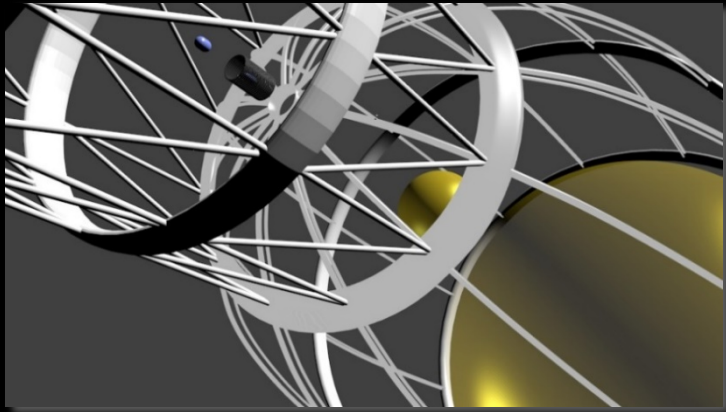# Preliminary Analysis of the Gradient Field Imploding Liner Fusion Propulsion System

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NIAC
NASA Innovative Advanced Concepts

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A robust deep space exploration program requires high energy propulsion systems

$$\frac{m_f}{m_0} = e^{-\Delta v / v_e}$$

- Solar system destinations require $\Delta v \approx 10^4 - 10^5$ m/s
- High exhaust velocity required for reasonable payloads

Multiple studies have shown the benefits of fusion energy for rapid trip times to Mars and the outer solar system...

- High specific power (kW/kg)
- High exhaust velocity (specific impulse)

...if we can get it to work

Rocket equation: (m_f/m_o) = fraction of initial mass delivered to destination; Δv = required mission velocity; v_e = propellant exhaust velocity

NIAC Phase I study takes advantage of ground-based research in Magnetoinertial Fusion (MIF)

Multiple approaches: Z-pinch, Θ-pinch, Liner-driven FRC, etc.

Θ-pinch concept
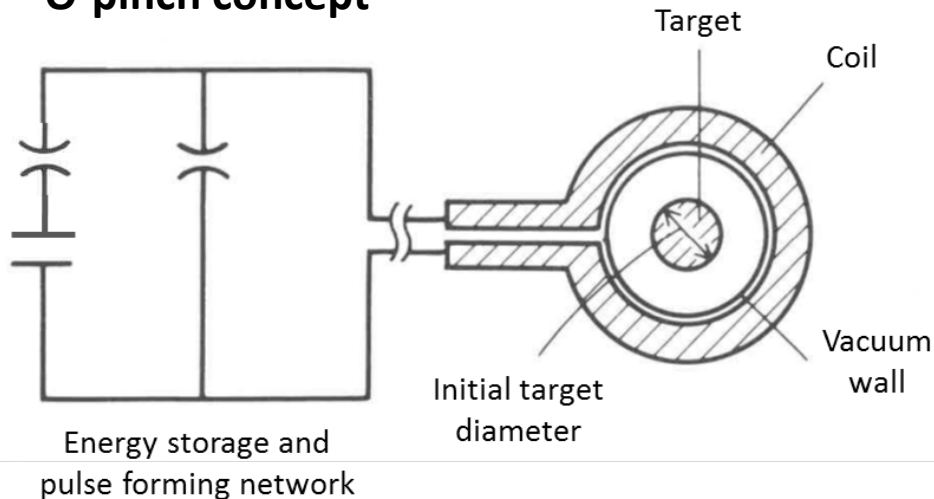
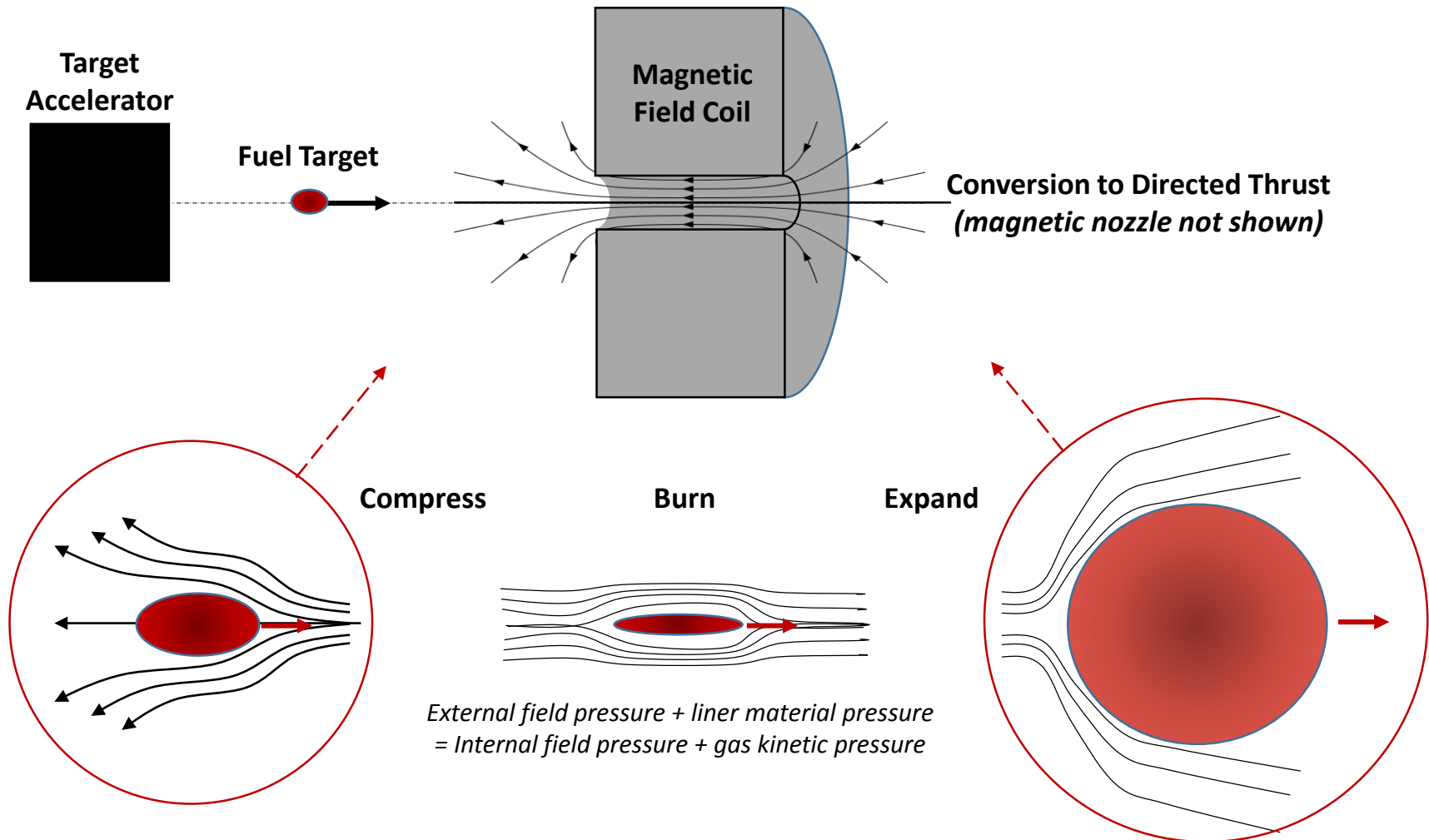Adapted from Miyamoto, K. *Plasma Physics for Nuclear Fusion*, MIT Press, Cambridge, MA (1987)

- Pulsed current in an external coil generates strong axial magnetic field, induces azimuthal current in target liner

- Radial $j_\Theta B_z$ Lorentz force implodes the liner to compress the target fuel

- At maximum compression, pressure is balanced between the stagnating liner material, external magnetic field, trapped internal magnetic field, and fuel pressure

Energy storage, resistive coil, pulse repetition all present challenges

Reformulate the θ-Pinch Concept

- Replace the time changing magnetic field generated by the pulsed current coil with a fusion target moving rapidly into a steady-state magnetic field gradient

  - Equivalent to a time changing magnetic field observed in the target frame of reference

$$\dot{I} \propto \dot{B}_z = v_z \frac{\partial B}{\partial z}$$

- The rapidly changing magnetic field observed in the target frame of reference induces a strong azimuthal current in the target liner

- The combination of axial magnetic field and azimuthal liner current generates a radial Lorentz force that rapidly compresses and heats the target, similar to a θ-pinch

Preliminary Concept

Target Accelerator

Fuel Target

Magnetic Field Coil

Conversion to Directed Thrust
(magnetic nozzle not shown)

Compress　　**Burn**　　**Expand**

External field pressure + liner material pressure
= Internal field pressure + gas kinetic pressure

How Does This Help?

- Replaces pulsed drive coil with steady-state superconducting magnet, mitigating issues with repetitive, high current pulse generation
  - Reduces energy storage requirements, coil resistive losses
  - Reduces demands on switches, power components, etc.

- Fairly compact linear geometry for in-space applications
  - Strong gradient field produced by small bore magnet
  - Readily incorporates magnetic nozzle for directed plasma thrust

- Moves the challenge from pulsed coil to target accelerator
  - However, the target can be accelerated over a longer time period

- Opportunity for relatively low cost ground testing
  - Validate target acceleration, preheating, and compression physics
  - Adaptable once MIF conditions for fuel breakeven are demonstrated

Goals

- Model target injection and compression dynamics

- Evaluate fusion fuel target designs (geometry, density, liner)

- Evaluate high velocity target acceleration options (several km/s)

- Evaluate magnetic field requirements and solenoid coil designs

- Incorporate MIF concepts of target preheating and internally compressed magnetic fields to reduce particle thermal transport

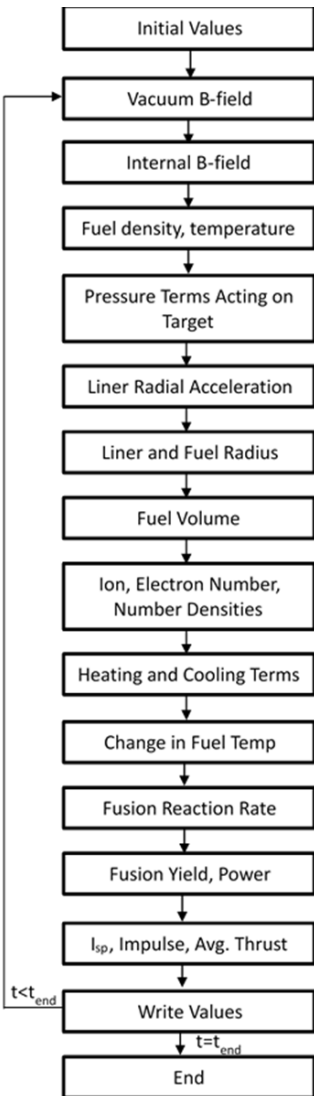- Estimate performance (yield, specific impulse, average thrust)

Pull it all together into an initial vehicle design and comparative mission analysis

Semi-Analytic Model

Based on MIF model of McBride and Slutz (2015)

- Adiabatic heating
- Optional fuel preheating (laser absorption)
- Fusion byproduct (α) energy deposition within target
- Radiative losses from high temperature plasma
- Radial ion and electron thermal conduction losses
- Mass and energy end losses from the compressed target
- Fusion cross sections and reaction rates
- Energy yield and gain, energy balance calculations
- Semi-analytic model was modified for target injection
- Partially validated with adiabatic compression model

Numerous trade studies performed to evaluate optimum engine performance

Flowchart (top to bottom):

- Initial Values
- Vacuum B-field
- Internal B-field
- Fuel density, temperature
- Pressure Terms Acting on Target
- Liner Radial Acceleration
- Liner and Fuel Radius
- Fuel Volume
- Ion, Electron Number, Number Densities
- Heating and Cooling Terms
- Change in Fuel Temp
- Fusion Reaction Rate
- Fusion Yield, Power
- I_{sp}, Impulse, Avg. Thrust
- Write Values
- $t = t_{end}$
- End

$t < t_{end}$ (loop back to Vacuum B-field)

*McBride, R. and Slutz, S., "A semi-analytic model of magnetized liner inertial fusion," Physics of Plasmas **22**, 052708 (2015)*

Reaction	Energy Release
$D + T \rightarrow \alpha + n$	17.59 MeV
$D + D \rightarrow T + p$	4.04 MeV
$D + D \rightarrow {}^3He + n$	3.27 MeV
$D + {}^3He \rightarrow \alpha + p$	18.35 MeV
$D + {}^6Li \rightarrow 2\alpha$	22.374 MeV
$D + {}^6Li \rightarrow p + {}^7Li$	5.026 MeV
$D + {}^6Li \rightarrow n + {}^7Be$	3.38 MeV
$p + {}^{11}B \rightarrow 3\alpha$	8.68 MeV
$n + {}^6Li \rightarrow T + \alpha$	4.86 MeV
$n + {}^7Li \rightarrow T + \alpha + n$	-2.87 MeV

Cross section vs. center of mass energy
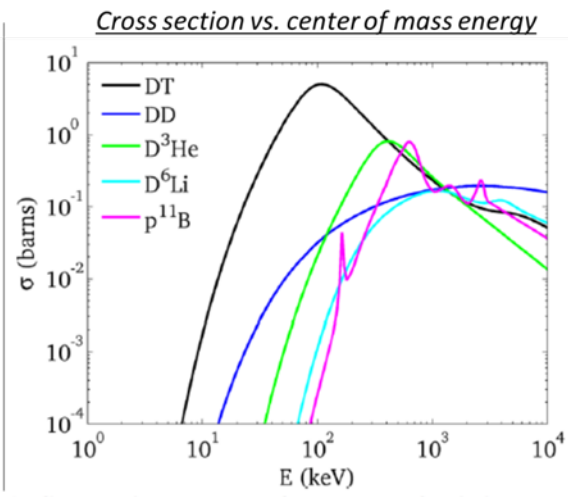
Fuel: Deuterium-Tritium

- Yields α(3.5 MeV) + n(14.1 MeV)
- "Easiest" to ignite, but issues with neutrons

Cassibry et al., "Case and Development Path for Fusion Propulsion," Journal of Spacecraft and Rockets, 52 (2), pp. 595-612, March-April 2015 (and references therein)

Conductive target liner

- Carries induced azimuthal current for radial Lorentz compression
- Evaluated aluminum (Al), lithium (Li) and beryllium (Be) liners
- Fixed target aspect ratio (AR) ≤ 6 to mitigate Rayleigh-Taylor Instability

$$\text{AR} = \frac{R}{\Delta R} = \frac{\text{outer radius of the target (including liner radius)}}{\text{liner thickness}}$$

- Light Gas/Rail Guns
  - Experimentally demonstrated to several km/s
  - Potential erosion of rails/component
  - May be useful for initial ground tests

- Electrothermal Accelerators
  - Investigated to refuel tokomak reactors
  - Ablative plasma arc drives electromagnetic acceleration
  - Experimentally demonstrated to a few km/s with 1-g pellets

- Electromagnetic Accelerators
  - e.g. pulsed inductive macron accelerator ≈ 1-gram at 5-10 km/s

- **Laser Ablation Accelerator**
  - Rapid ablative acceleration of target material
  - Experimentally demonstrated to several 10's of km/s
  - Laser may also be used for preheating the fuel target

Laser Acceleration Example

Ablated material plays the role of reaction mass expelled from the system:*

$$\Delta v = v_e \ln\left(m_0/m_f\right)$$

or:

$$1 - m_f/m_0 = 1 - \exp\left(-\Delta v/f \cdot v_e\right)$$

The required pellet velocity (Δv) is $\approx$ 10 km/s; "f" is an empirical exhaust shape factor $\approx$ 0.6

Assuming the energy imparted to the ablated material is converted to kinetic energy of the ablated ions:

$$v_e = \left(\frac{4\,I}{n_c m_i}\right)$$

where
- I = laser intensity (W/m^2) illuminating the target
- n_c = critical density at which the incident laser light frequency equals the vaporized liner plasma frequency; for CO_2 laser (10.6 μm) = 2.52x10^{23}/m^3
- m_i is the mass of the (liner) ion species being accelerated (Al: m_i = 4.52x10^{-26} kg)

*Jarboe,T., "Confinement and acceleration of pellet material by one-sided laser irradiation," Phys Fluids B: Plasma Physics 5, 1332 (1993)

Laser power of 10-kW on a 1-cm² cross section Al target ($I = 3.18 \times 10^7$ W/m²) imparts an ion velocity of:

$$v_e = \left(\frac{(4)(3.18 \times 10^7)}{(2.52 \times 10^{23})(4.52 \times 10^{-26})} \right)^{1/2} = 1.06 \times 10^5 \frac{m}{s}$$

The fraction of ablated liner mass required to provide a Δv of 10 km/s is:

$$1 - {m_f}/{m_0} = 1 - \exp \left({-10^4}/{(0.6)(1.06 \times 10^5)} \right) = 0.15$$

=> ablate 15% of the liner mass to provide a target velocity of 10 km/s

Increasing the incident laser energy increases the ablated ion velocity and reduces the amount of ablated material required to reach a desired injection velocity; e.g., Al liner, ablative acceleration to a target velocity of 10-km/s:
- 5% of the liner material at 100 kW
- 1.5% of the liner material at 1-MW

Option to use tailored laser pulse to preheat the fuel prior to compression

Study Approach

- Performed several trades on target design, injection velocity, fuel density, magnetic field values, coil size, etc.; optimized for maximum energy release and high specific impulse

- Results used to evaluate engine performance:

$$v_e = v_{z_0} + \left(\frac{2\eta E}{m}\right)^{1/2} \text{ (m/s)}$$

Vz_0 = initial target velocity; E = net energy release; m = target mass; η = conversion efficiency (0.7)

$$I_{bit} = mv_e = \frac{mI_{sp}}{g_0} \text{ (N–s)}$$

I_{bit} = impulse bit (N-s); Isp = specific impulse (s)

$$F_{av} = f(Hz) \cdot I_{bit} \text{ (N)}$$

F_{av} = average thrust; f(Hz) = pulse repetition frequency
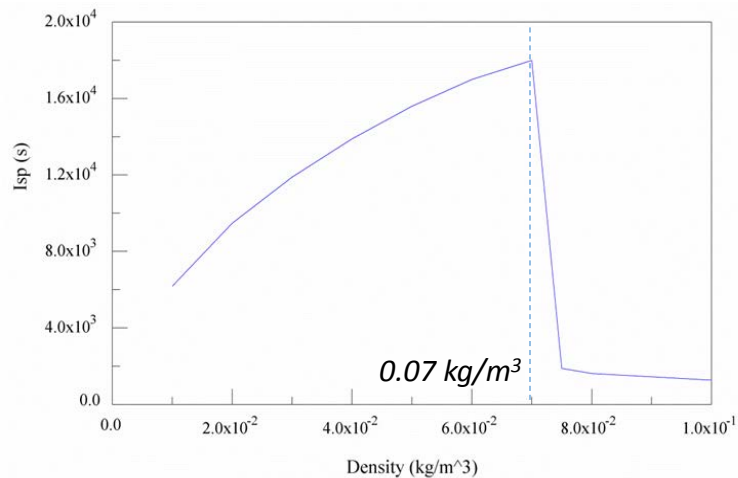
Isp as a function of initial fuel density
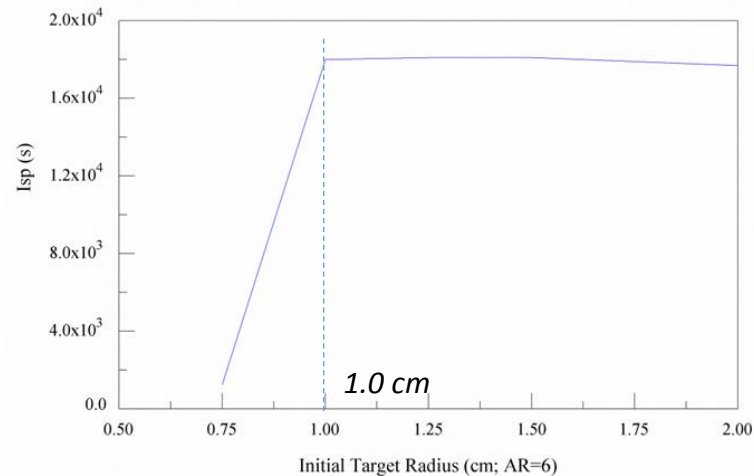
Isp as a function of initial target radius
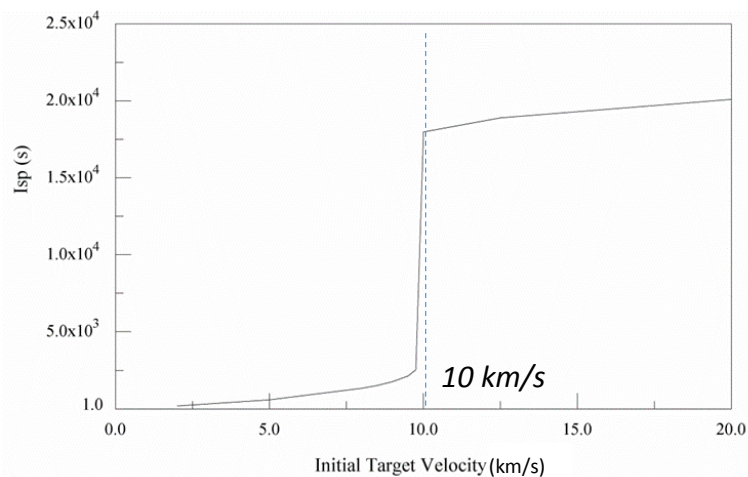
Isp as a function of initial target velocity
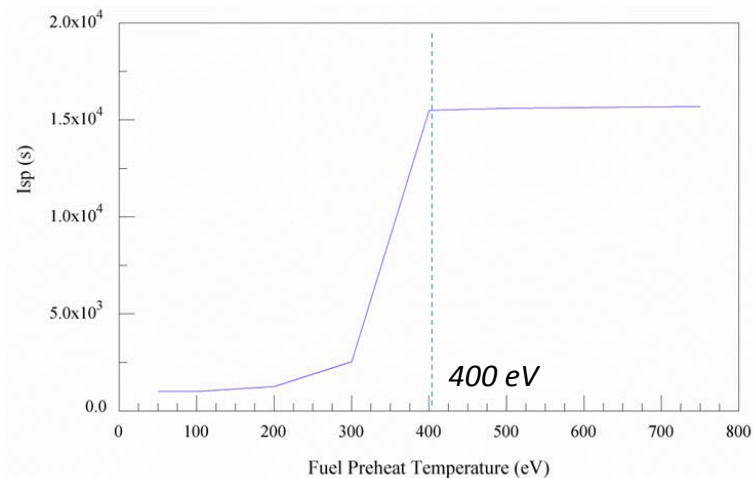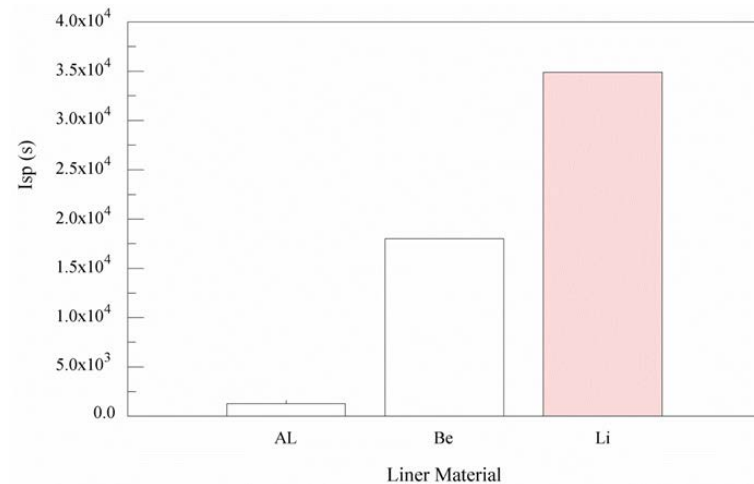

Isp as a function of fuel preheat temperature
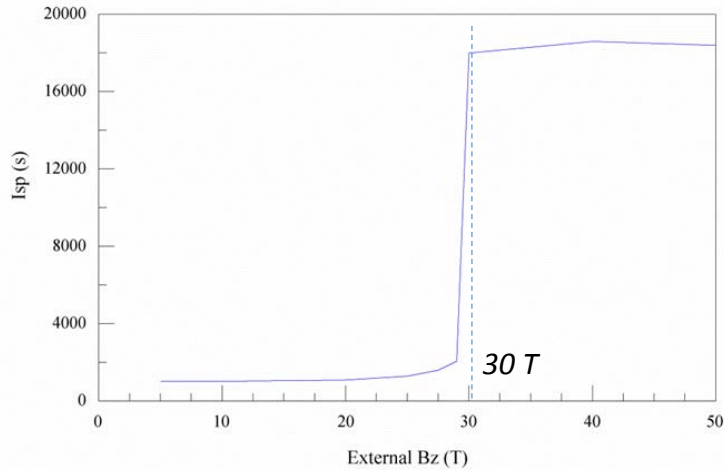
Isp as a function of constant external magnetic field
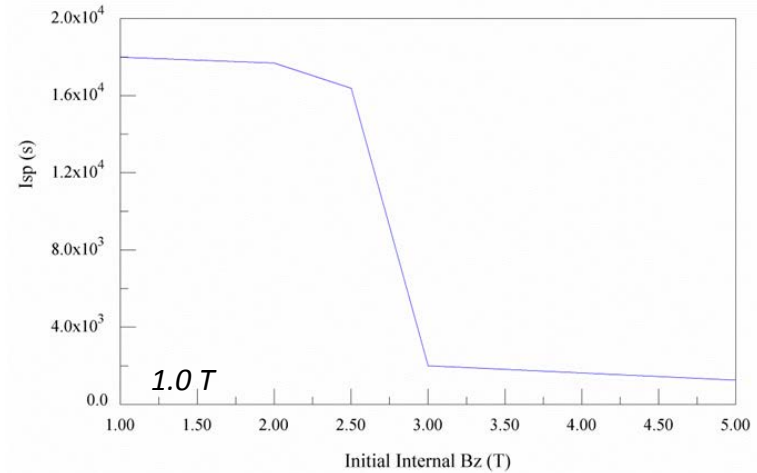
Isp as a function of initial internal target magnetic field
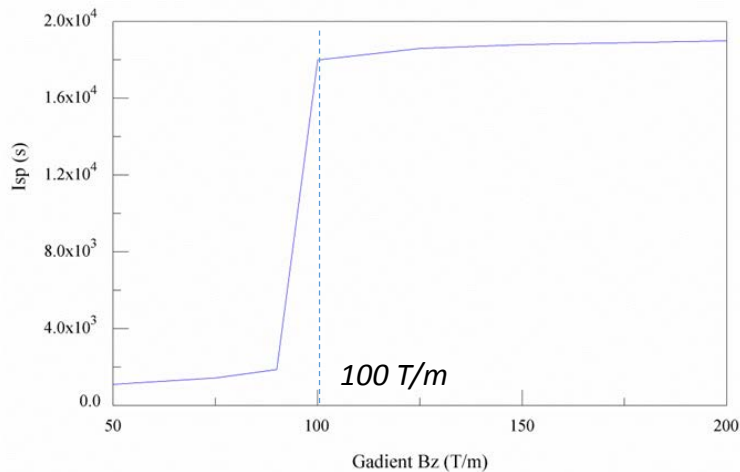

Isp as a function of constant magnetic field gradient

Isp as a function of target liner material (Al, Be, Li)

Using optimized initial values, semi-analytic model was used to evaluate the time evolution of key parameters:

- Magnetic fields

- Target radius

- D-T mass density

- D-T number density

- D-T fuel temperature

- D-T fusion yield

- Neutron production

Results were used to estimate engine performance and perform preliminary vehicle design and mission analysis
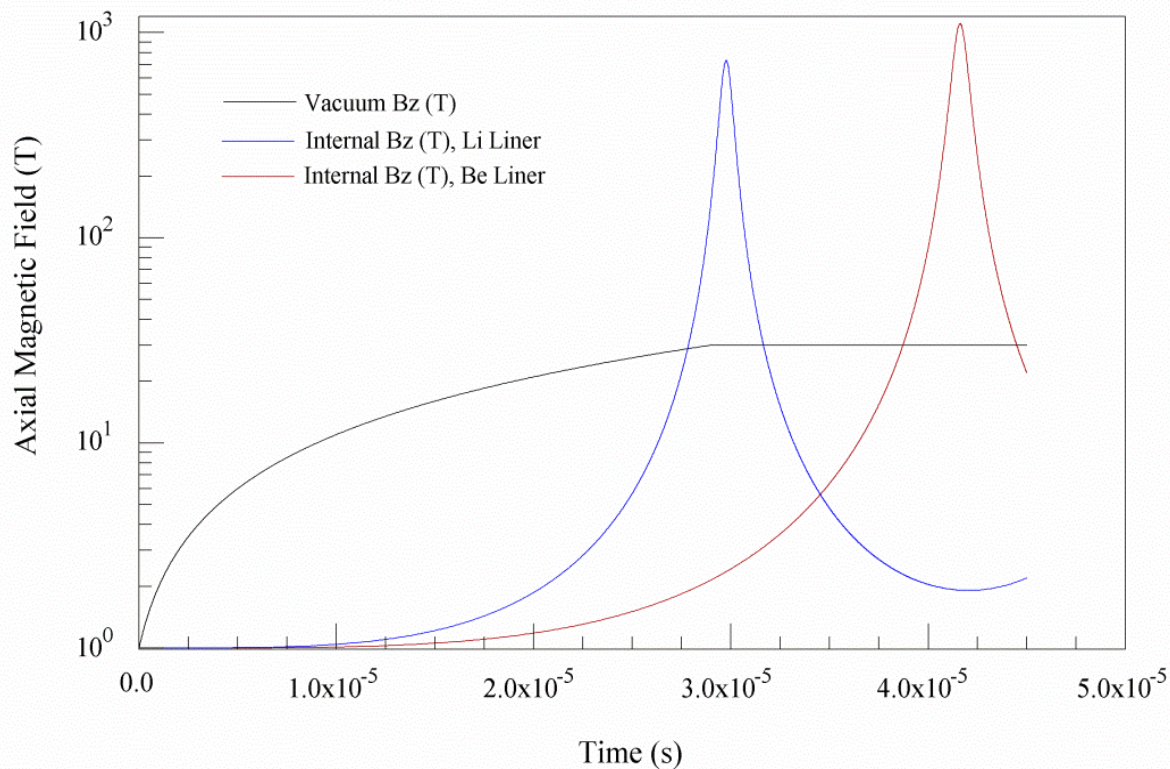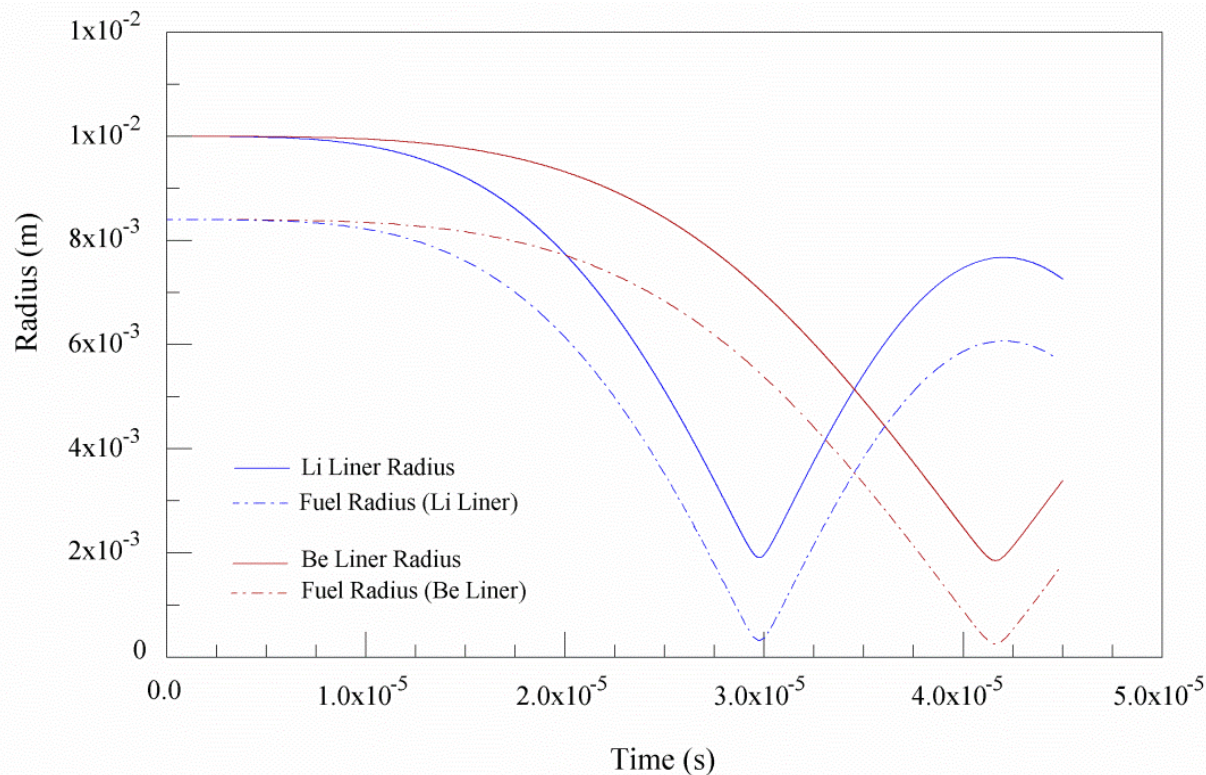
External and internal magnetic field values for Be and Li lined targets

Vacuum Bz field as observed by injected target traversing static magnetic field gradient

Internal Bz fields rapidly increase within target during compression (conserve flux)

Note: magnetic field diffusion times (ms) through the conducting liners >> compression times

Evolution of liner and fuel radius with time

Lithium lined target reaches maximum compression at an earlier time that the beryllium lined target due to the higher radial acceleration of the lower mass Li liner compared to the Be lined target

Expansion occurs after initial compression as fuel pressure exceeds external magnetic field pressure
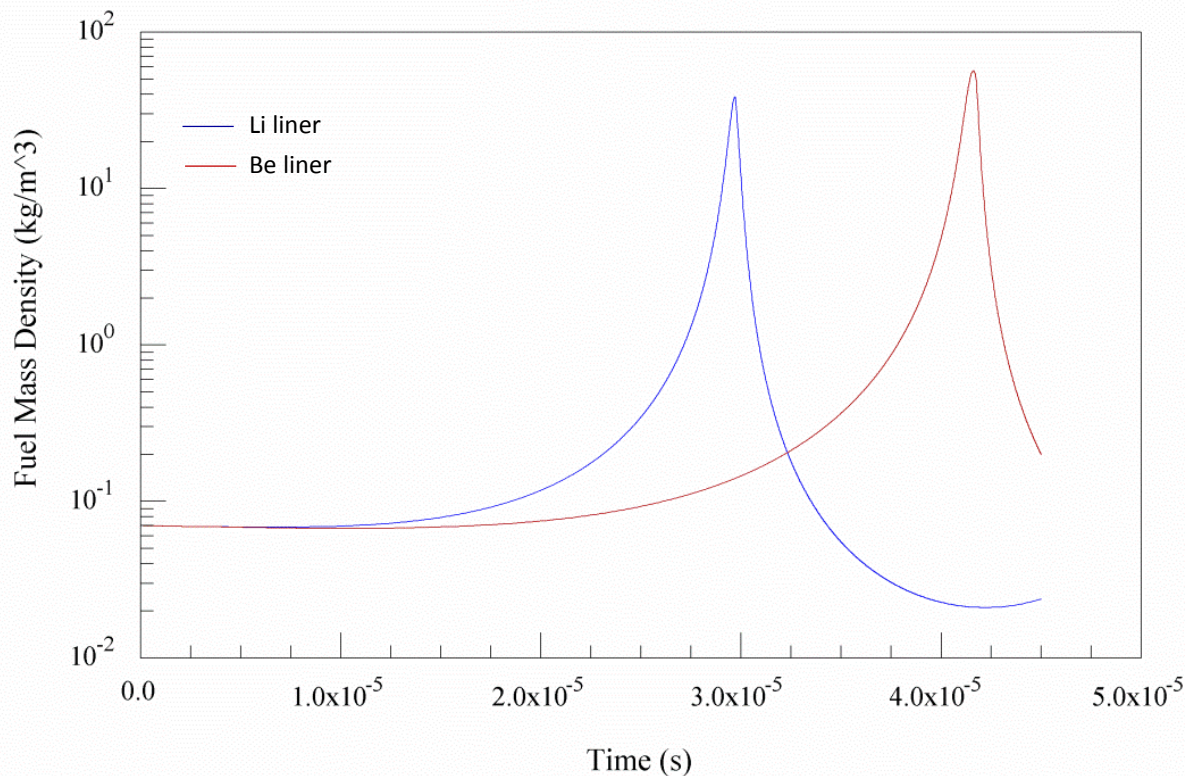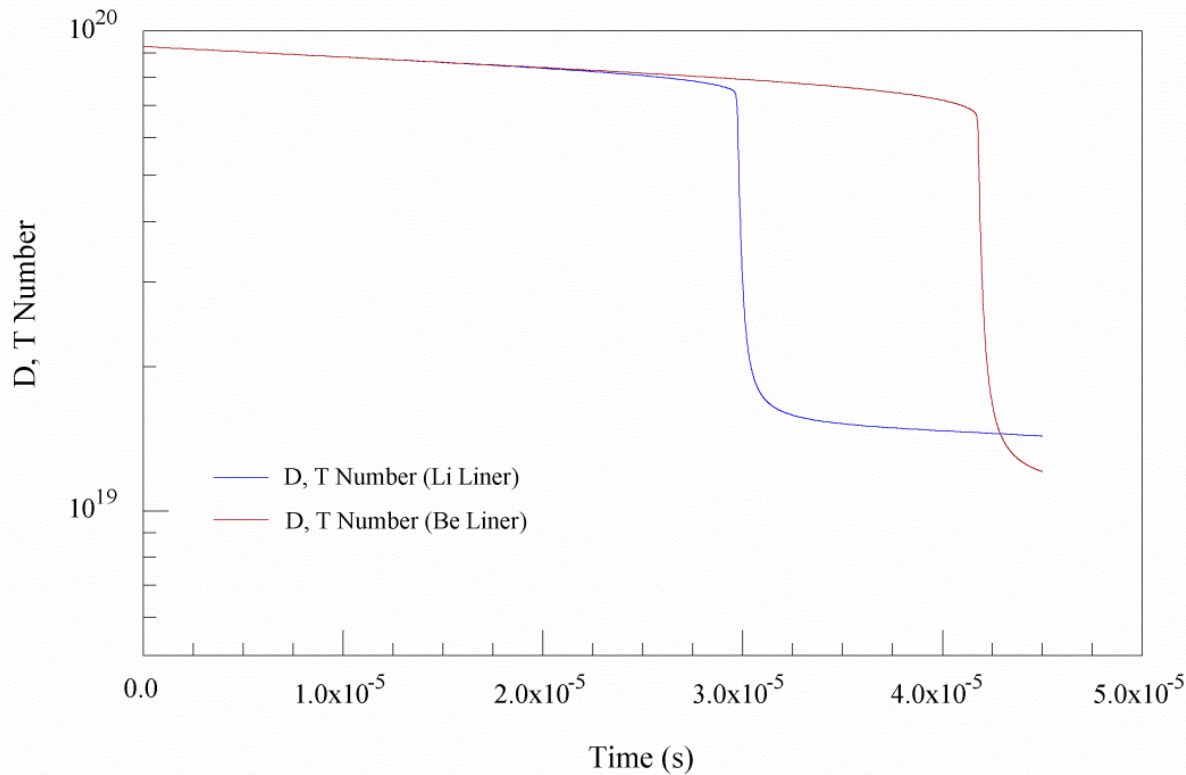
Evolution of fuel mass density with time

Lithium lined D-T target fuel density increases from 0.07 kg/m^3 to ≈ 37 kg/m^3 before target begins to expand

Beryllium lined target fuel density increases to a higher value of 57 kg/m^3 before target begins to expand (higher liner mass to drive compression)
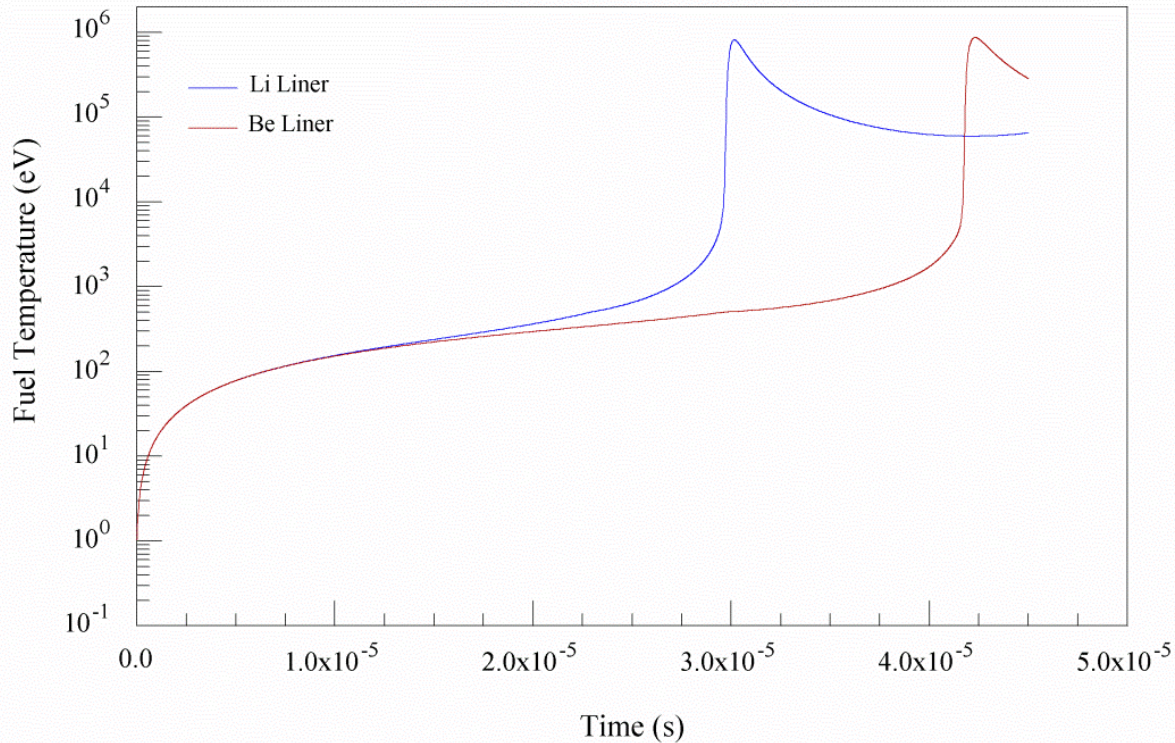
Evolution of D-T ion number with time

Evolution of D-T ions due to fusion and end losses during compression

For a 50:50 mixture of D-T, the evolution of ion number is identical for each species

Fairly rapid initiation and burning of D-T fuel at maximum compression

Evolution of fuel temperature with time

Laser preheating raises Initial temperature from 1 eV to 400 eV, followed by rapid heating due to adiabatic compression

Fusion α-particles trapped within the target contribute to the rising fuel temperature

Includes radiative, thermal conduction losses

Internal fuel pressure eventually exceeds the compressive magnetic force, causing target expansion and cooling
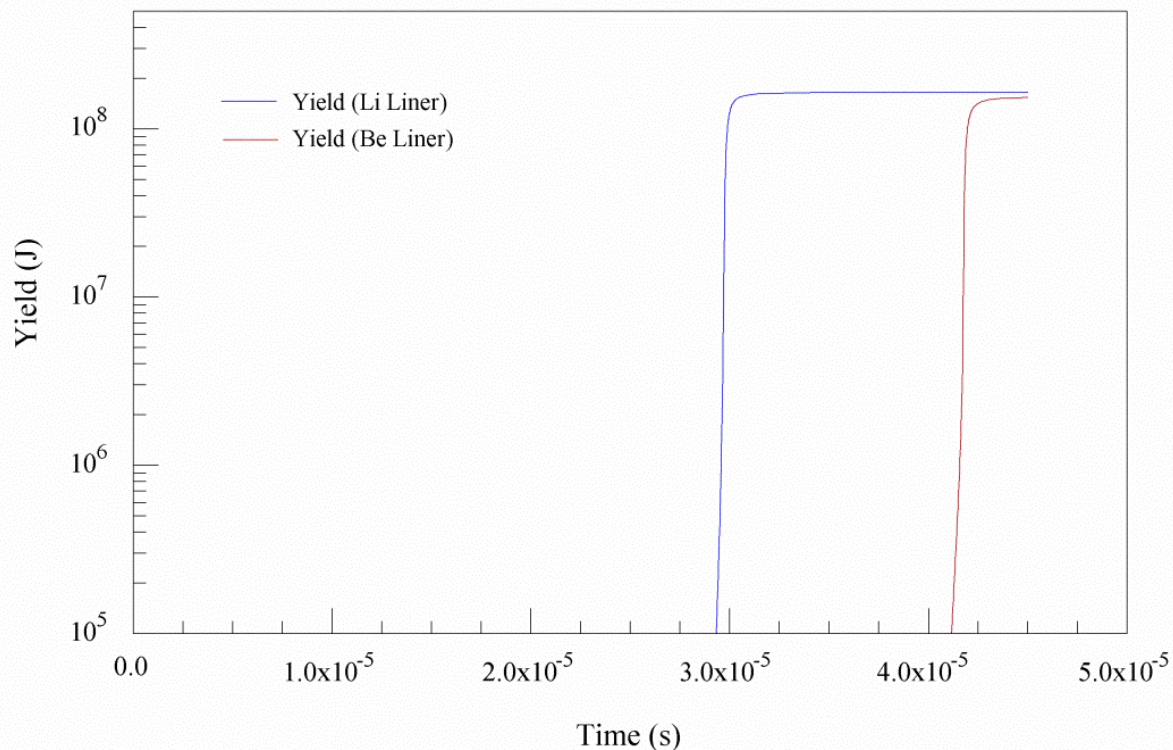
Evolution of cumulative fusion yield with time

Upon ignition, the D-T fuel rapidly generates energy in the form of α-particles and neutrons, with a combined energy release of 17.6 MeV (2.8×10^{-12} J) per fusion event

For sufficiently strong internal magnetic fields, the α-particle energy (3.5 MeV) is deposited in the fuel and contributes to a rapid increase in the fuel temperature
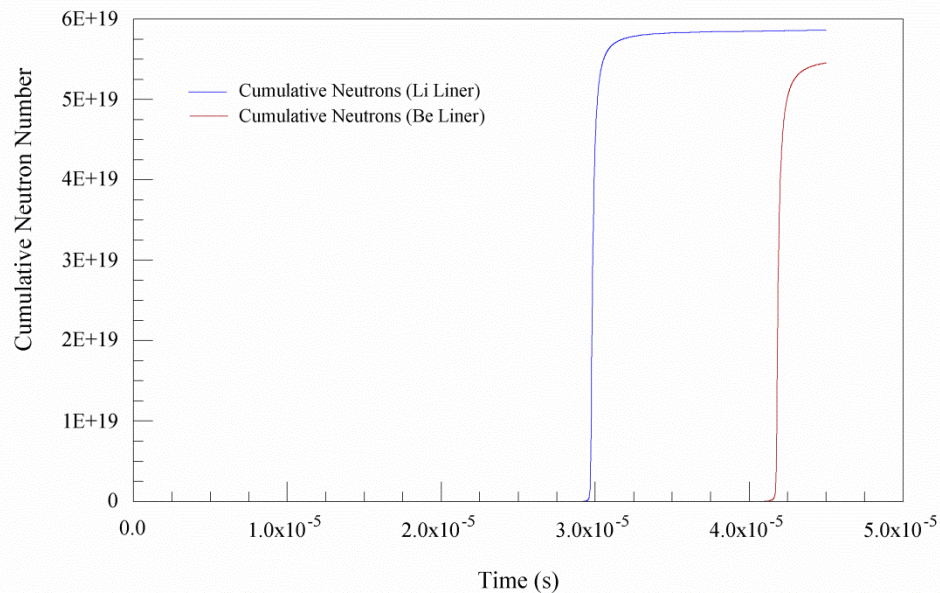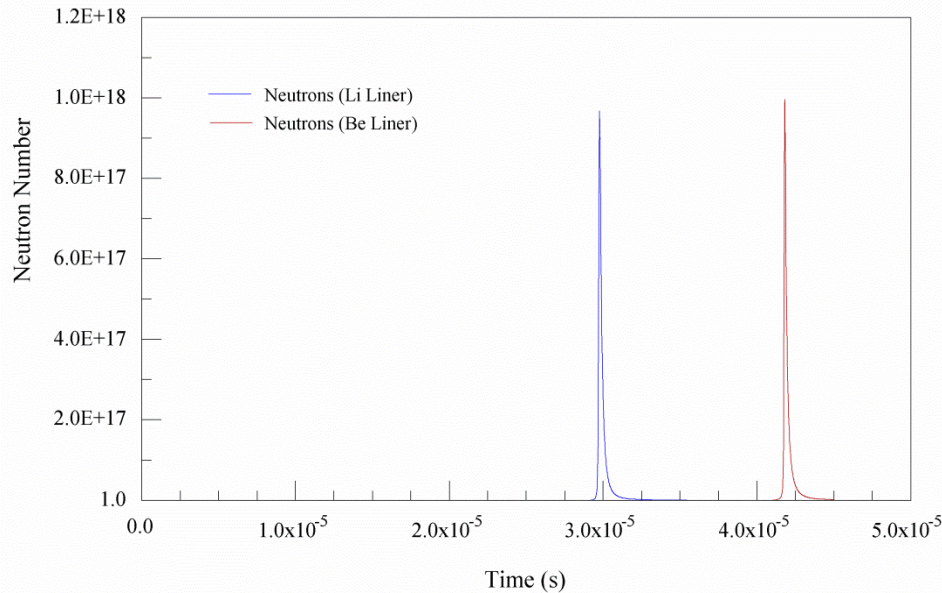
Copious amount of neutrons are produced in each fusion event

- Li target: 5.8×10^{19} neutrons (energy ~ 1.3×10^8 J)

- Be target: 5.4×10^{19} neutrons (energy ~ 1.2×10^8 J)

If not absorbed or reflected by the liner material, the 14.1 MeV neutron may escape the target and impact the surrounding magnet or support structure, depositing energy and causing embrittlement which must be taken into account in vehicle designs

Optimized Parameters

Initial Fuel Density	Initial Target Radius	Aspect Ratio	Injection Velocity	Preheat Fuel Temp	Coil Axial B-Field	Initial Target B-Field	Axial B-field Gradient
0.07 kg/m^3	1.0 cm	6	10 km/s	400 eV	30 T	1.0 T	100 T/m

Corresponding Engine Performance

Specific Impulse (s)		Impulse (N-s)		Yield (J)		Gain (100% efficiency)	
Li Liner	Be Liner	Li Liner	Be Liner	Li Liner	Be Liner	Li Liner	Be Liner
32,200	17,145	780	1445	1.65x10^8	1.53x10^8	982	323

Assumes 70% magnetic nozzle conversion efficiency (plasma energy into directed kinetic energy)

Results are undoubtedly optimistic, but demonstrate potential feasibility with engine performance values of interest for deep space exploration

Rapid Mars Trip with Orion Module and Deep Space Habitat

System	Mass (mT)
Prop Tanks	5.0
Thermal	13.6
Propulsion	75.4
Structural	17.3
Avionics	3.5
Mass Growth Allowance	58.4
Inert Mass	*173.2*
Payload	50.0
Dry Mass	*223.2*
Ullage	1.5
Inert Mass	*224.7*
Propellant	48.5
IMLEO	***271.6***
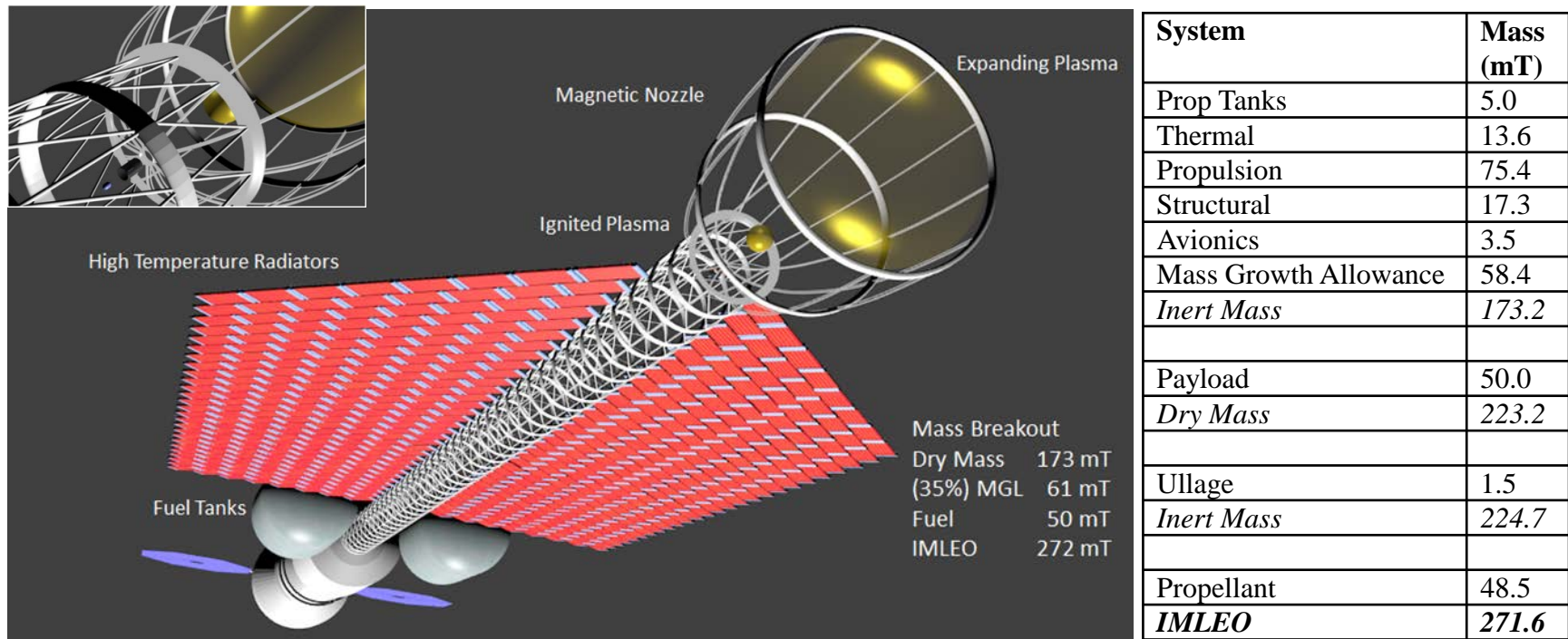
- **Mass parameters based on related prior work:**
  - Adams, R. B., R. A. Alexander, J. M. Chapman, S. S. Fincher, R. C. Hopkins, A. D. Philips, T. T. Polsgrove, et al. 2003. *Conceptual Design of In-Space Vehicles for Human Exploration of the Outer Planets*, NASA-TP-2004-213089.
  - Miernik, J., G. Statham, L. Fabisinski, C.D. Maples, R. Adams, T. Polsgrove, S. Fincher, et al. "Z-Pinch Fusion-based Nuclear Propulsion," *Acta Astronautica,* 82 (2), pp. 173-182, 2013

Based on the equivalent length method of Zola*

- An equivalent length, derived from detailed trajectories over a range of acceleration levels, is essentially invariant to the magnitude of the vehicle acceleration

- This length, together with an assumption of travel in field free space, allows simplified rectilinear analysis of missions

- Provides rapid estimation of mission performance over a wide range of propulsion systems and mission times

- Used with the optimized engine performance values to scope vehicle performance for one way rendezvous missions to Mars and Saturn

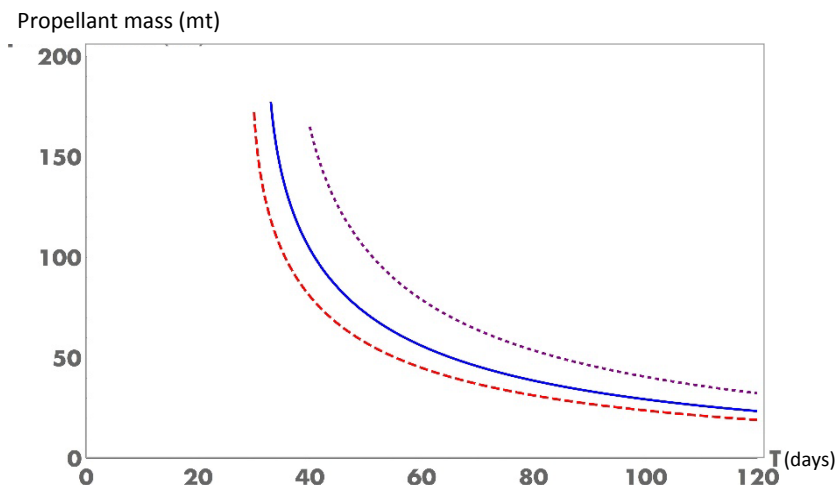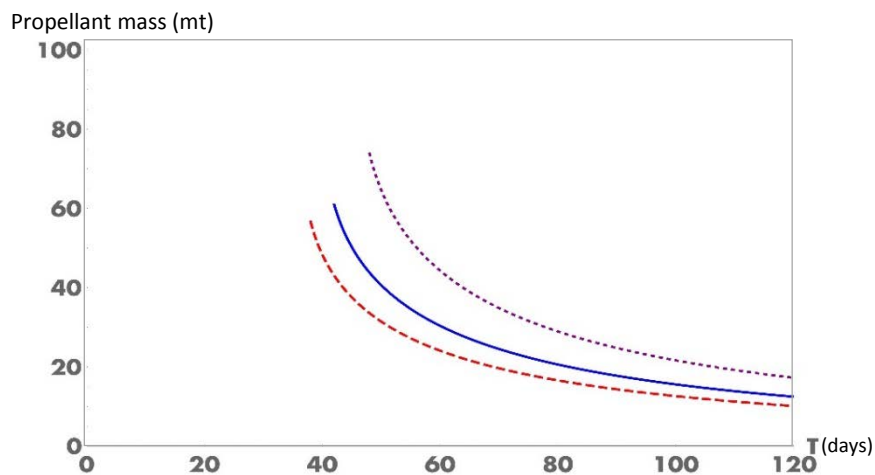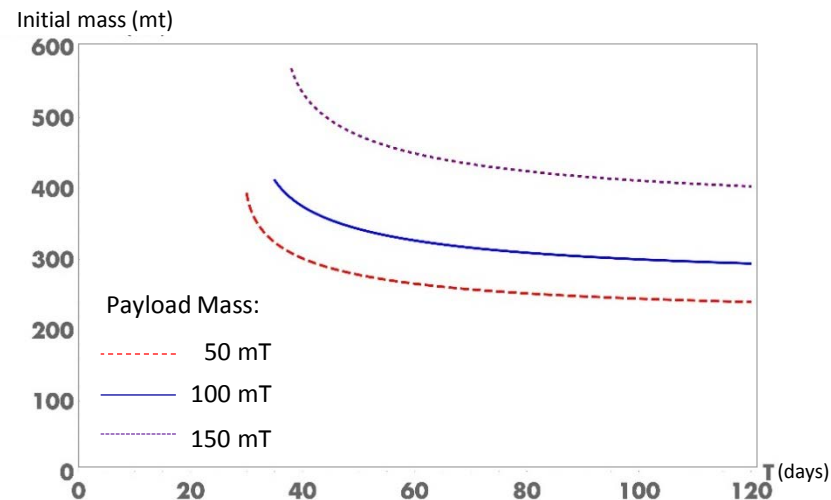| Specific Impulse (s)		Impulse (N-s)		Yield (J)	
Li Liner	Be Liner	Li Liner	Be Liner	Li Liner	Be Liner
32,200	**17,145**	**780**	**1445**	**1.65x10^8**	**1.53x10^8**

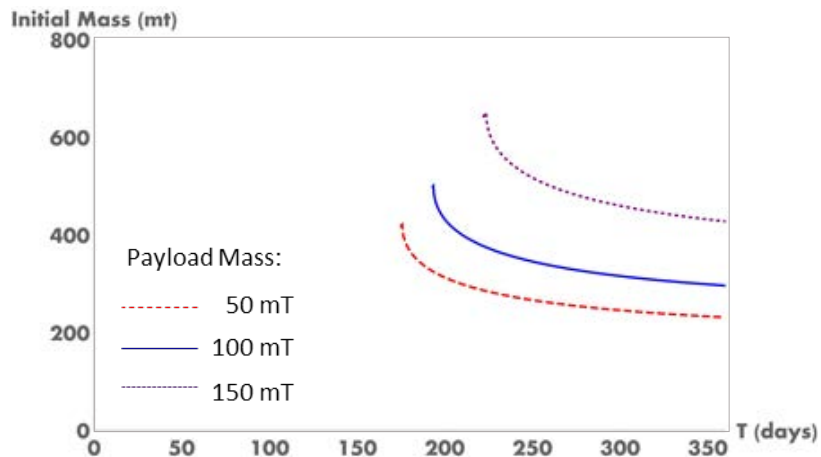*Zola, C., "A Method of Approximating Propellant Requirements of Low-Thrust Trajectories," NASA TN D-3400, Apr 1966*
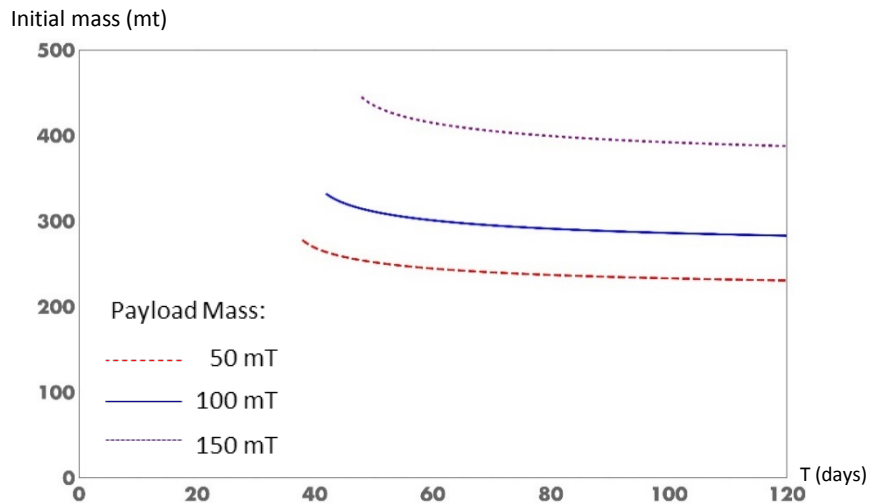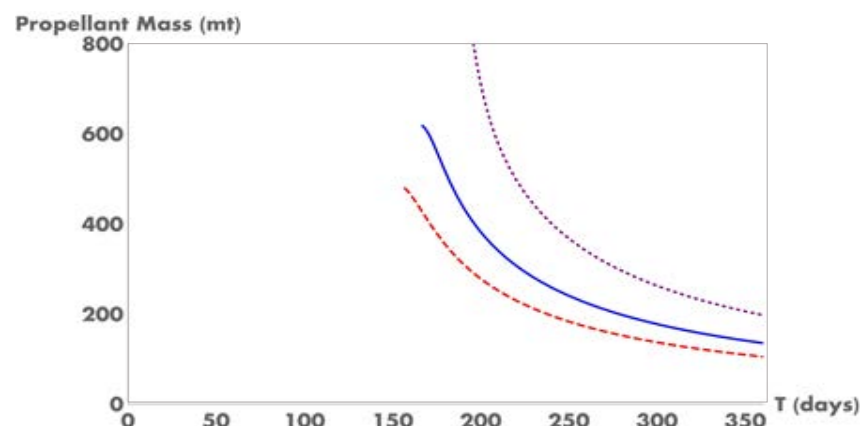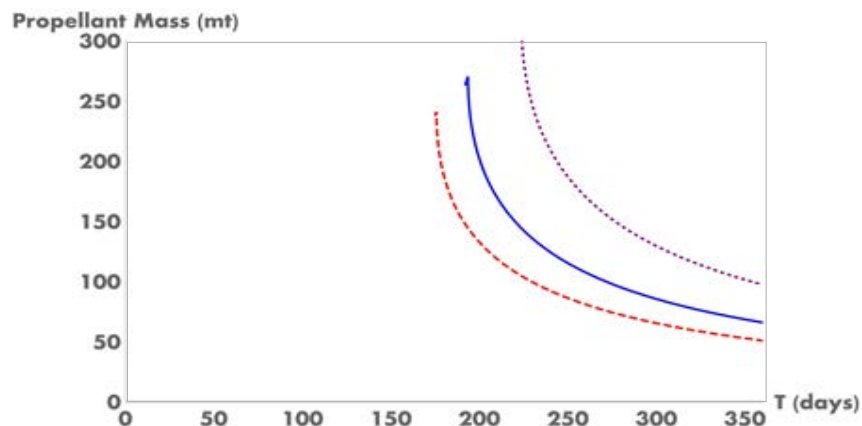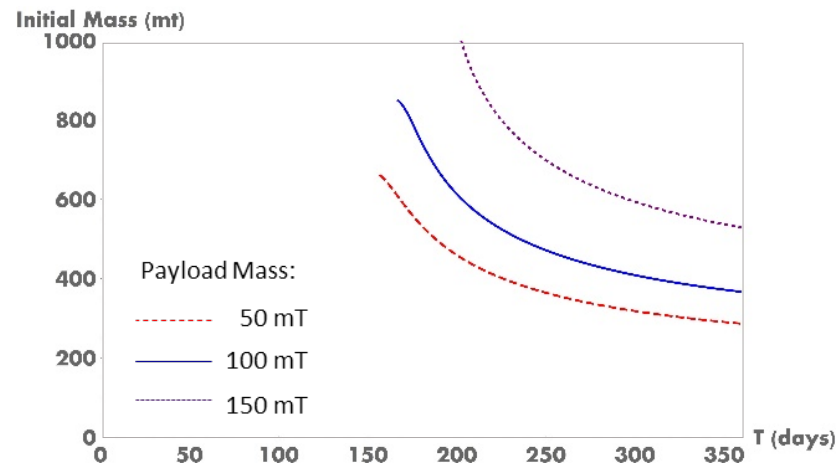
Example: Initial vehicle mass of 320 mT with a 100 mT payload would require 45 days and use 50 mT of propellant for a 1-way trip to Mars using the Li-lined system, and approximately 70 days for the Be-lined system

Example: Initial vehicle mass of 400 mT with 100 mT payload would take 200 days and use 190 mT of propellant for a 1-way trip to Saturn with the Li lined target system, and approximately 320 days with the Be lined target system

Mars:

- Fastest trip times are constrained by the all propulsive limit, in which the vehicle is constantly accelerating for the entire trip
- The required propellant mass rapidly diminishes with longer trip time, to the point that vehicle mass becomes essentially linear with payload mass
- The Be liner case, with lower Isp, can provide somewhat shorter trip times at the cost of essentially twice the propellant mass

Saturn:

- For one way trip times under a year, there is a greater sensitivity of propellant mass due to the higher energy mission requirements
- There is significant benefit in using the Li liner system due to its higher Isp; propellant masses are substantially reduced, while accessible trip times are essentially the same

Detailed 3D simulations with SPFMax

- Smooth Particle Hydrodynamics with Maxwell equation solver developed by UAH to model magnetoinertial fusion physics
  - J. Cassibry, R. Cortez, C. Cody, S. Thompson, and L. Jackson, "Three Dimensional Modeling of Pulsed Fusion for Propulsion and Terrestrial Power Using Smooth Particle Fluid with Maxwell Equation Solver (SPFMaX)," 53rd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2017-4677)

Ground-based experiments to validate models

- Experimentally demonstrate target compression physics
  - 2-stage light gas gun using instrumented hollow or filled projectiles
  - Water cooled coils to generate various magnetic field geometries
  - Accelerate targets into known magnetic fields to evaluate compression and compare with model predictions
- Pulsed laser ablation studies of liner materials
  - Materials on thrust stand illuminated by well characterized laser pulse to evaluate ablative acceleration and material loss

Summary

- The semi-analytic model indicates the concept can generate radial implosion of a lined target similar to more standard MIF devices

- Accelerating the fuel target into a static magnetic field offers benefits for in-space propulsion

- Based on the analytic results, the engine can provide rapid transit for both crew and cargo to solar system destinations of interest for human exploration

- Significant work remains to more accurately simulate the implosion physics and to validate the models with ground based experiments

- Our thanks to the NASA Innovative Advanced Concepts Program for supporting this Phase I study

NIAC Phase I call for proposals will be released in early August
www.nasa.gov/niac