The University of Alabama in Huntsville
Propulsion Research Center

H$_2$OTSTUF – Appropriate Operating Regimes for Magnetohydrodynamic Augmentation
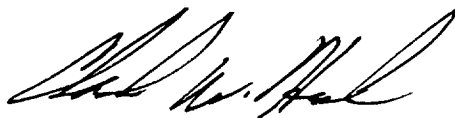
FINAL REPORT

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Abstract

A trade study of magnetohydrodynamic (MHD) augmented propulsion reveals a unique operating regime at lower thrust levels. Substantial mass savings are realized over conventional chemical, solar, and electrical propulsion concepts when MHD augmentation is used to obtain optimal I_{sp}. However, trip times for the most conservative estimates of power plant specific impulse and accelerator efficiency may be prohibitively long. Quasi-one-dimensional calculations show that a solar or nuclear thermal system augmented by MHD can provide competitive performance while utilizing a diverse range of propellants including water, which is available from the Space Shuttle, the Moon, asteroids, and various moons and planets within our solar system. The use of in-situ propellants will reduce costs of space operations as well as enable human exploration of our Solar System.

The following conclusions can be drawn from the results of the mission trade study:

- There exists a maximum thrust or mass flow rate above which MHD augmentation increases the initial mass in low earth orbit (LEO).
- Mass saving of over 50% can be realized for unique combination of solar/MHD systems.
- Trip times for systems utilizing current power supply technology may be prohibitively long. Theoretical predictions of MHD performance for in space propulsion systems show that improved efficiencies can reduce trip times to acceptable levels.
- Long trip times indicative of low thrust systems can be shortened by an increase in the MHD accelerator efficiency or a decrease in the specific mass of the power supply and power processing unit.
- As for all propulsion concepts, missions with larger Δv's benefit more from the increased specific impulse resulting from MHD augmentation.

Using a quasionedimensional analysis, the required operating conditions for a MHD accelerator to reach acceptable efficiencies are outlined. This analysis shows that substantial non-equilibrium ionization is desirable.

Introduction

MHD augmentation has been discussed, analyzed, and experimentally evaluated for over 50 years. In fact, Hartmann carried out the first investigation of MHD channel flow in the 1930s, examining MHD effects in a steady incompressible conducting fluid. Beginning in the late 1950s, MHD was looked at to provide electrical power, hypersonic testing facilities, drag reduction, air flow manipulation, and augmentation to propulsion systems. It is estimated that over 1000 man-years have been spent analyzing MHD effects since 1960.

In recent years there has been a renewed interest in MHD for use in hypersonic testing facilities. Igor V. Adamovich and J. William Rich of Ohio State University working with Gordon L Nelson of MSE, Inc. completed a feasibility study on MHD acceleration in seeded and unseeded airflow. In the unseeded airflow, an electron beam sustained ionization. At high pressures electron beam ionization was shown to be ineffective due to high collision frequencies. However, at lower pressures non-equilibrium ionization was effective, although test section pressures would be too low to allow its use in hypersonic wind tunnels. While externally sustained ionization will not work for wind tunnel applications it shows promise for use in MHD augmented upperstage propulsion systems.

Several recent reports and papers have been published on the feasibility of using MHD augmentation for upperstage propulsion systems. Schulz and Chapman have shown that a MHD augmented chemical thruster can achieve specific impulses up to 4000 m/sec. Bagher M. Tabibi et. al. have explored the use of MPD augmentation of solar propulsion systems. To date, no system level study has been completed to determine the optimal operating regime for MHD augmented systems.

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Formulation of Optimization Equation and Assumptions

As with any electric propulsion system, MHD augmented systems have an optimal specific impulse. The optimum specific impulse is a result of the mass of the power supply increasing faster than the mass of the propellant saved by the increased specific impulse. Figure 1 shows the relationship between the initial mass of a spacecraft, the power supply mass, and the mass of the propellant.
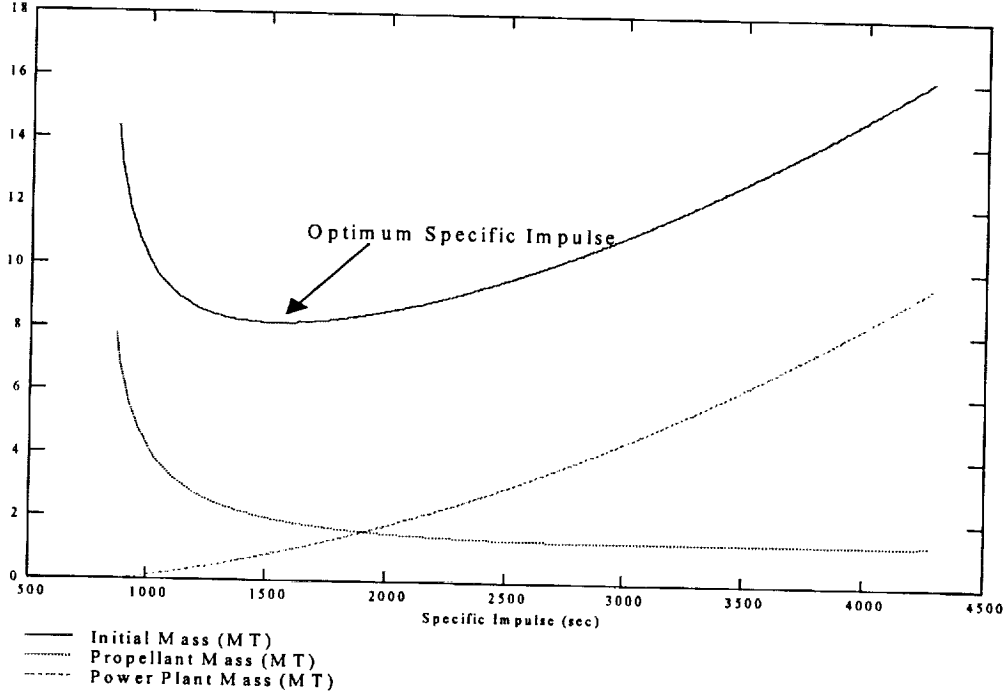

—— Initial Mass (MT)
········ Propellant Mass (MT)
– – – – Power Plant Mass (MT)

Figure 1: The relationship between the initial mass, power plant mass, and propellant mass.

The kinetic power of the exhaust jet is given by

$$P_{jet}(T, I_{sp}) := \frac{1}{2} \cdot g \cdot T \cdot I_{sp} \qquad (1)$$

Where T is the thrust of the rocket, g the acceleration of gravity at the earth's surface, and I_{sp} is the specific impulse of the rocket. The corresponding mass flow rate is then given by

$$m_{dot}(T, I_{sp}) := \frac{2 \cdot P_{jet}(T, I_{sp})}{(g \cdot I_{sp})^2} \qquad (2)$$

Keeping the mass flow rate constant, the jet power of the MHD system for a given bus power and efficiency of conversion of bus power to kinetic energy in the exhaust (η) is determined by

$$P_{jet\_MHD}(T, I_{sp}, P_{bus}, \eta) := P_{jet}(T, I_{sp}) + P_{bus} \cdot \eta \qquad (3)$$

Then the specific impulse of the MHD augmented system is simply

$$I_{sp\_MHD}(T, I_{sp}, P_{bus}, \eta) := \frac{1}{g} \cdot \sqrt{\frac{2 \cdot P_{jet\_MHD}(T, I_{sp}, P_{bus}, \eta)}{m_{dot}(T, I_{sp})}} \qquad (4)$$

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Likewise the thrust of the MHD augmented system is obtained by

$$T_{MHD}(T, I_{sp}, P_{bus}, \eta) := m_{dot}(T, I_{sp}) \cdot g \cdot I_{sp\_MHD}(T, I_{sp}, P_{bus}, \eta) \qquad (5)$$

With the thrust and specific impulse of the MHD augmented system defined as functions of the thrust and specific impulse of the unaugmented rocket, electrical bus power, and efficiency of the MHD system, the performance of the system can be examined. In order to do so, the mass of the propulsion system and the electrical power plant must be defined. The electrical power plant mass is simply

$$m_{elect}(\alpha, P_{bus}) := \alpha \cdot P_{bus} \qquad (6)$$

Where α is the specific mass of the power system. In this study the mass of the power-processing unit has been included in α. It was assumed that a SP-100 nuclear power system was available to deliver the electrical power. The specific mass of this system is 12 kg/kW. The specific mass of the power processing and conditioning system was set at 7 kg/kW giving $\alpha = 19$ kg/kW. The affect of decreasing the specific mass of the power supply (α) will also be looked at.

The mass of the solar thermal system can be broken up into two parts, the mass of the mirrors or concentrators and the mass of the thermal rocket engine. For a lightweight continuous thrust system the mass scaling is given by equation 7.

$$m_{STR}(T) := 0.125 \cdot T^{1.15} \qquad (7)$$

Where the thrust, T, is in Newtons. Marshall Space Flight Center has also used the following scaling for solar thermal systems, which utilize a store and burn technique.

$$m_{STR\_S}(T) := 6.38 \cdot T \qquad (8)$$

The mass of the concentrator array can be expressed as

$$m_{array}(T) := 6.34 \cdot T \qquad (9)$$

The dry mass of the vehicle can then be calculated as

$$m_{dry\_STR}(m_{prop}, TF, T, P_{bus}, \alpha) := TF \cdot m_{prop} + m_{elect}(\alpha, P_{bus}) + m_{STR}(T) + m_{array}(T) \qquad (10)$$

where TF is the tankage fraction for a given propellant. The mass of the vehicle at burnout is the sum of the payload mass plus the dry mass.

$$m_{b\_STR}(m_{prop}, TF, T, P_{bus}, m_{pl}, \alpha) := m_{dry\_STR}(m_{prop}, TF, T, P_{bus}, \alpha) + m_{pl} \qquad (11)$$

The process of determining the initial mass of the spacecraft and propulsion system involves an iterative procedure. First an educated guess is made of the required mass of the propellant. Using this guess the initial mass can be calculated by the rocket equation.

$$m_o(m_{prop}, TF, T, P_{bus}, \alpha, m_{pl}, \Delta v, I_{sp}, \eta) := m_{b\_STR}(m_{prop}, TF, T, P_{bus}, m_{pl}, \alpha) \cdot \exp\left(\frac{\Delta v}{g \cdot I_{sp\_MHD}(T, I_{sp}, P_{bus}, \eta)}\right) \qquad (12)$$

A new value for the mass of the propellant can be obtained by realizing that the mass of the propellant is the initial mass minus the mass at burnout. Mathcad's find function, which uses the Levenberg-Marquardt method, was used to converge on a final value for the mass of the propellant. This formulation lets us vary tankage fraction, bus power, specific power, payload mass, Δv, I_{sp}, and MHD efficiency.

The trip time required for the transfer is calculated by dividing the required mass of propellant by the mass flow rate.

$$t_{Transfer} := \frac{m_{prop}\left(P_{bus}, T, I_{sp}, \eta\right)}{m_{dot}\left(T, I_{sp}\right)} \qquad (13)$$

Calculating the transfer time in this manner assumes a continuous burn.

The mission Δv required for a given mission is a function of the initial thrust to mass ratio, and the number of burns in the case of multiple impulse burn trajectories. The gravity losses associated with very low thrust/to weight ratios can be substantial. The Δv required for a typical impulsive LEO-GEO transfer using a chemical upper stage is 4.2 km/sec, while the same mission utilizing a low thrust to weight ratio must have an effective Δv of over 5.9 km/sec (Reference 15 –D180-26680-2). Other studies have shown that the losses due to low thrust to weight ratios may has much as double the required Δv, especially when large plane changes are required, such as LEO-GEO transfers with a 28.5° planed change. A Δv of 6 km/sec was used in this mission trade study for LEO – GEO transfers, which corresponds to a continuous spiral burn.

LEO to GEO Orbit Transfer

The LEO to GEO orbit transfer mission defined for this study delivers a 5,000-kg payload from low earth orbit to geosynchronous orbit. Low thrust mission Δv's are a function of the thrust to mass ratio of the vehicle. A mission Δv of 6 km/sec was used. Unless otherwise stated the efficiency of the MHD system was conservatively set at 20%.

To get a feel for how MHD augmentation affects the initial mass of the vehicle, the I_{sp} of the solar thermal rocket was fixed at 860 seconds and its thrust varied. This is equivalent to varying the mass flow rate of the solar thermal rocket. The variation of the initial mass as a function of the bus power or augmented I_{sp} is shown in Figure 2 for unaugmented thrust of 1, 5, and 10 Newtons. As we increase the thrust or mass flow rate, we quickly decrease the mass savings. Thus, there exist a maximum mass flow rate or thrust above which MHD augmentation will increase the initial mass required to deliver the payload to its desired orbit. For the current mission ($\Delta v = 6.6$ km/sec, $m_{payload} = 5000$ kg, $\eta = 20\%$, $\alpha = 19$ kg/kW) this maximum thrust is around 7.5 Newtons, which corresponds to a mass flow rate of 0.9 gm/sec. This maximum occurs because the power supply required to obtain a sufficient increase in the I_{sp} at larger mass flow rates is to large for the mass of propellant saved to compensate for its mass as shown in Figure 1.
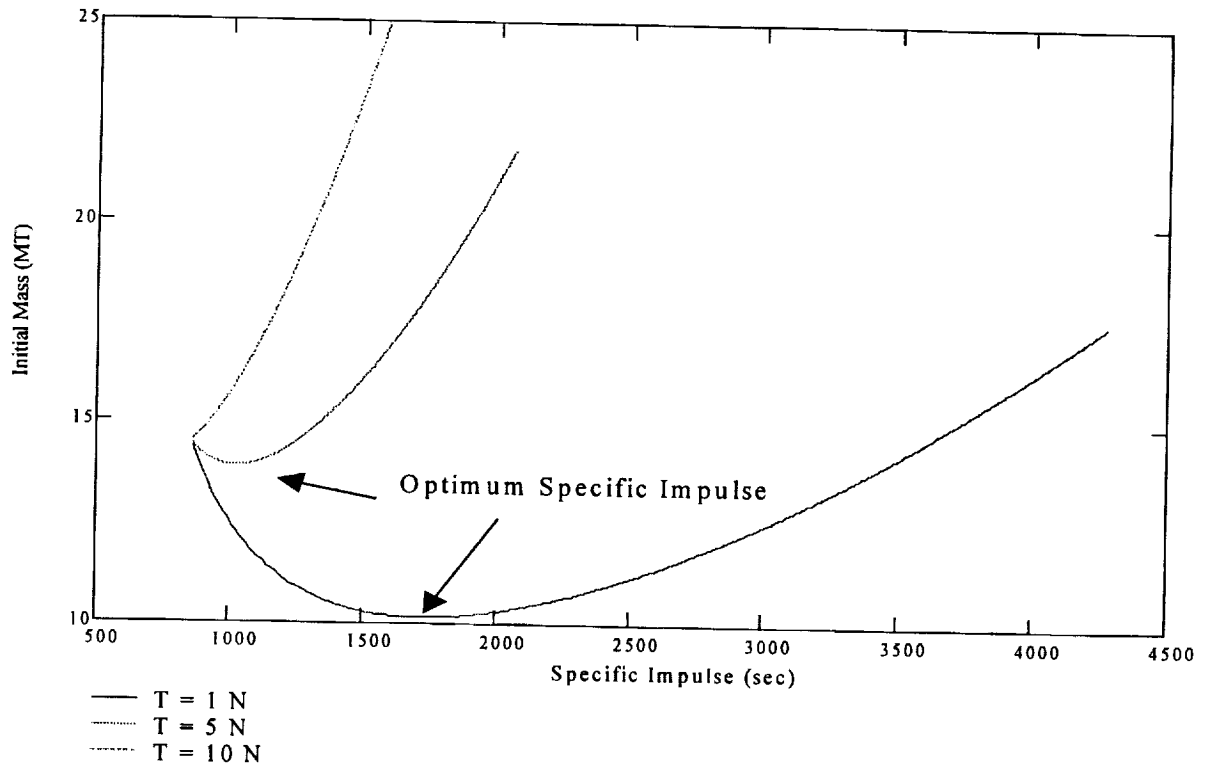
Figure 2: Initial mass as a function of the I_{sp} of the augmented STR and the thrust of the STR only.

Flow rates, smaller than the maximum possible flow rate, have an associated optimal I_{sp} or electrical bus power. Figure 2 shows an optimal I_{sp} of 1700 sec for $T_{STR} = 1$ Newton and 1030 sec for $T_{STR} = 5$ Newtons. Note that there is no optimal I_{sp} for $T_{STR} = 10$ Newtons, because it is above the maximum thrust or flow rate. The decrease in initial mass due to MHD augmentation is 4.2 MT for the 1 Newton STR and 0.45 Newtons for the 5 Newton STR. The power required to achieve the optimal I_{sp} for the 1 Newton STR is found from Figure 4 to be 62 kW, while the augmented thrust is increased to 2 Newtons as shown in
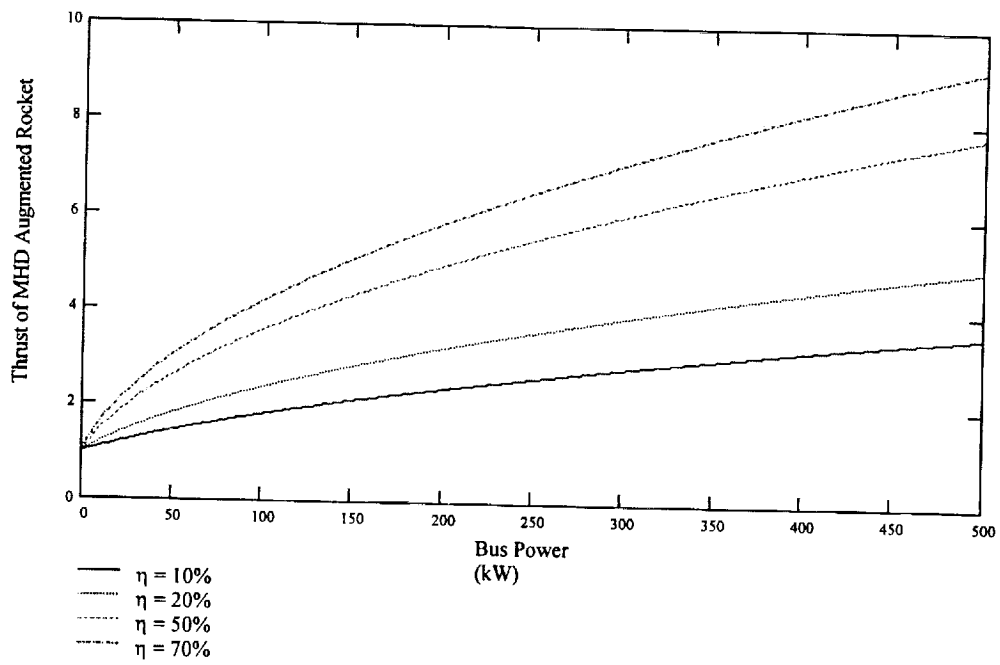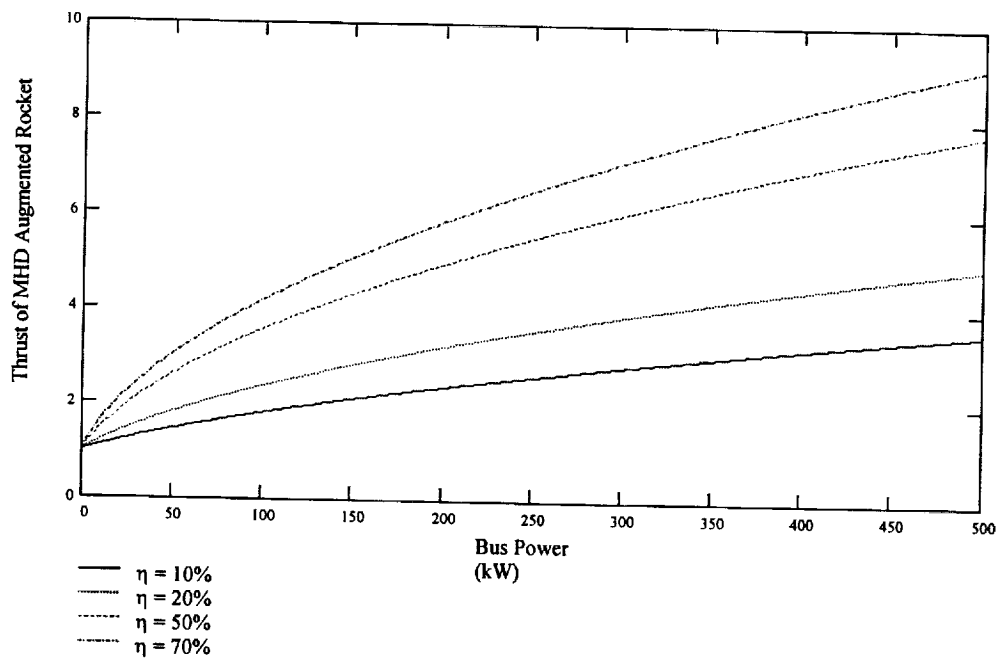
Figure 3.

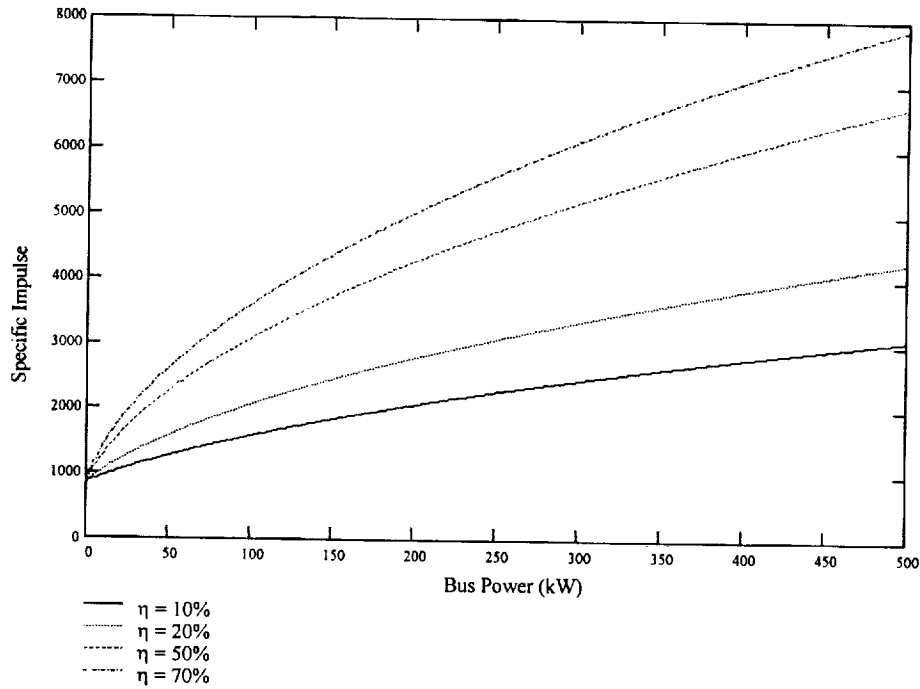**Figure 3:** Thrust of MHD augmented STR versus bus power.

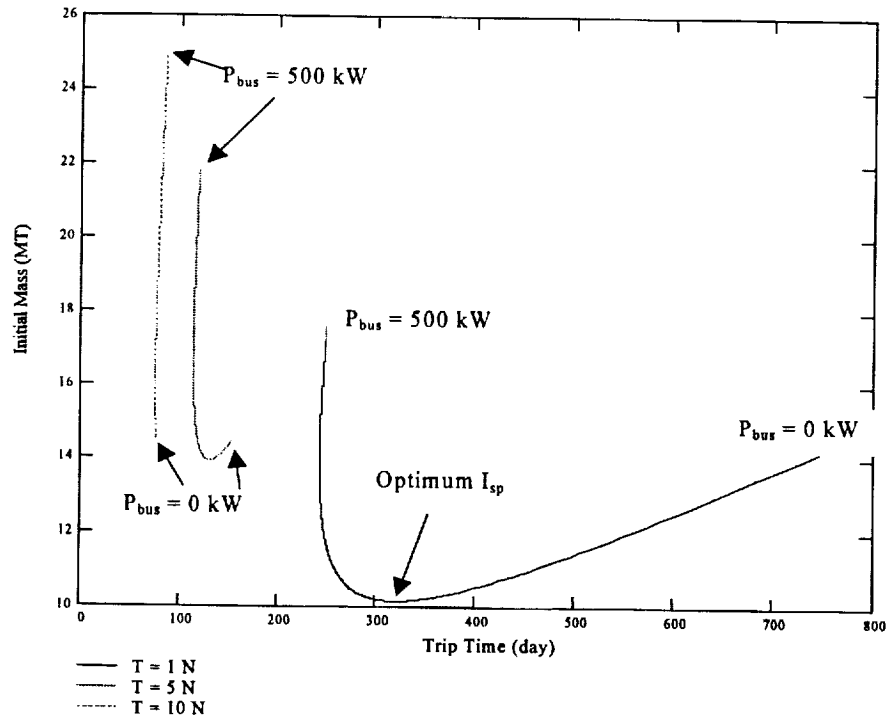**Figure 4**: Specific Impulse of the MHD augmented STR versus bus power.

Figure 5: Relationship between initial mass and trip time for several values of thrust.

Figure 2 shows that a significant mass saving is realized through MHD augmentation; however, is the trip time required to transfer the payload to geosynchronous reasonable? Figure 5 shows that the trip time for the 1 Newton augmented STR is 320 days at the optimum I_{sp}. While this cuts the transfer time by more than a factor of two from that of the unaugmented 1 Newton STR, it is still unreasonable for most missions.

Increasing the bus power further will further decrease the trip time, however, if shorter trip times are the desired outcome, then we are much better off putting all of the power into thermal propulsion. If the 62 kW of electrical power required to reach the optimal I_{sp} were used in a STR, an achievable thrust of 50 Newtons would cut the transfer time to under 15 days. So the quick truth is that the battle between long trip times and optimal mass savings cannot be solved with MHD augmentation using current power supply technology.

An improvement in either the efficiency or power supply specific mass will result in reduction in both trip time and initial mass in LEO. Figure 6 illustrates this for the efficiency of the MHD accelerator. Curves are shown for efficiencies of 20, 40 and 70%. Thrust of the STR is varied from a maximum of 26 Newtons to 1 Newton along each curve. The initial mass is plotted versus the trip time corresponding to the optimum I_{sp} for each value of thrust. As expected the trip time and initial mass decrease for all thrust values as the efficiency of the MHD accelerator is increased. The effect of the maximum thrust for effective augmentation can be seen in the rolling over of the curves for 20% and 40% efficiency. The maximum thrust for effective augmentation at 70% efficiency is around 26 Newtons; therefore, it does not roll over in Figure 6. Finally, if an arbitrary limit of a 100 day trip time is imposed, the efficiency of the MHD augmentation must be greater than 20% to be beneficial. Thrust levels greater than 3 Newtons and 5 Newtons result in trip times less than 100 days for efficiencies of 70% and 40% respectively. The power required to achieve these trips times, while operating at optimal I_{sp}, is given in Figure 7 as 62.4 kW and 67.7 kW for efficiencies of 70% and 40% respectively.
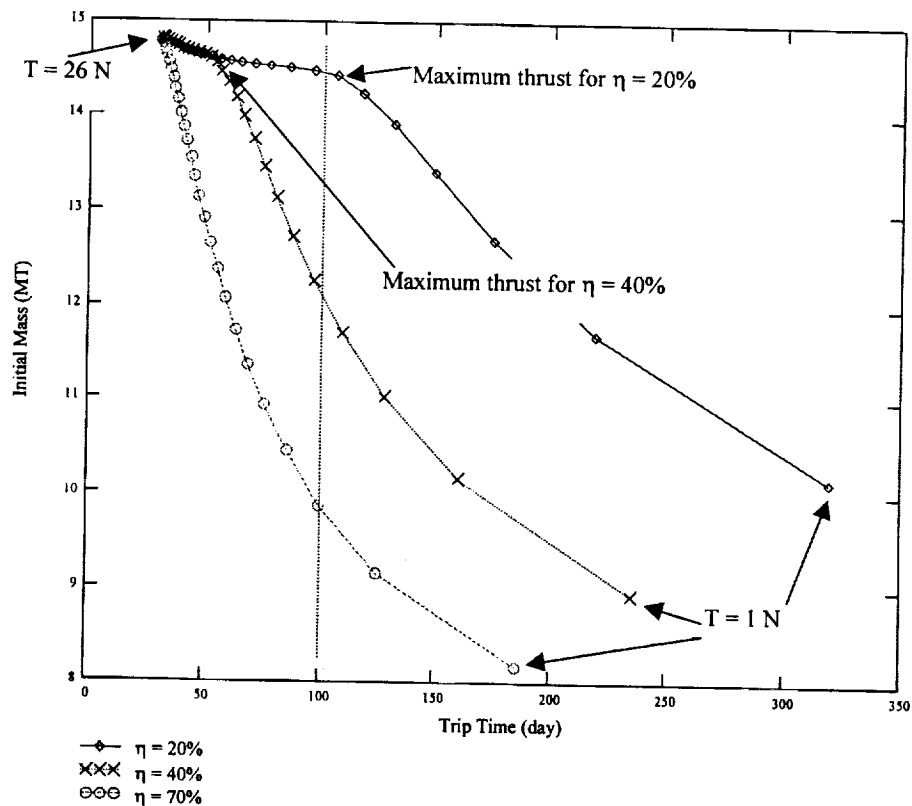

Figure 6: Initial mass versus trip time for optimum I_{sp} conditions.
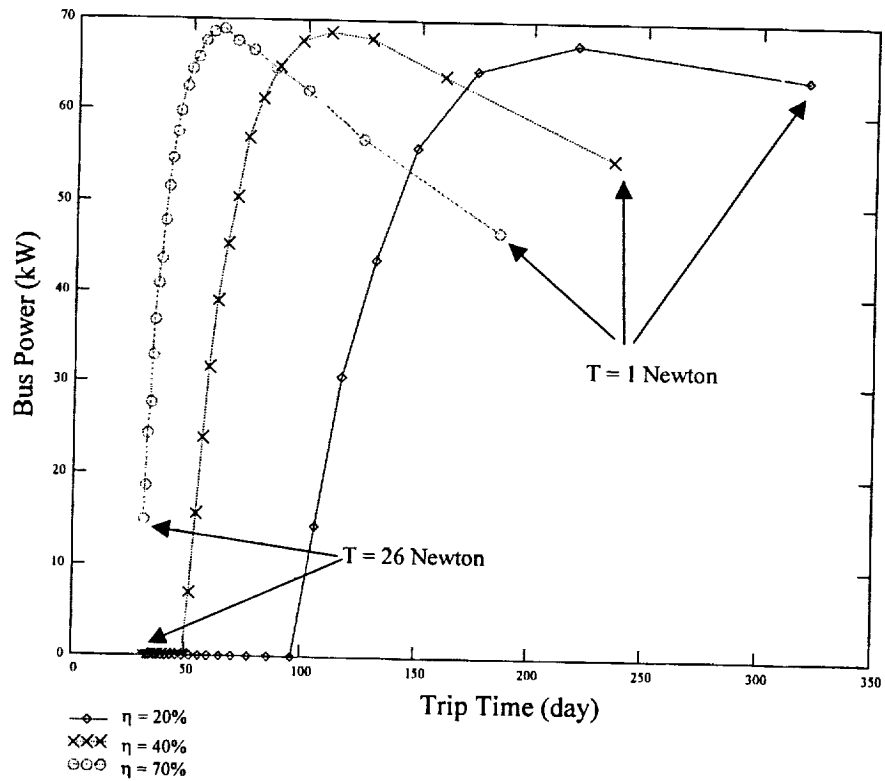
Figure 7: Bus power versus trip time.

It is also instructive to evaluate performance for different mission Δvs. Figure 8 shows the mass saving that can be realized for Δv's of 4.2, and 8 km/sec. The mass saving as a function of trip time and thrust is also given for a Mar's mission in Figure 10.
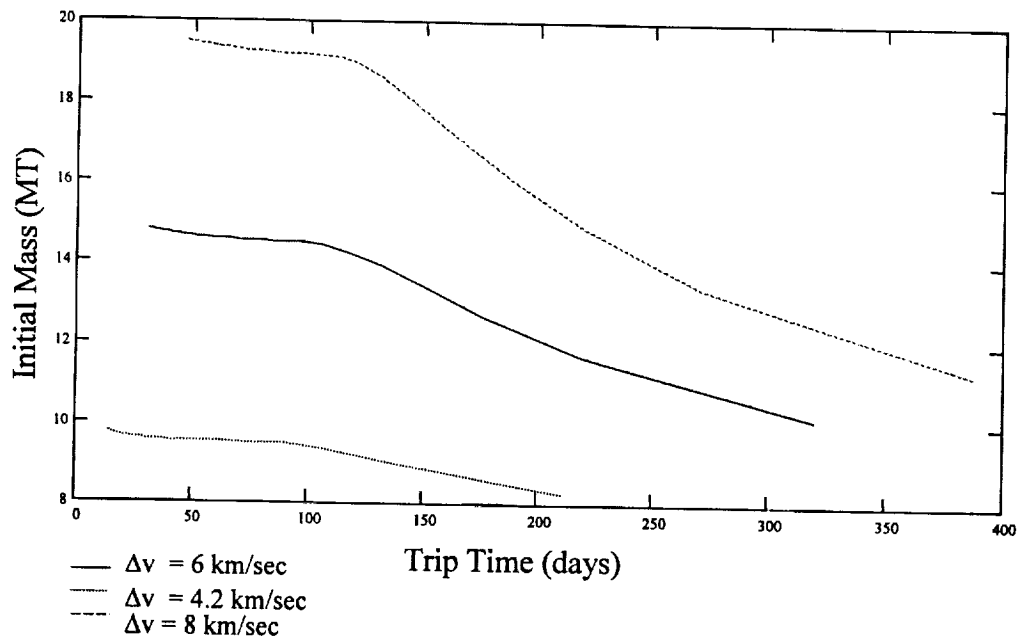

Figure 8: Trip time vs. initial mass for Δv of 4.2, 6 and 8 km/sec.
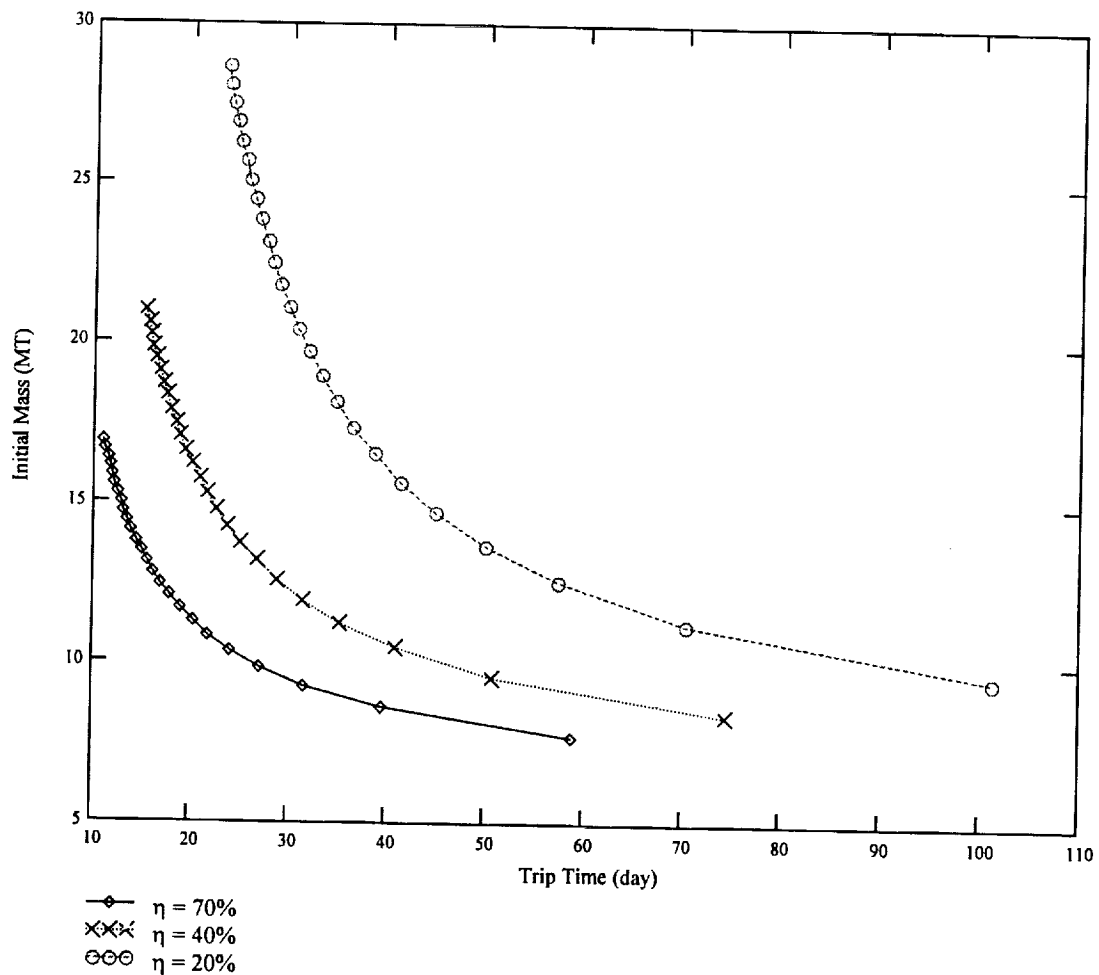
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Figure 9: Initial mass versus trip time for augmentation of a solar thermal steam rocket with an I_{sp} of 300 sec and a futuristic 5 kg/kW specific power.

Augmentation also shows a much greater mass saving when augmenting rockets with a lower initial I_{sp}. For an advanced power supply with a specific power of 5 kg/kW, the initial mass can be cut in half while the trip time is doubled. Although 5 kg/kW is optimistic it should be noted that a propulsion system utilizing water has options that other systems do not. First the tank does not have to be kept thermally isolated as in the case of cryogenic propellants. It can be used as a heat sink and its surface can be a radiator. Unique power supplies that use superconducting magnets to supply the magnetic field for the MHD system and store energy may be used for a pulsed system.
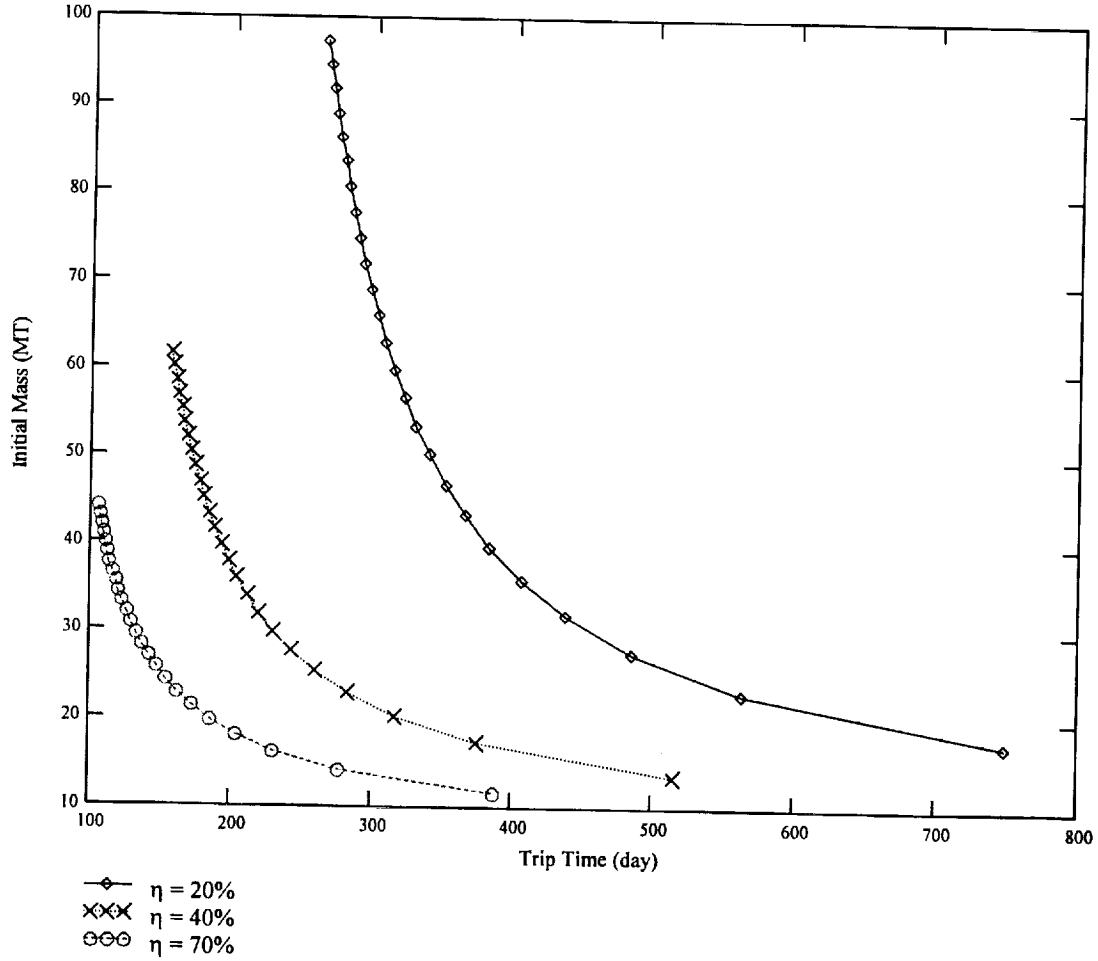
Figure 10: Initial mass versus trip time for a Mar's mission with a Δv of 14.5 km/sec.

Quasi-one-dimensional Analysis

The system study showed that to achieve a trip time less than 100 days an efficiency greater than 40% must be obtained. A quasi-one-dimensional analysis will give the minimum plasma conductivity needed to achieve this efficiency. The conversion efficiency of a MHD accelerator can be defined as (Macheret, Miles, and Nelson) as the ratio of the push work to the joule heating in the channel. For a Faraday accelerator where jx equals zero this reduces to

$$\eta\left(n_e\right) := \frac{\sigma_1\left(n_e\right) \cdot u \cdot B_z}{j_y + \sigma_1\left(n_e\right) \cdot u \cdot B_z}$$

Where u is the flow velocity, Bz is the applied magnetic field and jy is the current in the channel. The electrical conductivity as a function of electron number density is can be approximated by

$$\sigma_1\left(n_e\right) := \frac{n_e \cdot q_e^2}{m_e \cdot c_e \cdot \left(n_n \cdot Q_{en} + n_e \cdot Q_{eI}\right)}$$

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Where ne is the electron number density, nn is the neutral number density, ce is the electron thermal velocity and me is the mass of the electron. Qen and QeI are the electron – neutral and electron ion collision cross sections. Using these relationships the efficiency of an ideal Faraday channel is shown in Figure 11 as a function of number density.
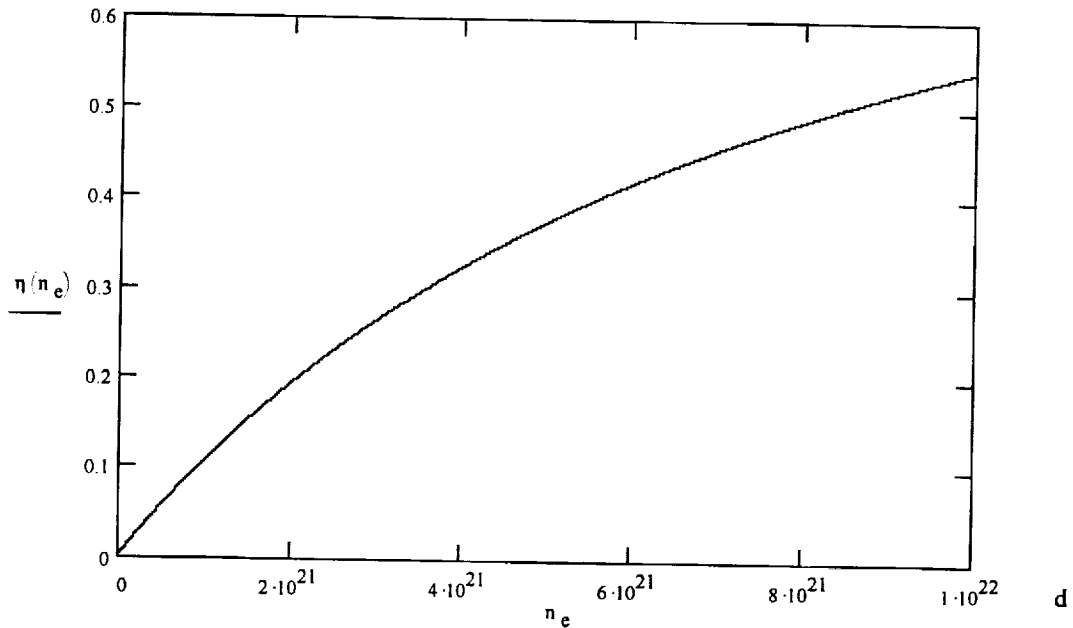

Figure 11: Faraday channel efficiency as a function of electron density for an accelerator operating at 0.1 atm.

To obtain an efficiency greater than 40% requires electon density over $6*10^{21}$ e/m3. In this analysis the electron collision cross section of the gas is assumed to be 10^{-15} cm^2 and the potasium seed $40*10^{-15}$ cm2. A gas in thermodynamic equillibrium must be at very low pressures and high temperature to achieve this level of conductivity. It is hoped that microwave will create a non-equilibrium plasma that will obtain the same electron density at much lower gas temperatures.

Conclusions

MHD augmented propulsion offers unique performance characteristics. If non-equilibrium plasmas can be created and sustained then over 50% mass saving may be realized. When one considers adavances in both permenant magnet field strengths and high temperature superconducting magnets, examining MHD augmented propulsion systems becomes attractive.

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