The Case and Development Path for Fusion Propulsion

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Abstract

The objectives of this paper are to demonstrate why fusion propulsion is needed for interplanetary space travel, show why the magneto-inertial fusion (MIF) parameter space may facilitate the most rapid, economic path for development, justify the choice for pulsed z-pinch, and provide a potential development path leading up to a TRL 9 system. We show that round trips of less than one year to Mars are only possible with fusion systems. We strongly emphasize that a fusion system will require a small on board nuclear fission reactor for reliable start ups, so fission and fusion development for space is mutually beneficial. We review the 50+ year history of fusion propulsion to serve as a reference, and we summarize results from a recent paper focused on the fusion parameter space for terrestrial power to suggest that the magneto-inertial fusion parameter space is perhaps the smallest, most economical approach for fusion propulsion development. Emerging experimental data and theory show that among MIF concepts, pulsed z-pinch fusion has solutions to some of the most deleterious instabilities, and scaling to fusion breakeven is almost within reach of current pulsed power facilities. We offer a potential development path to a TRL 9 flight system, starting from an assumed TRL 2 for the current state of fusion propulsion.

Nomenclature

a	acceleration [m/s^2]
g_0	gravitational acceleration at Earth's surface [m/s^2]
J	mission difficulty parameter [m^2/s^3]
k	ratio of tank to propellant mass
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
n	number density
N	total number of stages, number of fusion reactions
P	power [W]
R	distance traveled [m]
t	time [s]
T	total trip time, and time [s]
v_j	jet or exhaust velocity [m/s]
$\mathcal{V}$	reacting volume [m^3]

Y	fusion energy yield [J]
α	propulsion system specific mass [kg/W]
β	mission type multiplication factor
γ	ratio of propulsion system to initial mass of nth stage
Δv	velocity increment [m/s]
λ	payload mass fraction
τ	characteristic time [s]
subscripts	
0	initial
1,2	dummy subscripts indicating different species
burn	propulsive burn
c,coast	unpowered coasting
d	dwell, as in dwell time τ_d
f	final
jet	jet, as in for jet power P_{jet}
n	number of the stage
opt	optimum
p	propulsion time
pay	payload
pn	propulsion time for nth stage (as in for T_{pn})
pr	propellant
ps	propulsion system
t	tank

I. Introduction

The human predilection to explore and ultimately thrive in new environments – no matter how inhospitable or hostile – is well-known from throughout our history. We do so for many reasons: more food, preferable climate, improved trade routes, scientific discovery, and sometimes even just plain boredom. Currently, there is no conclusive economic incentive for going beyond earth orbit, and there will likely be none for a long time. And while we could fill volumes with all the potential scientific discoveries and technological spinoffs that would come from developing space worthy vehicles to carry humans throughout the solar system, we do not need to: human exploration of the solar system is already underway and will continue to get easier and become more enriching.

So where should we go and how should we get there? In terms of distance, the Moon is our nearest neighbor, and can be visited readily using chemical propulsion. However, mission Δv and crew safety may actually be more important figures of merit than simple distance. A recently proposed strategy involving piloted trips to destinations, and with robots deployed to the surface of those bodies (the 'flexible path'), could be the most feasible near-term approach to space exploration.[1] Regardless of whether this approach is chosen, once we get beyond the Earth/moon system, other means of propulsion will have to be utilized to make the trip rapidly.

II. Why We Need Fusion for Interplanetary Space Travel

The rocket equation is derived from the application of Newton's second law to the motion of a spacecraft. Neglecting gravity and assuming constant exhaust velocity, it can be shown that

$$\Delta v = v_j \ln \frac{m_0}{m_f} \tag{1}$$

Thus at fixed payload mass fractions, vehicle Δv increases linearly with exhaust velocity. This does not necessarily translate into faster trip times, however. As Jahn points out[2], increasing exhaust velocity typically is done at the expense of thrust, because more energy per unit mass is required in order to accelerate gases for propulsion, and increased energy usually requires increased power supply mass. This tradeoff is also true in chemical propulsion, and is one of the reasons lower stages involve higher molecular weight propellants for higher thrust while upper stages frequently use LOX-hydrogen.

The rocket equation can be rearranged as

$$\frac{m_f}{m_0} = e^{-\Delta v / v_j} \tag{2}$$

which more accurately reflects how vehicles are constrained. To the first order, the mission Δv is determined by the destination and the exhaust velocity is determined by the propulsion technology. The optimum exhaust velocity is vehicle dependent, but will be of the same order as the mission Δv, so as to produce a reasonable tradeoff between payload mass fraction and trip time.

To further justify the remaining discussion, we consider the merits of both payload mass fraction and trip time. Shorter trip times are safer for astronauts, because they lower the radiation doses from cosmic rays and solar events. Additionally the psychological impact of long term space travel as well as the atrophy of skeletal and muscle tissue are both lessened. Increased payload mass fractions result in more room for habitation, science experiments, and recreation.

Since mission Δv's beyond the moon, but within the solar system, vary from $\sim 10^4$ to $\sim 10^5$ m/s, either we must develop propulsion systems that completely circumvent the rocket equation or investigate concepts that enable sufficiently high exhaust velocities without sacrificing thrust. While a number of advanced propulsion concepts do 'short circuit' the rocket equation, such as solar sails and beamed energy[3], the only approach that has been utilized for primary propulsion in deep space requires accelerating gases at high velocity out of a nozzle. Assuming that this continues to be the case, we must investigate concepts which accelerate gases or plasmas to high velocity.

There are three common ways to add energy from an on-board source to a propellant for acceleration: 1. add enthalpy through combustion, 2. accelerate ionized gases directly via electrothermal and electromagnetic body forces (i.e. electric propulsion), and 3. add enthalpy through nuclear reactions. Combustion depends on the release of chemical binding energies and produces ~10 MJ per kg of propellant. Placing an upper limit of about 50 MJ per kg on the most advanced chemical reactions, applying a 1D energy equation to a control volume with boundaries at the combustion chamber walls and the nozzle exit, and assuming all enthalpy is converted to exhaust velocity, one obtains $u_{e,max} = \sqrt{2 \cdot 50 \times 10^6} = 10^4$ m/s. Thus chemical propulsion reaches its practical limits for even the easiest of potential interplanetary missions: Mars.

The remaining two methods will converge to the same solution based on our arguments; and we start with electric propulsion. Exhaust velocities can be quite high (10^5 m/s for ion thrusters), and some concepts may produce a sufficiently high thrust, but an external power supply is required. This demands either a solar array, beamed power, or an on-board nuclear reactor. Since solar power falls off as $1/r^2$ with the distance (r) to the sun, any mission beyond Mars will require a reactor. Beamed power is a possible solution but may require a network of power stations placed throughout the solar system, or extremely long range precision vehicle targeting for deep space applications. This leaves two options for the reactor: nuclear fission or nuclear fusion.

Thermal-to-electric power conversion, which is necessary for nuclear electric propulsion (NEP), is about 30% efficient and is fundamentally limited by the Carnot cycle (2nd Law of Thermodynamics) efficiency. This means that much of the thermal power has to be rejected by heavy radiators. The primary reason that fusion propulsion systems have much higher theoretical specific powers, when compared with NEP, is because the thermal-to-electric power conversion inefficiencies can be offset by the high gain of the fusion system[4]. Direct conversion of the plasma exhaust energy, a viable approach for fusion, can yield efficiencies approaching 70% of the total fusion power, making thermal-to-electric conversion unnecessary.

The third approach to propellant acceleration is derived from the conversion of energy from nuclear forces, binding subatomic particles in atomic nuclei, into kinetic energy. Both fission and fusion systems release approximately 10^{14} J per kg of propellant, which is a factor of 10^6 or 10^7 higher than any chemical reaction. The challenge to both fission and fusion systems is to overcome the thermal stresses and radiative flux on the nozzle, and the other vehicle components facing the reacting fuel. Nuclear thermal propulsion (NTP) accomplishes this by merely passing a working fluid – such as hydrogen – over a reactor. The heat transfer adds enthalpy to the gas, which is then expanded out of a nozzle to produce thrust. Thermal limitations to chamber and nozzle walls mean that exhaust velocities are limited to $\sim 10^4$ m/s. It is important to note that many important missions are enabled by NTP, including piloted trips to Mars; but beyond Mars the trip times become too long. Nuclear Gas Core Rockets[3,5] hold promise of high thrust (10's of kN) and high exhaust velocities (20-50 km/s), but a number of problems related to uranium plasma containment may make development too costly. Nuclear pulse propulsion (e.g. Orion, [6]) involves low yield (0.1 kiloton) nuclear explosions detonating near a pusher plate, and could enable 25 to 1500 km/s exhaust velocities with a thrust-to-weight ratio of about 4. Various international treaties prohibit atmospheric testing, and there are formidable political hurdles to pursuing such an approach.

Finally, there is fusion propulsion. There are two significant roadblocks against fusion. Firstly, there are currently no reactor concepts that have demonstrated breakeven (where the energy output exceeds the energy input); and secondly, typical vehicle concepts are so large, that they would require numerous launch missions <u>and</u> in-orbit assembly. While we do not pretend that fusion is the only concept that can potentially enable human planetary space travel, we argue that it is the most promising candidate to enable the flexibility of exploring the solar system within the orbit of Pluto and perhaps even beyond. Because of the immense gains realized with solving the physics and engineering problems of fusion, it merits serious investigation. We also do not pretend to have all the answers to these problems, but intend to present the case for what we believe to be one of the quickest, most cost-effective development paths for a working fusion propulsion system. The remainder of this paper begins with calculation of mission performance, to illustrate why fusion is needed for interplanetary travel. A brief overview of fusion confinement is then given, followed by a history of fusion propulsion concepts. Recent theoretical insights into the fusion propulsion parameters space are reviewed in the context of fusion propulsion. Next we summarize our planned approach based largely on the conclusions reached from the review of open literature, and we offer a sustainable development roadmap.

III. Calculation of Mission Performance

The objective of this section is to determine the relationship between distance traveled R and time elapsed T in terms of rocket parameters. These results are based on a model derived by Moeckel.[7] For clarity and completeness, we summarize the derivation of the performance equations here. Two types of spacecraft were investigated in Moeckel's paper and are compared here, Type I and Type II (see section III.2). Type I is an approximation for impulsive propulsion systems (where the burn time is small compared to the coast time, such is the case for chemical and nuclear thermal systems), and Type II is for systems in which the burn time is comparable to the coast time (such as nuclear electric and fusion systems). Three missions are examined: flyby, rendezvous, and roundrip. Here, R is defined as the distance from the starting point to the destination. For example, a mission to Mars would be roughly 0.5 AU, and this applies to the flyby, rendezvous, and roundtrip. The equations R = f(T) are interpreted as follows. They mean: 'The distance R that can be reached by a spacecraft is equal to this function of time T and/or rocket parameters.

III.1 Type I and II calculation of mass

To meet the objective, Moeckel[7] solved the equation 'distance equals rate multiplied by time'. The most difficult part of this calculation is the determination of velocity; because the mass of the vehicle changes as the propellant is expelled over the course of time, while the thrust may be relatively constant or impulsive. The basic concept is that the vehicle consists of N stages, and once the fuel is burned for one stage, that stage is ejected so that the new vehicle mass does not include the propulsion system or tankage for the previous stage:

$$m_{0,n+1} = m_{0,n} - m_{pr,n} - m_{t,n} - m_{ps,n} \tag{3}$$

A linear relationship is assumed between the tank and propellant mass, and propulsion system of the nth stage to the initial mass of the nth stage ($k \equiv m_t / m_{pr}$ and $\gamma \equiv m_{ps,n} / m_{0,n}$). Inserting these definitions into the mass equation and solving for the new to previous stage initial masses,

$$\frac{m_{0,n+1}}{m_{0,n}} = 1-(1+k)\frac{m_{pr,n}}{m_{0,n}} - \gamma \tag{4}$$

The propellant mass is given by the rocket equation

$$m_{pr,n} = m_{0,n}\left(1-e^{-\Delta v_n / v_j}\right) \tag{5}$$

Equation 4 becomes

$$\begin{aligned} \frac{m_{0,n+1}}{m_{0,n}} &= 1-(1+k)\left(1-e^{-\Delta v_n / v_j}\right) - \gamma \\ &= (1+k)e^{-\Delta v_n / v_j} - k - \gamma \end{aligned} \tag{6}$$

This expression can be considered the kernel upon which the performance model developed by Moeckel[7] is built. The vehicle has N stages. Consider the net payload to be in the N+1 stage. Using Eq. 6,

$$\frac{m_{pay}}{m_{0,N}} = (1+k)e^{-\Delta v_N / v_j} - k - \gamma \tag{7}$$

Assuming all the Δv's are the same for all stages,

$$\begin{aligned} &\frac{m_{pay}}{m_{0,N}}\frac{m_{0,N}}{m_{0,N-1}}\cdots\frac{m_{0,2}}{m_{0,1}} = \prod_{n=1}^{N}\frac{m_{0,n+1}}{m_{0,n}} \\ &= \frac{m_{pay}}{m_{0,1}} = \left[(1+k)e^{-\Delta v_N / v_j} - k - \gamma\right]^N \end{aligned} \tag{8}$$

One of the main points of this exercise is to calculate a velocity increment. We now can do that by solving for the velocity increment,

$$\Delta v = N\,\Delta v_n = N\,g_0\,I_{sp}\ln\left[\frac{1+k}{(m_{pay}/m_{0,1})^{1/N} + k + \gamma}\right] \tag{9}$$

III.2 Type II rockets

For Type II rockets, Moeckel made the approximation $\gamma \gg k$. k is roughly fixed regardless of type of rocket, based on material choice for the tank and the surface to volume ratio. γ is bigger for type II because it tends to be electrical, where electrical storage has a much lower energy density then chemical systems. What it means is that the propulsion system mass is large, and similar to the rest of the vehicle. For type II rockets under this assumption, Eq. 4 becomes

$$\frac{m_{0,n+1}}{m_{0,n}} = \left[1+\frac{\alpha J_n}{2\gamma}\right]^{-1} - \gamma \tag{10}$$

and propellant mass ratio is

$$\frac{m_{pr,n}}{m_{0,n}}=1-\left[1+\frac{\alpha J_n}{2\gamma}\right]^{-1} \tag{11}$$

where α is the propulsion system specific mass

$$\alpha\equiv\frac{m_{ps}}{P_{jet}}=\frac{m_{ps}}{0.5\dot{m}v_j^2}=\frac{2m_{ps}}{\dot{m}(I_{sp}g_0)^2} \tag{12}$$

and J_n is the mission difficulty parameter[8] for stage n

$$J_n\equiv\int_0^{T_{pn}}a^2\,dt\equiv a_0^2T_{pn} \tag{13}$$

Differentiating Eq. 10 with respect to γ, setting to 0, and solving for γ, finds the optimum gamma which maximizes the n+1 stage mass to the n stage mass ratio, gives

$$\gamma_{opt}=\left(\frac{\alpha J_n}{2}\right)^{0.5}\left[1-\left(\frac{\alpha J_n}{2}\right)^{0.6}\right] \tag{14}$$

Substitution of Eq. 14 For γ_{opt} into Eq. 10 gives

$$\frac{m_{0,n+1}}{m_{0,n}}=\left[1-\left(\frac{\alpha J_n}{2\gamma}\right)^{0.5}\right]^2 \tag{15}$$

The payload ratio for N stages becomes

$$\frac{m_{pay}}{m_{0,1}}=\left[1-\left(\frac{\alpha J_n}{2}\right)^{0.5}\right]^{2N} \tag{16}$$

Solving this expression for αJ_n gives

$$\alpha J_n=2\left[1-\left(\frac{m_{pay}}{m_{0,1}}\right)^{\frac{1}{2N}}\right]^2 \tag{17}$$

The overall mission difficulty is N J_n. By the definition, then the overall propulsion time is then

$$T_p=N\,T_{pn}=\frac{N\,J_n}{a_0^2} \tag{18}$$

or

$$J=T_p a_0^2 \tag{19}$$

The velocity increment Δv is related to the acceleration and propulsive time according to

$$\Delta v = a_0 T_p = \sqrt{J T_p} \tag{20}$$

With Eqs. 17 and 18, Moeckel[7] concluded

$$\Delta v = \sqrt{2 N T_p / \alpha} \left[1 - \left(\frac{m_{pay}}{m_{0,1}} \right)^{\frac{1}{2N}} \right] \tag{21}$$

III.3 Mission Performance, R vs T equations for Type I and II Rockets

We are now ready to obtain expressions for distance in terms of trip time and rocket parameters. We do this by superposition (adding) of acceleration periods and coasting periods. Burn periods are of the form

$$R_{burn} = \frac{1}{2} a_0 T_p^2 \tag{22}$$

Coast periods are

$$R_{coast} \equiv R_c = v_0 T_c = T_r a_0 (T - T_p) \tag{23}$$

For a flyby mission,

$$R = R_c + R_{burn} = \frac{1}{2} a_0 T_p^2 + a_0 T_p (T - T_p) \tag{24}$$

With

$$a = \sqrt{J / T_p} \tag{25}$$

$$R = \sqrt{J / T_p} \left(T_p T - \frac{1}{2} T_p^2 \right) \tag{26}$$

Differentiation with respect to T_p gives $T_{opt} = 2/3\, T$. Then

$$R = \Delta v \left(\frac{2}{3} T \right) \tag{27}$$

We can then make the substitution for Δv into this equation as was first done by Moeckel.[7] It is more convenient to put this in terms of R, and specify a destination. The equation is identical, apart from a factor β, for the flyby, rendezvous, and roundtrip missions.

$$\begin{aligned} &Type\ I \quad T=\frac{3\beta R/7}{N v_j \log_{10}\left(\dfrac{1+k}{\lambda^{1/N}+k+\gamma}\right)} \\ &Type\ II \quad T=\left(\frac{8\beta R\sqrt{\dfrac{\alpha}{2N}}}{1-\lambda^{1/(2N)}}\right)^{2/3}\frac{3}{2} \end{aligned} \tag{28}$$

where $\lambda \equiv m_{pay}/m_{0,1}$. According to Moeckel, the trip distance R for rendezvous and roundtrip are 1/2 and 1/8 of the flyby. This means that for a given set of rocket parameters and time T, one could travel R, 1/2 R and 1/8 R. These fractions are multiplied by the f(T) side. When solved for T, one multiples R by the reciprocal of these factors, and this is how β is defined, Table 1. Plots of Eq. 28 relate trip time and payload mass fraction to rocket parameters for a fixed destination. The equations and some results are given in the next section.

Table 1. Values of β as a function of trip type. Flyby refers to passing the destination, rendezvous refers to the spacecraft stopping at the destination, and roundtrip refers to stopping at the destination, then returning back to Earth.

Trip	**β**
Flyby	1
Rendezvous	2
Round Trip	8

III.4 Payload Mass Fraction

We solve the equations in the previous section for λ. We have

$$\begin{aligned} &Type\ I \quad \lambda=\left[\frac{1+k}{10^{\frac{3\beta R}{7 N v_j T}}-k-\gamma}\right]^{N} \\ &Type\ II \quad \lambda=\left[1-\left(\frac{2}{3}T\right)^{-3/2}\beta R\sqrt{\alpha/(2N)}\right]^{2N} \end{aligned} \tag{29}$$

These equations are plotted below for Mars and Saturn missions of interest. One assumes values for N, α, and λ, and picks a distance R. For example, R~5.0 AU for Jupiter, and that applies for flyby, rendezvous, and roundtrip. 1.0 AU is about 1.5×10^{11} m.

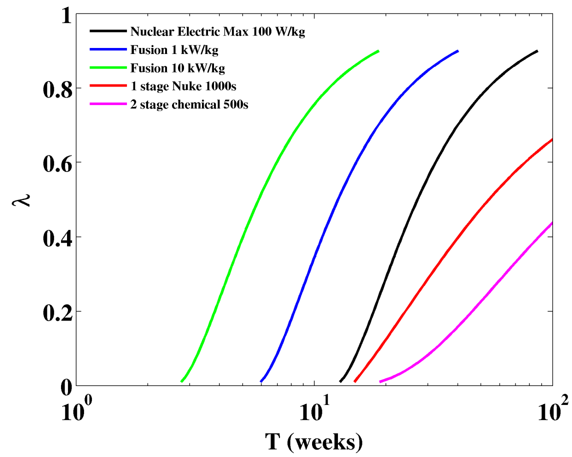


Figure 1. Payload mass fraction vs T for Mars rendezvous. R=0.5 AU.

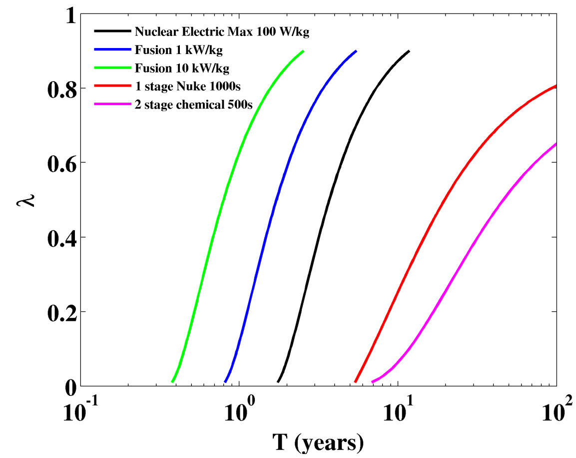


Figure 2. Payload mass fraction vs. T for Saturn rendezvous. R = 9.5 AU.

For calculating vehicle mass, one has to assume the payload mass at the destination. Assuming 100 mT (1000 kg), IMLEO (initial mass in low earth orbit) can be plotted as shown in Figs. 3 and 4, which would connect with the vehicle cost because launch cost scales with initial vehicle wet mass.

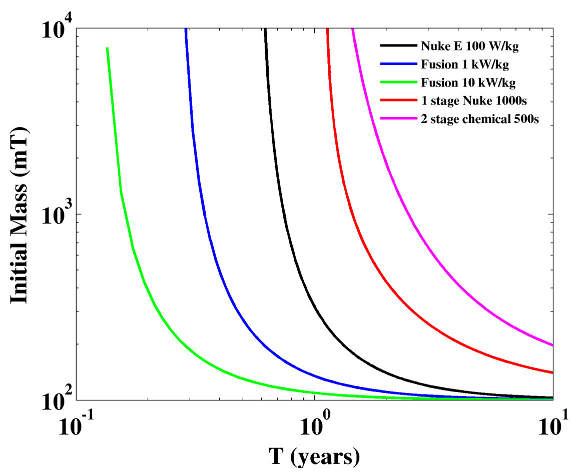


Figure 3. Mars roundtrip. R = 0.5 AU.

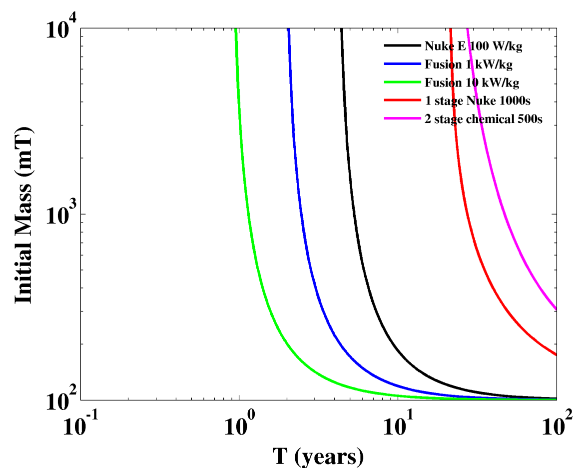


Figure 4. Saturn roundtrip. R = 9.5 AU.

Figures 1–4 illustrate how difficult it is for chemical systems to reach interplanetary destinations in a short time compatible with human piloted missions. For the Mars mission, it becomes feasible with nuclear thermal and advanced nuclear electric propulsion, but cannot become routine unless fusion propulsion becomes possible. Missions to Saturn are not realistic at all unless advanced fusion systems are built.

IV. Introduction to fusion and fusion confinement

The basic challenges to fusion for propulsion are two-fold. First, thermonuclear fusion requires fuel temperatures of ~10^8 K or greater. Second, the reaction products are born with kinetic energies in the MeV-range. Such products are difficult to thermalize in short distances, which leads to large reactor size. Perhaps more importantly, the neutron flux is roughly an order of magnitude greater than that from nuclear fission, and this requires significant advancements in materials compared with fission reactors.

Because of these challenges, fusion is often classified according to the method utilized for confining the plasma. Among the most commonly studied approaches to nuclear fusion are Magnetic Confinement Fusion (MCF), Inertial Confinement Fusion (ICF), Magneto-Inertial Fusion (MIF), and Inertial Electrostatic Confinement Fusion (ICF). In order to facilitate the discussion on the fusion history – and our own technical plans –we include a brief summary of the primary confinement approaches.

IV.1 Magnetic Confinement Fusion (MCF)

MCF utilizes strong magnetic fields to confine low-density plasma over a large spatial and temporal scale (ion density ~10^{15} cm^{-3}, a volume of hundreds of cubic meters and a continuous, steady state operation), establishing the conditions for thermonuclear fusion. MCF takes advantage of the fact that magnetic fields keep the ions (which carry a significant portion of the energy) within the "reaction domain" and therefore reduce thermal losses. The primary type of device used to confine the fusion is the tokamak,[9] although there are numerous spin-offs which differ primarily in geometry of the magnetic field i.e. spheromaks, Reversed Field Pinch (RFP) and stellarators. The Polywell and Reversed Field Configuration (FRC) fusion approaches can be partially categorized as MCF, although they involve some inertial aspects as well (magneto-inertial hybrids) and their construction and magnetic field structure is quite different from the tokamak-type machines. There are currently more than 20 different MCF devices in the world, all of which are primarily concerned with performing fundamental plasma research in support of the main "flagship" of MCF – namely ITER (International Thermonuclear Experimental Reactor),[9] situated in the south of France.

IV.2 Inertial Confinement Fusion (ICF)

ICF[10] utilizes a spherically symmetric distribution of high-energy laser pulses or heavy ion beams to compress a solid-state ~2 mm target. The target is typically a hollow shell with stratified layers consisting of hydrocarbons doped with various additives in the outer layers and deuterium-tritium (DT) ice on the inside. The process of target implosion can be broken into four phases: ablation, implosion, stagnation, ignition, and burn; and will be discussed in the context of direct-drive laser fusion. During the ablation phase, laser energy is deposited into the plastic outer layer. This ablates the outermost material, and the reactive pressure drives the remaining target material inward. At ~10 ns, the resulting shock reaches the inner layer of the shell, and the laser power is ramped up. Ablation-induced pressure peaks at ~100 Mbar and the plastic layer is almost entirely ablated. The material absorbs about ~1 MJ of energy and reaches a radial speed of about 350 km/s. The inner material reaches the center after around 25 ns, creating a 10 keV central hotspot; and fuel pressure reaches 250 Gbar. These conditions last for ~20 ps, during which ignition occurs; with a burn wave flowing outwards and consuming the fuel layer. There are numerous ongoing ICF experiments. The largest scale device is the National Ignition Facility (NIF), and claims have been made that NIF will breakeven in the next few years.[11]

IV.3 Inertial Electrostatic Confinement (IEC)

Inertial electrostatic confinement (IEC)[12] involves a (typically) spherical electrostatic field produced by a grid or other means to radially confine ions. The ion energies are determined by the potential well depth, and the simplicity has facilitated a sizable number of researchers and hobbyists to build table top fusion reactors in spite of comparatively little funding in this area. Ion and energy confinement, as in most fusion approaches, are among the critical issues. Recent work has shown that the physical processes that limit ion lifetime inside the well include charge exchange with the background gas, defocusing of the ions, and bombardment with the external grid.[13] A number of approaches are seeking to mitigate these problems, such as employing an external cusp field as is done in the Polywell concept.[14]

IV.4 Magneto-Inertial Fusion (MIF)

Magneto-inertial fusion (MIF)[15–17] uses a magnetic field in an inertially confined fusing plasma to reduce thermal losses and to enhance alpha particle self-heating of the fuel. This reduces the areal density (ρr) threshold for ignition[13]. Success of the MTF approach relies on the liner, which must be energetic enough to compress the target to ignition, behave as a stable magnetic flux conserver, and confine the target long enough so the fusion yield exceeds the liner driver and target generation energies. While solid liners are a mature technology,[19] they may suffer from potential engineering difficulties in the context of a reactor concept due to reasons such as non-reusability, manufacturing costs, and debris deposits along the interior of the wall.[20] Plasma liner driven magneto-inertial fusion (PLMIF)[20,21] aims to overcome these problems. PLMIF potentially allows all the driver hardware to be far enough away from the fusion pulses to avoid significant damage during operation. The drivers could be, for example, railguns.[22] Other variants of MIF are of interest, including the proposed magnetized pulsed z-pinch experiment MagLIF,[15] in which 1D Lasnex[23] simulations show that gains of 100 and 1000 are feasible with 60 and 70 MA of current, respectively.

IV.5 Fission fusion hybrids

Fission-fusion hybrid reactors[24] have been established for over a half-century, but research has mainly been for military applications. The power generation community has largely eschewed fission/fusion hybrid research, choosing instead to pursue the notion that pure fusion reactors will be more environmentally benign. However the difficulty over the decades in developing a practical fusion reactor has driven the fusion community towards those fuels with the lowest ignition temperature, which unfortunately also produce high energy neutrons at a higher rate than most fission reactions. While there has been relatively little work in this area, there have been some recent theoretical developments by Winterberg.[25,26] Winterberg's concept involves a relativistic central electron beam to magnetized and preheat a central fuel target with a high voltage pulse, with compression and confinement provided by a surrounding liner driven by a high current z-pinch. Hybrids are also discussed significantly in Winterberg's recent book on ICF.[27]

V. Summary of past fusion concepts

The main problem of fusion propulsion is the fact that fusion energy with gain in excess of unity has only been achieved in weapons, not in terrestrial reactors. Nevertheless, there has been over a half century of research conducted. Progress has yielded steady advances in the development of appropriate models and into making viable estimates about such propulsion systems. We attempt to summarize many of these efforts in rough chronological order. This summary has three sub-sections: 1) early history from 1958 to ~1990, 2) Major NASA programs from 1958 through 2004, and 3) other recent programs spanning 1990 to the present.

V.1 Early Fusion Propulsion History

The idea of thermonuclear fusion for propulsion has at least been around since the late 1950's.[28,29] Notable works come from Englert[30] and Hilton[31], who primarily discussed the magnetic mirror approach. It was quickly recognized that a clear weight advantage over pure fission electric systems could be realized if the fusion plasma was utilized for either direct conversion to electricity or for direct production of thrust[29]. Both approaches circumvent the need for a thermodynamic heat cycle limited by the 2nd law of thermodynamics for the primary power and/or propulsion system, which yields a significant saving in radiator mass. It was also recognized that there is a tradeoff between specific impulse and thrust, and that moderate to high thrust systems would require mixing and thermalizing of the fusion plasma with a heavier exhaust stream. One of the first interstellar propulsion systems utilizing fusion was the Bussard ramjet, proposed in 1960.[32] Of note was the requirement that the ion collector – needed to scoop up sufficient protons in the interstellar medium – required a radius of 60 km. Further feasibility studies determined that first generation interplanetary systems would be relatively low thrust (thrust to weight ratios of ~10^{-4})[33] but that they would be sufficient for rapid interplanetary space travel and precursor interstellar flight.[34] Gradecak[35] provides a nice overview of the unconventional propulsion systems of the time and also –though briefly – compares fusion to electric propulsion. He claims that a fusion propulsion system, similar to ones described by Hilton and Englert, can achieve specific impulse up to 5×10^5 s.

In 1971, Reinmann[36] discussed another magnetic mirror concept, claiming specific impulses of 2×10^5 s and a power to mass ratio of 2.5 kW/kg. Daedalus[6] was a feasibility study that was meant to provide an insight into what would it take to reach another star within a human lifetime. The project was never meant to develop detailed blueprints for an interstellar mission, as most of the necessary technological advancements had to be reasonably extrapolated based on the current state-of-the-art technology. The final result of the study was a detailed report on a 190 meters tall, two-stage, fusion-propulsion based, unmanned probe that needed to carry about 50000 tons of fuel, travelling on average around 0.12c, so it would reach Barnard's star within 46 years, and this study remains as one of the (only) detailed fusion concepts which was specifically designed for an interstellar mission. According to a current effort 'Project Icarus',[37] dubbed the 'Son of

Daedalus', Project Daedalus was influenced by Winterberg[38], whose work appears to be the first proposed pulsed fusion propulsion system.

Borowski[39] provided a good comparison between compact toroid tokamaks, spherical torus tokamaks and ICF approach fusion propulsion systems. Borowski's ICF approach showed possible access to 53 GW of total power, with specific impulse as high as 2.7×10^{5} s and power to mass ratio of 110 kW/kg. Santarius[40] provided another overview of fusion propulsion concepts, claiming specific impulses up to 10^{6} s, while also stating that it is feasible to achieve power to mass ratios of 10 kW/kg.

V.2 Major NASA Programs

The longest sustained NASA program dedicated to fusion energy for space propulsion and power, ran from 1958 to1978. It was concentrated on: basic plasma physics, cryogenic and superconducting magnet development, and high temperature confinement[41]. In this program a magnetic confinement approach was adopted, and subsequently a balanced research program ensued, involving theory, mission analysis, critical technology development, and reactor-relevant plasma confinement experiments. Plasma confinement was initially studied in a reactor called the Pilot Rig, a magnetoelectric confinement experiment that made use of a modified Penning discharge in a superconducting magnetic mirror. Success in the Pilot Rig led to approval of the Electric Field Bumpy Torus (EFBT), which involved 12 Pilot Rigs connected together and bent into a torus. Of particular interest were the production of 100 μW of neutron power (the maximum allowed by radiological safety standards at the facility). A type of diverter was invented to remove escaping unburned fuel and reaction products in the form of a unidirectional beam, which was suitable for propulsion or power production. The end of the Apollo-era funding at NASA brought heavy pressure to cut programs that did not support development of the space shuttle, and the fusion research program was one of the casualties.

More than a decade later, interest was renewed in advanced propulsion technologies for interplanetary and interstellar travel. According to Santarius,[40] this was attributed to identification of ^{3}He as a lunar resource,[42] a new (~1989) national space policy supporting expansion beyond LEO, and the emergence of high power-density fusion reactors. A major catalyst came in the form of a 497 page NASA technical memorandum published by Norman Schulze in 1991 titled "Fusion Energy for Space Missions in the 21st Century".[43] In this very thorough document, Schulze discussed many of the important topics concerning a serious fusion development program for space power and propulsion, including: high energy missions requiring such technology, fusion reactions, theoretical performance, flight system considerations, potential systems-level interactions of propulsion system with the spacecraft, fuel and design options, political and public acceptance, safety, and recommended strategies. Schulze concluded that advanced reactor designs not currently pursued by the U.S. DOE were better choices for propulsion.

Perhaps one of the most profound observations made in the Schulze memorandum was about the disparate roles that DOE and NASA play. Schulze stated that, if NASA endeavors to pursue high energy missions requiring fusion, then waiting for DOE to solve the breakeven problem would not lead to a reactor suitable for space power and propulsion. He states this is due in part to key differences in the missions of DOE and NASA. Fusion makes up a relatively small amount of the DOE budget, and its focus within fusion is ostensibly to make reactors for terrestrial power that are profitable. NASA is required instead to focus on technologies that are mission-enabling. Currently, there is an abundance of terrestrial energy, and the world does not require fusion for electricity. However there are some missions which can *only* be enabled by fusion propulsion. A second reason comes from development cost considerations. Mission failures in space are very expensive to correct, because launch costs are of the order of $1 billion per launch for large systems. However an increased investment during development will usually be only a small fraction of the launch cost, and may result in a considerable improvement in reliability. This argument does not apply so well for terrestrial applications, where failures can be fixed much more readily. Finally, the terrestrial and space operating environments are very different. For example, water is plentiful on earth and cheap, and reactors can be designed readily to use it. In space, regenerative- and radiative-cooling are the only thermal control methods that are available.

A second program, primarily conducted at NASA Marshall Space Flight Center, began in the late 1990's focusing on plasma jet-driven magneto-inertial fusion (PJMIF), which at the time was referred to as magnetized target fusion (MTF) [20,21,44] – a variant on inertial fusion in which a plasma liner compresses a magnetized target. In 1999, Thio et.al. presented their conceptual paper[44], where they describe the magnetic target fusion (MTF) approach. The authors give a very good mathematical description of the physics and explained principles of the system, while providing values for specific impulse of 7.7×10^4 s, power to mass ratios of up to 1.14 MW/kg at repetition rate $\omega = 100$ Hz, thrust of 340 kN, jet power of 128 GW and total system mass of 112 t. Pulsed electromagnetic plasma accelerators were tested[45] and modeled[46] as potential candidate drivers for the plasma liner. The NASA MSFC Advanced Concepts Office conducted a detailed mission analysis for a human piloted mission to Callisto, summarized in a 140-page analysis of interplanetary mission with human-crew, with PJMIF as primary propulsion.[47] The study provides detailed analysis of different technical components i.e. magnetic nozzle construction, plasma gun distribution, detailed power and energy flows, precise mass estimates and material considerations, while providing a large variety of useful figures, few of which are used in this paper.

During the 2nd program, a NASA fusion propulsion workshop was held on November 8 and 9, 2000.[48] Part of the motivation for the meeting was to elevate awareness to the propulsion community of the recent and rapid advances toward fusion reactor breakeven. Seventeen fusion propulsion concepts were discussed. Among these there were three concepts with a dry mass below 80 metric tons with specific powers above 30 kW/kg with specific impulse above 5×10^4 s.

After the Shuttle Columbia tragedy, NASA shifted priorities away from advanced propulsion and other basic research, halting further progress in PJMIF for propulsion. The target generation system was evolved into an electric propulsion effort denoted the Plasmoid Thruster Experiment (PTX).[49] A conceptual design of a fusion propulsion system was derived from PTX called Fireball.[50] Separately, the plasma liner effort continued as a U.S. Department of Energy program by a collaborative group lead by Los Alamos National Laboratory (LANL), [51] and considerable advancements have been made in the design of the plasma guns,[22] which will be utilized as the driver for the imploding plasma liner. One-dimensional[52] and three dimensional[53] modeling has yielded new insights into the scaling of pressure with plasma liner parameters and the processes of plasma liner formation from discrete jets.

V.3 Other Efforts

Other efforts supported by NASA, DOE, and other sources occurred during the late 1990's to 2000's. They are too numerous to be discussed fully, but we attempt to summarize some of the major efforts, grouping them according to theme or fusion concept. We begin with the various summary papers, which themselves reference additional studies. Williams and Borowski[54] assessed 13 fusion propulsion system studies in a 1997 paper. They concluded that system mass estimates were incomplete, radiation losses were often neglected, and design efforts in thrust generation and nozzle efficiency were lacking. Their suggestions for improvement in part led to AIAA's "Recommended Design Practices For Conceptual Nuclear Fusion Space Propulsion Systems"[55], and in 2004, Williams[56] made a good summary of providing a simplified form of the report and bringing out some good examples of technological extrapolations. Adams and Cassibry[57] wrote a motivational paper revising some of the previous fusion concepts, followed by a similar paper by Romanelli and Brunno[58] in 2006, where the latter authors have a table clearly showing significantly higher power to mass ratios of the PJMIF concept.

V.3.1 Inertial Electrostatic Confinement

Bussard made several contributions in the area of inertial electrostatic confinement (IEC) during this period. First, in 1990 he conducted a fundamental mission analysis study showing that a high gain (~50) fusion system serving as an electric propulsion device could produce high acceleration sufficient for lunar and rapid interplanetary travel.[4] The requirement for high gain was later confirmed by Chakrabarti and Schmidt using a separate approach.[59] It should be pointed out that high accelerations can potentially be achieved at lower gains, provided the fusion product exhaust stream is mixed with a higher mass flow rate propellant, and that this was neglected in both studies. After the 1990 paper, Bussard considered the physical feasibility for the Polywell IEC reactor, showing very favorable gain scaling with system size. The concept was later evaluated for a variety of propulsion applications from air-breathing to interstellar flight.[60] Experimental work has continued through a contract with the U.S. Navy, but currently the results have been classified making it difficult to comment on further progress.

V.3.2 Gasdynamic Mirror

In the second half of the nineties Kammash and Lee[61] argued that their gasdynamic mirror approach can reach specific impulse values of 4.07×10^5 s, with a remarkable 670 GW of total power, but with a "low" power to mass ratio of only 6.35 kW/kg; this led to a total mass estimate for the system of 105 kt. It was subsequently recognized that the positive potential left by the initially escaping electrons in a mirror system leads to enhanced specific impulse and thrust.[62] A small scale experiment was constructed and tested by Emrich,[63] in which an MHD instability was identified in the nozzle throat that could lead to departure from the predicted performance. This appears to be specific to the relatively high density operation of the GDM system, but could perhaps be overcome given the maturity of steady state magnetic nozzle systems in electric propulsion.[64]

V.3.3 Closed Field Magnetic Confinement

While closed field magnetic confinement fusion has been dominated by tokamak research, fusion propulsion system studies have favored spherical torus[65,66] and field reversed configuration (FRC)[67] due to the potentially higher power density of these types of reactors. Steady state FRC reactors were highly recommended in the late 1980's and early 1990's.[38], [41], and new insights led to pulsed FRC[68] or plasmoid[50,69] propulsion systems later on. While FRC has a clear definition,[70], 'plasmoids' more generically refer to a self-organized plasma blob with embedded fields, with the term perhaps first coined in 1962.[71] Both pulsed approaches have their roots in a 1981 fusion reactor study CTOR.[72] It should be noted that total system masses for pulsed plasmoid and FRC propulsion systems have been estimated to be significantly smaller than the ICF or MCF systems, and similar to MIF systems. Pulsed FRC and plasmoid systems can in fact be classified as a magneto-kinetic variant on MIF in which the kinetic energy of the magnetized plasma is utilized in self-compression through a compression cone or converging magnetic field lines.

V.3.4 Inertial Confinement

One of the most detailed and well-known studies to date was of an ICF concept called Vehicle for Interplanetary Space Transport Application Powered by Inertial Confinement Fusion (VISTA).[73,74] VISTA was a single stage interplanetary vehicle design study conducted by the Lawrence Livermore National Laboratory sponsored by DOE, and based on an earlier concept advanced by Hyde.[75] The propulsion system was assumed to be a diode-pumped solid-state laser, driving a spherical array of lasers to compress ‘tritiated’ deuterium pellets at a maximum rate of 30 Hz. In this concept the pellets would compress to thermonuclear ignition, expanding against a magnetic nozzle. A significant level of detail went into many of the subsystems anticipated for an actual vehicle, including the design and performance of the nozzle. The system analysis resulted in a 6000 mT vehicle producing ~2×10^6 N of thrust, with a specific impulse of 27,000 s, and capable of round-trip Mars missions lasting 150 days.

An ongoing ICF effort is Project Icarus,[37] a mostly volunteer program initiated by the British Interplanetary Society and the Tau Zero Foundation and currently being managed by Icarus Interstellar Inc. This group endeavors to produce a credible conceptual design for an interstellar probe to be used in the future. Project Icarus is derived from the aforementioned Project Daedalus,[6] and with this new conceptual design, comparisons will be made to that earlier 1970's era study to assess the progress that has been made in fusion technology for space propulsion. It has been concluded that interstellar travel is possible within one human lifetime with realistic extrapolation from existing technologies.

V.3.5 Pulsed Z-pinch

Early work in steady state fusion focused on z-pinch, and in fact the first fusion propulsion system proposed was based on such a steady state device with a magnetic nozzle for deriving thrust.[28] Instabilities discouraged long term research in this area, but with the emergence of pulsed power technology, pulsed z-pinch has shown a very favorable fusion yield scaling with peak current ($\sim I^4$),[76] and new theoretical insights have have led to ways of overcoming Rayleigh-Taylor instabilities.[77] One of the best sustained efforts devoted in part to propulsion is Schumlak's ZAP concept.[78] In ZAP, the pinch is stabilized by a shear flow generated by a coaxial plasma gun during the collapse of the pinch, which is stable for ~2000 instability growth times. A more recent theoretical study also suggests that magnetic shear may provide some stabilization as well.[79] A recent effort by ERC Inc., ISS Inc., Qualis Corp Jacobs ESTS Group, NASA MSFC, University of Alabama Huntsville, and SAIC was conducted for a crewed mission to Mars using a z-pinch fusion propulsion system.[80] The vehicle design required a minimum mass in low earth orbit of 500 mT due to scaling issues for fusion propulsion systems. Z-pinch offered substantial improvements to previous fusion concepts and a way to make Mars missions quick and routine with reusable vehicles and substantial payload margins, and both 30 day and 90 day one way trip times were evaluated.

V.3.6 Summary

Many fusion propulsion concepts have been proposed for propulsion over the course of a half century. While the world has yet to yield a breakeven fusion reactor, the potential performance is generally recognized with specific powers ranging from 1 to 10 kW/kJ, specific impulse from 10^4 to 10^6 s, and thrust in the 10's of kN or higher, assuming mixture of the fusion with a higher mass flow rate propellant. There is a wide variability in the estimated vehicle system size, with masses ranging from <80 mT to >1000 mT. Generally, we have observed that smaller system sizes are estimated for MIF-based fusion propulsion systems. In the next section, we discuss some potential reasons for this, and motivate our choice for pulsed z-pinch.

VI. A set of guiding parameters suitable for in-space propulsion

The path to fusion propulsion will be shortened by reducing the development cost and reactor mass. These two factors are coupled, because the cost of a system depends on the reactor size. Additionally, it is worth revisiting the fuel cycles to consider how costs may be lowered by considering alternatives to the usual DT or D^3He reactions. Below we discuss the parameter space to justify our choice for MIF-based systems, followed by a discussion on fusion fuel options.

VI.1 Fusion parameter space

Scaling of reactor depends on the type of confinement approach, and this is discussed thoroughly by Lindemuth and Siemon.[81] In this section we summarize the points of their paper of primary relevance to propulsion, and then explain why we have chosen the MIF parameter space to pursue for fusion propulsion research and development.

Figure 5 illustrates the parameter space for magnetic fusion energy (MFE), MIF, and ICF in density/plasma energy space. The blue, magenta, and black lines represent transport of energy via electron thermal conduction and radiation, and reactors must be scaled such that fusion power exceeds these losses. The black line is only relevant to ICF, because it is the electron transport in absence of magnetic fields.

MFE represents tokamaks, spherical torus, steady state FRC, and other steady state reactors in which an externally applied magnetic field confines the plasma. Plasma density in MFE systems is ~10^{14} to 10^{15} ions/cm^3, and is limited by the applied magnetic field. Large reactors are needed at such low densities in order to produce sufficient power, and while higher densities could be achieved, the neutron flux to the plasma facing wall surface is too high for materials to survive for durations of a mission. Reactors exceeding breakeven are of the order of sports stadiums.

ICF is represented on the far right of Figure 5. The reacting volume is significantly smaller, and in fact is practically negligible. However, ICF systems scale with the power required to compress the solid pellets to 100 times solid density. This power scales with electron thermal transport as shown, and requires lasers or ion beams with deposition powers in the petawatt range. The total capacitor bank energy needed to drive the lasers scales with the total implosion kinetic energy required for the pellet, and has to account for the poor efficiencies from electric to laser, laser to xray energy, xray to deposition, and deposition to implosion energy. As a result, the laser and capacitor banks in NIF, which is anticipated to breakeven in the near future, require a footprint of ~3 football fields.

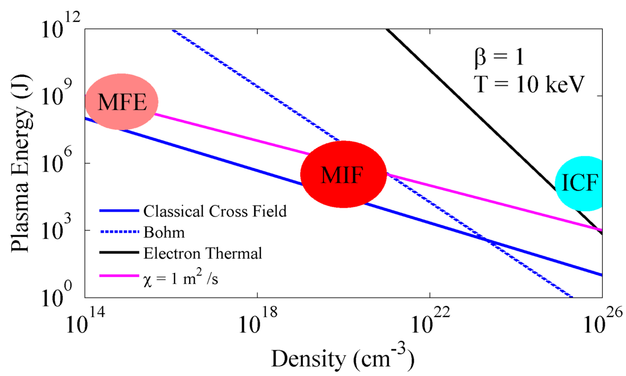


Figure 5. The parameter space for magnetically confined fusion energy (MFE), magneto-inertial fusion (MIF), and inertial confinement fusion (ICF).

The MIF parameter space is significant for a number of reasons. First, the relatively high density (roughly between sea level air and liquid densities) enables much smaller reacting volumes compared to MFE. The limiting radiative and transport losses intersect at an energy level of 1 to 100 MJ. Further, the embedded magnetic field suppresses the cross field thermal conduction, lowering the power required to drive the compression compared with ICF. Finally, implosions in this regime can be driven by liners via electromagnetic acceleration, which has a much higher overall efficiency compared with lasers and does not require extrapolation from existing pulsed power capabilities.

Based on the known energy, size, power, and costs associated with ITER (an MFE system) and NIF (an ICF system), both of which are designed to be breakeven fusion systems, Lindemuth and Siemon developed a cost scaling law as a function of the fusion parameter space tied to constraints with fusion power balance laws required for a breakeven system.[81] They determined that the estimated cost for developing a fusion breakeven facility minimizes in the MIF parameter space, based on the assumption that cost scales with the total energy and power required for the system. Consequently, the system mass is also a minimum in this physics regime. The result that MIF systems require relatively low energy for breakeven is independently supported by a separate theoretical study by Drake et al.[82] in which a z-pinch, FRC, and spheromak were evaluated for the target in an MIF system. In the study by Drake et al., it was found that breakeven may be feasible with less than 1 MJ of energy.[82]

VI.2 Fusion fuels

Given the favorable scaling of MIF systems, which is consistent with the observation we made that fusion propulsion system studies utilizing MIF approaches tend to be considerably smaller than their ICF and MCF/MFE counterparts, we now consider fuels that may simplify development. The importance of a reaction is based on a couple of factors. First, the number of reactions per second is given by the reaction rate,

$$\frac{dN}{dt} = n_1 n_2 < \sigma v >_{12} \mathcal{V} \tag{30}$$

where dN/dt is the rate of reactions occurring per second, n is the number density in #/m^3, $<\sigma v>$ is the reactivity, and $\mathcal{V}$ is the volume of the reacting plasma. For this reason, the DT reaction is favored because the cross section is higher by an order of magnitude or more compared with all other reactions. (For a thorough comparison of numerous reactions, see Howerton.)[83] Another issues is whether or not it produces neutrons. In this regard, D^{3}He has been popularized for space propulsion because of the abundance of ^{3}He throughout the solar system, and more importantly because it is the reaction with the 2nd highest reactivity beyond 10 keV. Due to DD side reactions, D^{3}He systems are not purely aneutronic. The p^{11}B is almost entirely aneutronic, apart from a very small fraction of side reactions involving pairs of protons, and because of this has gained much attention. However, the reactivities are very low and require 100 keV temperatures or higher for ignition. The third issue, frequently ignored, is the local abundance and cost of fuel. Based on this, arguably the most important reactions are

$$\begin{array}{rcll}
D+T & \rightarrow & \alpha+n & 17.59 \text{ MeV} \\
D+D & \rightarrow & T+p & 4.04 \text{ MeV} \\
D+D & \rightarrow & {}^3He+n & 3.27 \text{ MeV} \\
D+{}^3He & \rightarrow & \alpha+p & 18.35 \text{ MeV} \\
D+{}^6Li & \rightarrow & 2\alpha & 22.374 \text{ MeV} \\
D+{}^6Li & \rightarrow & p+{}^7Li & 5.026 \text{ MeV} \\
D+{}^6Li & \rightarrow & n+{}^7Be & 3.38 \text{ MeV} \\
p+{}^{11}B & \rightarrow & 3\alpha & 8.68 \text{ MeV} \\
n+{}^6Li & \rightarrow & T+\alpha & 4.86 \text{ MeV} \\
n+{}^7Li & \rightarrow & T+\alpha+n & -2.87 \text{ MeV}
\end{array} \tag{31}$$

The D+D reactions above occur with roughly equal probability, and have reactivities somewhat lower than D^3He. The D^6Li reactions occur with roughly equal probability among each other and are comparable to the $p^{11}B$ reaction. Neutron capture is important for protecting hardware from damage. The fusion neutrons are very powerful and will cause dislocations in the lattice of structures, and some materials have good neutron absorption, meaning fusion neutrons could create hazardous radioactive isotopes out of some materials. Lithium is often favored as a liquid layer to shield the first solid wall against neutron flux. As seen above it can be used to breed tritium, and in case of ^6Li, the reaction is exothermic.

The D^6Li fuel cycle is rarely found in current literature in the context of reactors for power or for propulsion. We summarize the relevant work of which we are aware here. This fuel cycle was included in an early textbook by Miley.[84] McNally showed that next to DD, the fuel cost per kg was cheaper than virtually any other option by orders of magnitude.[85] Winterberg has written extensively on utilization of this fuel cycle, especially in the context of weapons physics and inertial confinement fusion.[27] Martin and Ekridge[50] considered lithium-lined cones in which FRC's are compressed to thermonuclear ignition in their FIREBALL fusion propulsion concept.

The motivation for investigating a solid as a potential fusion fuel is three-fold. First, the rate equation for a fusion reaction, which gives the number of reactions that occur per second, is

$$\frac{dN}{dt} = n_1 n_2 < \sigma v > V \tag{32}$$

where n_1 and n_2 are the number densities of the fuel, $<\sigma v>$ is the reactivity, and V is the volume of the fuel. Assuming a 50/50 mixture of each species, the reactivity is quadratic with n. Current z pinch experiments start with a gas puff with densities of the order 10^{25} #/m^3, and require considerable compression, so working with solid targets obviates the need for compressional work and creates initial conditions for a highly reactive burning plasma. D^6Li exists as a salt with mass density of approximately 800 kg/m^3, which corresponds to ~10^{29} #/m^3. Second, while ICF utilizes solid targets (frozen DD or DT ice), D^6Li is a solid at room temperature, so no cryogenic storage is required. Third, D^6Li is the only fuel which has exceeded the energy input: thermonuclear bombs. The challenge to safe utilization of D^6Li is then to exploit significant advancements in pulsed power to replace the fission trigger with electrical power.

Burning D^6Li plasmas actually include the following reactions

$$\begin{gathered} D+D \rightarrow T+p+3.02\,MeV \\ D+D \rightarrow {}^3He+n+3.45\,MeV \\ D+{}^6Li \rightarrow 2\,{}^4He+22.4\,MeV \\ D+{}^6Li \rightarrow {}^7Li+p+5.0\,MeV \\ D+{}^6Li \rightarrow {}^7Be+n+3.4\,MeV \end{gathered} \tag{33}$$

and numerous exothermic side reactions involving the reaction products and reactants. The overall reactivities for the reactions above are shown below, along with those of D^3He and DT for reference, Fig. 6.

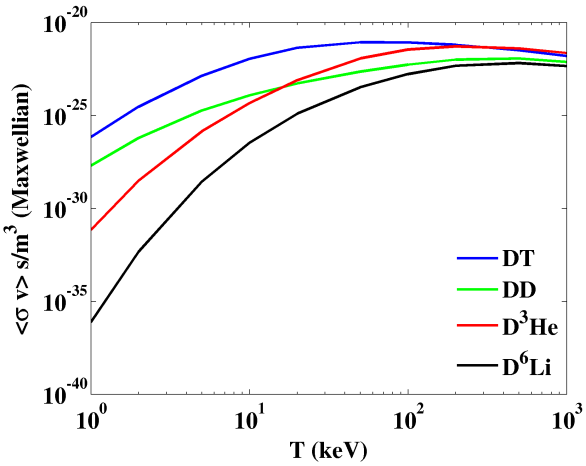


Figure 6. Overall reactivities for lithium deuteride. Those of DT and D^3He are shown for comparison.

VII. Summary of Proposed Pulsed Zpinch Concept

Thus far in the paper, we have shown our motivation for fusion based on the interplanetary missions enabled only with such technology. Based on a review of fusion propulsion in the literature and the fusion parameter space, we have concluded that magneto-inertial fusion is the approach most likely to yield a short development time and relatively small, affordable vehicle for deep space exploration. Because of the abundance of relatively low cost, non-radioactive fuel and the fact that it can be stored as a solid at room temperature, we are going to investigate D^6Li. Further, due to the very favorable scaling of fusion energy output with current,[15,86] and emerging theoretical insights into the suppression of deleterious instabilities,[77–79] we have concluded the pulsed z-pinch approach is perhaps the most direct route to development of fusion propulsion.

VII.1 Description of the Charger 1 Facility

The University of Alabama in Huntsville (UAH), working with co-authors at the local Boeing Company, has been successful in obtaining a 3 TW pulse power machine, the Decade Module 2 (DM2), from the Defense Threat Reduction Agency (DTRA) to pursue fusion research. DM2 is a ~500 kJ pulsed power facility capable of 2 MA discharges at 3 TW of instantaneous power. For comparison, the electrical power in the entire global grid is 15 TW. DM2 was the last prototype serving as a test bed for the design and construction of the much larger Decade Machine which was built and utilized at Arnold Air Force Base in Tennessee for nuclear weapons effects (NWE) testing. DM2 was built by Physics International around 1995, and has had an active and important role in the development of advanced Plasma Radiation Sources (PRS) for the Defense Threat Reduction Agency's (DTRA) cold X-ray source development program. DM2 now resides at a laboratory at UAH and is under construction supported by UAH, MSFC, and The Boeing Company. Once DM2 arrived, we renamed it the Charger 1 facility because of the UAH mascot and the bad pun. We use 'Charger 1' and DM2 interchangeably in the remainder of the document.

VII.2 Planned Experiments

While we intend for Charger 1 to be a multi-purpose pulsed power laboratory, the fusion propulsion relevant experiments involve testing of z-pinch diodes and pulsed magnetic nozzle experiments. A Z-pinch diode operates when extremely high electrical currents propagate through materials generating sufficient Lorentz force to compress the diode material reaching temperatures of kilo-electron volts (>100 million degrees Kelvin) sufficient to initiate thermonuclear reactions. In our experiments we plan to test wire array diodes, beginning with copper or aluminum wire arrays for experimental benchmarking, Fig. 7a. Next we intend to test lithium wires with a D^6Li core, Fig. 7b. Lithium melts at temperatures above 180°C while D^6Li melts at temperatures above 692 °C. As with solid metals and salts, these apparatus must be developed in dry nitrogen. Thus, thin jets of liquid metal and salt can be injected into the pulse power diode, Fig. 7c. In a multiple shot environment, we can anticipate sufficient energy to melt the fuel. Details of these experiments are beyond the scope of this paper.

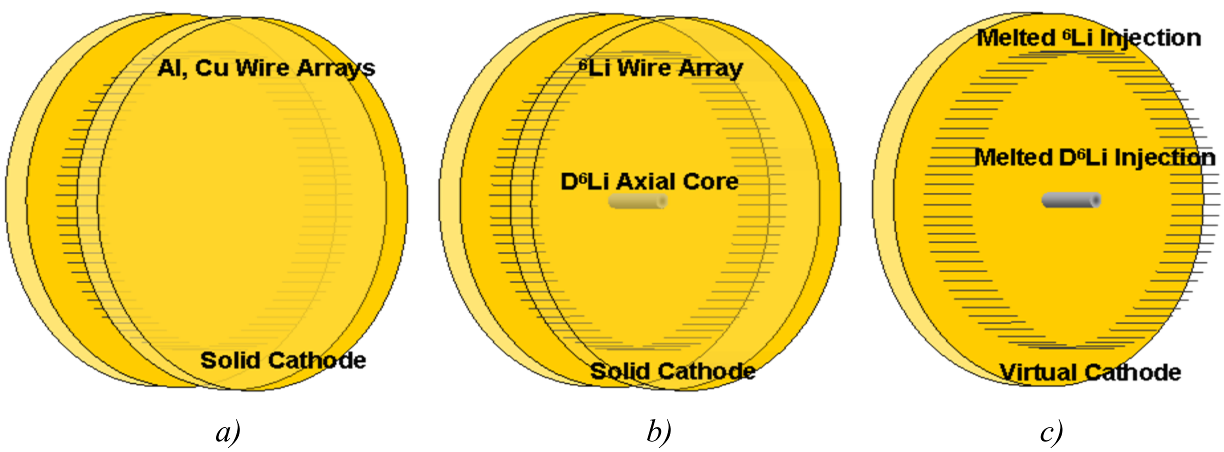


Figure 7. Planned wire array diodes for Charger 1 with a) aluminum or copper wires, b) lithium wires with D^6Li core, c) molten lithium and D^6Li injection.

It is imperative that magnetic nozzle experiments be conducted early on and in parallel with the fusion experiments so that the means for deriving propulsion from the fusion output can be better understood. The physical components of such a nozzle are a number of current-carrying rings, which are positioned so that they fall on a parabola (which is itself a cross-section through a paraboloid of revolution), which has its focus at the point of fusion – which is also the point about which the plasma shell is expanding. When electrical current is passed through the rings the resulting magnetic field is as shown in Fig. 8.

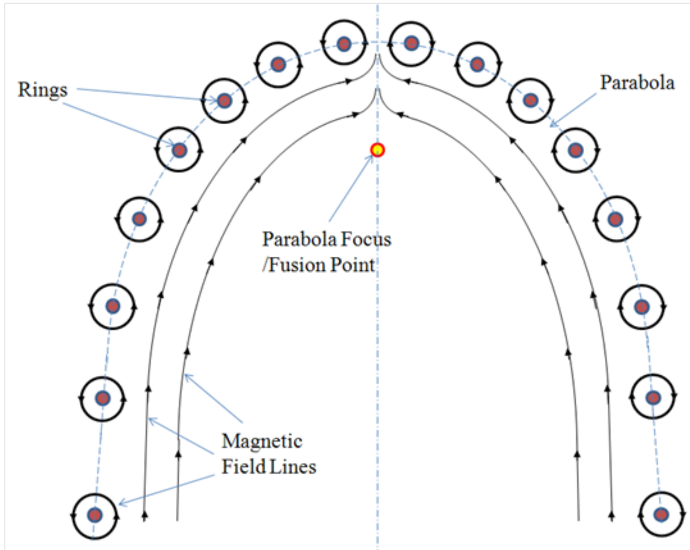
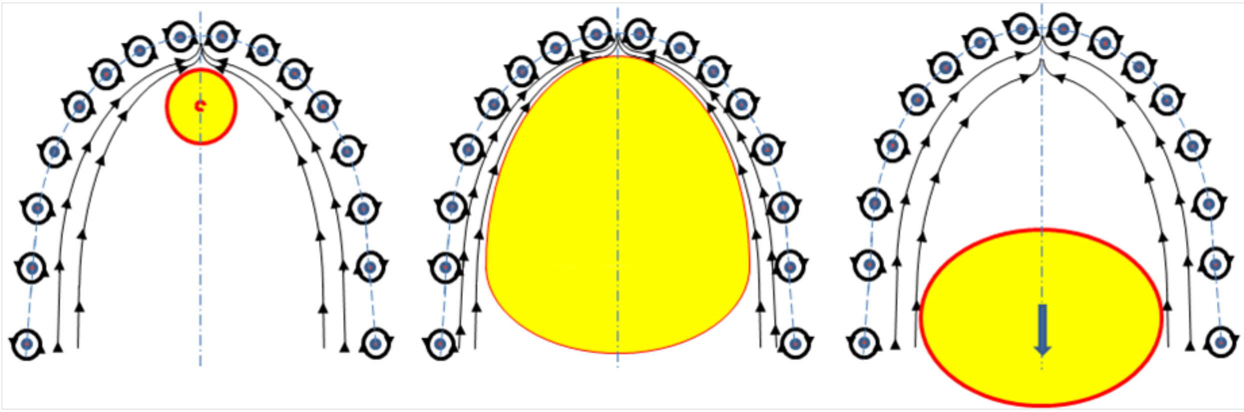


Figure 8. Example of a parabolic magnetic nozzle.

The hot expanding plasma is highly conductive, which means when it encounters an external magnetic field, internal currents are induced within the plasma in such a way as to oppose the intruding magnetic field. The net effect is to resist the intrusion of the external magnetic field into the plasma. This means that as it moves outwards, the expanding plasma shell pushes the magnetic field lines back towards the current-carrying rings and thus compresses the field into a smaller and smaller paraboloid-annular region. As the magnetic flux is compressed, the field strength (B) increases and so does the magnetic pressure (B^2/μ_0).

It is the cumulative effect of the increasing magnetic pressure, acting against the expanding plasma shell, that finally halts its expansion at the top and sides of the nozzle. This magnetic pressure also acts on the current carrying rings, exerting both a radial force and an axial force, which acts along the main axis of the nozzle, thus providing a propulsive thrust. After the radial expansion of the plasma shell has ceased, the compressed magnetic flux will begin to expand again – rather in the manner of a spring that has compressed and then recoils outwards – and will thus expel the plasma from the nozzle. The entire process of nozzle operation is illustrated in Fig. 9 with views of three time-steps: (a) immediately following the fission-fusion event; (b) after the plasma has expanded to its fullest extent and largely fills the nozzle; and (c) during expulsion of the plasma.

Some mention should be made of previous magnetic nozzle efforts. The principle of such a fusion propulsion magnetic nozzle concept has been well described by several previous studies [6,44,47]. The modeling approach used in Adams, et al.[47] was also used in a more recent Z-pinch study.[80] Additionally, the interested reader can refer to other fusion studies which included thorough treatment of magnetic nozzles via 'Godzilla'[87,88] and VISTA.[74]



a) b) c)

Figure 9. Process of magnetic nozzle operation.

The goal with these experiments is to research some of the critical technologies that would enable a fusion propulsion system for deep space exploration. We have a plan for such a system which we anticipate will evolve over time as the feasibility is assessed through experiments and extensive numerical modeling. Currently, our concept uses a combination of pulse power fusion that generates sufficiently high temperatures to ablate a radiation heat shield that adds to the thrust from the propulsion system, Fig. 10. Molten D^6Li will be injected along the axis of a cathode and serve as a virtual cathode as well as providing the thermonuclear fuel. The return current will take the form of a molten ^6Li liner surrounding the pinch. Such 'plasma structures' will need to survive on time scales of 1-10 μs, and this structure will provide some attenuation of the radiation from the pinch, as well as propellant for added thrust. The ^6Li-D^6Li mixture will be expelled from a magnetic nozzle.

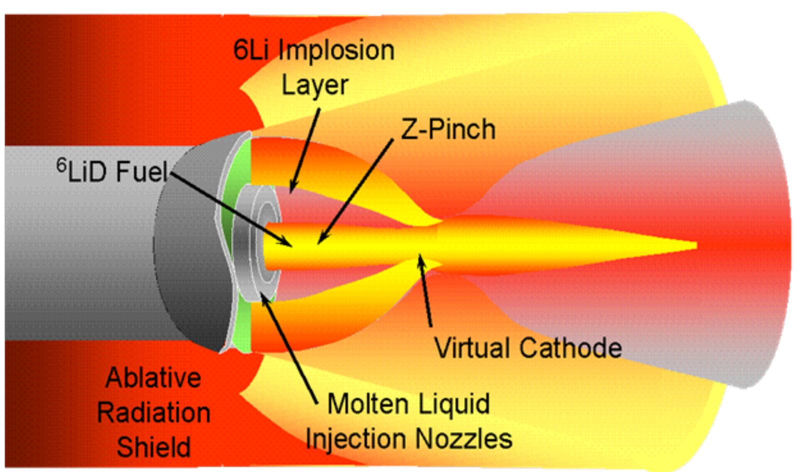


Figure 10. The Advanced ^6Li - D^6Li Fusion Propulsion concept uses fusion to vaporize and control an ablative radiation shield.

VII.3 Estimates for D6Li Fusion Energy Scaling with Current

Here we discuss anticipated scaling of the D^6Li diodes with pulsed current. Considerable revision to this estimate is anticipated with forthcoming experiments, but the estimate is rooted in existing empirically based scaling laws. Fusion energy yield (Y [Joules]) is computed with

$$Y = \int_0^{\tau_d} n_1 n_2 < \sigma v > \mathcal{V}\, dt \tag{34}$$

where τ_d is the dwell time of the fusion fuel at thermonuclear conditions, and the number densities decrease with time as the fuel is burned up. Z-pinch yields have been found to scale as $\sim I^4$, where I is the current supplied by the pulsed power system.[76] The reasons for this are because the line mass of the z-pinch load μ [g/cm] scales as I^2, density (n) scales as μ and thus I^2, and reactivity scales as n^2. The relevant volume V is the volume of the central hotspot inside the pinch column which is produced for cylindrical and spherical implosions. Colgate et al have found that about 5 to 10% of the implosion energy will be transferred to the central hotspot.[89] Assuming a temperature of 10 keV, this suggests the hotspot mass of $\sim .05 \times E_{stored} /(R\ 10^8)$, where R is the gas constant of the fuel.

Assuming that fuel compression ratio C goes as I^2 as has been observed in the DD experiments, and further assuming that DM2 is the base point at which so that $C \sim (I[MA]/2)^2$, we now can evaluate the fusion yield as a function of current for D^6Li salts. The results are shown in Fig. 11. Recent experiments and analyses by Sandia National Laboratories (SNL), the Naval Research Laboratories (NRL) and the Blackett Laboratory, Imperial College London have demonstrated Deuterium-Deuterium (D-D) fusion production outputs of 3×10^{14} neutrons (up to 28 Joules of fusion energy shown as blue data points for comparison, and are in good agreement with experimental DD gas puff scaling. DT is shown to indicate the benefit of that fuel, for which the fusion cross section is significantly higher . The reason that D^6Li is significantly higher than both gas puff DD and DT is because the fuel starts at solid densities, so that reactivities are 8 orders of magnitude higher prior to compression. We must caution that this result assumes that there is a central hotspot for which enough material reaches 10 keV. Whether or not we can achieve that will be dependent on careful design of the diode. Higher temperatures may be reached by applying an external static field to suppress electron thermal conduction losses. We also note that our scaling estimate did not account for bootstrap burn of the surrounding cold fuel layer, or secondary reactions which will enhance the yield. If the z-pinch load ignites and propagates a burn wave, then the yield could be higher.

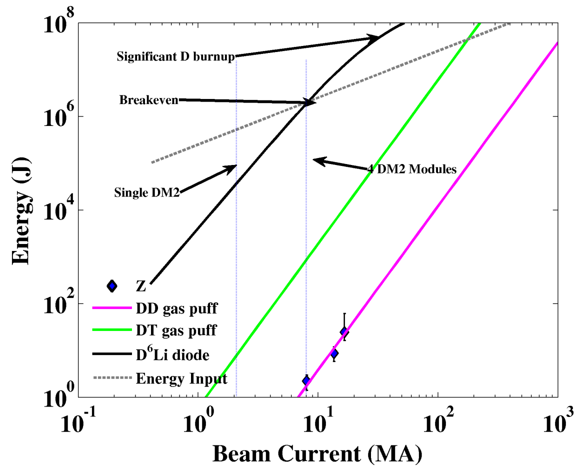


Figure 11. Energy (Yield) scaling for a D^{6}Li z-pinch load, along with known scaling for DT and DD gas puff loads.

VII.4 Fusion Propulsion Roadmap Beginning With Charger 1

We begin with a brief discussion on the roadmap and plan for sustainability, facilitated by Fig. 12. The inception of our program began with the arrival of DM2 in the late spring of 2012, thus providing us with a facility capable of producing plasmas with thermonuclear temperatures. In the first few years, we plan to develop and test the fusion diode and magnetic nozzle experiments as briefly discussed above. Due to volatility in funding, the facility will almost certainly have to be maintained and upgraded by conducting other pulsed power experiments to support other programs. Some possible examples include materials research for radiation shieding and laboratory astrophysics. Near term upgrades to the facility (3-5 years) will enable higher scale tests but will most likely fall short of breakeven. Farther out, a breakeven facility is intended to be designed, built and tested. A fusion demo mission may involve a nuclear electric powered space craft that partially drives a subscale fusion propulsion system to test thermonuclear fusion devices in the space environment. With confidence in a full scale system, robotic missions to the outer gas giant planets will likely be the first applications, well before program managers will trust the technology for humans. With confidence in human exploration of Mars with nuclear thermal and nuclear electric systems, the way will be paved for faster fusion propulsion systems in the far term.

Given the state of fusion technologies, we assume that fusion propulsion is currently at TRL 2. Below we discuss what we anticipate will be required to traverse the TRL ladder to full scale in flight systems.

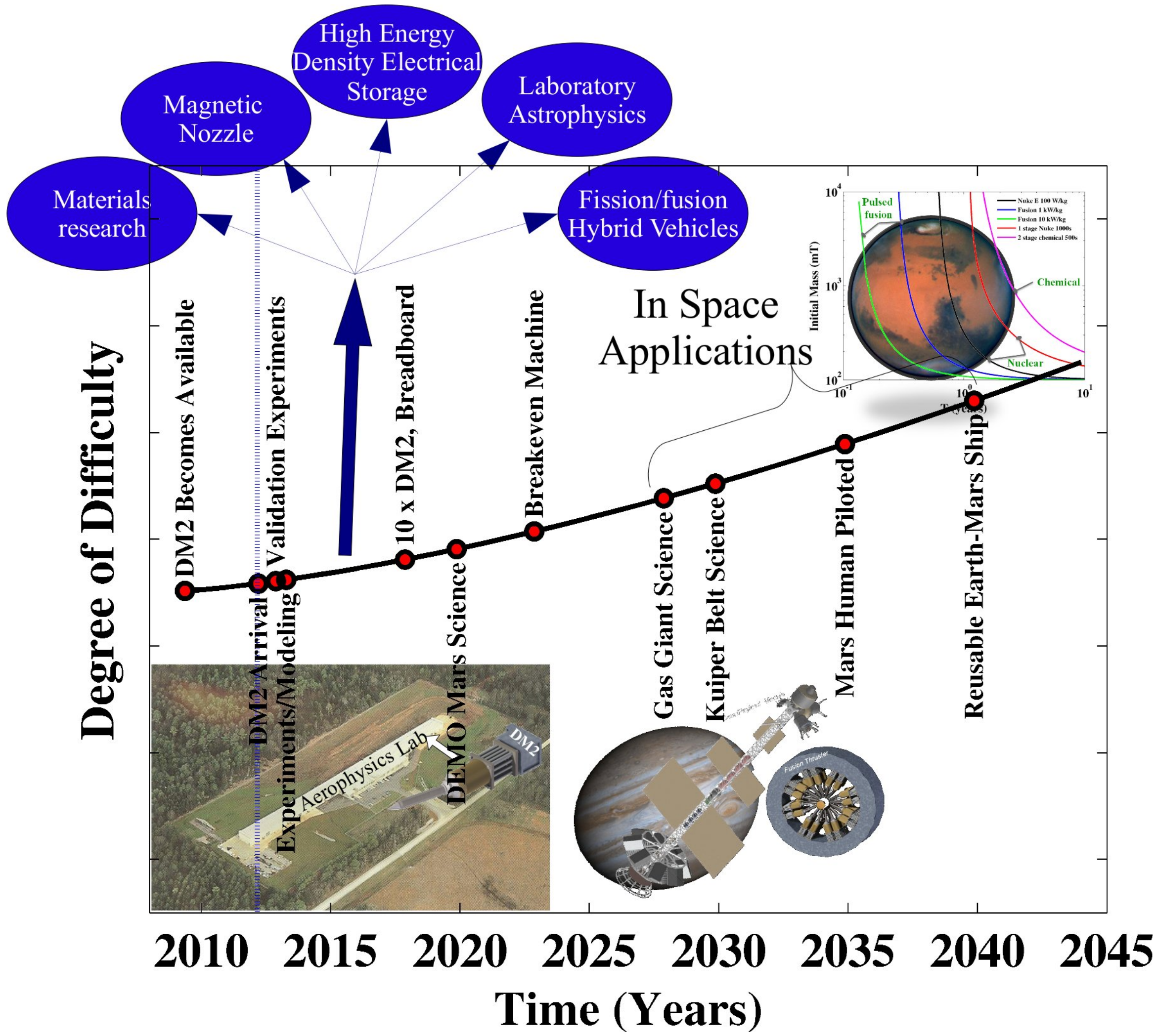


Figure 12. Potential Roadmap for Fusion Propulsion Development.

VII.4.1 TRL 3

Using the Charger -1 facility enables proof of concept experiments to determine the best ignition mechanism (Z-pinch, Dense Plasma Focus, jet impingement or similar), fuel combination (D-T, D-Li, D-He3, and fission ignition of same), and control and direction of expanding plasma (magnetic nozzle or other). This facility will likely not achieve breakeven fusion, and recharge times preclude demonstration of multiple pulses per test. However these TRL 3 experiments will demonstrate the effectiveness of the magnetic nozzle concept and provide fundamental research in plasma instabilities plaguing fusion efforts.

VII.4.2 TRL 4

A new facility will be designed and constructed that will become the prototype ground test facility for pulsed fusion propulsion. Here new technologies will be incorporated and will likely involve linear transformer drivers (LTD) for conditioning of the electrical pulse.[90] LTD's promise a lighter weight alternative to current technologies. TRL 4 efforts will focus on demonstrating scaling up to and including break-even fusion. The most promising propellant options and ignition methods from the TRL 3 efforts will be incorporated here.

Step two for achieving TRL 4 is demonstrating the ability to recharge and fire the next pulse automatically. A sufficiently high pulse rate is necessary to justify specific power calculations for the proposed engine, which in turn justify mission capabilities for the engine. Here the system will incorporate sufficient control authority to automate firings from one pulse to the next. Here the major hurdle will be to design a system that can recharge and fire continuously for a short period of time (approximately 10 Hz for 1 second). One challenge is the design of a capacitor bank or induction coil for energy storage between pulses. The recharge circuit must be flexible enough to insure sufficient energy is captured from the previous pulse to enable the next pulse. Propellant feed systems that can pulse at the needed frequencies will be necessary as well.

VII.4.3 TRL 5

The facility above will be upgraded to incorporate more flight-weight components. Also the facility will have to demonstrate the ability to operate for durations commensurate with mission operations (weeks to months continuous). Thus the highest priority for TRL 5 activities will be design and testing of flight weight equipment with high durability in high wear areas. Such areas will include the injector and magnetic nozzle as well as portions of the recharge circuit.

VII.4.4 TRL 6

TRL 6 activities depend on the answer to the following question: does the entire propulsion system need to be operated in a vacuum environment? If no, then TRL 6 activities will be relatively light. The high powers generated by a fusion propulsion system means there is less need to optimize the engine mass. Any high mass systems not already converted to light weight options in TRL 4/5 activities would be addressed here. Currently no extra effort is envisioned. All other masses could be optimized as time and funding permits. It is possible that given no need for full system vacuum testing the majority of TRL 6 activities would be bypassed.

VII.4.5 TRL 7

At this point it is expected that a new flight weight engine would be constructed based on the end iteration of the TRL 4-6 facility. It is expected that only small changes in power and thrust level would be made from the TRL 6 baseline. Additionally check out testing would be done in the TRL 4-6 facility. Subscale testing of fusion propulsion is generally not feasible, there is a minimum power level that must be reached to achieve fusion conditions. The TRL 7 engine should be designed near the minimum power level to achieve the required demonstration at minimal cost. The engine will need to be operated at significant duration, creating a very high ΔV for a reasonable payload. Thus the demonstration mission should be outfitted with a robotic payload for a mission that requires high ΔV, such as an exploration mission to the edge of the solar system and near interstellar space.

VII.4.6 TRL 8-9

The engine with minor modifications could be then used singly for robotic missions to deep space and small crewed vehicles in the inner solar system. Multiple engines could power larger colonization vehicles, or crewed vehicles in the outer solar system.

VIII. Summary

This paper provides a reference for other researchers wanting to advance fusion propulsion for deep space exploration while providing the motivation, justification, and development path for our own plan. Our specific objectives are to demonstrate why fusion propulsion is needed for interplanetary space travel, show the parameter space which may facilitate the most rapid, economic path for development of fusion propulsion, justify the choice for pulsed z-pinch, and provide a potential development path leading up to a TRL 9 system. First we qualitatively discuss the motivation, capabilities, and limitations of chemical, fission, and fusion propulsion. We summarize mission performance analysis using the gravity free assumption originally developed by Moeckel and show that single stage round trip missions to Mars within two years is only possible with nuclear technology, and round trips of less than one year are only possible with fusion systems. Three year or less round trip missions to Saturn are only possible with fusion. We emphasize that fusion propulsion will most likely require a separate on board nuclear fission reactor for reliable start ups of the fusion reactor, so the fusion propulsion community should champion the advancement of nuclear fission technologies for space.

Motivated by missions that are only enabled by fusion, we provide a brief overview of the dominant fusion confinement approaches, and we review the 50+ year history of fusion propulsion. Numerous fusion confinement schemes have been considered for propulsion, and there is yet no clearly preferred path for propulsion. We turn to a recent paper focused on the fusion parameter space for terrestrial power for insight, which shows that the cheapest, smallest reactors will emerge from the so-called magneto-inertial fusion (MIF) parameter space. This physics regime is a hybrid between the low density magnetic confinement and beyond solid density inertial confinement. We observe that many of the smallest proposed fusion propulsion systems are in fact MIF systems, consistent with this recent study.

Among the various MIF confinement schemes, we observe that pulsed z-pinch based approaches have potentially solved many of the perceived problems associated with instabilities, and that breakeven systems may require only ~60 MA of current. Such a current level is only a factor of 3 away from current capabilities at the Sandia Z Machine and a factor of 30 away from a new pulsed power facility being reassembled at the University of Alabama in Huntsville in collaboration with NASA MSFC and The Boeing Company. We offer a potential development path to a TRL 9 flight system, including potential side experiments that can be done to help pay for the development and upgrades to our facility. The road to fusion propulsion is going to be a long one, and will require much creativity to sustain regular progress. When we as a community finally develop fusion propulsion systems, rapid exploration of the solar system can become a reality.

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