

# Nuclear Propulsion based on Inductively Driven Liner Compression of Fusion Plasmoids

John Slough<sup>1</sup> and David Kirtley  
*University of Washington, Seattle, WA, 98195*

A critical limitation for the exploration and development of space stems from the fact that existing propulsion technology can not achieve cost effective payload delivery due to the low exhaust velocity and specific energy provided by chemical combustion compared to that required for rapid planetary travel. In the propulsion system described here, the optimal velocity and thrust is obtained with a solid propellant that is initially in the form of an assembly of metal rings or liners that are inductively driven both radially inward and axially by electromagnetic coils. The large specific energy required for rapid manned space travel is obtained from the dual use of the metal liners for compression of a magnetized target plasmoid to fusion conditions as well as a propellant. With an inductively driven, axially segmented metal liner a fully three dimensional target compression can be realized. This permits a wider range of fusion reactions including D-T, D-D and D-<sup>3</sup>He that can be employed to provide for efficient coupling of the fusion energy into propulsion and electricity. During the fusion burn, the drifting liner is rapidly heated by fusion products, plasma radiation and Ohmic heating that powers a rapid re-expansion of the liner. With the liner at this point having drifted into a divergent magnetic field, the liner expansion is reacted against the ambient magnetic field causing flux compression which provides for a direct method for extracting the electrical power via the back emf experienced by the magnetic field coils. The divergent field geometry also acts to convert any remaining liner thermal energy into directed thrust at high Isp. An analysis of the conditions required for unity gain fusion as well as other possible embodiments for the fusion based thruster will be presented.

## Nomenclature

D- <sup>3</sup> He	=	Deuterium – Helium fusion reaction
FRC	=	Field Reversed Configuration
Isp	=	specific impulse (s)
LC	=	circuit comprised of Inductor and Capacitor
MHD	=	Magneto-Hydrodynamics
M <sub>L</sub>	=	Liner mass (kg/m)
NTR	=	Nuclear Thermal Rocket
P	=	plasma pressure (Pa)
Q <sub>fus</sub>	=	ratio of fusion energy production to fusion plasma energy loss
T <sub>i, iavg</sub>	=	Ion or average ion temperature (eV)
v <sub>d,r</sub>	=	directed velocity, radial velocity (m/s)

## I. Introduction

**T**HE future of manned space exploration and development of space depends critically on the creation of a dramatically more efficient propulsion system for lifting payloads into orbit as well as in-space transportation. This has been recognized for many years. In response, various rocket and turbine based air breathing concepts have been proposed for future launch propulsion systems. While SCRAM jets and ram rockets do improve the efficiency,

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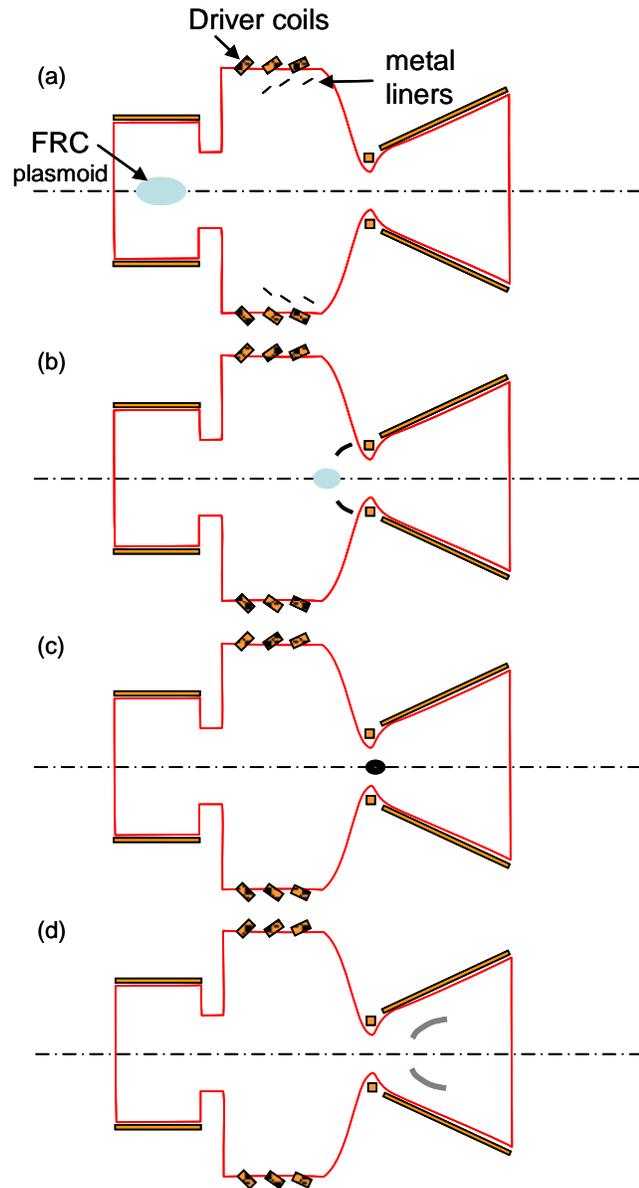
<sup>1</sup> Department of Aeronautics and Astronautics, Box 352400, AIAA Member

they are essentially bound by the same limitations of current rockets. These propulsion concepts have only limited or no applicability in space transportation.

A very persuasive reason for investigating the applicability of nuclear power in rockets is the vast energy density gain of nuclear fuel when compared to chemical combustion energy. The combustion of hydrogen and oxygen has an energy release of 13 MJ/kg, whereas the fission of  $^{235}\text{U}$  yields approximately  $8 \times 10^7$  MJ/kg and the fusion of deuterium and a helium has a  $3.6 \times 10^8$  MJ/kg yield. So far, the use of fission energy represents the nearest term application of nuclear power for propulsion. Several fission based propulsion schemes have been proposed for in-space transportation, including pulsed nuclear explosions and the Nuclear Thermal Rocket (NTR)<sup>1</sup>. NTRs have the highest applicability. Fusion-electric will be taken up later, and nuclear explosions need no discussion.

In the NTR a cooling fluid or propellant is passed through a core of material that has been heated by fission. This makes the NTR effectively a heated gas rocket. Since the NTR is a heat transfer rocket, the propellant can be selected to maximize performance of the propulsion system. With the present limitations of materials, NTR gas temperatures cannot exceed chemical propulsion gas temperatures but the use of a low molecular mass propellant provides for an exhaust velocity much greater than that of chemical rockets. The use of hydrogen provides for an increase in Isp from  $\sim 300$  s for a high Isp chemical rocket to 900 s for an NTR based on the particle bed reactor (PBR)<sup>2</sup>. With  $\Delta v \sim 9$  km/sec the propellant mass is reduced by an order of magnitude for a given spacecraft mass. This is somewhat offset by spacecraft mass (payload, structure, avionics, tankage etc.) increases due to the increase in tank mass required for the low mass density propellant ( $\text{H}_2$ ). The specific gravity of liquid hydrogen is around 0.07, compared to 0.95 for an  $\text{O}_2\text{-H}_2$  chemical engine.

Fusion nuclear, at least in the form that the world has pursued with the vast majority of its research investment – the tokamak - is wholly inappropriate for space transportation. A primary reason is that the principle objective of the current fusion effort is the generation of electric power in the form of multi-GW<sub>e</sub> power stations. The threshold size of a steady state, D-T based fusion reactor to achieve the required power for ignition, while maintaining safe, protective shielding is quite large. This has driven the scale, capital costs and time for developing fusion power to levels that are well beyond what would



**Figure 1. Schematic of one embodiment of the inductively driven segmented liner compression of a magnetized plasmoid for propulsion.** (a) Metal liner material is driven at the proper angle and speed for convergence onto target plasmoid at thruster throat. Target FRC plasmoid is created and injected into liner chamber. (b) Target FRC is compressed by axial magnetic field from liner driver coils as it translates through chamber eventually stagnating at the thruster throat. (c) Target FRC compressed to fusion conditions by converging liner segments. (d) Re-expansion of the fusion heated liner material and fusion products does work on axial magnetic field of the expansion chamber resulting in the generation of electricity and the directed flow of the liner material out of the thruster.

appropriate for propulsion. The straight forward application of a reactor-based fusion-electric system creates a colossal mass and heat rejection problem for space application. In a detailed analysis for the most compact tokamak concept, the spherical torus, spacecraft masses of 4000 MT were projected<sup>3</sup>. The maximum launch mass would need to be less than 200 MT if current chemical rockets are used for launch to LEO.

A practical path to fusion propulsion can only be achieved by creating fusion conditions in a different regime at much smaller scale. For small scale fusion systems, such as the inductively driven, metal liner fusion based on the magnetic compression of plasmoids considered here, the possibility of a near term application to propulsion becomes feasible<sup>4</sup>.

The fusion concept to be described here takes advantage of the very compact, high energy density regime of fusion employing a compact toroidal plasmoid commonly referred to as a Field Reversed Configuration (FRC)<sup>5</sup>. The liner driven compression of the FRC has several attractive features for space propulsion applications. This particular system can be made electrically very efficient, which allows for operation at the lower fusion gain appropriate for space propulsion, and minimizes the radiator mass required for heat rejection. The reactive expansion of both the liner and FRC plasmoid after fusion burn provides for a mechanism to extract electrical power for the driver. This direct conversion of thermal energy is accomplished via the electromotive force that is produced from flux compression driven by the plasma liner expansion. The exhausting of the fusion heated liner through a magnetically insulated nozzle provides for efficient conversion of the fusion particle energy as well as the radiation and remnant liner thermal energy into directed propulsive power at high thrust. A description of what is entailed in this process will now be discussed.

## II. Inductively Driven Liner (IDL) Fusion

To employ fusion energy as the power source, the requirements for achieving and confining a fusion plasma must be met as well as an efficient mechanism for converting the fusion energy into directed propulsive energy flow. The exhausting of the fusion plasma alone would not be a suitable propellant due to the mismatch in optimum velocity for planetary travel ( $v_d \sim 10\text{-}30$  km/s). A 10 keV fusion ion would have a directed velocity of  $v_d \sim 10^3$  km/s which is far in excess of that desired. With a nuclear electric propulsion (NEP) system, while the production of the plasma propellant could be made efficient, a very large reactor and radiator mass would be required since the conversion of the energy of the fusion products into electric energy via a conventional thermal cycle is quite inefficient ( $\sim 35\%$  at best). In fact, the radiator mass (typically  $>10$  kg/kW) dominates the mass of NEP systems.

What is proposed here is a system that can provide for the direct conversion of the fusion energy into the propellant flow at the desired range of thrust and Isp, as well as provide a method for the direct production of the electric power needed for the generation of the fusion plasma and the magnetically driven acceleration of the liner. The overall description of the IDL fusion propulsion system is found in Fig. 1. The plasmoid to be compressed is introduced via an axial guide magnetic field. The proper initial field, density, and temperature for the plasmoid is determined by the requirements for fusion gain as well as the range of compression to be achieved. It is believed that the initial plasma requirements will be no greater than what can be accomplished currently in the laboratory.

The method for achieving fusion conditions at high energy density is to employ the kinetic energy of a significantly more massive liner to compress the target plasmoid to high density and temperature. The energy density of the fusion plasma system considered here is intermediate between the typical Magnetic Fusion Energy (MFE) regime of the tokamak and Inertial Confinement Fusion (ICF) driven by an array of lasers. As such it is potentially a much better match for efficient power conversion. For the liner based systems, the achievement of fusion gain is a hybrid of both MFE and ICF in that the presence of the magnetic field in the target plasma suppresses the thermal transport to the confining shell, thus lowering the imploding power needed to compress the target to fusion conditions. Unlike MFE, the confinement time is not determined by the energy confinement of the magnetized plasma, but instead by the liner dwell time

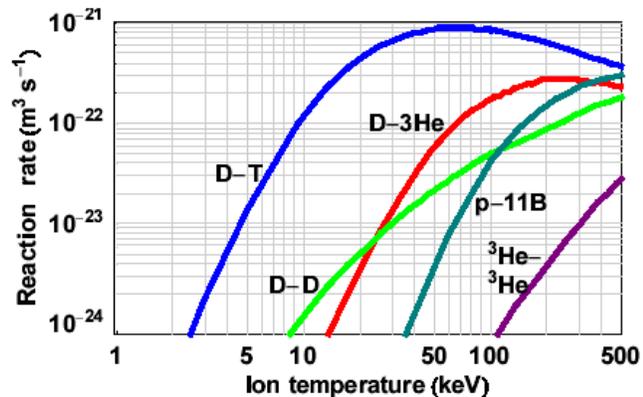


Figure 2. Fusion reaction rate for various reactions as a function of the ion temperature.

determined by the liner inertia. This area of fusion research has thus been dubbed Magneto-Inertial Fusion, or MIF.

Certainly MIF has favorable advantages in terms of reactor power density and size, but technological challenges and low driver efficiencies can easily remove these advantages if care is not given to the regime in which MIF is to be employed. It would be hard to argue that it is not of paramount advantage to employ a closed field line plasma that has intrinsically high beta, and can be readily translated and compressed as the primary target plasma for MIF. Of all fusion reactor embodiments, only the FRC has the linear geometry high plasma  $\beta$ , and closed field confinement required for magnetic fusion at high energy density. Most importantly, the FRC has already demonstrated the confinement scaling with size and density required to assure sufficient lifetime to survive the compression timescale required for MIF over a wide range of conditions. Therefore the target plasma for the IDL fusion engine considered here will be an FRC plasmoid. It is worthwhile to give a short analysis of a ‘‘Lawson criteria’’ for MIF with an FRC target in order to appreciate the trade-offs between different regimes, and to understand why the IDL is a good match for propulsion applications.

For this analysis cylindrical symmetry will be assumed with the primary confining field the axial magnetic field (a prolate FRC). For the FRC in this geometry the plasma pressure is equal to the external magnetic field pressure. It will also be assumed that the plasma density is adjusted so that at maximum compression the plasma ion temperature is  $\sim 60$  keV. At this ion temperature the fusion cross section for D-<sup>3</sup>He reaction is similar to that for the D-T reaction at 10 keV (see Fig 2), and at the same time have a significantly larger cross section than D-D to minimize neutron generation. From radial pressure balance one has:

$$n_0 = \frac{B_0^2}{2\mu_0 kT} = 4.1 \times 10^{19} B_0^2, \quad (1)$$

where the zero subscript indicates values at peak compression. It will be assumed that the liner is incompressible and that the liner radial implosion kinetic energy per unit length,  $E_k$ , is transferred into compression of both the FRC and axial magnetic field energy with no losses, i.e.:

$$E_k = \frac{1}{2} M_L v_L^2 = \frac{B_0^2}{2\mu_0} \pi r_0^2. \quad (2)$$

where  $M_L$  is the liner mass per unit length. The liner dwell time,  $\tau_D$ , is characterized by the terminal liner velocity,  $v_L$ , and the minimum liner radius,  $r_0$ ,

$$\tau_D \sim \frac{2r_0}{v_L}. \quad (3)$$

Using Eq. (2) to solve for  $v_L$ , one has for the criteria for fusion breakeven for the FRC based MIF:

$$n\tau \sim n_0 \tau_D = 2.6 \times 10^{16} M_L^{1/2} B_0. \quad (4)$$

There are several notable conclusions one can draw from this expression. First, there is no explicit dependence on the liner material, its density or conductivity. More significantly, there is no explicit dependence on size. There can thus be a very wide range of liner masses and materials that could be employed to achieve fusion gain. There are of course hidden implications and dependencies that need to be elucidated once a liner velocity and mass are chosen, but there have in fact been a wide range of liner implosion schemes that have been proposed in the past that support the general relationship expressed in Eq. (4)<sup>6</sup>. On the high mass end, one has slow liner concepts with the LINUS reactor<sup>7</sup> as a prominent example. Here  $M_L$  was  $2.7 \times 10^3$  kg/m. The liner served as the fusion blanket, and the liner was rotated for stability and to provide for repetitive operation. The principle issue became the long timescale for compression ( $t_{\text{comp}} \sim 30$  msec) which made a suitable plasma target difficult to sustain during compression. At the other end of the spectrum there is the plasma liner where the liner mass can be as low as of  $10^{-2}$  kg/m<sup>8</sup>. With the momentum flux being delivered by a low mass, but high velocity imploding plasma shell, many of the difficulties encountered in imploding a solid metal liner would be eliminated or minimized. Melting and vaporization of the liner are significant issues at higher magnetic field compression. This is not an issue for a plasma liner, but it can easily be a limiting factor for solid liners. The issue for the plasma liner is the low inertia of the plasma. Intermediate to these is the MTF device ( $M_L \sim 1$  kg/m) now being actively investigated at LANL<sup>9</sup> and AFRL<sup>10,11</sup>. It is worth noting that all three approaches can and do employ the FRC as the target plasma for compression.

To take advantage of this smaller scale, higher density regime of MIF fusion, an efficient method for achieving the compressional heating is required to bring the conventional FRC to fusion gain conditions. This method needs to

be simple and capable of repetitive operation. The conversion of fusion energy into useful electrical energy can be made considerably more difficult by the large kinetic energy required to implode the liner. The subsequent rapid and large energy yield from the fusion burn makes repetitive operation very challenging. Clearly a compression scheme that minimizes the liner kinetic energy required to reach fusion gain would be of tremendous advantage. Previous analysis has shown that it may be possible to accomplish this at sub-megajoule energies<sup>12</sup>.

To have a realistic hope of inexpensive, repetitive operation, it is imperative to have the liner kinetic energy no more than a few megajoules which allows for the survivability of nearby coils, walls, or power systems. At small scale, the implosion speed must be reasonably fast to maintain the FRC equilibrium during compression. These additional considerations all imply that a relatively thin liner will be optimal. For a thin solid liner there is an additional constraint due to joule heating of the liner. Vaporization of the liner during implosion significantly increases the liner resistance and dramatically reduces its ability to trap and compress the magnetic field. It was first pointed out by Cnare in his landmark foil compression experiments<sup>13</sup> that this process limits the ultimate liner velocity that can be attained. The material properties relating to this heating (electrical conductivity, melting point, heat capacity, etc.) can be characterized by a parameter  $g_{\text{mat}}$  defined by the “action integral”:

$$v_m \propto \int_0^{t_m} I^2 dt = g_{\text{mat}} A^2 \quad (6)$$

where  $I$  is the liner current flowing through the material cross-sectional area,  $A$ , in the direction of current flow. Normalizing to the action constant for the vaporization of aluminum from 300 °K one has for the maximum velocity:

$$v_m = 7 \times 10^{10} g_{\text{Al}} \frac{\delta_L}{\rho_L}, \quad (7)$$

where  $\rho_L$  is the liner material density and  $\delta_L$  is the liner thickness. As a point of comparison, copper has a value of  $g_{\text{Al}} = 1.8$  in relation to aluminum. It should be noted here that this value was obtained for liner currents in the theta ( $\theta$ ) direction. Typically an axial ( $Z$ ) current is employed to drive the liner as it is deemed to be easier and allows for liner drive to small radius. It should be noted however that there are several advantages to inductive drive using a  $\theta$ -pinch coil rather than a  $Z$ -pinch. With the  $\theta$ -pinch the liner currents are isolated electrically from the driver circuit. Without electrical contacts, the experimental apparatus and vacuum system can be greatly simplified. Difficulties with the post implosion structural integrity of the thruster are also much easier to avoid. With no electrode contacts to maintain, repetitive operation over long periods is now feasible. Recuperative energy techniques are also possible as the driving circuit remains intact providing for a means to recover unutilized magnetic energy, and thereby significantly increase the overall driver energy efficiency. It is also much easier to produce shaped liner implosions for additional axial (3D) compression as well net liner motion. Both of these features are essential to the fusion approach described here. High compression magnetic fields can be obtained even with a poorly optimized compression bank. The megagauss fields produced in the Cnare experiments were obtained with a theta pinch compression employing a 100 kJ bank with a very large stray inductance.

From Eq. (4) it is clear that having a high liner velocity is important, so that it will be assumed that the liner velocity  $v_L$  is close to the maximum velocity consistent with melting. Also from Eq. (4) it can be seen that the last critical parameter for maximizing the fusion gain is achieving the minimum radius which is a reflection of the liner driver parameters. The determination of the minimum radius will now be considered.

### Magnetic Field Compression

With the use of a theta pinch to drive a relatively thin metal liner there is a hidden benefit in that the seed compression field is provided from flux leakage through the liner during the initial stages of acceleration. With the initiation of the  $\theta$ -pinch current the field rises rapidly in the small radial gap between the external coil and the liner as the liner acts to shunt almost all of the coil inductance. A large driving field is developed, and this external field then diffuses into the cylinder with a characteristic diffusion time given by:

$$\tau = \frac{1}{2} \mu_0 r_L \delta_L \sigma_L \quad (8)$$

where  $r_L$  is the initial (inner) cylinder radius, and  $\sigma_L$  is its electrical conductivity. The diffusion of the field is then governed by the equation:

$$\tau \frac{dB}{dt} = B_{\text{ext}} - B \quad (9)$$

For a simple radial compression the dynamics of the liner implosion are then governed by the equation:

$$M_L \frac{d^2 r}{dt^2} = \left( \frac{B^2}{2\mu_0} - \frac{B_{\text{ext}}^2}{2\mu_0} \right) 2\pi r \quad (10)$$

An approximate analytical solution to this equation was obtained as well as a numerical solution<sup>14</sup>, with the result being a close match to the results of the Cnare experiments. An expression for magnetic field at minimum radius attained at maximum compression was derived from the equation of motion Eq. (10). Stated in terms of experimentally relevant quantities, it is

$$B_m = \frac{\mu_0^2}{2\sqrt{7}} \frac{V_c \delta_L \sigma_L}{L_{\text{tot}}} (1 + \varepsilon^2)^{-1/2}, \quad (11)$$

where  $L_{\text{tot}}$  is the total driver circuit inductance including stray, and  $V_c$  is the charge voltage on the capacitor bank,  $\sigma_L$  is the liner conductivity, and  $\varepsilon$  is the initial coil (liner) length to diameter ratio ( $l_c/2r_c$ ). For a properly designed driver circuit, the coil inductance will be the dominant inductance with  $r_c \sim r_L$  and  $l_c \sim l_L$ . For this case

$$L_{\text{tot}} = K_L \mu_0 \frac{\pi r_c^2}{l_c} \cong K_L \mu_0 \frac{\pi r_L^2}{l_L} \quad (12)$$

The correction for finite length  $K_L$  can be approximated by  $1/2 (l_L/r_L)^{1/2}$  for short liners. For  $l_L = 0.5r_L$ , one has then  $L_{\text{tot}} = 1/\sqrt{2} \mu_0 \pi r_L$ . Substituting these values into Eq. (11) one has:

$$B_0 = 1.0 \times 10^{-7} \frac{\delta_L \sigma_L V_c}{r_L}. \quad (13)$$

The liner mass per unit length can be restated in terms of the liner material density  $\rho_L$ :  $M_L = 2\pi r_L \delta_L \rho_L$ . Substituting this expression and Eq. (12) into Eq. (4) yields:

$$n_0 \tau_D = 6.5 \times 10^9 \delta_L^{3/2} \sigma_L V_c \left( \frac{\rho_L}{r_L} \right)^{1/2}. \quad (14)$$

It is clear that the fusion gain is most easily increased by employing a thicker, denser liner, however it must be tempered by the consideration that the larger the liner mass, the greater the energy release and collateral impact will be on the fusion system. Another consideration in determining suitable liner parameters comes from the desire to have a sufficiently high liner exhaust velocity from the system. While the fusion particle and radiation energy imparted to the liner is available to increase the liner directed energy in the nozzle, the desire is to extract a good portion in the form of electrical generation. The liner exit velocity is thus likely to be no more than double the entrance velocity. Taking an initial liner speed of 3 km/sec liner speed is a reasonable minimum. Equation (7) can now be used to eliminate liner mass density of the liner in Eq. (14):

$$n_0 \tau_D = 3.1 \times 10^{13} \delta_L^2 \sigma_L V_c \left( \frac{g_{Al}}{r_L} \right)^{1/2} \quad (15)$$

There are potentially several metals that could be employed as the liner, and the most promising are tabulated in Fig. 3. Not surprisingly, Aluminum is a strong contender. It has a maximum velocity for a given liner thickness that is second only to Beryllium, which would be a rather exotic, expensive, and difficult material to be employed as propellant in any case. The relatively strong dependence on conductivity also favors a good conductor such as Aluminum.

At this point it is useful to see what reasonable and conventional values of these parameters would yield. Recalling the relation stated in Eq. (15) was derived assuming an ion temperature where  $D\text{-}^3\text{He}$  cross section is similar to that for  $D\text{-}T$  reaction at the conventional 10 keV of MFE. Thus an appropriate target value for a  $Q \sim 1$  would be  $n_0 \tau_D \sim 10^{20} \text{ m}^{-3}\text{-s}$ . Assuming then an Aluminum liner driven by a driver coil with an applied voltage of  $\pm 40 \text{ kV}$  on a coil of 0.5 m radius - the same being developed at the FRC facility at the University of Washington - one can infer from Eq. (15) a minimum liner thickness with the result that  $\delta_L = 1 \text{ mm}$ . Recalling the full liner aspect ratio being 0.25 one finds that the total liner mass is 2.1 kg. The initial kinetic energy of the liner for the 3 km/s velocity

is ~ 10 MJ. All are feasible numbers with some headroom for gain increases from thicker, faster liners albeit at higher net liner and fusion energy yields.

### III. Discussion and Conclusion

While the overall concept envisioned with the IDL fusion outlined here appears feasible, there are still many elements that need to be resolved to make it practical. Some obvious ones are the stability of the post-fusion, expanding liner. To avoid stability issues and liner breakup it will be essential to add a rotational momentum to the liner during launch and convergence. There are some thoughts on how to impart this momentum from rotating barrier fields. There is also the issue of introducing the new liners into the system for each pulse. Assuming a 10-20 MJ of directed energy per pulse, a rep rate of 1 Hz would provide thrust power sufficient for most manned missions. A slower rep rate at higher energy yield would make mechanical insertion much easier as the liners would also be thicker. For high rep rate one is led to consider creating the liners by a spray condensation from a liquid phase. This would be easiest for Lithium or Aluminum. Another possibility is to form the liner from an array of smaller components. This has actually been investigated in another concept referred to as Macron Initiated Liner Fusion (MLF)<sup>15</sup>. MLF has the advantage of accelerating the liner elements from simple coil guns. The uniformity of the liner is a concern with this method, but preliminary modeling and calculations look quite favorable in this regard.

Among other considerations to be evaluated is the fusion cycle. The liner thickness at peak compression for the conditions stated above would yield a radius of ~ 6 cm, assuming liner trajectories that lead to a final spherical convergence for the liner. Achieving the fusion same conditions with a lithium liner, the liner thickness at peak compression would be ~ 9 cm which is approaching the mean free path for neutron adsorption ( $1/\Sigma_{\text{tot}} \sim 14$  cm). With a somewhat thicker liner it would then be possible to adsorb a significant fraction of the fusion neutron energy directly into the liner from either the D-T or D-D fusion cycles. It would thus be possible to employ these neutronic fusion fuel cycles. As with charged particle fusion products, the fusion energy is deposited in the liner and is converted through liner expansion pressure into either electricity or directed energy. The most significant issue with D-T cycle comes from obtaining sufficient tritium for long planetary missions. The world's reserves are mainly accumulated from tritium production in CANDU fission reactors. The continuous operation of a 20 MW thruster would require roughly 2 kg/yr of T which would not seriously deplete the supply of roughly 30 kg. There are also other issues such as cost and possible handling concerns from such a highly radioactive fuel. With D-D fusion there is certainly no problem in obtaining an adequate supply or any issues as a biohazard. This makes pure Deuterium the most promising fuel as <sup>3</sup>He is rare on earth and must be mined on the Moon or Mars, or collected from the atmospheres of the gas giants. This however may actually not be as daunting a task once planetary travel is routine. In the meantime it could well be that IDL fusion based on the D-D reaction will provide the best solution for both manned space travel as well as domestic energy production.

In conclusion, an analysis of IDL fusion compression of magnetized plasmoids shows promise for direct application to planetary space propulsion. Several types of liners and fusion reactor topologies are feasible and a range of liner "propellants" have been found to

have applicability with each having specific technical strengths and weaknesses. The IDL based fusion concept would provide for direct fusion power at high efficiency and relatively low power. Specifically, it would enable 10<sup>7</sup>s of MW of thrust power employing only deuterium fuel together with a solid lithium propellant at specific impulses relevant for rapid manned interplanetary space travel.

Element	Current Intgrl.	Ratio to Al	$v_{\text{max}}/\delta$ (m/s)	Ratio to Al
Ag	1.53E+17	1.51	9.19E+06	0.39
Al	1.01E+17	1.00	2.37E+07	1.00
Al (6061)	1.07E+17	1.05	2.49E+07	1.05
Au	1.39E+17	1.37	4.53E+06	0.19
Be	9.24E+16	0.91	3.15E+07	1.33
Cu	<b>2.33E+17</b>	<b>2.30</b>	1.64E+07	0.69
Li	1.36E+16	0.13	1.61E+07	0.68
Na	1.19E+16	0.12	7.70E+06	0.33
Pb	5.79E+15	0.06	3.21E+05	0.01
Mg	2.20E+16	0.22	7.95E+06	0.34

Figure 3. Candidate materials for liner.

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