Hypersonic MHD Propulsion System Integration for the Mercury Lightcraft

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Abstract. Introduced herein are the design, systems integration, and performance analysis of an exotic magnetohydrodynamic (MHD) slipstream accelerator engine for a single-occupant "Mercury" lightcraft. This ultra-energetic, laser-boosted vehicle is designed to ride a 'tractor beam' into space, transmitted from a future orbital network of satellite solar power stations. The lightcraft's airbreathing combined-cycle engine employs a rotary pulsed detonation thruster mode for lift-off & landing, and an MHD slipstream accelerator mode at hypersonic speeds. The latter engine transforms the transatmospheric acceleration path into a virtual electromagnetic 'mass-driver' channel; the hypersonic momentum exchange process (with the atmosphere) enables engine specific impulses in the range of 6000 to 16,000 seconds, and propellant mass fractions as low as 10%. The single-stage-to-orbit, highly reusable lightcraft can accelerate at 3 Gs into low Earth orbit with its throttle just barely beyond 'idle' power, or virtually 'disappear' at 30 G's and beyond. The objective of this advanced lightcraft design is to lay the technological foundations for a safe, very low cost (e.g., 1000X below chemical rockets) air and space transportation for human life in the mid-21st Century - a system that will be completely 'green' and independent of Earth's limited fossil fuel reserves.

INTRODUCTION

The objective of the present effort is to lay down the technological foundations for advanced air and space transportation, using 'Highways of Light' - for which the principal infrastructure is a grid of remote energy-beaming power plants located either in space or on the ground. In the mid-21st Century, extremely energetic laser-propelled 'lightcraft' will ride these virtual energy 'highways' - no longer burdened with massive on-board fuel loads. The present paper investigates a representative engine/optics/airframe design for an advanced laser-electric type of airbreathing propulsion for a minimum-volume, single occupant space capsule.

The conceptual design for a one-place, laser-boosted Mercury lightcraft was recently reviewed in [1], covering the engine/optics/airframe integration process and geometry for the 'lift-off' propulsion mode – a rotary pulsed detonation thruster [2]. The present paper focuses on the hypersonic propulsion mode – which is based on a magnetohydrodynamic (MHD) slipstream accelerator (Fig. 1). In essence, this engine momentarily transforms the transatmospheric acceleration path into an extremely long electromagnetic 'mass-driver.' The hypersonic engine relies on action-at-a-distance forces to electromagnetically scavenge reaction mass from the atmosphere - for efficient momentum exchange. The MHD engine is derived from an earlier Rosa

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concept [3-5] for an electric airturborocket cycle called the 'MHD fanjet,' designed for single-stage-to-orbit flights with an on-board nuclear electric powerplant.

Figure 1 gives a side view of the Mercury lightcraft with its shroud retracted for MHD operation. The principal components of the MHD engine are the: a) laser-induced "airspike" [6] to externally pre-compresses the inlet air while simultaneously reducing forebody drag and heat transfer; b) annular MHD air accelerator, inclusive of 24 strut-type electrode-pairs, and 2-Tesla (Helmholtz-type) superconducting magnet [7-8]; c) four laser-heated, hydrogen-fueled MHD generators (also with superconducting magnets) that are rocket-driven and open-cycle [9-10]; and, d) solid state, power-electronics system to connect (i.e., for switching, load management, etc.) the four MHD generators to the annular MHD air accelerator. The following sections discuss the conceptual design, physics, and performance estimates for these ultra-energetic, hypersonic engine components.

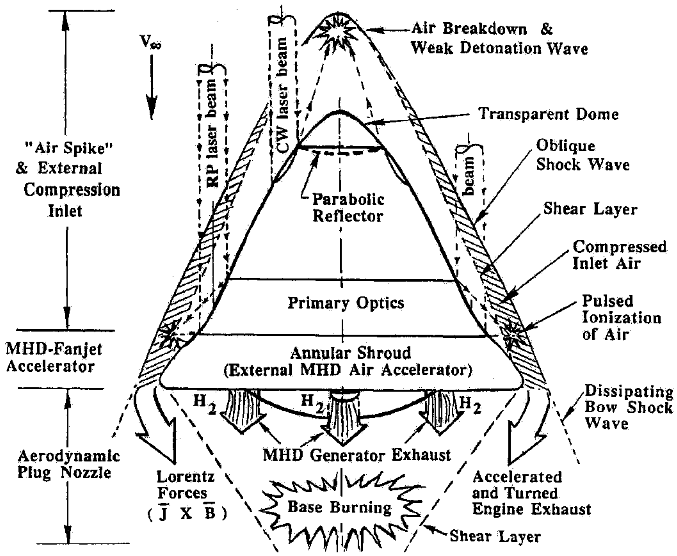


FIGURE 1. Hypersonic MHD Slipstream Accelerator Mode for the Mercury Lightcraft.

MHD SLIPSTREAM ACCELERATOR CONCEPT

The heart of the MHD slipstream accelerator is a pair of simple superconducting magnetic field coils, arranged in a Helmholtz configuration to produce an azimuthal magnetic field – directed radially outward through the annular shroud (Fig. 2). Once energized prior to lift-off, these well-insulated superconducting magnets will need no additional power in flight. Note in Figs. 1 & 2 that the external MHD accelerator 'duct' is formed by the annular stream-tube of inlet air that is trapped between the bow shock wave and the external shroud surface.

The applied 2-Tesla magnetic field cuts at right angles to the slipstream air in this annular MHD channel which is divided into 24 sections, each about 28-cm wide. The positive and negative electrodes in each 28-cm channel are integrated into the left and right surfaces of each strut (Fig. 3). The 24 struts, which 'anchor' into the vehicle airframe, are the principal structural supports for annular shroud. To function properly, an electric arc (actually, a distributed diffuse discharge) is struck between the electrode pairs of each accelerator channel. The interaction of this electric discharge and magnetic field gives rise to the J X B body (Lorentz) force that accelerates air through the channel - resulting in propulsive thrust.

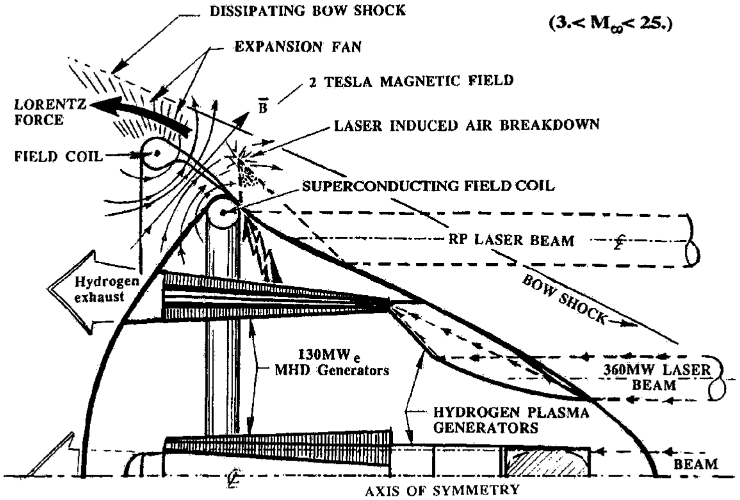


FIGURE 2. Cutaway view showing principal MHD engine components.

Of course, conceptual elegance does not necessarily lead to practical engineering solutions. One must first ask some difficult questions. In the case of the MHD-slipstream accelerator engine, the three most fundamental questions are:

- Will the magnetic coils be sufficiently light?
- Will the power required to ionize or "break down" the air and hence render it electrically conducting, be sufficiently low? (Clearly, the air in the MHD duct must be electrically conducting in order to be moved by the J X B forces.)
- Will the electrical power source be sufficiently lightweight and compact?

Today, advances in superconducting magnet technology makes it possible to answer the first question with a confident "yes." The two ring-shaped Helmholtz coils in Fig. 2 will need a conductor diameter of ~1 cm and conduct a current of one megampere each. Acting together they create the 2 Tesla magnetic field, oriented perpendicular to the shroud upper surface, as required for the MHD slipstream accelerator. Their combined mass fraction (including insulation material in the 12 cm diameter magnet housing/structure) is estimated at 17% of the gross vehicle mass -- or just 60 kg. The twin 'saddle-type' superconducting magnets for each of the rocket-driven MHD generators must apply a 3.5 to 5.0 Tesla field at right angles through the hydrogen plasma flowing through their ducts. However, this again is entirely within the realm of existing low-temperature superconductor materials.

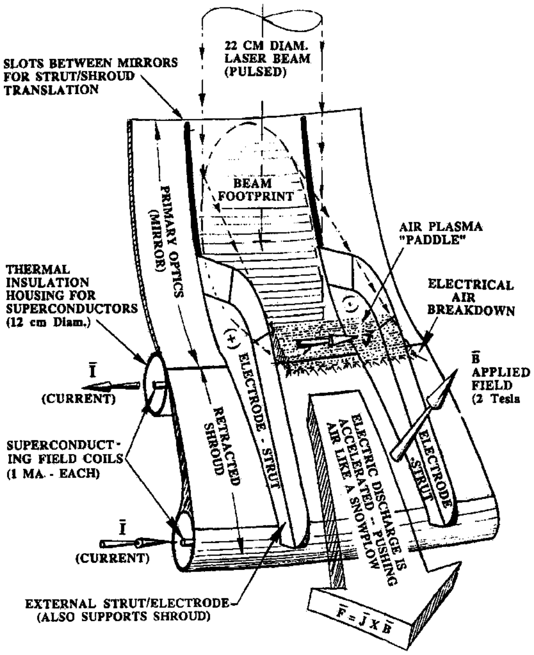


FIGURE 3. Close-up view of MHD slipstream accelerator, showing electrode/struts, superconducting magnets, primary optics, and retracted shroud. (Section shown is 1/12th of the annular shroud.)

The second question on 'ionization power' is a bit more subtle. The situation is difficult, but not so much that a modest amount of ingenuity can turn the trick. The thermal power required to a ionize 20 cm diameter, 30 cm long 'plasma paddle' at the entrance to each of the 24 identical MHD accelerator channels (Fig. 3) – will come from appropriately timed laser pulses delivered onto the individually-targeted primary mirror surfaces (Fig. 4). The energy required for electrical breakdown of air at the line focus of these primary optics (needed just prior to laser-supported detonation heating) can come from either the laser pulse itself (if pulse energy is sufficient), or augmented by an on-board microwave or E-beam source; the higher flight altitudes will definitely require such augmentation.

Each laser pulse (Fig. 3-4) creates a cylindrical blast wave inside a 1-cm diameter focal region, with an initial pressure ratio of 1000 across the shock. The shock and plasma contact surface do not separate until the pressure ratio falls to 10, when the shock wave hits the shroud [8]. At the MHD channel entrance, sufficient levels of electrical conductivity are reached within this 20-cm diameter plasma cylinder (or 'paddle'). As the paddle is accelerated by MHD forces, electrical conductivity is maintained in thermal equilibrium by resistive heating of the air plasma. Note that these MHD-driven 'plasma paddles' are somewhat analogous to the physical fan-blades in today's turbofan engines. The objective of the 'paddle' approach is to avoid ionizing the entire slipstream working fluid, which would greatly reduce the energy efficiency of this MHD accelerator concept.

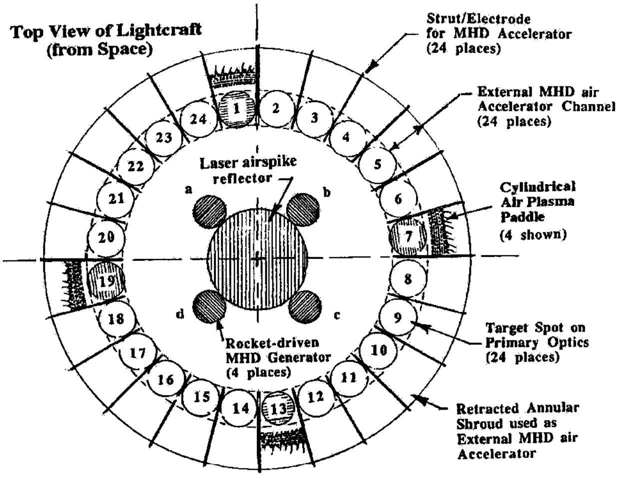


FIGURE 4. Top view of lightcraft forebody showing 24 target sites on annular primary optic used to trigger laser-induced air breakdown for cylindrical plasma paddles. Also shown are central reflector for laser-energized airspike, and four high power laser windows for rocket-driven MHD generators.

The final 'power system' question requires a 'flight-weight, high-energy source. Getting to orbit from a standing start on Earth is a not-impossible but nevertheless highly difficult feat requiring a hyper-energetic approach. Neither nuclear power, nor antimatter is realistic for manned vehicles because of the massive radiation shields (e.g., 100 metric tons of lead) required for human payloads. Exotic future propellants, commonly known as High Energy Density Materials (HEDM), could become candidates once they become available; researchers have theorized >100 MJ/kg might even be feasible. Stuck with today's physics however, the most viable answer is a continuous-refueling operation along the entire trajectory to orbit - accomplished by beaming electromagnetic energy to on-board power converters. The Mercury lightcraft exploits just such a device: a laser-heated, rocket-driven, open-cycle MHD generator (Fig. 5) - as elaborated upon below.

'FLIGHT-WEIGHT' ELECTRIC POWER PLANT

The principal design goal for this open-cycle MHD power converter is to minimize the ejected mass flow rate of unseeded hydrogen – i.e., the lowest molecular weight option) to secure the highest overall engine specific impulse. For highest efficiency, the electric airturborocket engine cycle requires the extraction of a large enthalpy change from a very small mass flow rate of consumables (ejected H2); this power is subsequently transferred electromagnetically - to accelerate a large mass flow rate of air. Each laser-to-electric power converter in Fig. 5 supplies 130 MWe to one-quarter of the lightcraft's external slipstream airflow. A detailed theoretical analysis of this ultra-high temperature, unseeded H2 MHD generator concept is given in [9-10].

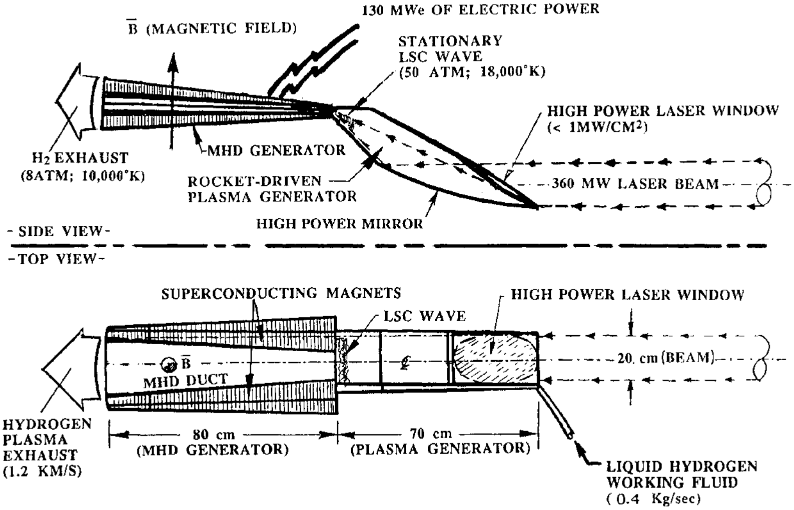


FIGURE 5. Top and side views of a 130 MWe rocket-driven, open-cycle, MHD generator specifically designed for the Mercury lightcraft. Unseeded liquid hydrogen is the proposed working fluid, with partial regenerative cooling. The converter may require additional water coolant, expended as steam.

The 'flight-weight' power plant for the Mercury lightcraft incorporates four such laser-heated rocket-driven MHD generators to provide 520 MWe with a laser-to-electric conversion efficiency goal of 36%. After exiting the MHD generator duct, the high temperature hydrogen is vented at out the lightcraft afterbody at a velocity of 1.18 km/s, temperature of 8500 K and pressure of 7.8 bars [10]. As indicated in Fig. 1, the unburned hot hydrogen will combust with local oxygen (i.e., "base burning") within the aft aerodynamic or 'plug-type' nozzle - to help reduce or eliminate base drag. This rocket exhaust will add ~10% more thrust to that developed by the MHD slipstream accelerator (i.e., momentum exchange with the atmosphere) alone.

Laser-Heated Plasma Generator Design

As shown in Fig. 5, a 360 MW plane-polarized laser beam first passes through a high power laser window set at the Brewster angle with an intensity of less that 1 MW/sq.cm, before coming to a 20-cm line focus just upstream of a 2-dimensional rocket nozzle throat. The focusing function is provided by cylindrical mirrored surfaces inside the plasma generator's pressure vessel. The focused beam maintains a standing laser-supported combustion wave (i.e., a continuous optical discharge) within subsonically flowing hydrogen gas, at a stagnation pressure of ~50 atmospheres. Basically, the LSC wave wants to propagate towards the laser source, so the converging duct contour must enable the incoming hydrogen to blow the LSC wave back into equilibrium. Numerical simulations of 10.6 um laser-sustained plasmas in 50 Bar hydrogen with 2-dimensional geometries indicated maximum focal line power densities in the range of 1.5 to 3 MW/cm, as reported in [11].

The Mecury lightcraft plasma generators are designed for a linear source thermal power of 360 MW/ 20cm = 18 MW/cm, which requires the use of 0.35 um to 1.0 um radiation Near ultraviolet laser frequencies may be an ideal choice for the high altitude MHD flight regime, in part because any 'spilled' laser power would be heavily attenuated by the dense lower atmosphere. Each laser-heated rocket gas generator section is designed to accelerate roughly 0.4 Kg/s of H2 through a throat measuring 1.7 cm by 20 cm, into the entrance of the MHD generator. This design goal represents an electrical/propellant utilization efficiency of 130 MWe/ 0.4Kg/s = 325 MJ/Kg.

MHD Generator Design

The most important parameter in the design of ultra-high power density, MHD generators, propellant utilization efficiency, has been examined on a first-order basis by the second author, in performance calculations that properly account for the ionization of hydrogen, but don't include a detailed treatment of radiation heat transfer. Nevertheless, the trends displayed in Fig.6 are very interesting, because they indicate values of power per unit mass flow as high as 800 MJ/Kg.

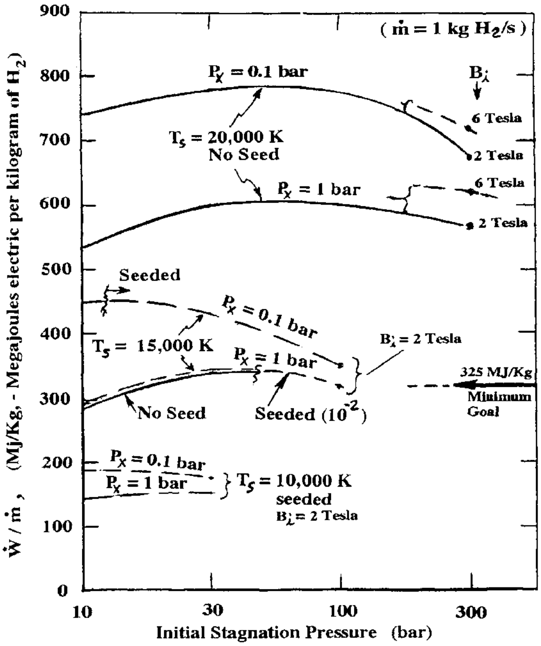


FIGURE 6. Ultra-high temperature, hydrogen-fueled MHD generator performance

Note these "un-optimized" calculations were made for a H2 mass flow rate of 1 kg/s, peak magnetic fields in the range of 2-6 Tesla, and MHD generator lengths of somewhat less that 1 meter; the seeded cases assume 1% potassium. The optimum initial pressure seems to be in the range of 40-50 bar, if convective heat loss only is considered (what radiation will do is addressed in Ref. 9-10). However, the use of seed is incompatible with the 'environmentally friendly' objective of this lightcraft transportation system.

Note that for a stagnation temperature of 20,000 K at the entrance of the MHD generator, no seed is needed. For 15,000 K it's needed if one wishes to expand down to an exit pressure of 0.1 bar, but not if it exits at 1 bar and did not start above 40 bar. Also, note the magnetic fields are smaller. No attempt has been made in these calculations to optimize the choice of magnetic field strength. In many cases at high temperature one might expect the optimum to be less than 2 Tesla; hence, the coil mass would be practically negligible, in part because of the extremely high power densities (i.e., small volume). By far the major question with such high temperature, high power density MHD generators is going to be: What happens at the electrode wall when the current density is several thousand amperes per square centimeter? However, since Hall effects are going to be very small and since the lightcraft application does not call for long periods of operation, it may well be entirely feasible.

LH2 Tankage Requirement

Of the 3 cubic meters internal volume available in the Mercury lightcraft aeroshell, roughly one-third is dedicated to liquid hydrogen storage, another third for magnets and propulsion-related hardware, leaving nearly one cubic meter for the occupant - similar to the original Mercury spacecraft capsule. Roughly 70 kg of LH2 can be stored on-board at launch, representing a propellant fraction of 20% for a lightcraft gross lift-off mass of 350 kg. In order for the SSTO craft to climb directly into LEO, the MHD engine must have a sufficiently high fuel specific impulse (Isp).

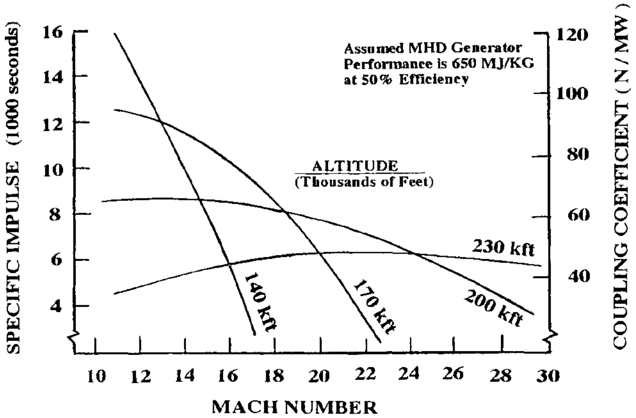
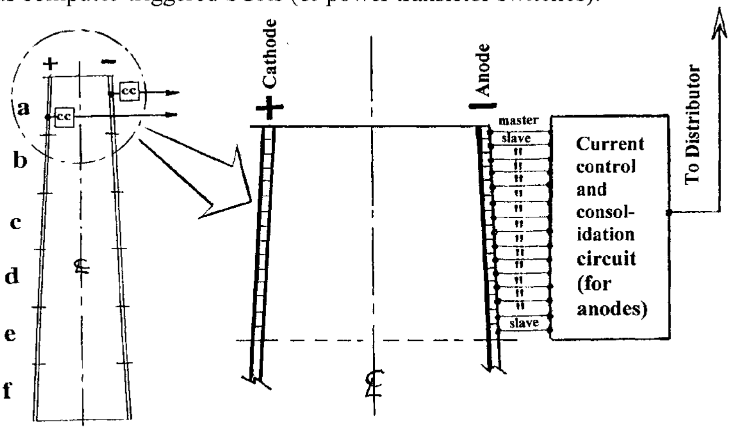


FIGURE 7. MHD Slipstream accelerator performance calculation from [12].

Transatmospheric flight simulations were conducted in [12] using the SORT code - focused on a 5-place 'Apollo' lightcraft with a 5m diameter and 5550 kg gross lift-off mass. The study assumed a LH2 propellant utilization 650 MJe/Kg for the laser-heated, rocket-driven MHD generator with an optimistic 50% laser-to-electric conversion efficiency. The Apollo lightcraft achieved mission success (i.e., orbital velocity at the top of the atmosphere) with calculated Isp values ranging from 6000 to 18,000 seconds (Fig. 7) - with a LH2 mass fraction of only 6%. However, exceedingly low vehicular drag coefficients were needed throughout the hypersonic regime, which can best be achieved with a directed-energy airspike. It would be most useful to re-visit this 1987 study to determine what airspike geometries and airspike powers could make these drag coefficients feasible.

ELECTRIC POWER MANAGEMENT SCHEME

Figures 8-12 give circuit diagrams for electrical hookup of the MHD generators to one-quarter of the MHD Fanjets annular shroud. The combined output from four 130 MWe rocket-driven MHD generators is delivered to 24 identical accelerator channels, so that each generator drives 6 shroud accelerator segments (e.g., those bounded by struts 1,2,3,4,5,6,&7 in Figs. 9-10). Power distribution in Fig. 10 is carried out by numerous computer-triggered SCRs (or power transistor switches).



MHD Generator **First Generator Section "a"**

FIGURE 8. MHD generator hookup diagram (one section of 6 is shown).

As shown in Fig. 8 and 9, each 80 cm long MHD generator duct is of the Faraday type with parallel electrodes numbering perhaps 90 in all. The duct is divided into six sets (see a, b, c, d, e, & f) of 15 electrode pairs per set. Each set would have one "master" electrode pair, with the other 14 pairs "slaved" to it (Fig. 8), to enhance electrical circuit stability; for more information on control consolidation circuits see [13-14]. Note that every pair of shroud support struts (Fig. 3) channelizes the MHD-accelerated airflow. Each strut is covered by parallel strip electrodes that are 36 cm long, on both sides as illustrated in Fig. 11.

In Fig. 12, note that the electrically conducting plasma paddles are staggered across the one-quarter-shroud accelerator surface. This deliberate staggering is to prevent short circuiting across adjacent MHD accelerators, i.e., from arcing over the top of the struts. Finally, Fig. 24 attempts to dramatize the movement of paddle positions vs. time (i.e., increments - i,ii,iii,iv,v,vi,&vii) for a one-quarter shroud section.

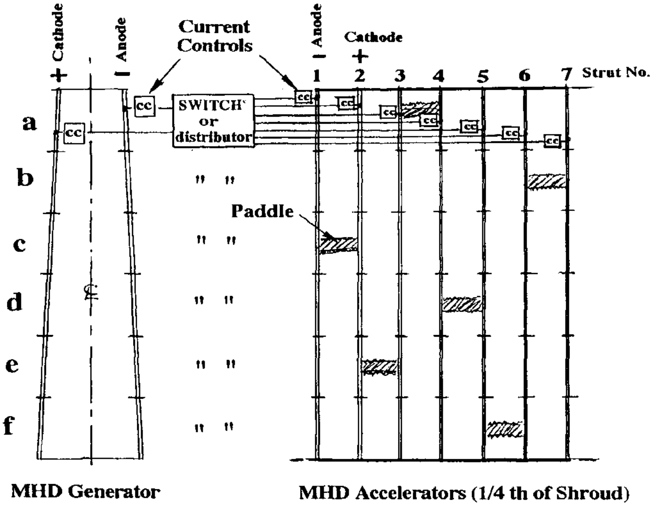


FIGURE 9. Electrical circuit diagram for MHD generator and MHD slipstream accelerator.

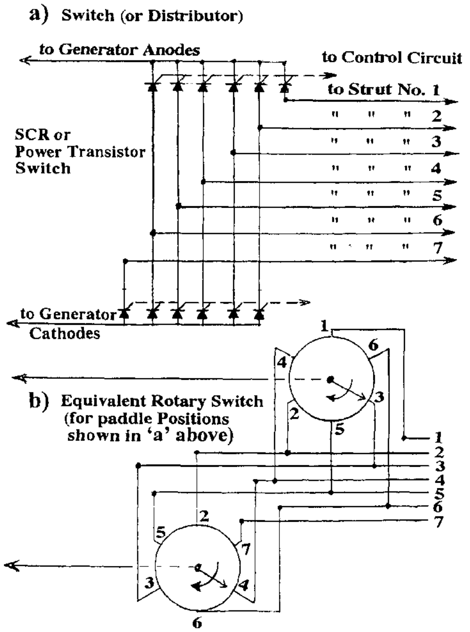


FIGURE 10. Distributor circuit diagrams for MHD engine, showing: a) solid state switch or distributor version, and b) Equivalent rotary switch – for paddle positions shown in 'a' (above).

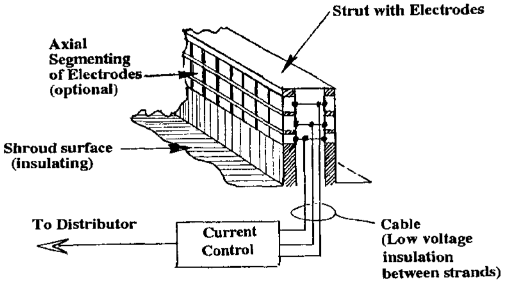


FIGURE 11. Electrical hookup for strut electrodes (only 3 electrodes are shown).

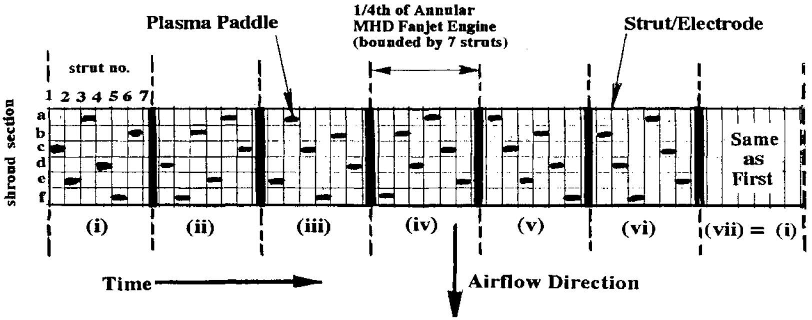


FIGURE 12. Plasma 'paddle' positions vs. time. Note one-quarter of shroud is displayed at 6 different times of (i) through (vi).

SIMPLE MHD ACCELERATOR ANALYSIS

The big advantage of an MHD slipstream accelerator over conventional "heat engines" like the turbojet, ramjet or scramjet is that deceleration of the incoming airflow is not necessary for its operation -- and therefore the very large stagnation pressure loss in an inlet diffuser at high Mach number can be avoided. MHD accelerators also avoid the combustor-related pressure losses from fuel-injection and the complexity of chemical combustion processes in supersonic engine air. Accordingly, what is calculated here is the performance of a "pure" external MHD accelerator in which the entering velocity is roughly equal to that delivered by the airspike at the annular shroud 'inlet' location.

Analytical Model Description

For the purpose of this first-order analysis, the MHD accelerator is assumed to be a rectangular duct (Fig 13) of cross-section A and length L, with an impressed magnetic field B normal to the flow direction, and an ionized paddle of length Lp inside. Note that the width of the duct is Y, Z is the height, and j is the current density through the paddle. Ionization is assumed to be thermal with the air plasma conductivity being a function of temperature and pressure as given in Fig. 19 of [15]. It is assumed here that only one paddle is inside the duct at all times.

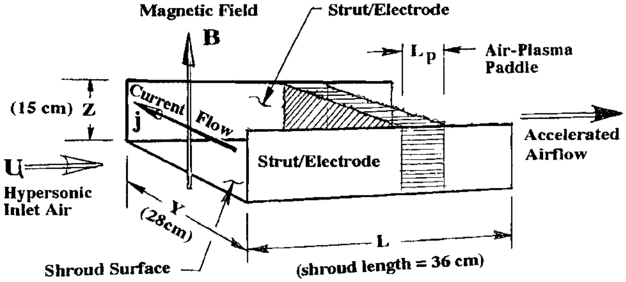


FIGURE 13. Assumed rectangular duct geometry for MHD slipstream accelerators (24 total).

The electrical power actually applied in accelerating the air flow is

$$\text{Push Power} = f\,\dot{m}\,U^2_\infty/2, \qquad (1)$$

where $f \approx 1/10$. So, $juB * YZL_p = f\rho uYZ\,U^2_\infty/2$, or if I is the total current ($= jZL_p$),

$$I = \frac{fZU^2_\infty/2}{B\rho} \qquad (2)$$

It is assumed that all quantities in these equations are average values, appropriately weighted. Then,

$$\text{Push Power} = \omega_{\text{push}} = YIuB \qquad (3)$$

$$\text{Mass Flow Rate} = \dot{m} = Yz\rho u \qquad (4)$$

Now for specified paddle temperature, T_p;

$$\text{Conductivity} = \sigma_p = \left(\frac{1}{\sigma_{\ell o}} + \frac{1}{\sigma_{hi}}\right)^{-1}, \qquad (5)$$

where: $\sigma_{\ell o} \approx 300(T_p/6000)^{10}/\sqrt{P/0.1}$, and

$\sigma_{hi} \approx 2000(T_p/8000)^{3/2}/(P/0.1)^{0.16}$

Here P = pressure in bar. The paddle length L_p is now given by

$$L_p = \frac{I}{Z\zeta\sigma_p uB} \qquad (6)$$

$$\text{where } \zeta = \text{electrical "inefficiency"} = \frac{E - uB}{ub} \qquad (7)$$

The mean power Wpm required to maintain the paddle at its original width is assumed to be that required to heat up the gas contained in a volume ($YZ2\,L_T$) to a mean temperature ($Tp + T_I$)/2, where L_T is the thermal diffusion length (or "heat penetration distance") in one flow time, L/u, i.e.,

$$L_T = \sqrt{\frac{K_t}{\rho C_p}\frac{L}{u}} \qquad (8)$$

$$W_{pm} = 2YZL_T\bar{\rho}C_\rho \frac{(T_\rho - T_1)}{2}\frac{u}{L} \tag{9}$$

where K_t = the turbulent effective thermal conductivity, and T_1 is the entrance gas temperature.

$$\bar{\rho} \simeq \frac{1}{2}(\rho+\rho_p) = \left(1+\frac{(T_1)}{T_p}\right)\rho/2 \quad p \tag{10}$$

Assuming K_t = 100*K, this should give a reasonable 'ball-park' estimate -- unless Rayleigh Taylor instability messes things up.

Input Assumptions

For example, let's assume that the 2.56-m diameter laser Mercury lightcraft is accelerating through Mach 11 at 33-km altitude (110-kft) where the ambient air density is 0.01 kg/cu.m. The mass flow of air (ρAV) that will be entering each of the 24 MHD accelerators will be roughly 260/24 = 10.8 kg/s. Let us assume that this air enters the channel inlet with dimensions measuring 28 cm wide by 15 cm tall, at a velocity of 3740 m/s, density of 0.069 kg/cu.m., and pressure of 0.17 bars. The representative MHD channel is adequately modeled with the following input assumptions:

- Magnetic field B = 2 Tesla
- Inlet dimensions of Y = 28 cm and Z = 15 cm.
- 'Inefficiency' = E/uB - 1 = 0.2
- 'Push Power' / (mass flow rate) = (0.1) $(U^2_\infty/2)$
  {i.e., 10 % of the kinetic energy of the free stream.}
  (Push power per unit volume = $\underline{u} \bullet \underline{j} \times \underline{B}$)
- The paddle loses heat to the gas ahead of it, and behind it, as if it's effective turbulent thermal conductivity was 100 times the handbook ('molecular') value for air.

Furthermore, we assume that an input 'push power' (Wpush) of 15.5 MW is available for accelerating this flow. Whereas 129/6 = 21.5 MW is actually delivered per channel, we will want to allow some margin (say, 28%) for losses in this process. Remember that even though the power required to create each 'thermal paddle' is already accounted for (by direct laser heating), additional power is necessary for maintaining the plasma paddle at its original dimensions (cross-sectional area of 314 sq. cm.), and temperature. For convenience in this calculation, the paddle is assumed to have a rectangular cross-section of 15cm by 20 cm (i.e., same conductor area as a 10 cm diameter cylinder) and temperature of 5000 K.

SAMPLE RESULTS FROM THE MODEL

The results from a sample calculation with this 'first-order' analytical model are summarized as follows. To absorb the full 15.5 MW into the duct flow, the total current into the paddle is 13,000 amps, and the average Faraday voltage is 1400 V. The combined MHD thrust from all 24 accelerators (neglecting rocket thrust from the

MHD generator's exhaust, as well as base drag and airspike pressure drag) is F = Wpush/U = 100,000. newtons. For a vehicle gross mass of 350 Kg, this represents a thrust/weight ratio of roughly 30. The ratio, Wpm/Wpush = (time-averaged power to maintain one paddle) / (push power) is only 0.051 or just over 5%, which is extremely good. Wpm is only 0.8 MW; this rate of Joule dissipation (normally occurring in the paddle) is judged sufficient to make up for conduction, convection, and radiation from the paddle.

Electric power from the MHD generators must begin to flow shortly before the cylindrical paddle expands to its full 20 cm diameter, and before its pressure relaxes to local ambient (perhaps a factor of two above local ambient pressure in the duct). There is no particularly good reason to maintain the plasma paddle temperature above 5000 K (e.g., to obtain a better conductivity), even though the electrical conductivity is only 36 mho/m. The additional electrical power that must be spent to maintain such higher temperatures results in a significant decrease in overall accelerator efficiency.

It is useful to calculate the specific impulse (Isp) and impulse coupling coefficient (CC) for this MHD accelerator, and to compare the performance with that presented in Fig. 7 from Ref. 12. The total electric power consumed by the MHD accelerator is 24 X (15.5 + 0.8 MW) = 391 MW, which at 325 MJ/Kg means that the hydrogen consumption rate is 391/325 = 1.2 kg/sec.(or 11.8 N/sec). Exhausted at 1200 m/s (from Ref. 10) the rocket thrust is (Vex)(m) = (1200 m/s)(1.2 kg/s) = 1440 N, or only 1.44% of the MHD accelerator thrust. Again neglecting drag, one finds that the specific impulse is 100,000 N/ 11.8 N/sec = 8470 seconds.

If the converter had an efficiency of 650 MJ/kg, as in Fig. 7, the Isp would be (650/325)(8470) = 16,900 seconds. To compute the CC, we divide the total laser power beamed to the rocket-driven MHD generators (i.e., 391 MWe/0.36 = 1090 MW) into the MHD Fanjet thrust: (100,000 N)/(1090 MW) = 92 N/MW. If the laser-to-electric conversion efficiency were 50% (as assumed in Fig. 7), the coupling coefficient would be (0.5/0.36)(92) = 128 N/MW. Although no MHD engine performance is reported for an altitude of 33-km (110-kft) in Fig. 7, our predicted values of CC and Isp are in the same 'ballpark.' Note that these figures ignore the additional laser power spent on creating the airspike and 24 plasma paddles.

Perhaps the most critical question about these MHD air accelerators has to do with the stability of, and energy loss from the paddle. Temporal variations in the paddle electrical conductivity, electron density, pressure and temperature should be examined – as well as an assessment of the permeability and stability (e.g., against kink, or pinch distortion). It would also be interesting to investigate how well the accelerator will work if the paddle does break up into separate, more or less typical, arc columns. Losses would almost certainly go up, but the increase might not seriously affect overall performance. (For energetically reasonable paddles and currents, the magnetic Reynolds number is always small compared to one; the self field is always pretty small.)

Another question relates to the dynamics of paddle formation as well as MHD acceleration, in conjunction with the paddle's continuously expanding radial dimension. Clearly, the initial heating process (a laser supported detonation) that first created the cylinder is of short duration relative to the time spent expanding to 10 cm radius, so the gasdynamic process can be modeled as an *unpowered cylindrical* expansion. However, once the electric power begins to flow, the paddle must now be treated as a *weakly-powered cylindrical* expansion. Furthermore, once the cylindrical blast wave contacts the shroud (at 11-cm radius), it will reflect and thereby double the pressure at the shroud surface. This effect might well be used to significant advantage in the MHD accelerator, because with local (free-stream) ambient pressure in the duct, the Hall parameter is about 5, which is bearable. However when the pressure suddenly doubles, the Hall parameter may be cut in half -- which incidentally, is more in line with that presently demonstrated in today's MHD devices (e.g., around 2.0). Alternatively, the geometry of the airspike can easily be adjusted at will to provide this additional compression at the MHD accelerator inlet.

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