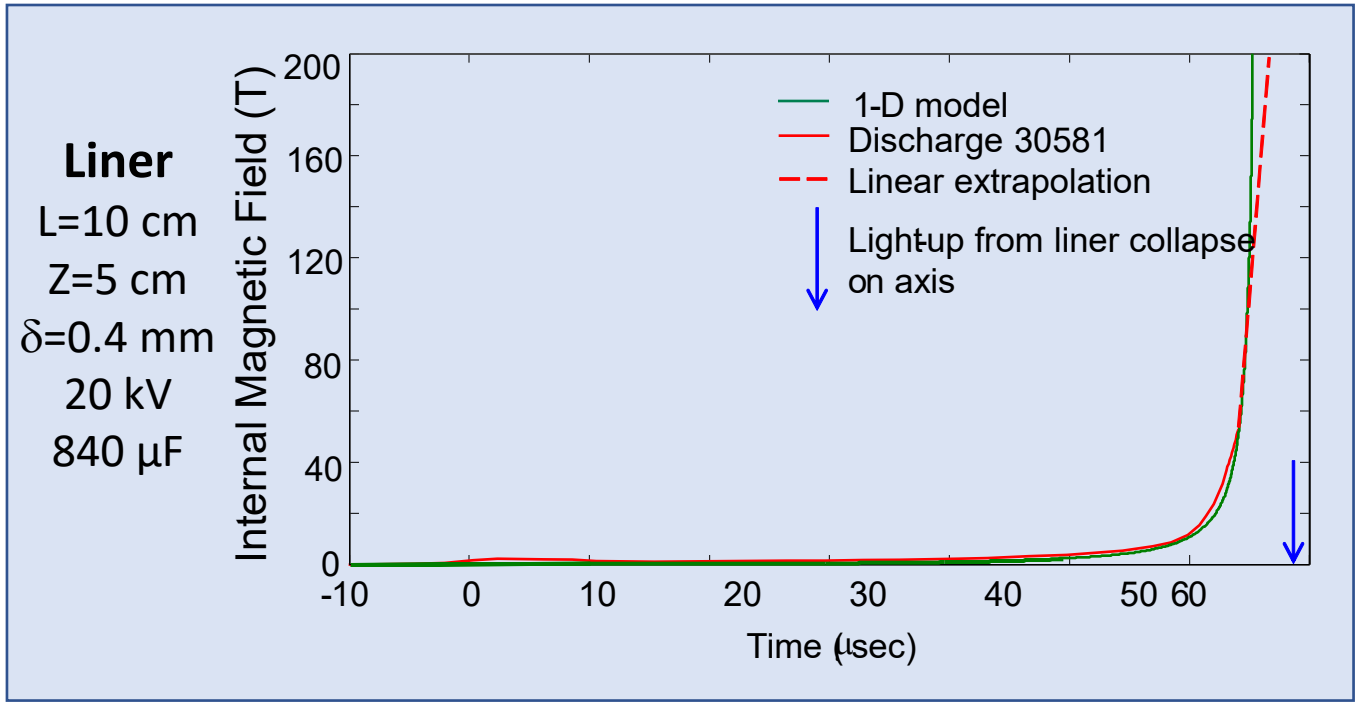
CAD drawing of IDL showing the collapsing Al liners under the external driver coils. Green Garolite vacuum wall insulates liners from driver coils

Experimental Results



¼ Power Aluminum Liner Testing for code Validation

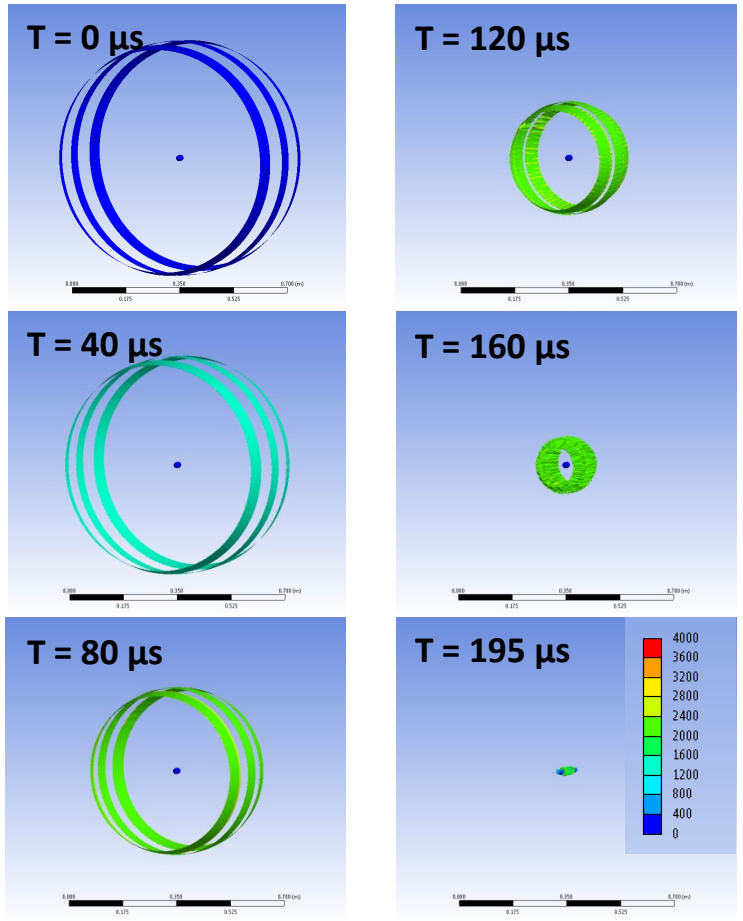


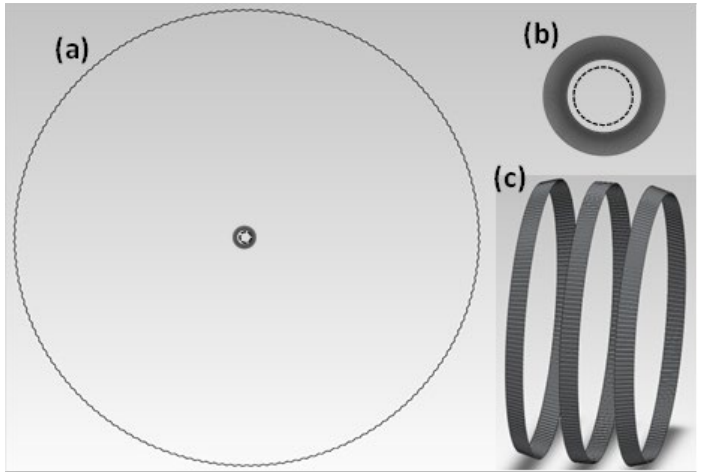


Conditions: bank voltage – 20 kV
Bank capacitance – 840 uF
Al liner Thickness – 0.4 mm
Al initial diameter – 0.8 m

Optimization of the implosion geometry employing the 3D ANSYS Explicit Dynamics Solver (AEDS)

- Three 0.4 m radius, 5 cm wide, 0.2 mm thick Aluminum liners converging onto a stationary test target.
- The scale of the ellipsoid target (1×3.5 cm) is that anticipated for the final FRC compressed to over 1 megabar (10^{11} Pa) energy density
- Aluminum rings quickly yield to the pressure equivalent of a 7 T magnetic field (~ 6 Mpa).
- A high order buckling is observed later during implosion but does not inhibit convergence where **v_L ~ 2.4 km/sec**





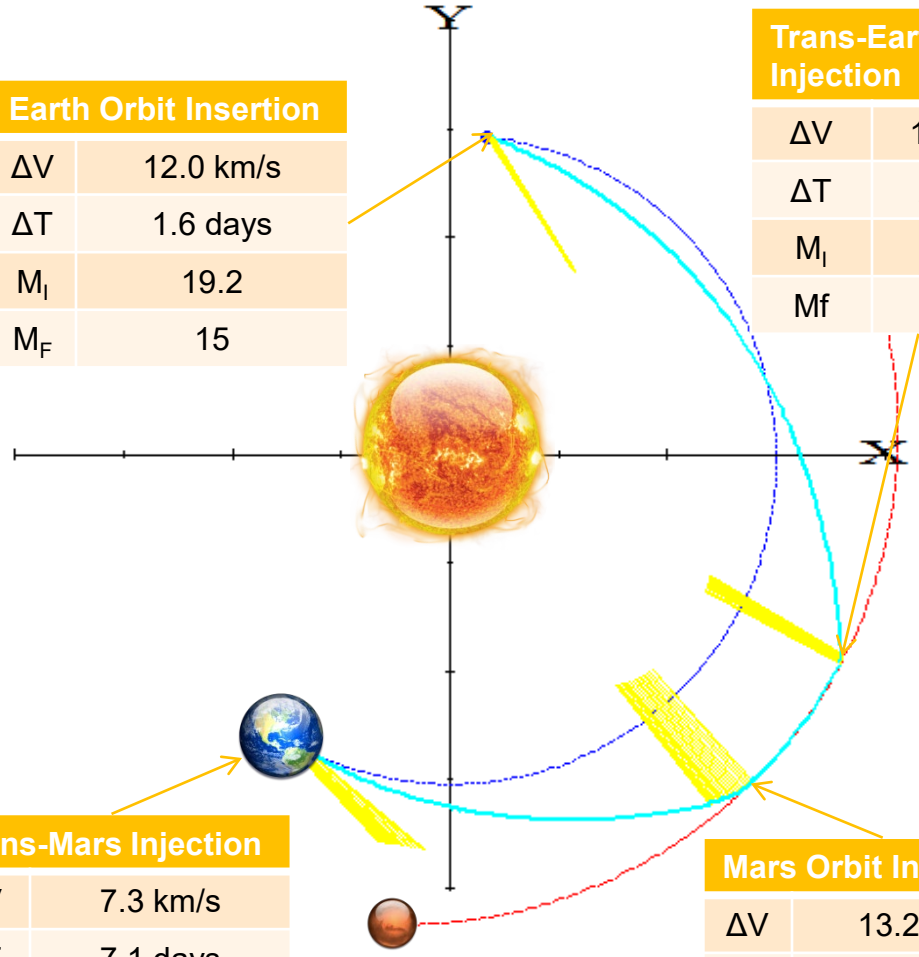
(a) End-on CAD drawing of an aluminum pleated liner with 180 folds dimensioned for the megabar experiment (r= 40 cm, □ = 0.2 mm).
(b) Pleated liner collapsed to inner fold contact point. dashed line is minimum radius at peak compression
(c) three liner assembly

Liner behavior very close to ideal 1D approx. assumed in analysis

Mars 210 day Round-trip Mission (Details)

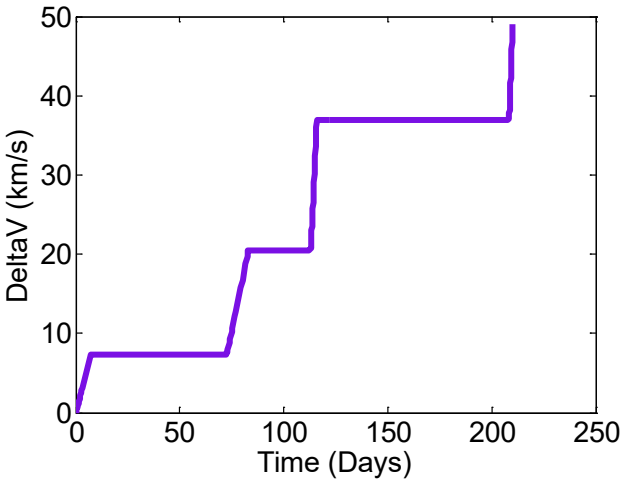
Earth Orbit Insertion	
ΔV	12.0 km/s
ΔT	1.6 days
M_I	19.2
M_F	15

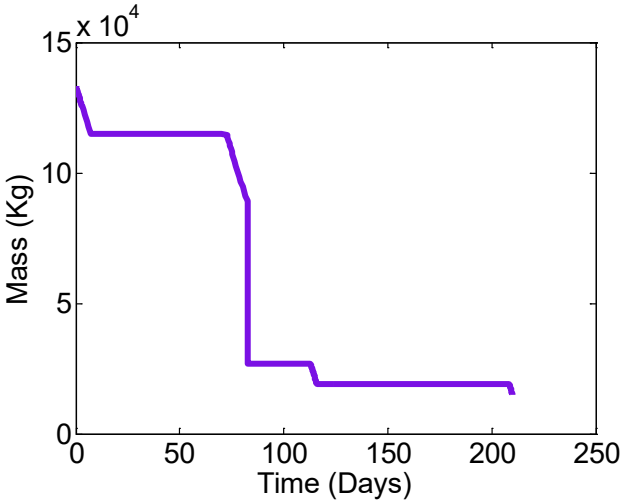
Trans-Earth Injection	
ΔV	16.5 km/s
ΔT	2.9 days
M_I	26.8
Mf	19.2



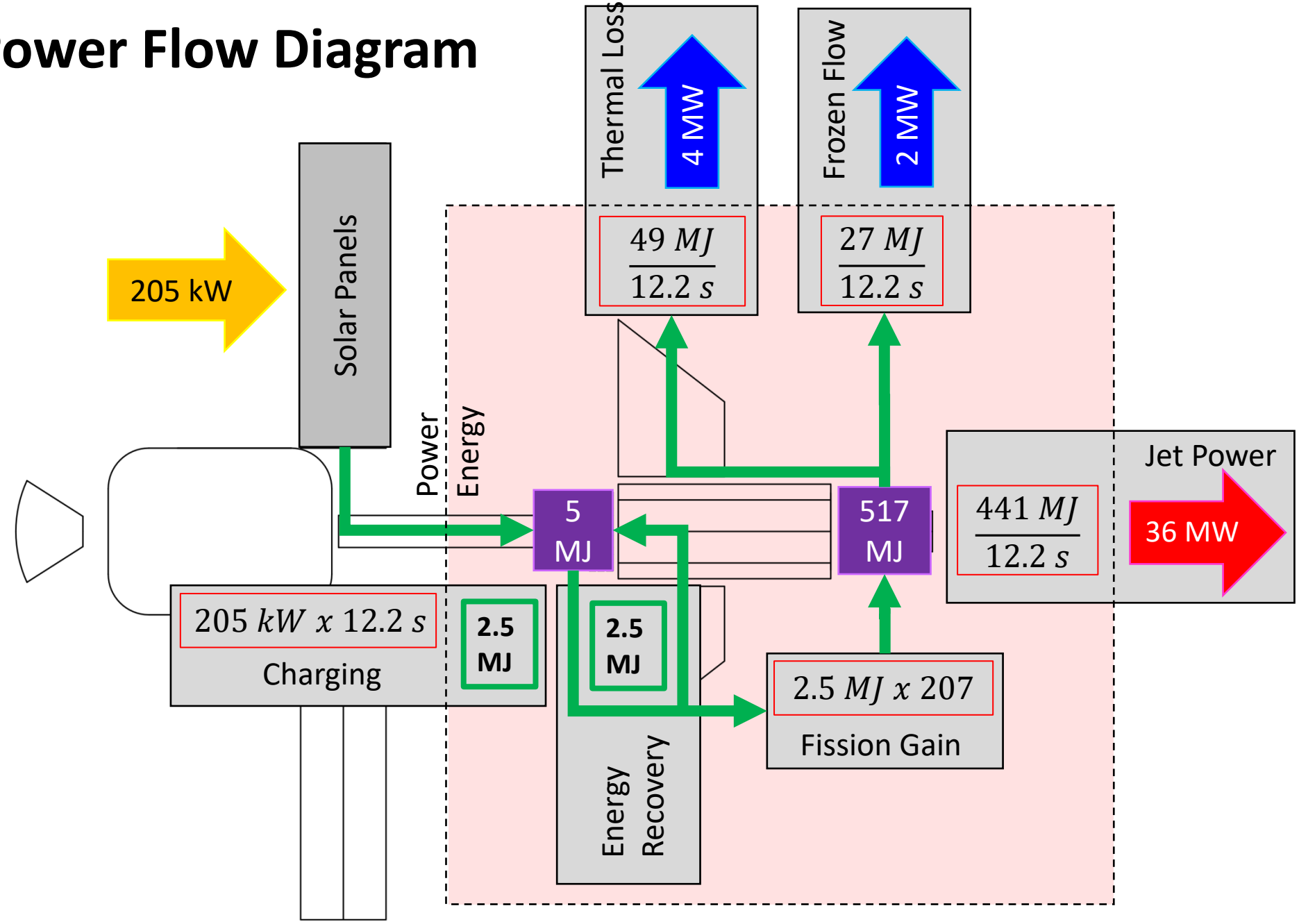
Trans-Mars Injection	
ΔV	7.3 km/s
ΔT	7.1 days
M_I	133.4
Mf	115.0

Mars Orbit Insertion	
ΔV	13.2 km/s
ΔT	10.5 days
M_I	115.0
Mf	87.8

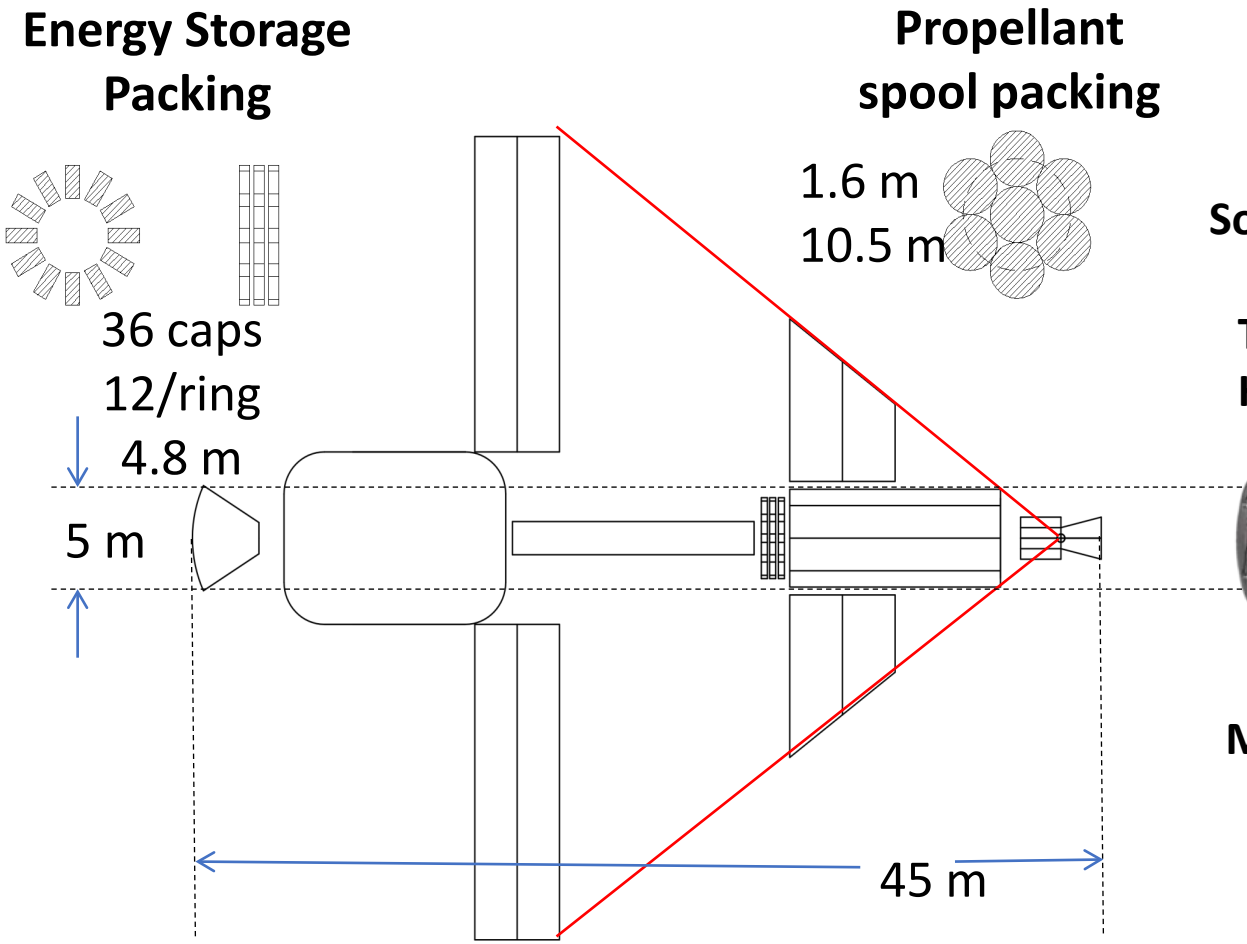


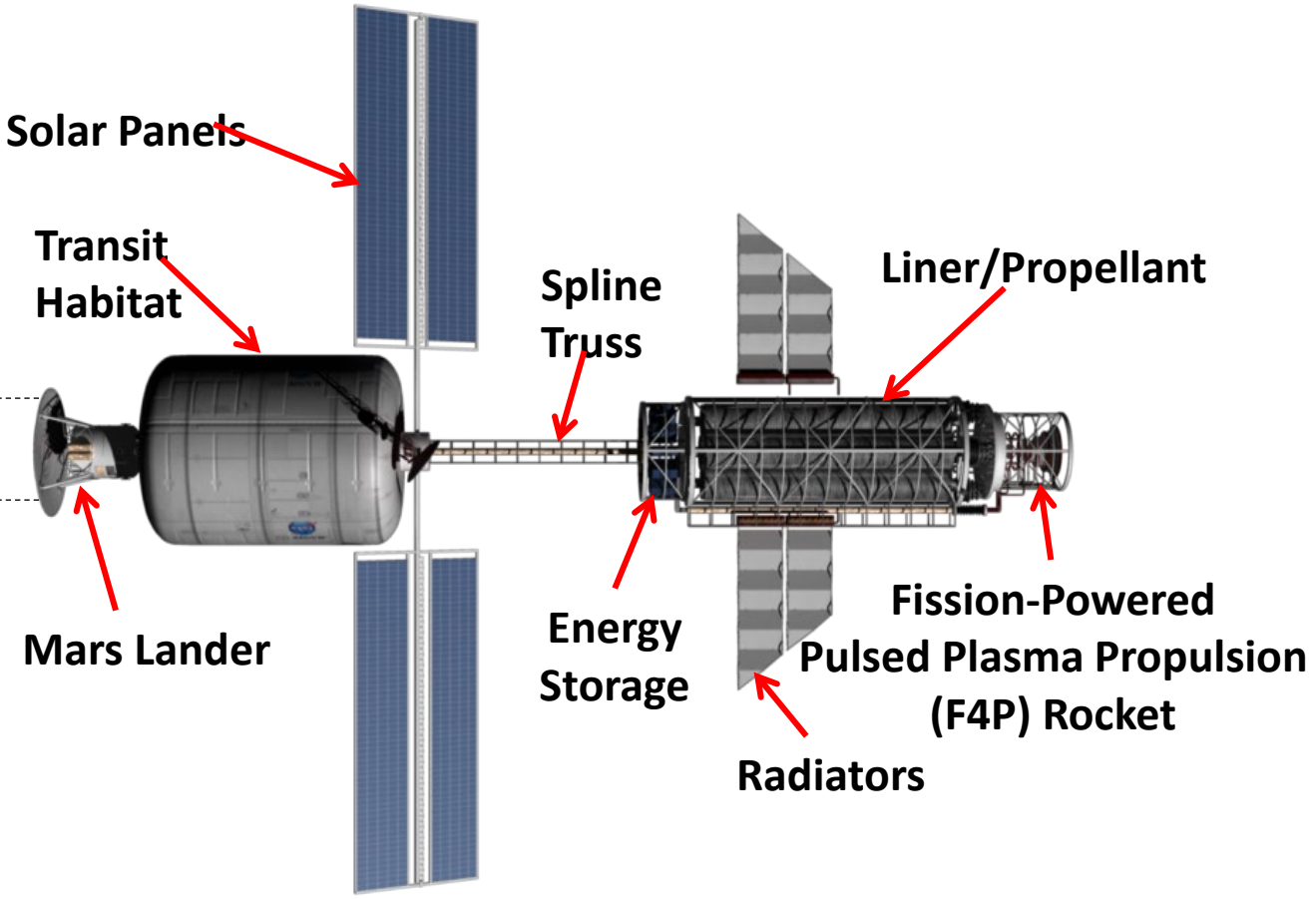


F4P Power Flow Diagram



F4P Spacecraft Layout





Schematic showing key elements and dimensions

CAD rendering

F4P Mass Budget

Spacecraft Component	Mass (mt)
Spacecraft structure[1]	2.7
Nuclear Materials and Delivery[2]	1.2
Energy storage[3]	1.7
Liner driver coils[4]	0.3
Pulse Electronics and cables[5]	0.8
Solar Panels[6]	2.0
Lithium containment vessel	0.1
Propellant Feed mechanism	0.7
Thermal Management	1.1
Magnetic Nozzle	0.4
Spacecraft Mass	**11**
Crew habitat (DRA5.0)	33
Lithium Compound Propellant	56
Space Exploration Vehicle Mass	7
SUBTOTAL	**107**
Margin (25% of subtotal)	27
Total Mass	**134**

Payload mass fraction 46%

Switches and cables equal to energy storage mass

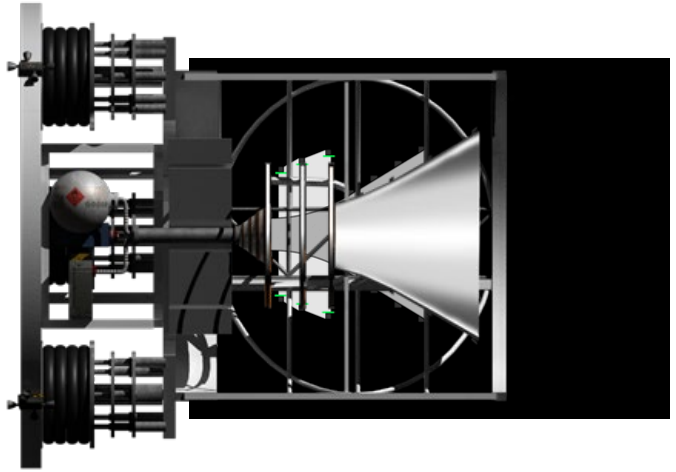
Simple aluminum coil, but most likely composites with We, Be, or Cu liners

Thermal control, 10% heat rejection @ 1 kW/kg with a margin of 3X

Propellant Feed – roll of film – ring formation and injection

1. Fairings, support structure, communication, data handling ACS, Batteries
2. Hardware responsible for injection of Fission material (U-235 or P-239)
3. Capacitors (1.8 MJ @ 1 kJ/KG), switches, power bus
4. Electromagnetic coil used to drive inductive liner
5. Pulsed power electronic components needed to control capacitor bank
6. 180 kW @ 200 W/kg (at Mars)

Fission-Powered Pulsed Plasma Propulsion (FP4)



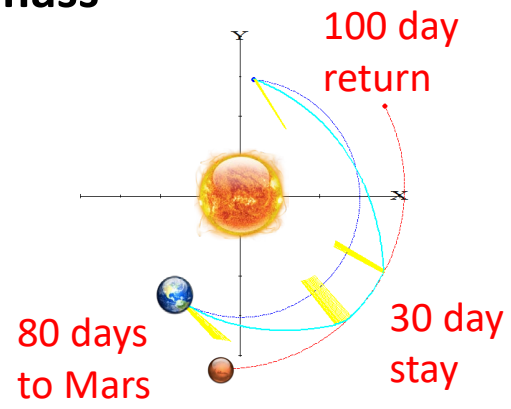
Simple, One Step Process to produce high Thrust & Isp:

Magnetically imploded cylindrical metal liners converge on fissile target to create fission gain conditions. Liners absorb fission products and are rapidly vaporized, ionized and ejected through magnetic nozzle.

- **200 kW Solar x 200 (Fission Gain) = 36 MW Jet Power**
- **Major reduction in trip time and propellant mass**

Mission Study Comparison:

KEY METRICS	Chemical	Nucl. Thermal	FP4
Number of Launches	12	9	1
Initial Mass in LEO (MT)	1,252	849	134
Mission Time (days)	914	914	210



UW/MSNW demonstration of large-scale liner implosion

