MHD Propulsion by Absorption of Laser Radiation

L. N. Myrabo*
University of California at San Diego, La Jolla, Calif.

The conceptual design for a laser-riding air-breathing single stage shuttle which would use magnetohydrodynamic (MHD) forces to accelerate the engine working fluid is introduced. A gigawatt power-level photon beam delivered from an orbital laser power station is focused by the shuttle craft onto internal engine working fluid to create, within an annular ionization chamber, a confined air plasma stationary wave. Free electrons are immediately pumped from the plasma and ejected into the external slipstream at the perimeter of the machine. The remaining positively charged working fluid is accelerated by gasdynamic expansion and the pinch-plasma effect, and discharged at a rear nozzle. The vehicle slipstream, now negatively charged and conducting, interacts with a concentric positively charged plasma core to provide quasi-steady flight propulsive forces in an externally-excited-field MHD accelerator. Continuous MHD engine electric currents in the near megampere range are attained through the use of: a) remote power ionization of engine working fluid, and b) electron beam space-charge neutralization techniques reported in recent literature on fusion research. A cursory examination of the required laser power, thrust, exhaust velocities, electric current, and working fluid electrical conductivity reveals operable engine parameters in an interesting range indicating that the system may be worthy of further examination.

I. Introduction

WITH the current interest in high-energy orbital laser power stations, space missions heretofore thought to be impossible are now demanding renewed examination. Exotic new propulsion systems comprised of remote laser power stations, high-energy transmission optics, and propulsion converters at the vehicle receptor site may soon be possible. The tasks of building large laser power stations in space or on Earth, and of transmitting the power appear to be accomplishable.[1-7] However, a new converter technology is needed since this final system component is now recognized as being the weakest link.[7] Consequently, two recent conferences on laser energy conversion have been sponsored by the NASA Ames Research Center, focusing on the major energy conversion forms: electrical, shaft horsepower, storable chemical, and propulsion.[7,8] This paper concerns itself with the latter, in a largely unexplored liaison of remote laser energy with magnetohydrodynamic (MHD) generation.

The potential for application of MHD generation to propulsion of nuclear/electric submarines in an ocean plasma has already received the attention of researchers.[9-19] The first experimental verification of a self-sufficient system was accomplished by S. Way on July 21, 1966, with a 10 ft model submarine powered by lead-acid batteries.[15] A number of analogous schemes for hybrid nuclear/electric space propulsion have been proposed with both open and closed thermodynamic cycles.[20-29] Most of these, however, have great difficulty showing performance gains large enough to justify the additional complexity and weight beyond a strictly nuclear rocket.[27] A possible exception is the more recent work of R. J. Rosa,[27,29] who suggests that when flying in an atmosphere, it might be possible to advantageously employ air augmenting, i.e., the use of some or all the electric output of the generator to drive an electric ramjet.[29] As an entertaining suggestion, Rosa proposes an extension of this scheme, which he dubbed the "MHD Lift Fan,"[30] an airbreathing space shuttle which would propel itself on lightweight high-power chemical batteries. He suggests that the craft might be recharged midflight by beaming energy from an orbital operations base.

Presented at the San Diego Section AIAA Students' Technologyfest, San Diego, Calif., April 29, 1975, and at the Region VI AIAA Student Conference, Stanford, Calif., May 1-2, 1975; submitted May 15, 1975; revision received March 12, 1976.

Index categories: Electric and Advanced Space Propulsion; Plasma Dynamics and MHD.

*UCSD Energy Center Research Assistant. Member AIAA.

Other serious attention in the past has been given to using the high altitude planetary atmosphere to propulsive advantage in both chemical and electrical systems. The work of S. T. Demetriades, the "Air-Scooping Orbital Rocket (ASCOR)," has been the most exhaustive.[31-34] Similar studies were carried out by other investigators.[35-39] It was determined that a large local power source of perhaps several megawatts capacity would be required to assist in the cryogenic propellant collection function, as well as in chemical or electrical heating of propellant in the thruster. Recent work by G. L. Cann, "The Space Electric Ramjet (SERJ)," explores a related solar powered scheme unencumbered with cryogenic collection.[40,41]

Clearly, the performance of these propulsion schemes would be greatly enhanced if they were somehow relieved of their weighty self-contained energy sources. The laser holds great promise for accomplishing this in space propulsion, as evidenced by much current literature on the subject.[42-49] The associated propulsion converters have largely been envisioned to use the remote laser power to heat on-board propellant (hydrogen), which is then expanded through a rocket nozzle. One exception which proposes to use the planetary atmosphere to advantage is the "Laser Powered Pulse-Jet,"[45,49] although its application as an orbital shuttle craft may be limited due to the unavailability of sufficient quantities of air required for successful operation at the higher altitudes with the expected range of engine exhaust velocities.

Several perceived problems with the ground launched laser-heated rocket systems have been mentioned.[48] One having far reaching economic consequences is that several power stations distributed along the launch trajectory must consecutively power the shuttle craft. It is anticipated that each ground-based power source must supply a hundred gigawatts (1 GW $=10^9$W) or more of peak power, indicating very large fixed systems costs.[48]

Stuhlinger and others have considered certain space-based cycles for converting remote laser energy into electric energy and electrostatic acceleration of ionized propellant.[20,50,51] However, no propulsion converter research has as yet been mentioned or proposed in the literature, which would use both the powerful air-plasma generating capabilities of a high-energy laser power source and the high temperature shock-ionized air plasmas naturally occurring with hypersonic flight through the atmosphere. Therefore, the examination of MHD generation for application in an air-plasma breathing laser propulsion converter appears appropriate. The liaison holds great potential for propelling space shuttle craft into orbit with an essentially infinite specific impulse, especially considering that MHD thrusters are known for their ability to produce the very high exhaust velocities required for realistic air-breathing propulsion at high altitudes.[52-54] The scheme becomes even more attractive when it is realized that higher propulsive efficiencies may allow a single orbital laser power station, perhaps attached to a space laboratory or colony,[55] to supply only several gigawatts of power. On a close fly-by orbit, radiant energy would be transmitted to the planetary surface, the shuttle craft "beamed-up," and docking in orbit would occur several thousand miles downrange. We shall now describe such a system.

II. Physics of Engine Concept

Illustrated in Fig. 1 is a functional diagram of the LASER/MHD propulsion converter concept shown intimately integrated with a compact shuttle craft airframe. Its maximum diameter is arbitrarily set equal to that of the Saturn V launch vehicle. A laser power station first transmits radiant power to the engine receptor site. As shown in Fig. 1, the beam is received by a mirrored upper superstructure, and then reflected and concentrated into an annular intake whose interior surfaces are also mirrored to enhance propagation of the beam down the passages. The radially partitioned passages provide an additional centrifugal compression function for pressurizing engine air entering the same annular opening.

Immediately upon entrance to the ionization chamber at the radial location denoted in Fig. 1, small beams of electrons are injected into the internal engine working fluid triggering inverse Bremsstrahlung absorption of this laser energy.[56-58] Substantial laser-induced electrical air breakdown (ionization) is anticipated at this time transforming the internal engine flow into a dense air plasma.[59-61] Radiation not absorbed in the gas will probably reflect downstream off the passageway walls heating the nozzle throat where heat transfer could be a major limiting factor to successful operation of the engine.[56]

Within the annular ionization chamber, a large number of diodes (e.g. several hundred) are evenly distributed about the vehicle rim. Each diode would be composed of two parallel flat plate electrodes with a small diameter hole in the anode (perhaps 1-2 mm diam) which would vent to the atmosphere at the rim of the machine. Application of a high voltage (i.e. ~ 1 MV) across a diode for a very short time period (i.e., many n/sec) would result in the extraction of a high current beam pulse (e.g. ~ 1 MA) from the internal fluid plasma,[62] followed by injection of that beam into the external vehicle slipstream. At the proper external electron seed fraction (i.e., about 0.1% injection "seed" electrons), the entire vehicle slipstream becomes a conducting air plasma, since it now contains a great quantity of highly mobile free electrons.[29,63] The kinetic energy of these electrons is subsequently increased by collisions with the slipstream air molecules as they are both swept downstream. The vehicle slipstream next to the diode would probably still contain a high electron population at the time of the next injection cycle.

An important background plasma function, which has been experimentally observed, is to provide an ion background of sufficient magnitude to help neutralize the electrostatic space charge which would build up along the electron beam axis (i.e., positive ions from the background plasma will be pulled into the beam center).[65-66] A second plasma function involves magnetic neutralization of the self-field (i.e., generated by the beam itself), which if not checked, may prematurely pinch off the propagating beam before the charge is completely ejected.[66,68] The anti-pinch phenomena, also observed experimentally, may be explained by assuming that the self-field, which would be generated, is cancelled by large numbers of slowly counter-streaming electrons in the background plasma.[67]

This electron beam discharge would pull a small percentage of electrons (e.g., 1-2%) from the available ionized molecules

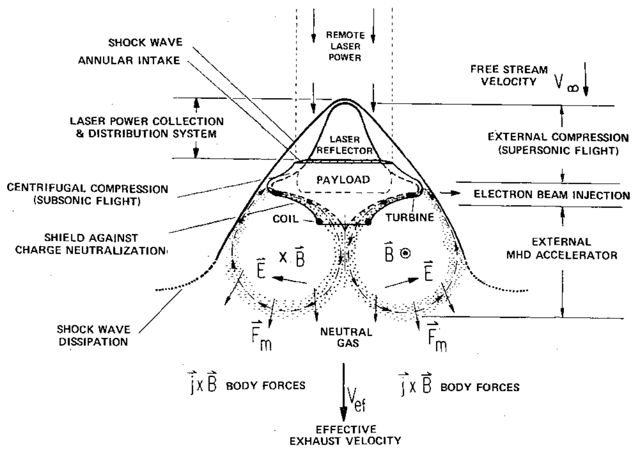

Fig. 1 Laser/MHD propulsion converter concept.

leaving the previously neutral internal working fluid with a net positive charge. The positively charged plasma will expand from the ionization chamber through the throat and into an adjustable blade-pitch turbine (or an equivalent sub-system), imparting the entire vehicle with the rotational velocity required for proper operation of the centrifugal compressor.† As this positively charged plasma continues to gas-dynamically expand down an internal nozzle, it shielded from mixing, and hence, from recombining with the external negatively charged slipstream shown in Fig. 1.

Reference to the MHD thruster configuration in Fig. 1 (i.e., the aft portion of the vehicle), suggests several distinct differences in arrangement from that of traditional MHD arc-jets described in the literature. First, the large diameter "rim-electrode" is negative (cathode) rather than positive; and secondly, it is placed upstream rather than downstream of the smaller diameter "central-electode," which in this case is the anode. A final major difference is that the anode exudes a powerful beam of positive ions, while the cathode emits radially symmetric streams of electrons.

The external vehicle slipstream would be accelerated using the volume energy addition mechanism of MHD generation in the following manner. The MHD thruster first showers free electrons from the periphery into the external vehicle slipstream to create an electrically conducting medium, acquiring in the process, a net negative space charge. Simultaneously, the thruster ejects a powerful beam of positive ions from a centered downstream nozzle. The presence of separated charge of opposite sign generates a strong radially symmetric, outward directed electric field within the exhaust plume. Since this charge is moving with respect to the machine, an azimuthally directed magnetic field is generated within the same toriod-shaped nozzle region. The field completely closes upon itself within the exhaust gases yielding a highly efficient acceleration mechanism, typical to high current MHD arc-jet thrusters. Interaction of these crossed electric and magnetic fields drive the conducting gases aft within the MHD 'nozzle' region in accordance with the following relation:

$$\vec{F}_m = \vec{J} \times \vec{B} \tag{1}$$

where $\vec{F}_m$ is the magnetic body force, $\vec{J}$ is the current density, and $\vec{B}$ is the self-induced magnetic field. Effective slipstream 'exhaust' velocities, V_{ef}, are attained just downstream of the region of significant electromagnetic interaction when these gases again become electrically neutral.

†The compressor, which forms an integral part of the upper vehicle superstructure, must provide a positive pressure ratio against which the higher ionization chamber pressures may do work on the internal engine working fluid, accelerating it after heat addition. At supersonic flight speeds, however, when ram air provides this function, the turbine blade pitch would be reduced to zero and the vehile would cease to rotate.

The detailed mechanism for self-field acceleration is today still inadequately understood, but is known to be the primarily responsible accelerating agent in the small experimental MHD arc-jet engines when the current range is extended beyond 2000 A.[69,70] Jahn[52] describes the MHD arc-jet as being a renegade violating our estimates of reasonable values for current density from an electrode, gas density, gas temperature, channel length, channel profile, gas conductivity, and magnetic interaction parameter. Furthermore, Jahn[52] suggests it is a device fortuitously embodying intensities and geometries of current and electric and magnetic fields which circumvent several of the classical limitations of the conventional electromagnetic and electrothermal accelerators.

We can, however, extract a certain amount of qualitative information about the proposed thruster operation by examining the following expressions for the self-magnetic field and the related gas-kinetic pressures originating within an electrical current configuration assumed to be an ideal toroid, for the sake of analytical simplicity. Figure 2 illustrates the toroid section properties for gas-kinetic pressure, $P(r)$, current density, $j(r)$, and magnetic induction field, $B(r)$, along an arbitrary radial line $A-A'$ which intersects the central toroid axis of radial symmetry. Also pictured in Fig. 2 is a segment of the positive-ion plasma-beam, the only portion of the complete toroid electric charge flowfield mechanically constrained by physical boundaries. The magnetic induction field within an ideal toroid is:

$$B=(\mu i/2\pi r) \tag{2}$$

for $r_3<r<r_4$ in Fig. 2 where μ is the magnetic permeability, i is total engine current, and r the radial distance from the toroid central axis. Anywhere outside the toroid, the magnetic induction field will be zero (i.e., $r_2>r>r_4$ in Fig. 2).

The gas-kinetic "pinch" pressure across any nozzle cross-sectional area S (pinch direction as shown) is:

$$P=(\mu i^2 \cos\theta)/S \tag{3}$$

for $0<\theta<90°$ in Fig. 2, where θ is measured as shown from a horizontal plane perpendicular to the axis of radial symmetry.

As the result of Eqs. (2) and (3), positive charge, in the form of discrete high current pulses, will expand down the aerodynamic plug nozzle with increasing supersonic velocity and see an increasing self-magnetic field inversely proportional to the shrinking plasma tube radius. Simultaneously, the moving charge generates a gas-kinetic pressure tending to 'pinch' the beam out of its plug nozzle. At the exhaust nozzle exit plane (see Fig. 1), the positive-ion plasma-beam will still be constricting toward its central axis. After exiting from the engine at a high velocity, the ion-beam may tend to supplement the MHD acceleration process by helping to accelerate the external, higher mass flow rate, conducting plasma slipstream in the manner of an MHD ejector.[71]

Having left the nozzle exit, the beam is no longer hollow, and the internal magnetic induction field may be expressed as:

$$B=\frac{\mu i r}{2\pi r_l^2} \tag{4}$$

for $r\leq r_l$ in Fig. 2, where r_l is the radius of the ion-beam edge. The associated gas-kinetic 'pinch' pressure[52] within the ion-beam is:

$$p=(\pi j^2/4)\ (r_l^2-r^2)\ +\ p_l, \tag{5}$$

for $\theta\approx 0$ in Fig. 2, where p_l is the ambient gas pressure outside the beam edge r_l.

The generation of the enclosed segment of the positive ion-beam, therefore, is the most responsible agent for accelerating the external conducting vehicle slipstream; the thrust is communicated by means of self-magnetic fields of this ion-beam segment. The exhaust gases, of course, similarly repel the positive ion gases which in turn, push against the upper internal nozzle passageways generating flight-directed gas-kinetic pressures, viz;

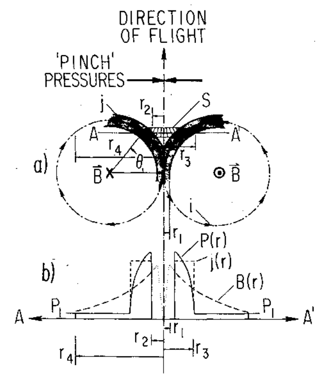

Fig. 2 Self-magnetic field and gas-kinetic pressures within the MHD thruster.

$$P=(\mu i^2 \sin\theta)/S \tag{6}$$

for $0<\theta<90°$ in Fig. 2. It is evident that any significant interruption of a radially uniform diode 'firing' pattern would result in a lifting of the favored side of the thruster, or in a lateral displacement of the vehicle, depending on thruster geometry. This condition would disrupt the MHD current geometry from a completely enclosed toroid discharge pattern to an open one more closely resembling the less efficient 'button-type' or 'rail-type' accelerators.[52]

An analysis of the energy balance within the proposed thruster scheme reveals the necessity for replenishing the significant losses suffered by the engine during electron beam ejections at the "rim-cathode." One method by which these loses may be regained would be to integrate into the propulsion system an inductor-capacitor (LC) circuit excited by the intense changing magnetic fields at the plug-nozzle exit. Equation (2) requires that the strongest self-magnetic fields occur at this minimum radial location. An excitation coil (see Fig. 1) will be exposed to an increasing field upon approach of the ion pulse, and to a diminishing field as it exits the nozzle opening. Because of the large pulsed energy requirements for extracting electron beams at near relativistic velocities and megampere peak currents, both inductor and capacitor components are likely to be large. For the purposes of this study, a sample calculation was carried out assuming the entire vehicle structure (excluding upper centrifugal compressor passages and the lower external charge neutralization shield) was to serve as one large ceramic dielectric capacitor. A dielectric material thickness of 1 cm (metalized on both sides) was assumed, as was an energy density of 0.2 J/cm^3 (this energy density agreeing well with that proposed in a paper by Winterberg[72]) and a total capacitator area (as estimated from vehicular dimensions in Fig. 1) of 219 m^2. The calculation revealed that the maximum charge stored in such a capacitor would be 1.3 C, while vehicle capacitance may reach 1.9 μF and the total stored electrical energy 4.4×10^5 J. (Other possible solutions to the charge storage problem are available, however. In a recent paper, H. Alfven reminds us that a thundercloud can store 10 to 50 C. He then suggests that if an electric powered shuttle is furnished with a number of sharp points, it could distribute charge through corona discharges to a vast region around it where the charge can be stored.[73]) Because of the large quasi-steady MHD engine electric currents required for peak thrust, the LC circuit will probably operate in the near megacycle frequency range.

Other possibilities to be explored for filling the 'electron beam extraction' energy deficit must certainly include the TELEC.[7] This laser energy converter requires inverse Bremsstrahlung absorption to provide heated plasmas for direct conversion to electricity. Hence, it is ideally suited for liaison with the proposed propulsion scheme, hereby expanding into a hybrid laser/electric/MHD cycle. The TELEC, which at best is expected to be 45% efficient, is closely related to a type of thermionic *rf* converter developed by Waymouth.[74]

The following expression for the thrust of self-magnetic field MHD arc-jet engines, expressed as a function of current, engine geometry, and total 'chamber' pressure has been introduced by Hügel, Kruelle, and Peters,[60,70] and will be used in this analysis of the MHD shuttle:

$$F=\left(\frac{\mu I^2}{4\pi}\right)\left[3/4+\ln\left(\frac{d_c}{d_a}\right)\right]+C_F P_0 A^* \tag{7}$$

where I is the accelerator electric current, μ the magnetic permeability, d_c the diameter of the 'rim cathode,' d_a the diameter of the positive-ion plasma-beam at minimum 'pinched' dimension, C_F the aerodynamic thrust coefficient, P_0 the total 'chamber' pressure, and A^* the nozzle throat area. Total theoretical thrust may be expressed as the sum of two major components. The first term is the thrust resulting from magnetic effects, while the second is generated by thermal or aerodynamic effects. A ratio of d_c/d_a equal to 10 is chosen for this analysis implying that the positive-ion plasma-beam will 'pinch' to a minimum diameter of 1 m. Thrust contributions from aerodynamic or thermal effects will be ignored.

III. Engine and Vehicle Performance

The shuttle craft pictured in Fig. 1 is envisioned as a single stage air-breathing orbital machine which uses to greatest advantage not only the air-plasma generating capabilities of the laser beam power source, but also the high temperature shock-ionized air-plasma associated with hypersonic flight through the atmosphere. Since no fuel is burned, the fuel specific impulse of the engine is infinity. Energy is not added to the engine working fluid by conventional gasdynamic and combustion means, but by MHD body forces acting on the entire external slipstream passing through its 'nozzle' region. Hence, many problems associated with combustor inlet temperature restrictions on the maximum allowable heat addition to the flow, supersonic combustion, and inherent necessity of a long hypersonic engine geometry are eliminated. At high Mach numbers, thermodynamic heat transfer and vehicular cooling requirements become increasingly important. Since these problems are functions of vehicular wetted area exposed to the high temperature flow, a low lift to drag ratio (L/D), compact type of air-breathing vehicle is desirable. In the supersonic flight regime, it is conceivable that wave drag created by a strong vehicle bow shock can potentially be eliminated, or at least greatly reduced, by MHD acceleration of the slipstream. As illustrated in Fig. 1, the shock may initially help direct expansion of the 'exhaust' gases aft prior to dissipation, saving an enormous amount of propulsive energy. At hypersonic speeds, significant electron densities forming in the shock-ionized slipstream will begin to penetrate the MHD 'nozzle' region. This phenomenon is expected to significantly increase electrical conductivity of the flow and, hence, the efficiency of the accelerator.

Because of the appearance of a plentiful shock-ionized air-plasma at the near orbital velocities, the engine may be able to sustain altitude with a relatively low power input. The vehicle may also be able to trade 'potential energy associated with height' for independently generated maneuvering forces during orbital reentry[75] until such a time when it will require a burst of remote laser power for breaking and touchdown. For simplicity, the vehicle should have no moving parts (except perhaps variable pitch turbine blades, unless replaced by an equivalent system, and a bearing supported payload module). Since the vehicle propulsion system produces intense rapidly fluctuating magnetic fields, extensive use of ceramic or other dielectric materials would be necessary in order to reduce magnetically-induced structural heating to a minimum.

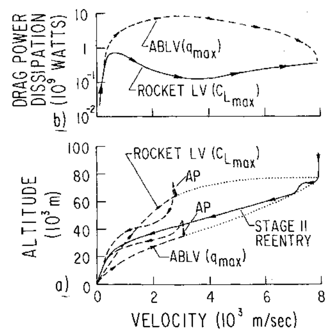

Fig. 3 Drag power dissipation along extrapolated orbital trajectories.

In order to provide an indication of the MHD propulsion system performance, a brief analysis of the required engine thrust, mass flow rate, exhaust velocity, and electric current along an orbital trajectory is useful. In addition, estimates are made for the electron seed fraction and the electron density within the MHD engine 'exhaust' plume to suggest an approximate air-plasma conductivity. For the purposes of this analysis, an arbitrary mass of 22,000 kg (~48,000 lb) is assumed for the vehicle of external dimensions shown in Fig. 1.

The two dashed lines in Fig. 3a illustrate the $q_{\max}$ trajectory (maximum dynamic pressure) for an air-breathing launch vehicle (ABLV) and the $C_{L_{\max}}$ trajectory (maximum coefficient of lift) for a two-stage rocket shuttle.[76] Both launch vehicle (LV) trajectories assume a maximum 3-g acceleration up to the point of departure from a smooth trajectory when the first-stage launch vehicles would perform a powered aerodynamic pullup (path segments "AP" in Fig. 3a) to a higher altitude for launch of the second-stage rocket powered shuttle, and then return for landing along the path shown. The smooth dotted lines running tangent off the dashed-line LV trajectories (before they abruptly pull up) and extending up to orbital velocity represent the two extrapolated trajectories initially examined for the air-breathing MHD shuttle engine calculations.

Using the ICAO standard atmosphere and sphere drag coefficients as a function of Mach number from Shapiro[77] for a 10 m diam sphere, it may be shown that the high dynamic pressure trajectory of the ABLV requires one to two orders of magnitude more power than that required along the rocket powered LV trajectory from drag considerations alone (see Fig. 3b). Consequently, the extrapolated rocket LV trajectory will be used for the balance of this study, since the MHD engine must additionally provide thrust for a 3-g acceleration along this path. However, the higher altitudes and associated lower ambient pressures demand that smaller MHD engine mass flow rates be accelerated to much higher exhaust velocities, indicating a higher required specific impulse. When the chosen extrapolated trajectory is compared with the flight envelopes for typical hypersonic air-breathing aircraft, it is found to exceed currently envisioned performance by air-breathing research vehicles beyond about Mach 3.[78]

The total thrust required by the MHD vehicle for a 3-g acceleration and the available MHD engine 'capture area' mass flow rate along the chosen orbital trajectory are shown in Fig. 4a. Drag calculations for a 10 m diam sphere previously used in the generation of Fig. 3b are also used here. Equation (4) may now be used to determine electrical current required by the MHD engine as a direct function of thrust along the trajectory. Again, the aerodynamic thrust component of Eq. (4) is ignored, since the predominant acceleration mechanism is expected to be due to self-magnetic field effects at these high electric current levels. Reference to Fig. 4b, shows that the required electric current increases from about 360,000 A at ground level to a peak at 600,000 A corresponding to the maximum required thrust for a vehicle velocity of 500 m/sec, and then reaches a low of about 280,000 A at orbital velocity.

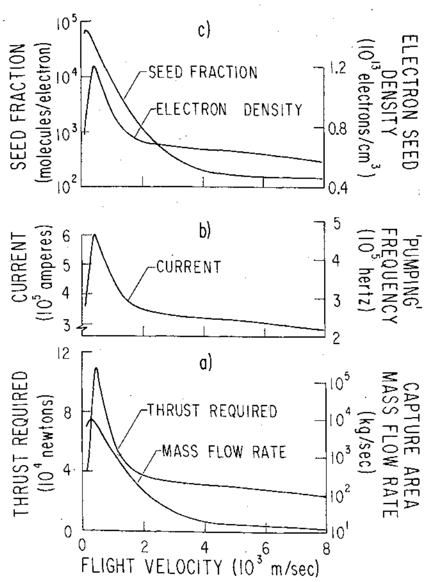

Fig. 4 Various calculated engine operating parameters along the chosen orbital trajectory.

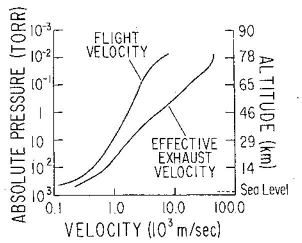

Fig. 5 Effective exhaust velocity and flight velocity plotted as a function of ambient pressure along orbital trajectory.

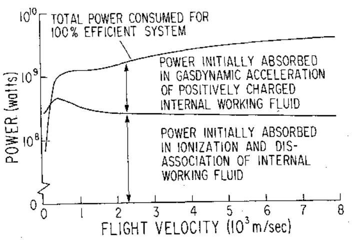

Fig. 6 Remote laser power requirements along orbital trajectory.

The 'pumping' frequency scale on the same plot indicates that the vehicular capacitor charge of 1.3 C may have to be cycled through the numerous perimeter diodes with a repetition rate approaching the megahertz range.

Displayed in Fig. 4c are estimations for two indicators of conductivity for gases residing in the 'nozzle' region of the MHD engine: electron seed fraction and relative electron density. The electron seed fraction is calculated directly from the available 'capture area' mass flow rate and the MHD electron current injected into this same slipstream flow at the minimum 'rim-volume' location. Note that the seed fraction parameter reaches a maximum of about 7×10^4 molecules/electron shortly after liftoff, but rapidly decreases to a value of 10^3 at a vehicle velocity of 2000 m/sec, then declining to about 150 molecules/electron at orbital velocity.

Comparison of these seed fractions with those used for MHD electrical power generators reveals that gases of low conductivity are typically seeded to 0.1% or less with a material (e.g. cesium or potassium) ionizing much more easily than the parent gas.[29] The addition of seed metals into a parent gas having a temperature lower than the melting point of metals will not improve the conductivity of the parent gas. However, for our application, *free* electrons serve as a nonthermal ionization mechanism to enhance conductivity.[63] Since the free electrons have no ions within close proximity with which to combine, increases in conductivity of the parent (slipstream) gas are largely independent of temperature.

The relative electron density within the MHD 'nozzle' region is calculated from a ratio of the number of electrons ejected per second, divided by the toroid shaped MHD 'nozzle' volume (outside diam of 10 m). This parameter assumes an arbitrary residence time for each electron of 10^{-3} sec. Note that the electron density in the upper plot of Fig. 4 peaks at 1.2×10^{13} electrons/cm^3 with maximum thrust production at a vehicle velocity of 400 m/sec, and declines to a value of about 0.6×10^{13} electrons/cm^3 beyond 2000 m/sec for the remainder of the trajectory. Comparison of these electron densities with those found in MHD electrical power generators indicates that 10^{13} electrons/cm^3 is typical.[29] When comparing these electron densities with that for shock-ionized flow near the stagnation point of a blunt reentry vehicle, it is found that densities there can range from 10^9 to 10^{16} electrons/cm,^{3} depending upon flight velocity and altitude.[79]

Figure 5 shows the effective exhaust and flight velocities plotted as functions of ambient pressure along the MHD shuttle trajectory. The effective engine exhaust velocity is calculated from the thrust required for 3 g acceleration, the available 'capture area' mass flow rate, $\dot{m}_{\text{capture}}$, and the free stream velocity, V_∞, as follows:

$$V_{ef} = \text{THRUST}/\dot{m}_{\text{capture}} + V_\infty \tag{8}$$

Successful operation requires that the MHD engine exhibit a broad range of exhaust velocities. At the associated ambient pressures, the engine must produce a V_{ef} of from several hundred m/sec near ground level to that of nearly 4.6×10^4 m/sec at low Earth orbital speeds. This range of exhaust velocities at the required ambient pressures has been demonstrated with MHD arc-jet accelerators.[52-54,80,81]

IV. Laser Power Requirements

Figure 6 illustrates the various internal power requirements of the proposed MHD engine throughout the orbital trajectory. The upper curve denotes the total 'thrust power' expended by the vehicle (i.e., product of instantaneous thrust and velocity) for a 3-g acceleration along this path. The propulsion device, however, will certainly be less than 100% efficient, but may perhaps approach the 50% efficiencies typical MHD arc-jets are exhibiting at low ambient pressures and flow rates. As shown in Fig. 6, total thrust power requirements increase rapidly at first, until a value of 1.35 GW corresponding to a flight velocity of about 750 m/sec, is reached. For flight velocities above about 1500 m/sec, the input laser power almost linearly increases to a maximum of 3.75 GW at orbital velocity.

The area below the lower curve represents the total power consumed by ionization of the internal engine air (15 eV/molecule of air) occuring upon inverse Bremsstrahlung absorption of the laser energy. It is assumed that the ejected beam electrons represent only 2% of those available from ionized molecules within the internal engine working fluid. Below a flight velocity of about 500 m/sec, more laser power will be required by the vehicle to generate electrons for electric current production than predicted by the 'thrust power' requirements alone, indicating a necessity for extracting a larger fraction of the available electron charge than 2% in this flight regime. This operating condition would, of course, leave the positive-ion plasma-beam with a greater net positive space charge and probably increase the expenditure of electical energy required in the electron beam extraction process.

The area between the upper and lower curves represents that original energy later transferred from the excited internal plasma electrons (following inverse Bremsstrahlung absorption) to heat the ions and residual neutral internal engine molecules by inelastic scattering. This heat energy is then converted to kinetic energy of the positive-ion plasma-beam as it gasdynamically expands down the internal plug nozzle with increasing supersonic velocity. The plasma-beam, however, suffers significant momentum losses along this path as its kinetic energy is subsequently transferred by self-magnetic fields to: a) accelerate the external conducting high mass flow engine gases, and b) generate electrical power within the exitation coil (upon exit of the ion beam from the internal nozzle), which in turn is used to extract electron beams from the ionization chamber. Even after exiting the nozzle, the plasma beam may continue to lose momentum to the external engine 'exhaust' gases, helping to accelerate them by the MHD ejector principle.[71]

If the projected thrust power in Fig. 6 was to be communicated uniformly across a 'nozzle' area equal to the projected frontal area of the vehicle, the input power density would reach 4780 W/cm^2 at orbital velocity. Reference 82 indicates that the proposed MHD engine would necessarily fall within the domain shared by the medium power density accelerators.

For the purposes of comparison, it may be interesting to contrast the electrical charge, current, and power requirements for this vehicle with that of natural occuring atmospheric lighting. We find from Ref. 83 that a total charge varying from 3 to 90 C ($\sim$25 C average) jumps through a potential difference of approximately 10 to 100 MV in a total elapsed time interval ranging from 10^{-2} to 2 sec (0.2 sec average) dissipating on the order of 2.5×10^9 W of power. During the discharge, lightning exhibits peak currents averaging from 10 to 20 kA and sometimes reaching 110,000 A. Consequently, this natural phenomenon has approximately equivalent average power and maximum peak electric current levels as the proposed MHD machine. Alfven notes that the total power to be transmitted at launch of such a vehicle is comparable to the power of a very large magnetic storm.[73]

V. Conclusions

The conceptual design for a laser-riding air-breathing single stage shuttle which would use magnetohydrodynamic forces to accelerate the engine working fluid is introduced. A cursory examination of the required thrust, exhaust velocities, electric current, working fluid electrical conductivity, and laser power reveals operable engine parameters in an interesting range indicating that the system may be worthy of further examination.

References

[1] Lubin, M.J., "Laser-Produced Plasmas for Power Generation and Space Propulsion," *Astronautics and Aeronautics,* Vol. 8, Nov. 1970, pp. 42-48.

[2] Ahlstrom, H.G., Christiansen, W.H., and Hertzberg, A., "Laser Power Transmission," *The Trend in Engineering,* Vol. 23, Oct. 1971, pp. 20-29.

[3] Hertzberg, A., Christiansen, W.H., et al, "Photon Generators and Engines for Laser Power Transmission," *AIAA Journal,* Vol. 10, April 1972, pp. 394-400.

[4] Hansen, C.F. and Lee, G., "Laser Power Stations in Orbit," *Astronautics and Aeronautics,* Vol. 10, July 1972, pp. 46-51.

[5] Christiansen, W.H. and Hertzberg, A., "Gasdynamic Lasers and Photon Machines," *Proceedings of the IEEE,* Vol. 61, Aug. 1973, pp. 1060-1072.

[6] Vetter, A.A., "Phased Arrays of Lasers for Power Transmission," *Proceedings of the Technical Program, Electro-Optical Systems Design Conference,* Sept. 18-20, 1973, pp. 283-293.

[7] Billman, K.W., "Laser Energy Conversion," *Astronautics and Aeronautics,* Vol. 13, July/Aug. 1975, pp. 56-65.

[8] Billman, K.W., "Laser Energy Conversion Symposium," NASA TMX-62, 269, Jan. 1973.

[9] Way, S., "Examination of Bipolar Electric and Magnetic Fields for Submarine Propulsion," preliminary Memorandum Communication to U.S. Navy Bureau of Ships, Oct. 1958.

[10] Rice, W.A., U.S. Patent 2997013, Aug. 12, 1961.

[11] Friauf, J.B., "Electromagnetic Ship Propulsion," *A.S.N.E.Journal,* Vol. 73, Feb. 1961, pp. 139-142.

[12] Phillips, O.M., "The Prospects for Magneto-Hydrodynamic Ship Propulsion," *Journal of Ship Research,* Vol. 5, March 1962, pp. 43-51.

[13] Doragh, R.A., "Magnetohydrodynamic Ship Propulsion Using Super-conducting Magnets," *Transactions of the Society of Naval Architects and Marine Engineers,* Vol. 71, 1963, pp. 370-386.

[14] Way, S., "Propulsion of Submarines by Lorentz Forces in The Surrounding Sea," ASME paper 64-WA/ENER-7, Winter Meeting, N.Y., Nov. 1964.

[15] Way, S. and Devlin, C., "Construction and Testing of a Model Electro-Magnetically Propelled Submarine," *Proceedings of the Engineering Aspects of Magnetohydrodynamics,* Stanford Univ., Palo Alto, Calif., 1967.

[16] Way, S. and Devlin, C., "Prospects for the Electromagnetic Submarine," AIAA Paper 67-432, Wash. D.C., 1967.

[17] Way, S., "Electromagnetic Propulsion for Cargo Submarines," *Journal of Hydronautics,* Vol. 2, April 1968, pp. 49-57.

[18] Way, S., "Research Submarines with Minimal Ocean Disturbance," SAE Paper No. 690028, presented at SAE Conference on Jan. 13-17, 1969.

[19] Cramer, K.R. and Pai, S., *Magnetofluid Dynamics for Engineers and Applied Physicists,* 1st ed., McGraw-Hill, New York, 1973, pp. 217-226, 226-232.

[20] Stuhlinger, E., "Design and Performance Data of Space Ships with Ionic Propulsion Systems," 8th IAF Congress, Barcelona, Oct. 1957, p. 403.

[21] Rosa, R.J., "An Electromagnetic Rocket System of High Specific Thrust," AVCO-Everett Research Laboratory, Everett, Mass., AVCO Research Report 103, April 1958.

[22] Ackeret, J., "A System of Rocket Propulsion Using Rockets and Gas Turbines," International Astronautical Congress, 9th, Proceedings, Vol. 1, 1959, pp. 277-281.

[23] Goldsmith, M., "Augmentation of Nuclear Rocket Specific Impulse Through Mechanical-Electrical Means," *ARS Journal,* Vol. 29, Aug. 1959, pp. 600-601.

[24] Resler, E.L. Jr. and Rott, N., "Rocket Propulsion with Nuclear Power," *ARS Journal,* Vol. 30, Nov. 1960, pp. 1099-1100.

[25] Berry, E.R., "Effect of Electrical Augmentation on Nuclear Rocket Flight Performance," *ARS Journal,* Vol. 31, Jan. 1961, pp. 92-93.

[26] Rosa, R.J., "Propulsion System Using a Cavity Reactor and Magnetohydrodynamic Generator," *ARS Journal,* Vol. 31, July 1961, pp. 884-885.

[27] Rosa, R.J., "Magnetohydrodynamic Generators and Nuclear Propulsion," *ARS Journal,* Vol. 32, Aug. 1962, pp. 1221-1230.

[28] Rosciszewski, J., "Rocket Motor with Electric Acceleration in the Throat," *Journal of Spacecraft,* Vol. 2, March-April 1965, pp. 278-280.

[29] Rosa, R.J., *Magnetohydrodynamic Energy Conversion,* 1st ed., McGraw-Hill, N.Y., 1968, pp., 19, 27, 189-193.

[30] Rosa, R.J., *Analog Science Fiction/Science Fact,* Vol. XC, Sept. 1972, pp. 64-71.

[31] Demetriades, S.T. and Kretschmer, C.B., "The Use of Planetary Atmospheres for Propulsion," Armed Services Technical Info. Agency DOC. AD 154-132, April 1958.

[32] Demetriades, S.T., "A Novel System for Space Flight Using a Propulsive Fluid Accumulator," *Journal of British Interplanetary Soc.,* Vol. 17, Oct. 1959, pp. 114-119.

[33] Demetriades, S.T., "Orbital Propulsion System for Space Maneuvering (PROFAC)," *Astronautical Science Review,* Vol. 1, Oct.-Dec. 1959, pp. 17-18, 26.

[34] Demetriades, S.T. and Young, C.F., "Orbital Refueling Satelloid," SAE/AFOSR Research Paper 230H, Oct. 1960.

[35] Berner, F. and Camac, M., "Air Scooping Vehicle," AVCO-Everett Research Lab., Everett, Mass., Research Rept. 76, Air Force Ballistic Missile Div. TR 59-17, Aug. 1959.

[36] Camac, M. and Berner, F., "An Orbital Air Scooping Vehicle," *Astronautics,* Vol. 6, Aug. 1961, pp. 28-29, 70-71.

[37] French, E.P., "Operation of an Electric Ramjet in a Planetary Atmosphere," *AAS* Preprint, Aug. 1960, pp. 60-90.

[38] Glassmeyer, J.M., AFRPL "Ideagram," *A-SCOR,* May 3, 1970.

[39] Corliss, W.R., *Propulsion Systems for Space Flight,* 1st. ed., McGraw-Hill, N.Y., 1960, pp. 147-152.

[40] Cann, G.L., "Advanced Electric Thruster (A Space Electric Ramjet)," Air Force Rocket Propulsion Lab., Wright-Patterson AFB, Ohio, Technical Report AF RPL-TR-73-12, April 1973.

[41] Cann, G.L., "A Space Electric Ramjet," AIAA Paper 75-377, New Orleans, La., 1975.

[42] Kantrowitz, A., "The Relevance of Space," *Astronautics and Aeronautics,* Vol. 9, March 1971, pp. 34-35.

[43] Rom, F.E. and Putre, H.A., "Laser Propulsion," NASA TM-X-2510, April 1972.

[44] Kantrowitz, A., "Propulsion to Orbit by Ground-Based Lasers," *Astronautics and Aeronautics,* Vol. 10, May 1972, pp. 74-76.

[45] Pirri, A.N. and Weiss, R.F., "Laser Propulsion AIAA Paper 72-719, Boston, Mass., 1972.

[46] Minovitch, M.A., "Reactorless Nuclear Propulsion – The Laser Rocket," AIAA Paper 72-1095, New Orleans, La. 1972.

[47] Baty, R.S., "Space Propulsion – Let's Do It Better Electrically," *Air University Review,* Vol. 25, Nov.-Dec. 1973, pp. 10-15.

[48] Cohen, W., "New Horizons in Chemical Propulsion," *Astronautics and Aeronautics,* Vol. 11, Dec. 1973, pp. 46-51.

[49] Pirri, A.N., Monsler, M.J., and Nebolsine, P.E., "Propulsion by Absorption of Laser Radiation," *AIAA Journal,* Vol. 12, Sept. 1974, pp. 1254-1261.

[50] Stuhlinger, E., Berlin. 5th International Astronautical Congress, Springer, Vienna, 1954, p. 100.

[51] Stuhlinger, E., Hale, D.P., Daley, C.C., and Katz, L., "The Versatility of Electrically Powered Spacecraft for Planetary Missions," AIAA Paper 69-253, Williamsburg, Va., 1969.

[52] Jahn, R.G., *Physics of Electric Propulsion,* 1st ed., McGraw-Hill, N.Y., 1968, pp. 235, 253, 236, 260, 115.

[53] Bruckner, A.P. and Jahn, R.G., "Exhaust Plume Structure in a Quasi-Steady MPD Accelerator," Vol. 12, Sept. 1974, pp. 1198-1203.

[54] Hügel, H., "Flow Rate Limitations in the Self-Field Accelerator," *AIAA Journal,* Vol. 12, Nov. 1974, pp. 1461-1462.

[55] O'Neill, G.K., "The Colonization of Space," *Physics Today,* Vol. 27, Sept. 1974, pp. 32-40.

[56] Buonadonna, V.R., Knight, C.J., and Hertzberg, A., "The Laser Heated Wind Tunnel – A New Approach to Hypersonic Laboratory Simulation," AIAA Paper 73-211, Wash. D.C., 1973.

[57] Stallcop, J.R. and Billman, K.W., "Analytical Formula for the Inverse Bremsstrahlung Absorption Coefficient," *Plasma Physics,* Vol 16, 1974, pp. 1187-1189.

[58] Stallcop, J.R., "Absorption of Infrared Radiation by Electrons in the Field of a Neutral Hydrogen Atom," *Astrophysical Journal,* Vol. 187, Jan. 1974, p. 179-183.

[59] Bunkin, F.B., Kazakov, A.E., and Fedorov, M.V., "Interaction of Intense Optical Radiation with Free Electrons (Nonrelativistic Case)," *Soviet Physics Uspekhi,* Vol. 15, No. 4, Jan.-Feb. 1973, pp. 416-435.

[60] Mongolfier, P., "Laser Induced Gas Breakdown: Electron Cascade," *Journal of Physics, D: Applied Physics,* Vol. 5, 1972, pp. 1438-1447.

[61] Vegrie, P. and Floux, F., "Breakdown Wave, Shock Wave, and Radiation Wave in Laser Created Plasmas," *AIAA Journal,* Vol. 8, Aug. 1970, pp. 1405-1411.

[62] Fleischmann, H.H., "High-Current Electron Beams," *Physics Today,* Vol. 28,May 1975, pp. 35-43.

[63] Sternglass, E.J., et al., "MHD Power Generation by Non-Thermal Ionization and its Application to Nuclear Energy Conversion," 3rd Symposium on Engineering Aspects of Magnetohydrodynamics, Gordon and Breach, N.Y., 1964, pp. 205-222.

[64] Dommasch, D.O., Sherby, S.S., and Connolly, T.F., *Airplane Aerodynamics,* 3rd ed., Pitman Publishers, N.Y., 1961, p. 192.

[65] Poukey, J.W. and Toepfer, A.J., "Theory of Superpinched Relativistic Electron Beams," *The Physics of Fluids,* Vol. 17, Aug. 1971, pp. 1582-1591.

[66] Yoshikawa, S., "Force-Free Configuration of a High-Intensity Electron Beam," *Physical Review Letters,* Vol. 26, Feb. 8, 1971, pp. 295-297.

[67] Hammer, D.A. and Rostoker, N., "Propagation of High Current Relativistic Electron Beams," *The Physics of Fluids,* Vol. 13, July 1970, pp. 1831-1850.

[68] Ivanov, A.A. and Rudakov, L.I., "Intense Relativistic Electron Beam in a Plasma," *Soviet Physics JETP,* Vol. 31, Oct. 1970, pp. 715-719.

[69] Hügel, H., Kruelle, G., and Peters, T., "Investigations on Plasma Thrusters with Thermal and Self Magnetic Acceleration," *AIAA Journal,* Vol. 5, March 1967, pp. 551-558.

[70] Hügel, H. "Self Magnetic Effect in Arcjet Engines," *AIAA Journal,* Vol. 6, Aug. 1968, pp. 1573-1574.

[71] Heiser, W.H., "Analysis of a Magnetohydrodynamic Ejector," *Journal of Applied Mechanics,* Vol. 32, Sept. 1965, pp. 680-683.

[72] Winterberg, F., "Rocket Propulsion by Thermonuclear Microbombs Ignited with Relativistic Electron Beams," *Raumfahrtforschung,* Vol. 15, Sept.-Oct., 1971, pp. 208-217.

[73] Alfven, H., "Spacecraft Propulsion: New Methods," *Science,* Vol. 176, April 1972, pp. 167-168.

[74] Waymouth, J.F., "Electrical Energy from High Temperature Plasma," *Journal of the Institute of Electrical Engineers,* Vol. 8, Aug. 1962, p. 380.

[75] Donaldson, C. duP. and Brunner, M.J., "Discussion of a Self-Powered MHD Control for Re-entry Vehicle Application," 3rd Symposium on Engineering Aspects of Magnetohydrodynamics, March 1962, pp. 559-577.

[76] Henry, J.R. and McLellan, C.H., "Air-Breathing Launch Vehicle for Earth-Orbit Shuttle – New Technology and Development Approach," *Journal of Aircraft,* Vol. 8, May 1971, pp. 381-387.

[77] Shapiro, A.H., *The Dynamics and Thermodynamics of Compressible Fluid Flow,* Vol. 1, 1st ed. Ronald Press., N.Y., 1953, pp. 190-218, 410.

[78] Edwards, C.L. W., Small, W.J., and Weidner, J.P., "Studies of Scramjet/Airframe Integration Techniques for Hypersonic Aircraft," AIAA Paper 75-58, Pasadena, Calif., 1975.

[79] Touryan, K.J., "A Hypersonic Plasma Power Converter," *AIAA Journal,* Vol. 3, April 1965, pp. 652-659.

[80] Garrison, G.W., and Smith, R.T., "Characteristics of a Magnetic Annular Arc Operating Continuously at Atmospheric Pressure," *AIAA Journal,* Vol. 8, Sept. 1970, pp. 1714-1715.

[81] Harry, J.E., "Characteristics of a Magnetic Annular Arc Operating Continuously at Atmospheric Pressure," *AIAA Journal,* Vol. 9, Aug. 1971, pp. 1660-1661.

[82] Kantrowitz, A., "Horizons in Plasma Physics," *Astronautics and Aeronautics,* Vol. 3, Jan. 1965, pp. 52-65.

[83] *Handbook of Chemistry and Physics,* 54th ed., Chemical Rubber Co. Press, Cleveland, Ohio 1973-1974, p. F-193.