Mission Design Architecture for the Fusion Driven Rocket

Anthony P. Pancotti, John T. Slough, David E. Kirtley, Micheal Pfaff, Christopher Pilh, George Votroubek
MSNW LLC, Redmond, WA, 98052

The future of manned space exploration and development of space depends critically on the creation of a dramatically more proficient propulsion system for in-space transportation. This has been recognized for many years, creating a persuasive reason for investigating the applicability of nuclear power in rockets. Nuclear fuel contains energy densities that dwarf the energy of any chemical combustion. However, many such nuclear based propulsion system are not truly feasible as space-based sytems due to size, complexity, cost, or potential hazard. The Fusion Driven Rocket (FDR) described in this work offers a realistic approach to fusion propulsion systems. FDR allows for direct energy transfer to the propellant requiring no conversion to electricity. Addtionally, the propellant requires no significant tankage mass by being a solid, yet can still be rapidly heated and accelerated to high exhaust velocity (> 20 km/s). But perhaps most importantly, unlike many other fusion and fission concepts, there is no significant physical interaction with the spacecraft thereby limiting thermal heat load, spacecraft damage, and radiator mass. This paper will discuss the basic physics of the FDR and the fusion method employed as well as focus on in-depth analysis of the mission architectures enabled by the FDR.

Nomenclature

α_{cap},	=	specific mass of the capacitors
α_{SEP}	=	solar panel specific mass
B	=	magnetic field
C	=	fusion constant, 4.3 x 10^{-8}
D-T	=	Deuterium – Tritium
ΔV	=	change in velocity for a mission or transfer
ΔT	=	length of mission or transfer
E_{in}	=	energy input into fusion reaction
E_{out}	=	energy released from the fusion reaction
E_k	=	kinetic or propulsive energy
f	=	frequency of operation
η_T	=	thrust efficiency
ETO	=	Earth to Orbit
FDR	=	Fusion Driven Rocket
FRC	=	Field Reversed Configuration
g_0	=	gravitational constant, 9.81 m/s^2
G_F	=	total fusion gain
G_I	=	gain from fusion igniton
ICF	=	Interial Confinment Fusion
LEO	=	Low Earth Orbit
MIF	=	Magneto Inertial Fusion
M_L	=	liner mass
MR	=	mass ratio
M_i	=	initial mass of spacecraft
M_f	=	final mass of spacecraft
M_S	=	mass of structure
M_P	=	mass of propellant
M_{PL}	=	mass of payload
P_{SEP}	=	power from solar panels

I_{sp} = specific impulse
R = radius of target
ρ = density of target
SEP = Solar Electric Power
V_L = linear velocity
ϕ_{ion} = Ionization energy, 75 MJ/kg

I. Introduction

THIS is certainly not the first time that fusion energy has been proposed as the ultimate solution for rapid manned space travel. Past efforts in this regard have all come to be dismissed, and rightfully so, primarily for the following two reasons. The first is that the propulsion system is reactor based. The straightforward 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. [1] The maximum launch mass would need to be less than 200 MT if current chemical rockets are used for launch to LEO.

The second is virtually all previous fusion propulsion systems needed to employ more advanced fusion reactions that produce primarily charged particles as fusion products to avoid the large energy loss from fusion neutrons. The most tenable were D-^{3}He $\Rightarrow$ P(14.7 MeV) + ^{4}He(3.6 MeV) and P-^{11}B $\Rightarrow$ 3 ^{4}He(2.9 MeV). These reactions require much higher plasma temperatures and are orders of magnitude more difficult to achieve than the fusion of D-T $\Rightarrow$ n(14.1 MeV) + ^{4}He(3.5 MeV) which is the most readily achieved reaction and the only one seriously considered for earth based fusion reactors. With the much lower fusion gain of these fuels, the recirculating power needed to produce the fusion reaction becomes enormous, dooming it to being no better than the fission reactor based alternatives.

What is required is a completely different approach to what has been considered in the past if one is to make practical use of fusion energy for space propulsion. It is illustrative to examine what makes chemical propulsion so advantageous. A principle reason is the fact that the power delivered through chemical combustion can be made as large or as small as needed; from the Atlas heavy rocket at 13 GW, to the conventional automobile at 130 kW. It is worth noting that at lower power, the combustion is pulsed to achieve the greater efficiency obtained at high temperature without incurring the massive cooling requirements and thermal damage that would result from continuous operation at small scale.

As first demonstrated by the Gadget device (fission) and the Mike device Elugelab (fusion), the ignition of nuclear fuels have certainly confirmed the ability to produce copious energy yields from nuclear energy, dwarfing that of the Atlas V by many orders of magnitude. The challenge is how to control the release of nuclear energy in such a manner as to be a suitable match to the requirements of manned spaceflight missions: multi-megawatt jet power, low specific mass α (~ 1 kg/kW) at high Isp (> 2,000 s). It would appear that, for at least nuclear fission, there is no real possibility of scaling down to an appropriately low yield as a certain critical mass (scale) is required to achieve the super critical chain reaction needed for high energy gain. Fission nuclear pulse propulsion then, such as that envisioned in the Orion project, ends up with a thrust in the millions of MT which would only be suitable for spacecraft on the order of 10^7 MT.

Fortunately, the scale for fusion ignition can be much smaller, and methods such as Magneto Inertial Fusion employed in FDR allow access to the massive amount of energy of nuclear material in a system that is appropriate in size, weight, power level, and cost to be useable for spacecraft propulsion system.

II. Physics of the Fusion Driven Rocket

The Fusion Driven Rocket is based on the concept of magnetically driven three dimensional implosion of metal foils onto an FRC target to obtain fusion conditions. This approach to fusion is a form of inertial fusion and can best be understood by first examining the fundamentals of Inertial Confinement Fusion (ICF). ICF fusion is accomplished by the three dimensional compression of a spherical cryogenic fuel pellet of millimeter scale. In this method it is assumed that the inertia of the small pellet is sufficient to confine the plasma long enough for the burn to propagate through the pellet and thereby produce an energy gain G ~ 200 or more (G = fusion energy/initial plasma energy). The ICF approach has been actively pursued by the National Nuclear Security Administration (NNSA) of the DOE for decades as it represents essentially a nano-scale version of a fusion explosive device. Because of the small scale and tiny masses, the energy delivery system required to heat the pellet to fusion temperature must be capable of doing so on the nanosecond timescale. It appears that the most promising solution to accomplish this is with a large array of high power pulsed lasers focused down onto the D-T pellet.

The National Ignition Facility (NIF) at Livermore National Laboratory is now in the process of testing a laser driven pellet implosion capable producing significant fusion gain for the first time. This will be a very significant milestone for the generation of fusion energy at small scale. While the expected energy yield is in the range appropriate for propulsion (E ~ 20-100 MJ), the scale and mass of the driver (lasers and power supplies) is not, as it requires an aerial photograph to image the full system.

Therefore, for a space application a different technique to achieve confinement is required. The notion of using other means than an array of high power lasers to compress the target to fusion conditions goes back as far as the 1950's. Heavy ions and metal shells (liners) were two of the most promising. Regardless of method, this compression must be uniform, intense and accomplished with great precision resulting in large, high voltage and expensive driver systems. By the mid-90's it was realized that the presence of a large magnetic field in the target would substantially suppress thermal transport, and thus lower the imploding power needed to compress the target to fusion conditions. With more time before the target plasma thermal energy was dissipated, a much more massive confining shell could be employed for direct compression, with the dwell time of the confining (metal) shell now providing for a much longer fusion burn time. The liner did not need to be propelled inward by ablation but could be driven by explosives or even magnetic fields. In a seminal paper by Drake et al. [2] it was shown that if the imploding shell onto the magnetized target were fully three dimensional, fusion gain could be achieved on a small scale with sub-megajoule liner (shell) kinetic energy.

There was no known way to accomplish this at that time, but it was feasible at least in theory. The second major theoretical result was obtained by Basko et al. [3] who showed that for a sufficiently magnetized target plasma, fusion ignition would occur even when the restrictive condition that $\rho \cdot R > 0.1$ g/cm^2 was far from being met. Ignition was now possible as long as the magnetic field-radius product, $B \cdot R > 60$ T-cm. Thus fusion ignition could be obtained for MIF targets with much lower compression than required for ICF. The final critical element to

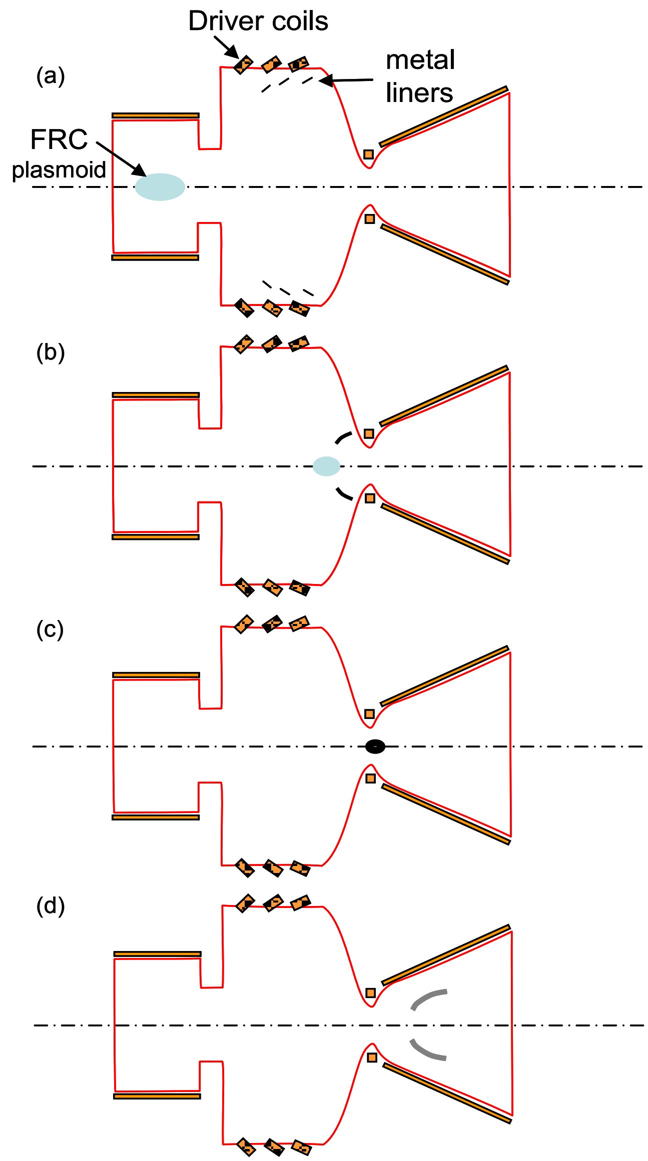

Figure 1. Schematic of the inductively driven metal propellant compression of an FRC plasmoid for propulsion. (a) Thin hoops of metal are driven at the proper angle and speed for convergence onto target plasmoid at thruster throat. Target FRC plasmoid is created and injected into thruster chamber.
(b) Target FRC is confined by axial magnetic field from shell driver coils as it translates through chamber eventually stagnating at the thruster throat.
(c) Converging shell segments form fusion blanket compressing target FRC plasmoid to fusion conditions.
(d) Vaporized and ionized by fusion neutrons and alphas, the plasma blanket expands against the divergent magnetic field resulting in the direct generation of electricity from the back emf and a directed flow of the metal plasma out of the magnetic nozzle.

enable the use of fusion energy for space propulsion was a practical method to directly channel the fusion energy into thrust at the appropriate I_{sp}. Or: This method, as developed by Slough [4], has been supported by both theory and experiment. A description of the operating principles and a basic scheme for FDR is illustrated and described in Fig. 1.

It was clear that fusion ignition conditions could be achieved at small scale by applying the kinetic energy of a significantly more massive metal shell to compress the target plasma to high density and temperature. In order to be made practical, what remained to be solved were the following four challenges:

(1) how to do this without invoking a massive and complex driver

(2) how to do it in a manner that is efficient and capable of repetitive operation

(3) how to create a suitable magnetized plasma target, and

(4) how to transfer the fusion energy into a suitably directed propellant.

The key to answering all four "how's" stems from current research being done at MSNW on the magnetically driven 3D implosion of metal foils onto an FRC target for obtaining fusion conditions. A logical extension of this work leads to a method that utilizes these metal shells to not only achieve fusion conditions, but then to become the propellant as well. The basic scheme for FDR is illustrated and described in Fig. 3. The two most critical issues in meeting challenges (1) and (2) for MIF, and all ICF concepts for that matter, is driver efficiency and "stand-off" – the ability to isolate and protect fusion and thruster systems from the resultant fusion energy. By employing metal shells for compression, it is possible to produce the desired convergent motion inductively by inserting the metal sheets along the inner surface of cylindrical or conically tapered coils. Both stand-off and energy efficiency issues are solved by this arrangement. The metal shell can be positioned a meter or more from the target implosion site with the coil driver both physically and electrically isolated from the shell. The driver efficiency can be quite high as the coil driver is typically the inductive element of a simple oscillating circuit where resistive circuit losses are a small fraction of the energy transferred. With an in-line element as rudimentary as a diode array, any magnetic energy not imparted to the liner can be recovered back into the charging system after the shell is driven off with the first half cycle. The feasibility of rapidly accelerating inward and compressing thin hoops of aluminum and copper in this manner was first demonstrated by Cnare [5]. Since then, the technique has been employed in several experiments to obtain very high magnetic fields as it will be done here.

Even though there is essentially no magnetic field within the hoops initially, there is enough flux leakage during the inward acceleration that at peak compression the axial magnetic field that is trapped inside the now greatly thickened wall can reach as high as 600 T [6]. As will be seen, this field is considerably higher than required for compression of the FRC to have ignition and substantial fusion gain.

The next challenge to be considered is the magnetized plasma to be used as the fusion target. Spaced-based fusion demands a much lower system mass. The lowest mass system by which fusion can be achieved, and the one to be employed here, is based on the very compact, high energy density regime of magnetized fusion employing a compact toroidal plasmoid commonly referred to as a Field Reversed Configuration (FRC). [7] It is of paramount advantage to employ a closed field line plasma that has intrinsically high β (plasma/magnetic pressure ratio), and that can be readily translated and compressed, for the primary target plasma for MIF. Of all fusion reactor embodiments, only the FRC plasmoid has the linear geometry, and sufficient closed field confinement required for MIF fusion at high energy density. Most importantly, the FRC has already demonstrated both translatability over large distances [8] as well as the confinement scaling with size and density required to assure sufficient lifetime to survive the compression timescale required for liner-based inertial fusion. FRCs have also been formed with enough internal flux to easily satisfy the B·R ignition criteria at peak compression.

At a nominal liner converging speed of 3 km/s, a 0.2 m radius FRC typical of operation on the LSX FRC device would be fully compressed in 67 μs which is only a fraction of the lifetime that was observed for these FRCs (~ 1 ms). [9] The target plasma to be employed in FDR will thus be an FRC plasmoid.

Finally, to complete the fourth challenge, a straightforward way to convert the fusion energy into propulsive energy must be devised. It is in this regard that the approach outlined here is uniquely capable. It starts by employing an inductively driven thin metal liner first to compress the magnetized plasma. As the radial and axial compression proceeds, this liner coalesces to form a thick ($r > 5$ cm) shell that acts as a fusion blanket that absorbs virtually all the fusion energy as well as the radiated plasma energy during the brief fusion burn time. This superheated blanket material is subsequently ionized and now rapidly expands inside the divergent magnetic field of the nozzle that converts this blanket plasma energy into propulsive thrust. It would be possible to also derive the electrical energy required for the driver system from the back emf experienced by the conical magnetic field coil circuit via flux compression. [10] It was found however that the power required for recharging the energy storage modules for the metal liner driver coils could readily be obtained from conventional solar electric power (SEP). As will be discussed, for very rapid, high power missions, the flux compressor/generator option could be developed.

For the near term manned mars missions the SEP requires the least technology development, lowest cost and highest TRL level.

III. Model of FDR and Mission Assumptions

An analytical model, based on a mission driven approach, was used to examine a direct Mars Transit utilizing a Fusion Drive Rocket (FDR). This was similar to the methodology employed by NASA's Copernicus software to determine accurate mission profile and ΔV requirements as a function of mission transfer time and thruster burn time. Analysis was focused on a 90-day transit time to Mars. It was felt that this timescale was an appropriate balance between fast transfer time, required to protect astronauts from harmful space radiation, while still providing high payload mass fraction and low initial launch masses. Moreover, a 90-day trip can easily be accomplished with a conservative estimate of fusion gains that will be discussed in detail later. While faster trip times are possible, they come of course at the cost of decreased payload mass fraction. These numbers can be greatly improved by simply attaining large fusion gain with a consequent higher Isp from the FDR. However it was the intent of this work to focus on how, even with conservative estimates of fusion yield, FDR could revolutionize interplanetary space travel.

In addition to the primary 90-day mission, more ambitious mission profiles such as a 30-day Mars transit were examined in particular with regard to increased fusion ignition yields. While these higher gains are quite feasible they are not certain at this time, and therefore were not assumed for the first implementation studies of FDR, but rather analyzed to illustrate, once the physics of the FDR has a sound footing in both experiment and theory, what the potential of this technology could provide to manned space exploration.

The most relevant metric of the Fusion Driven Rocket is the energy gain of the fusion reaction. Thus the mission analysis included a trade study of various fusion gains. The primary fusion gain can be stated as a function of the liner mass, M_L, and the terminal velocity, V_L, (i.e. liner energy) at which the liner converges.

$$G_F = M_L^{1/2} G_I C E_{in}^{11/8} \tag{1}$$

Where G_I is the ignition gain, C is a fusion constant equal to $4.3\text{x}10^{-8}$[4] and E_{in} is the energy input into the fusion reaction and is described by,

$$E_{in} = \frac{1}{2} M_L V_L^2 \tag{2}$$

For this analysis, the liner velocity was conservatively assumed to be no greater than 4 km/s. This is based on what has been demonstrated by previous experimental efforts, and is sufficiently less than the predicted vaporization limit of lithium due to inductive heating during liner acceleration [11]. A lower limit to the liner mass is found from the desire to have the liner thickness sufficient to have fusion neutron energy deposited in the liner [i.e. $r_L(\text{min}) \geq 5$ cm]. A mass of 0.37 kg was assumed for the total lithium liner mass which is well above the minimum amount of material (0.28 kg) needed.

In addition to this fusion gain, there is a likely possibility of an ignition gain due to additional heating of the plasma from the magnetically confined fusion product alpha (^4He) ions. The additional energy from fusion heated fuel varies significantly depending on assumptions of the liner dynamical behavior as well as the fusion burn propagation. The actual total gain that will be achieved is thus a complex hydrodynamic/materials physics question that will need to be addressed through further research. The codes for this calculation with modifications for a magnetized target are currently under development. The initial numerical calculations by Parks et al [12] indicate significant fusion ignition gains can be achieved even with only partial thermalization of the fusion alphas. While this secondary ignition gain of the FDR is unknown, it is likely to be at least 2. Therefore, for the mission analysis presented here, ignition gain enhancements of 1 (no ignition gain) and 10 are examined along with the nominal gain of 2. The 1 and 10 cases are meant to bound the likely yield. With the liner mass and velocity having been determined, the primary fusion gain is determined from Eq. (1) with a fusion gain of 20.

With the total fusion gain assumed, the energy from the fusion reaction, E_{out}, can simply be determined as the gain multiplier times the energy input, E_{in}, into the reaction.

$$E_{out} = G_F E_{in} \tag{3}$$

The amount of energy from the fusion reaction that is actually converted into kinetic or propulsive energy is decreased by a thrust efficiency factor, η_T, and the major loss mechanism - the ionization of the lithium liner. This is described by the equation,

$$E_{kinetic} = \eta_T E_{out} - \phi_{ion} M_L \tag{4}$$

Specific impulse can be determined as a function of the total gain (= fusion gain × a variable ignition multiplier) as shown in Fig. 2 and described by the following equation,

$$I_{isp} = \frac{\sqrt{2E_k / M_L}}{g_0} \tag{5}$$

The resulting minimum expected I_{sp} for FDR is therefore 2,440 s, and could range as high as 5,720 s. Notice that the I_{sp} drops quickly at lower fusion gains. This is due to the rising significance of the lithium liner's ionization cost.

For a given mission architecture and desired transfer time a corresponding ΔV can be determined, as will be discussed in Section IV. By knowing the exhaust products of the fusion reaction determined above and this ΔV requirement, the mass ratio, *MR*, is set by the simple rocket equation,

$$MR = e^{\frac{\Delta V}{I_{sp} g_0}} \tag{6}$$

MR can also be defined as the initial mass of the spacecraft, M_i, over the final mass, M_f, of the spacecraft as represented in Eq. (7). Here, the final mass is just the mass of the payload, M_{PL}, plus the structural mass, M_S, of the spacecraft represented in Eq. (8). The initial mass is the same plus the mass of the propellant, M_P, need to carry out the mission, shown in Eq. (9). This propellant mass represented in Eq. (10) is simply the mass of the liner from the fusion analysis times the frequency of operation, *f*, times the length of the mission, *ΔT*. The Mass of the Structure is broken down in Eq. (11). It is a function of the solar panel mass, capacitor mass need for the fusion propulsion system, and some addition mass, which has been chosen here to be 10% of the payload. The mass of the fusion system is defined as energy input into the fusion reaction divided by the specific mass of the capacitors, α_{cap}, required to supply that energy, and the mass of the solar panels is defined as the power required to charge the fusion caps divided by the solar panel specific mass, α_{SEP}. Finally the actually power need to run the fusion reactor is simple the energy input divided by the frequency of operation as written in Eq. (12).

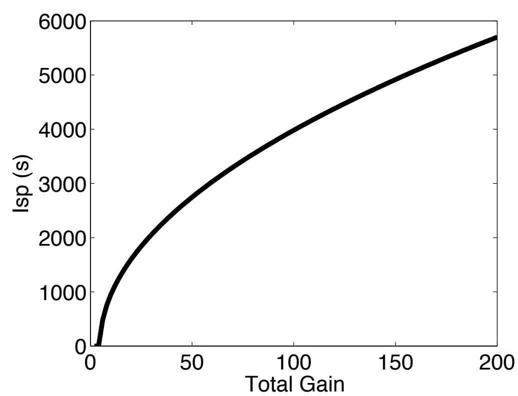

Figure 2: Projected Isp accounting for frozen flow losses as a function of total fusion gain.

$$MR = e^{\frac{\Delta V}{I_{sp} g_0}} \tag{6}$$

$$MR = \frac{M_i}{M_f} \tag{7}$$

$$M_f = M_{PL} + M_s \tag{8}$$

$$M_i = M_{PL} + M_s + M_P \tag{9}$$

$$M_P = M_L f \Delta T \tag{10}$$

$$M_S = \frac{E_{in}}{\alpha_{cap}} + \frac{P_{SEP}}{\alpha_{SEP}} + 0.1M_{PL} \tag{11}$$

$$E_{in} = \frac{P_{SEP}}{f} \tag{12}$$

Equations 7 through 12 represent a system of six equation and six unknowns: M_i, M_f, M_S, M_P, f, and P_{SEP}. Solving these equations simultaneously allows each to be determined and for an analytical feasibility study of FDR for a direct Mars transfer to be carried out.

There are several important assumptions made in the analytical analysis worth outlining here. The mass of the payload was chosen to be 61 MT, based on previous manned Mars mission analysis [13] [14]. It was estimated that the coupling coefficient, or the amount of energy that is transfered from the capacitor to the fusion liner, is roughly 50%. It is important to note that the other 50% is not lost energy, but is returned to the capacitors from the driver coils as a normal aspect of the electrical circuit behavior. Therefore a higher or lower coupling efficiency only acts to increase or decrease the size of the energy storage, but not the power required. The liner itself is assumed to be 50% ionized from the fusion reaction and plasma products. The ionization energy loss, as with all plasma based thrusters, shows up as a frozen flow loss and can influence the performance FDR especially at low gain levels (lower Isp), as will be discussed later. The spacecraft for this analysis is assumed to consist of three main masses: (1) the propulsion system, (2) power system, and (3) propellant. The mass of the propulsion system is driven by the capacitor specific energy which is assumed to be ~ 1 kJ/kg. This number is conservative enough (one half of current state of the art hardware) to include the necessary cables and switches as part of this mass, as these masses will also scale with capacitor mass. The mass of the power system is based on a solar panel specific mass of 0.2 kW/kg. And finally, the mass of the propellant system is primarily tankage and assumed to be 10% of the lithium propellant mass. While the propellant is solid lithium and would not require significant tankage itself, the transfer, feed and liner formation equipment will be added mass. The last assumption worth noting is that this initial analysis assumed full propulsion capabilities for all orbital maneuvers, including the Mars insertion orbit. While other Mars mission architectures propose aerocapture, it was deemed not worth the propellant mass savings to increase risk and uncertainty inherent with aerocapture for this first order manned mission analysis.

As a reference mission a manned mission to Mars similar to that of the Design Reference Architecture (DRA) 5.0 [14] was chosen. In doing so, it was not difficult to show the potential of the Fusion Driven Rocket compared to nuclear thermal propulsion systems in terms of trip time, payload mass fraction, and initial launch masses. However, the implications of the FDR are even more far-reaching and warrant additional benefit analysis on pre-deployed missions. Furthermore, as a result of the high payload mass fraction associated with the FDR, single trip missions with no pre-deployed assets can be readily achieved. While this ultimately may require higher fusion gains, they are not outside of the anticipated limits of fusion yield.

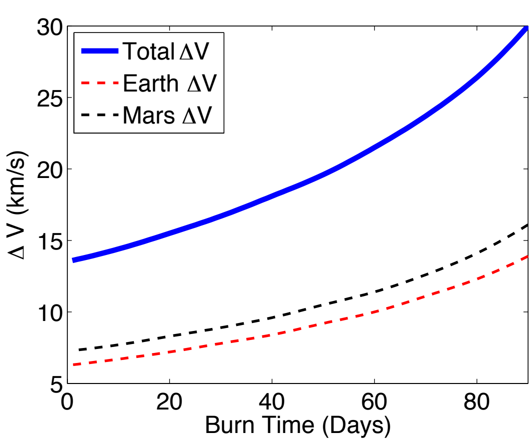

Figure 3: Delta V requirement as a function of burn time for a 90-day transit to Mars.

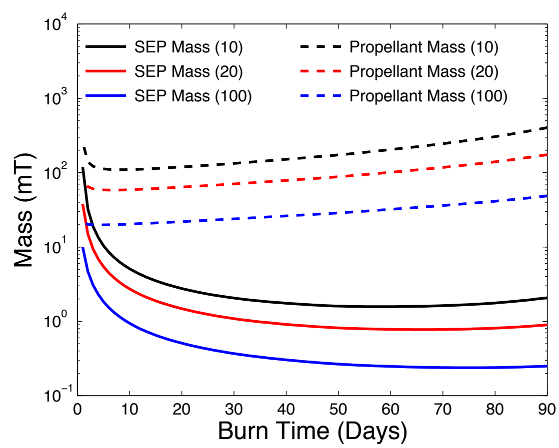

Figure 4: Mass of propellant and solar panel system as a function of burn time for a gain of 20, 40, and 100.

IV. Effects of Burn Time

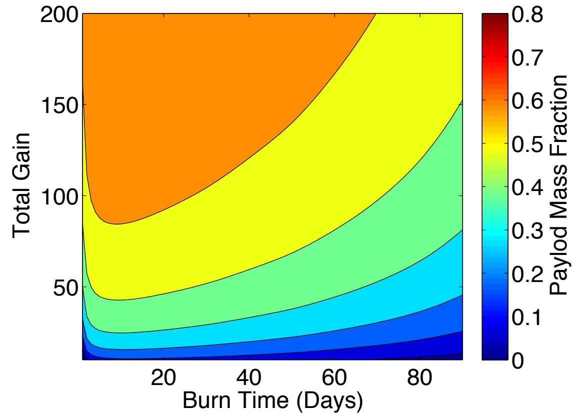

Figure 5: Payload mass fraction as a function of burn time and total gain

With Isp determined, various mission parameters can be examined for a given ΔV. The lowest ΔV for a direct interplanetary transfer is the solution to the Lambert problem where short finite burns occur at the beginning and end of the transfer. While this is ideal from a mission perspective, it is not necessarily an optimum from a propulsion system point of view. As part of this study a 90-day Earth-Mars transfer was examined for a variety of infinite burn times using the FDR. Fig. 3 illustrates the ΔV requirements from a one-day to a continuous 90-day burn. It can be seen that the faster and stronger the burn, the less demanding the ΔV requirements as the value approaches that of the Lambert solution. However, even though the ΔV requirements are less, shortened burn time requires more energy in a shorter period of time, greatly increasing the power requirements. This trade-off between the mass of propulsion system and ΔV (mass of propellant) are the major mass drivers for the spacecraft and mission design. What is uniquely different here with the FDR is that the solar panel mass scales with the jet power (for fixed fusion gain) but the capacitor mass does not as the capacitors can be operated at higher or lower rep rate to match power demand. The solar panel mass must increase if a higher power is desired in order to charge the capacitors at the higher rep rate. Figure 4 indicates the increase in propellant mass and decrease in solar panel mass as functions of burn time. These two mass functions create an optimal payload mass fraction for a given fusion gain, which can be seen for all possible gain cases within the design space as shown in Fig. 5. For all fusion gains this optimal payload mass fraction occurs at around a 10-day burn time. For the expected gain of 40 this results in a payload mass fraction of 0.47. Ten days is also the optimum burn time when considering initial mass, resulting in a minimum initial mass of 130 MT, which is consistent with a single ETO launch.

V. Effects of Solar Panel Size

From a mission perspective, solar panel size is determined from a desired payload mass fraction as shown in Fig. 6. One of the most important conclusions illustrated by this figure is that payload mass fraction does not vary significantly near the optimal payload mass fraction. So while the optimal payload mass fraction of 47% at a gain of 40 requires a solar panel power of 546 kW, this could be lowered to 300 kW, with a marginal change in the payload mass fraction to 45%. Furthermore, the initial mass of the spacecraft is also not particularly sensitive to solar power near the optimal value, as can be seen in Fig. 6. This is particularly true at higher gains. Ultimately, it will be necessary to determine the value of these trade-offs based on the desired characteristics of specific future Mars missions.

Total Gain	20	40	200
Liner Mass (kg)	0.365	0.365	0.365
Isp (s)	1606	2435	5722
Mass fraction	0.33	0.47	0.68
Specific mass (kg/kW)	0.8	0.53	0.23
Mass Propellant (MT)	110	59	20
Mass Initial (MT)	184	130	90
SEP (kW)	1019	546	188

Table 1: Summary of key mission parameters for various total gains.

In summary, Table 1 displays several important mission parameters for the complete range of fusion gain possibilities. It is clear that at an expected gain of 40 produces very favorable Isp, while keeping system mass and power requirements low for a 90-day transit to Mars. Even at an extremely low gain estimate of 20, the Fusion driven rocket still offers the best option for a manned mission to Mars, producing transit times and payload mass fractions that are not feasible with any other propulsion system

VI. Effects of Advanced Mars Capture

As described in the DRA 5.0, advanced aerocapture was critical for manned Mars missions even assuming Nuclear Thermal Propulsion (NTP). Up to this point the analysis performed here has primarily focused on a manned transit to Mars without relying on aerocapture as this has usually been deemed too risky. Aerocapture is, however, favorable for cargo missions using NTP and if this type of mission maneuver is performed successfully and frequently, it may even become favorable for manned missions as well. Therefore, a preliminary investigation of aerocapture in conjunction with the Fusion Driven Rocket was investigated. To do so the same ΔV requirement for the trans-Mars insertion burn was conducted propulsively, with the Mars insertion burn being replaced by an aerocapture maneuver. The ΔV requirement for the propulsion system was therefore significantly less, thereby decreasing the amount of propellant needed. However, an additional mass of 40 MT was added to the spacecraft mass consistent with heat shielding as stated in the DRA 5.0. Due to the high Isp of the FDR, the amount of propellant is much less than both chemical and NTP propulsion systems. Only at a gain of 10, where the Isp is as low as 1,600 s, does the mass savings of propellant equal the mass of the heat shield. Therefore, it is evident that for all mission profiles and all possible fusion gains, there is no need to invoke aerocapture for mission feasibility. It is far more favorable and much lower risk to use the Fusion Driven Rocket for all orbital maneuvers.

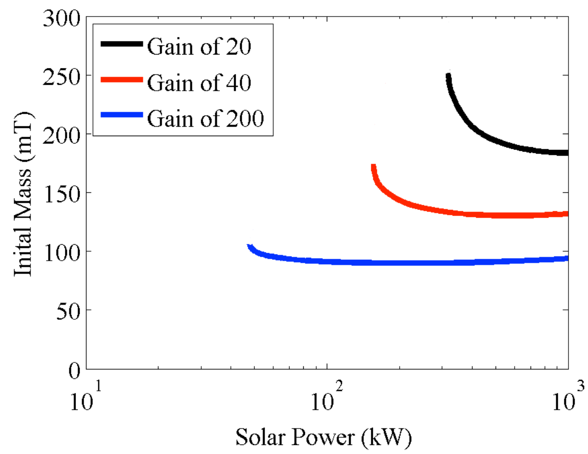

Figure 6: Inital mass as a function of required solar power for a gain of 20, 40, and 200.

VII. 30-Day transit to Mars

While a 90-day transit to Mars offers a good balance of payload mass fraction and transit time at even modest estimations of fusion gain, the possibility of very high energy yields make extremely rapid transits to Mars quite feasible. To investigate this, a 30-day transit to Mars was considered. The ΔV budget for such a mission is very high, ranging from 98 km/s at a full 30 day burn to 45 km/s for a 0.1 Day-burn (which approximates the Lambert problem). For such high ΔV's a fusion again of 40 would not result in optimal mission parameters. More ambitious gains of 200, however, show that his mission is quite favorable. The optimal burn time for such a mission is 6 days,

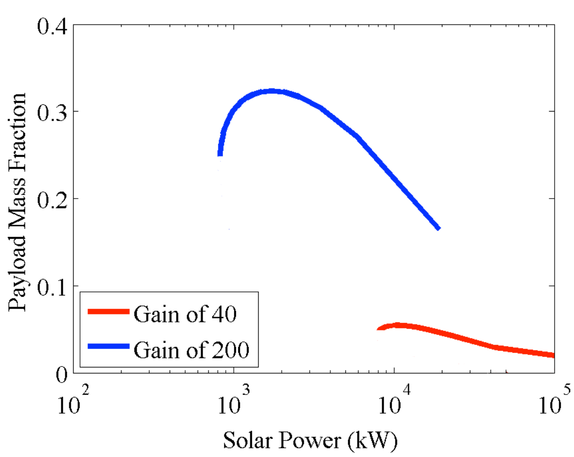

Figure 7. Payload mass fraction as a function of required solar power for a 30 day Mars transit for a total fusion gain of 40 and 200.

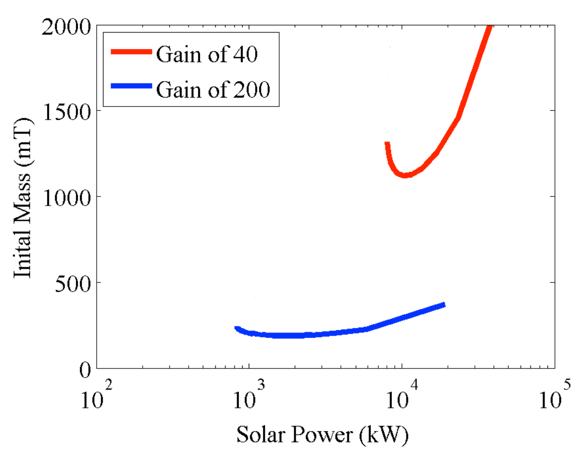

Figure 8. Initial Mass as a function of required solar power for a 30 day Mars transit for a total fusion gain of 40, and 200.

which results in a fairly high demand on solar power. As with the 90-day mission, a slightly off-optimal approach yields much lower solar panel mass without sacrificing much payload mass fraction or significantly increasing the initial spacecraft mass, as can be seen in Figs. 7 and 8. With one MW solar electric power, a 30% payload mass fraction can be delivered to Mars in 30 days. For the 61 MT payload mass assumed for the 90-day mission, this results in an initial spacecraft mass of a reasonable 200 MT.

VIII. Conclusion

A general explanation of the Fusion Driven Rocket was presented. This approach has shown to be the most viable approach for advanced in-space transportation. This work highlights the concept and fusion technique, and details the advantages over other forms of nuclear propulsion. It was explained that FDR is uniquely suited in size, weight, power level, and cost to provide an effective near-term propulsion system for a manned Mars mission. An argument was set forth, based on previous theoretical and experimental work, how fusion energy can directly provide propulsion without significant interaction with the spacecraft, using solid propellants which require minimal tankage. Not only was the feasibility of FDR discussed, but the game changing effect on space transportation was analyzed. Mission analysis and system level design have indicated payload mass fractions of 47% for a 90-day mars transfer assuming a modest gain of 40. Further, this work showed that even faster 30-Day transfers would be possible and illustrated the potential of a single launch from earth to Mars. This type of mission architecture is unique to FDR and could greatly change and enable many possible future space exploration missions.

Acknowledgments

Work supported by a grant from the NASA Institute for Advanced Concepts (NIAC). The author would like to also acknowledge NASA's Johnson Space Center (JSC) for licensing and support with the advanced trajectory design and optimization software – Copernicus.

References

[1] Williams, C.H., Borowski, S.K., Dudzinski, L.A., and Juhasz, A.J., "A Spherical Torus Nuclear Fusion Reactor Space Propulsion Vehicle Concept for Fast Interplanetary Piloted and Robotic Missions", 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 99-2704, June 1999.

[2] Drake, R.P., Hammer, J.H., Hartman, C.W., Perkins, L.J., and Ryutov, D.D., "Submegajoule liner implosion of a closed field line configuration" Fusion Technology, Vol. 30, pg. 310 (1996)

[3] M.M. Basko, A.J. Kemp, J. Meyer-ter-Vehn, "Ignition conditions for magnetized target fusion in cylindrical geometry"**,** Nuclear Fusion, **40**, 59 (2000).

[4] Slough, J., Kirtley, D., Pancotti, A., Pfaff, Pihl, C., Voltroubek, G., "A Magneto-Intertial Fusion Drivem Rocket", ICOPS 1P-125 (2012)

[5] Cnare, E.C., "Magnetic Flux Compression by Magnetically Imploded Metallic Foils", Journal of Applied Physics, Vol. 27, No. 10, pg. 3812, (1967)

[6] Y. H. Matsuda, F. Herlach, S. Ikeda, and N. Miura, "Generation of 600 T by electromagnetic flux compression with improved implosion symmetry"**,** Rev. Sci. Instrum**. 73** 4288 (2002).

[7] Slough J., et al., "Confinement and Stability of Plasmas in a Field Reversed Configuration", Phys. Rev. Lett., Vol. 9, 2212 (1992)

[8] G. Votroubek and J. Slough, "The Plasma Liner Compression Experiment", Journal of Fusion Energy **29**, 571 (2010)

[9] Slough J.T., et al "Transport, energy balance, and stability of a large field-reversed configuration", Physics of Plasmas **2,** 2286 (1995)

[10] A.A. Harms, K.F. Schoepf, G.H. Miley, D.R. Kingdom, 2002 Principles of Fusion Energy, World Scientific Publishing, Singapore 912805, pgs. 267-277.

[11] Kirtley, D., Slough, J., Schonig, J., Ketsdever, A., "Pulsed Inductive Marcon Propulsion", JANNAF 2010

[12] D.D. Ryutov and P.B. Parks, "Reaching High-Yield Fusion with a Slow Plasma Liner Compressing a Magnetized Target", Fusion Science and Technology, (2008)

[13] Drake, Bret G., Reference Mission Version 3.0 Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team, Lyndon B. Johnson Space Center, NASA/SP—6107–ADD, 1998

[14] Drake, Bret G., Mars Human Exploration Mission DRA 5.0, NASA-SP-2009-566, July 2009