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MHD Air Breathing Propulsion and Power for Aerospace Applications

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Summary

The paper reviews novel propulsion concepts utilizing plasmas (ionized gases) and magnetohydrodynamics (MHD). These concepts are shown to be attractive due to their potential to achieve propulsion and aerodynamic performance far beyond current conventional technologies. However, significant difficulties impede the development and application of these technologies; these include weight, complexity, higher power, and the need for complex and energy-consuming artificial ionization in "cold" air (at Mach <12).

A well-publicized Ajax concept of MHD energy bypass has been shown to be meaningless below at least Mach 12. In contrast, a new "reverse energy bypass" with Virtual Cowl is potentially practical for air-breathing hypersonic vehicles.

Applications of the Virtual Cowl and other plasma/MHD devices to reentry, global-strike hypersonic gliders, and aeroassisted orbital maneuvering are identified as promising in the near future. The ability of a plasma/MHD system to generate high power onboard and to provide L/D (lift-to-drag ratio) far beyond that possible conventionally makes these applications both feasible and desirable for national defense. However, these applications are also likely to be implemented by nations such as China, Japan, and Russia.

The outlook for uses and applications of MHD propulsion could increase dramatically if high-speed (hypersonic) vehicles begin to carry powerful onboard electricity sources, such as nuclear (fission or fusion) reactors.

For spacecraft, the current trend of replacing chemical rockets with electric propulsion systems will continue and is likely to become the standard. Electric systems can provide a much wider range of operation (e.g., low-thrust fine positioning/pointing, more frequent or nontraditional maneuvers, and longer times on station) than chemical systems can.

Chapter 1: Concept Overview

A flight vehicle's speed and altitude limit its available propulsion options. Traditional air-breathing systems (propeller, turbofan, and turbojet) are typically limited to altitudes below 80,000 feet. The existing and planned high-altitude vehicles utilize either high-speed propulsion with ramjet and scramjet engines or slow-speed systems with large propellers. Chemical rockets can operate at all altitudes but have limited burn times and require both fuel and oxidizer to be carried onboard.

High-speed air-breathing propulsion, based on ram/scramjet engines, have well-known difficulties: external and internal flow compression and shock control; shock-shock and shock-boundary layer interactions in the propulsion flowpath; mixing, ignition, and flameholding in the combustor; incomplete combustion and chemical energy release; and very high temperatures and wall heat fluxes in the combustor. There are limits to what can be done about these problems with conventional technologies, which is why the use of plasma (ionized gas) with or without electric and magnetic fields can offer additional opportunities for control and propulsion enhancement.

Onboard generation and storage of electric power is one of the main problems encountered with respect to high-altitude, high-speed flight. Hypersonic vehicles, both air-breathing and unpowered reentry "gliders," have no rotating turbomachinery to which an electrical generator could be connected. An attractive power option can be offered by magnetohydrodynamic (MHD) devices. For example, placing an MHD generator immediately downstream of a scramjet combustor can, given the high velocities and temperature of the flow and with metallic additives to the fuel, provide high power (from tens of kW to several MW) with no moving parts. For reentry vehicles, both external (i.e., surface-integrated) and internal-duct MHD generators can generate high power also without moving parts. Employing additional equipment like electrical generators imposes a weight penalty that must be optimized with vehicle performance.

The use of electric and magnetic systems can open new potential areas for aerospace propulsion. While chemical energy sources are limited by the energy available for particular reactions and are limited to operating conditions that are conducive to combustion, electromagnetic energy can be added to the flow over a much wider range of operating conditions. For example, at very high altitudes (>150 kft), it is difficult to get reliable combustion in hypersonic air-breathing engines. In an electrothermal system, the combustor would be replaced with an electrical heating source that can easily and reliably add enthalpy to the flow even at low pressure. The flow can also be accelerated by manipulating body forces (electric and magnetic) on charged particles (ion and electrons) within the flow.

Outside the atmosphere, we note that operation in space almost always requires rocket propulsion whether it be chemical, electric, or nuclear. The exceptions would be sails and tethers. Spacecraft are rapidly transitioning from chemical rockets to electric (plasma) for most space-based operations.[1] The higher specific impulse (I_{sp}) available for electric systems (2 to 100 times that of chemical) has a dramatic impact on the vehicle design and operation. Although electric (plasma) thrusters have been around for decades, their use in space was limited by the electric power available onboard the spacecraft.[2] The advent of high-power solar arrays has made systems from a few kW to tens of kW practical. Chemical systems will probably always be the primary choice for getting vehicles into space. The thrust levels for electric systems are too low to be practical for that purpose.

Chemical and electric (or electromagnetic) propulsion systems have intrinsic differences. For example, chemical propulsion is "energy limited" because the chemical reactants have a finite amount of energy per unit mass (i.e., their enthalpy of combustion or reaction), which ultimately limits their achievable exhaust velocity. However, because the propellants are their own energy source, the rate at which energy is supplied to the propellant (which is ultimately limited by the reaction kinetics) is independent of the mass of propellant, so very high powers and thrust levels can be achieved. By contrast, electric propulsion systems are typically not energy limited; an arbitrarily large amount of energy can be delivered (from the external solar, nuclear or chemical power system) to a given mass of propellant so that the exhaust velocity can be an order-of-magnitude larger than that of a chemical system. Instead, electric propulsion systems are "power limited" because the rate at which energy from the external source is supplied to the propellant is proportional to the mass of the power system. This has the result of limiting the thrust of the electric propulsion system for a given vehicle mass. Because of this, electric propulsion vehicles are typically low thrust-to-weight (T/W) ratio (i.e., low acceleration) vehicles.

WEAKLY IONIZED PLASMAS FOR PROPULSION APPLICATIONS

This review is devoted to a group of emerging technologies centering on weakly ionized plasmas for propulsion and power.[3] Charged particles (ions and electrons) must be present in the flow so that it can interact with applied electric and magnetic fields. Space thrusters operate at very low pressures (< 100 mTorr or < about 2 psi) with a significant fraction of the working fluid/gas being partially ionized (from a few percent to nearly 100 percent). In contrast, air-breathing systems operate at much higher pressures and have low ionization fractions. The ionization fraction of concern (i.e., the fraction of gas molecules that are ionized) ranges from as low as 10^{-8} to 10^{-2}, hence the term "weakly ionized." The gas pressure in the plasmas can take almost any value. In applications to high-altitude flight, the static pressure is on the order of 10-100 Torr, whereas combustion applications demand near-atmospheric (~760 Torr) or above-atmospheric pressures. The temperature of the gas can be near-ambient in low-pressure glow discharges, rising to 5,000-10,000K in arc or high-pressure microwave discharges, or even 20,000-30,000K in laser-generated sparks. The plasmas can be generated by electric or electromagnetic fields, from DC to RF, short pulses, microwaves, and optical (laser) beams, or by various combinations of the above. In general, low pressure plasmas tend to be uniform (diffuse) and nonequilibrium. The temperature of electrons and internal molecular modes can be very high, while the gas as a whole stays relatively cold. As the pressure and power loading increase, plasmas tend to become hotter, getting closer to thermal equilibrium, and also break into channels (streamers and arcs). The reality, however, is more complex. In some devices, such as dielectric barrier discharges, nonequilibrium plasmas are generated even at atmospheric pressure, and in devices such as the gliding arc, the plasma evolves from near-equilibrium to highly nonequilibrium during each of the periodically repeating cycles. In shock and boundary layers during reentry, the plasma is near thermal equilibrium while being diffuse. The primary reason for this behavior is that the ionization in those shock and boundary layers exists without any electric field and thus is not subject to arcing instabilities.

Plasma Features

What features or properties make weakly ionized plasmas interesting for propulsion and aerodynamic applications? The most obvious feature is heating—a consequence of Joule dissipation in an electrically conducting medium placed in an electric field. As a heating element, plasma has important advantages compared with conventional heaters. For example, even a surface electric discharge can effectively heat the gas flow much farther from the wall than a wall-imbedded conventional heater would. Microwave and laser beams can create plasmas and heat the gas even far from any surfaces, and the volume and shape of the heated region can, in principle, be adjusted. Since heated regions can significantly alter the flow by making the gas flow mostly around them, plasmas can form switchable, controllable, and tunable virtual bodies or surfaces. Such virtual surfaces can be deployed on demand for drag reduction, aerodynamic control (when applied asymmetrically), and optimization of engine inlet performance, to name a few. It is the localized and transient deployment of plasma virtual surfaces that results in the most interesting and complex interactions with gas flows while saving energy compared with large-volume, steady-state plasma utilization, and thus is especially promising for applications.

Another useful application of plasma heating is ignition. This may seem trivial; after all, spark plugs in conventional internal combustion engines are well-developed thermal plasma devices. However, thermal plasma ignition for scramjet engines is not that simple, since the ignition system would have to prevent the plasma from being easily blown away by the supersonic flow, and even if this problem is resolved, if not properly (and quite ingeniously) designed, the igniter would cause an unacceptably strong perturbation to the flow and loss of the stagnation pressure and would require extremely high power. As an example, plasma igniters based on subcritical microwave discharges are quite sophisticated.

Besides heating, the presence of charged particles is another obvious, and very important, feature of plasmas. Charged particles can be acted upon by electric and magnetic fields, and this action can be transferred to the bulk gas by ion-molecule collisions. Thus, magnetohydrodynamic (MHD) and electrohydrodynamic (EHD) interactions can be utilized to exert forces and to decelerate or accelerate the gas in both inviscid core flows and viscous boundary layers. The magnitude of such interactions depends on the ionization fraction and the magnetic or electric field strength.

MHD Interactions

The ionization fraction can be quite high in shock and boundary layers at very high Mach numbers (such as those in reentry flight), or just downstream of ram/scramjet combustors if alkali vapor is added to the gas. In those regions, MHD interactions can be promising for electric power generation or acceleration of the flow, as well as for flow control. However, at Mach numbers below about 12 (and excluding the combustor or the region just downstream of it), the air is too cold for a significant thermal ionization even with alkali seeding. The required level of ionization then has to be created and sustained by nonequilibrium (nonthermal) means and is associated with a very substantial power budget and additional heating. Therefore, the efficiency of ionization (which can vary by orders of magnitude depending on the particular means of ionization) is of first-order significance for the entire operation and efficiency of the device. Energy used to ionize and excite the gas molecules can be considered as loss in the system since this energy is rarely recovered in the form of directed kinetic or thrust energy. Note that in this regard, ionization by high-energy electron beams or by repetitive high-voltage nanosecond pulses are promising as the most energy-efficient means of nonequilibrium ionization.[4,5,6,7]

Even with the most efficient ionization techniques, the power budget and additional heating associated with the ionizer normally limit the achievable level of ionization. To have a substantial MHD effect,[8, 9] one has to either use a very strong magnetic field (which is associated with some practical issues) or use the MHD interaction in a localized and transient regime (e.g., for boundary layer control).

As for EHD interaction,[10, 11] it relies upon non-neutrality of the plasma and an electric field to impart momentum to the gas. Although EHD (or "ion wind") phenomena have been known for many years, the last several years saw a surge of new interest to this type of interaction. This new boom is due to the asymmetric dielectric barrier discharge (DBD)—a remarkably simple device that has been demonstrated to be very effective in delaying and controlling flow separation and perhaps even laminar-turbulent transition. Although details of the physics of DBD plasma actuators are still incompletely understood, the simplicity of these devices, their low power consumption, and the striking effectiveness in separation control bring these systems to the top of the list of plasma aerodynamics and plasma-assisted propulsion technologies that have near-term application prospects.

Combustion

Another area where nonequilibrium (nonthermal) weakly ionized plasmas are very promising is plasma-assisted combustion. Although heating induced by plasmas can ignite combustible mixtures, as mentioned above, it is the presence of "hot" electrons in a cold gas that makes nonequilibrium plasmas quite interesting for promoting chemical processes such as combustion. Electron-impact dissociation, excitation, and ionization of molecules can generate chemically active species such as radicals and excited atoms and molecules, and those species can initiate or accelerate chemical reactions that would otherwise be nonexistent or slow at low temperature. A number of novel techniques, including (but not limited to) high-voltage nanosecond pulses and the so-called "gliding arc" have been shown to be quite effective in plasma-assisted combustion. Investigation of detailed mechanisms (often quite complex and nontrivial) of the coupled physical and chemical processes in those plasmas can potentially lead to their better understanding and help them become practical.

ELECTRIC PROPULSION SYSTEMS

Electric propulsion thrusters can be divided into three categories: electrothermal, electrostatic, and electromagnetic. First, electrothermal thrusters use electric energy to directly heat the propellant and add enthalpy. The heated gas is then accelerated using a conventional converging-diverging gas-dynamic nozzle. Second, electrostatic thrusters use applied static electric fields to accelerate propellant ions via body forces. Third, electromagnetic thrusters use electromagnetic body forces (**E**x**B**) to accelerate a plasma (positive and negative charges). An electric propulsion system consists of a power source (e.g., solar or nuclear), power conditioning electronics, engine/thruster (including inlet for air-breathing systems), and fuel/propellant storage and feed subsystem.

Energy can be obtained from sunlight, a nuclear reactor, or chemical sources. In the case of solar electric propulsion (SEP), solar photons are converted into electricity by solar cells. The energy could also be beamed to the vehicle using laser or microwave sources. Beaming the power allows for higher power densities but with the added complications of needing a power station and a means of getting the power to the vehicle (direct illumination or via a relay system). In nuclear electric propulsion (NEP), thermal energy from the nuclear reactor is converted into electricity by either a static or dynamic thermal-to-electric power conversion system. Static systems have the advantage of no moving parts for high reliability, but they have low efficiency; dynamic systems have moving parts (e.g., turbines and generators) and do not scale well for small systems, but they do have higher efficiency. Other onboard energy storage systems such as high-density capacitors, flywheels, or fuel cells could be used.

Power conditioning systems are required to convert the power system voltage to the form required by the electric thruster. For example, an SEP power system produces low-voltage DC (typically ~100V); this would need to be converted (via transformers, etc.) to kilovolt levels for use in an ion thruster. The power-conditioning system is often referred to as the power processing unit (PPU); this is, in turn, part of the vehicle's overall power management and distribution (PMAD) subsystem.

Various combinations of thruster and propellant are possible, depending on the specific application. The propellant or working fluid can be either stored on board and used in a rocket mode or collected from the atmosphere in an air-breathing mode. The natural system-level trade between these propellant methods is fuel/propellant mass versus power system mass. Air-breathing systems require less propellant mass but require higher energies to perform similar missions. Although rockets will operate in a space or air environment, their thrust durations are limited by the amount of propellant that can be carried.

Key performance parameters determine the relative strengths and weaknesses of different propulsion technologies. The fuel/propellant efficiency is characterized by the specific impulse (I_{sp}) for rockets and by the thrust-specific-fuel-consumption (TSFC) for air-breathing systems. It is a measure of how much thrust (F_{th}) is produced from each mass unit of propellant. The thrust efficiency (η) is a measure of how much of the power/energy that is available results in directed kinetic energy (thrust power) in the flow. The thrust density is a measure of how much thrust is produced per unit cross-sectional area, A_c (area perpendicular to the flow direction). Although the thrust density is a packaging issue for spacecraft, it is critical for air vehicles where drag is present. The thrust-to-power measures the acceleration efficiency. Traditionally a trade exists between fuel/propellant efficiency and thrust-to-power (speed vs. economy). The final parameter is the specific mass or weight (mass)-to-power ratio. In most cases the efficiencies improve with the size of the system (economy of scale).

Measures of performance are fundamentally different between air-breathing and rocket systems due to the inlet on the air-breathing system.

Rocket

$$\begin{aligned} F_{TH} &= \dot{m}_e u_e + A_e (P_e - P_{amb}) \\ &= \dot{m}_e \left[u_e + \frac{(P_e - P_{amb})}{\dot{m}_e} A_e \right] \\ &= \dot{m}_e u_{eq} \end{aligned}$$

$$\begin{aligned} I_{SP} &\equiv \frac{\text{Thrust}}{\text{propellant weight flow rate}} \\ &= \frac{F_{th}}{\dot{m}_e g_0} = \frac{u_{eq}}{g_0} \end{aligned}$$

$$P_{jet} = 1/2\ \dot{m}_e u_{eq}^2 = 1/2\, F_{th}\, I_{SP}\, g_0$$

$$\eta \equiv \frac{P_{jet}}{P_{elect}} = \frac{F_{th}\, I_{SP}\, g_0}{2\, P_{elect}} = \frac{1/2\ \dot{m}_e u_{eq}^2}{P_{elect}}$$

Air-Breathing

$$\begin{aligned} F_{TH} &= \dot{m}_e u_e - \dot{m}_a u + A_e (P_e - P_{amb}) \\ &= \dot{m}_a \left[(1 + f) u_e - u \right] + A_e (P_e - P_{amb}) \end{aligned}$$

$$\dot{m}_e = \dot{m}_f + \dot{m}_a \qquad f = \dot{m}_f / \dot{m}_a$$

$$I_{SP} \equiv \frac{\text{Thrust}}{\text{fuel weight flow rate}} = \frac{F_{th}}{\dot{m}_f\, g_0}$$

$$TSFC \equiv \frac{\text{fuel mass flow rate}}{\text{Thrust}} = \frac{\dot{m}_f}{F_{th}}$$

$$P_{jet} = 1/2 \left(\dot{m}_e u_{eq}^2 - \dot{m}_a u^2 \right)$$

$$\eta \equiv \frac{P_{jet}}{P_{elect}} = \frac{1/2 \left(\dot{m}_e u_{eq}^2 - \dot{m}_a u^2 \right)}{P_{elect}}$$

Above, $\dot{m}_a$ is the mass flow rate of the air, $\dot{m}_f$ is the mass flow rate of the fuel, $\dot{m}_e$ is the exit flow rate, g_0 is the acceleration of gravity (reference point, Earth), u_e is the nozzle exit velocity, u is the flight/vehicle velocity, u_{eq} is the equivalent exit velocity, A_e is the nozzle exit cross-sectional area, P_e is the nozzle exit pressure, P_{amb} is the ambient/environmental pressure, P_{jet} is the jet-kinetic power (thrust power) produced by the engine, and P_{elect} is the electrical (or other external source) power supplied to the propulsion system. For air-breathing systems the mass flow rate of the fuel is very small relative to the mass flow rate of the air.

Note that an air-breathing system can never fly faster than its exhaust velocity. Rockets, because they carry an onboard oxidizer, do not have this restriction and, therefore, have no flight-speed limits. The jet power for high-speed air-breathing engines is larger than the equivalent jet power for a rocket due to the inlet and is the difference of two large numbers.

Large power levels are required for aircraft and launch vehicles. For example, an SR-71 cruising at Mach 3.2 produces a thrust of 24,700 lbf (110 kN) and a jet power of 104 MW. Climb and maneuver thrust is much higher. Similarly, an RL10 rocket engine produces 15,000 lbf (66.7 kN) thrust at an I_{sp} of 433 seconds, and has a jet power of 142 MW. By comparison, a Nimitz class nuclear aircraft carrier propulsion system is 194 MW, and the Hoover dam produces about 2000 MW. Therefore, any electric system replacing these applications must be capable of processing a lot of power. Spacecraft propulsion systems are typically hundreds of watts to tens of kW. This, in addition to powerplant weight issues, is a primary reason why electric propulsion systems are currently being used on spacecraft and not on aircraft. Historically, electric thrusters for spacecraft were available for flight decades before the power systems.[12]

Figure 1. Electrothermal Arcjet Thruster. Photograph of a 30-kW arcjet thruster being tested at the Jet Propulsion Laboratory.[13]

Electrothermal thrusters use electric energy to heat the propellant and add additional enthalpy. This can be done with simple resistive heating or by passing the propellant gas through an arc plasma discharge. The plasma can be generated through a high-current discharge or by absorption of microwaves. The hot pressurized gas is then accelerated out of the thruster using a conventional converging-diverging gas-dynamic nozzle. An example of an electric arc heated thruster or arcjet thruster is shown in Figure 1.

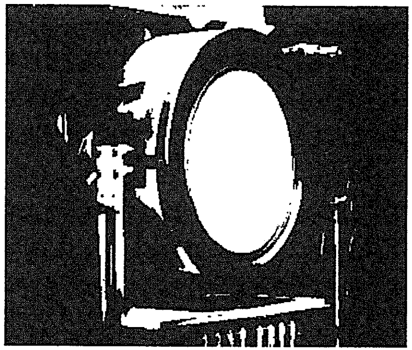

Figure 2. Electrostatic Gridded Ion Thrusters. Photograph of a gridded 30 cm diameter ion thruster being tested at the Jet Propulsion Laboratory.[14]

Electrostatic thrusters use an applied static electric field to accelerate propellant ions. Strong electric fields are created in the engine which then accelerate the (positive) ions to high velocities. The accelerating field can be applied using physical grids such as those used in ion engines or using "virtual grids" generated by an applied magnetic field that traps the electrons as is done in Hall-effect thrusters. A photograph of the NASA ion engine used on the Deep Space One spacecraft is shown in Figure 2. While gridded electrostatic thrusters like ion thrusters are capable of very high I_{sp} (1,000 to >20,000 seconds) values they have very low thrust densities (1–5 N/m^2) due to the space-charge current limit in the accelerator system. Hall-effect thrusters do not have this space-charge limit but also have thrust density limits due to the annular geometry (tens of N/m^2). Typical power levels are from watts to 50 kW.

In the Hall field orientation, the electric field causes electrons to flow upstream and the ions to drift toward the exhaust as shown in Figure 3.[15] The electrons and ions transfer equal and opposite amounts of momentum to the air, resulting in zero thrust when no magnetic field is present. However, with the application of a transverse magnetic field, the forward flow of electrons is slowed while the aft flow of ions is nearly unaffected. Consequently, there is a net momentum transfer resulting in thrust on the vehicle.

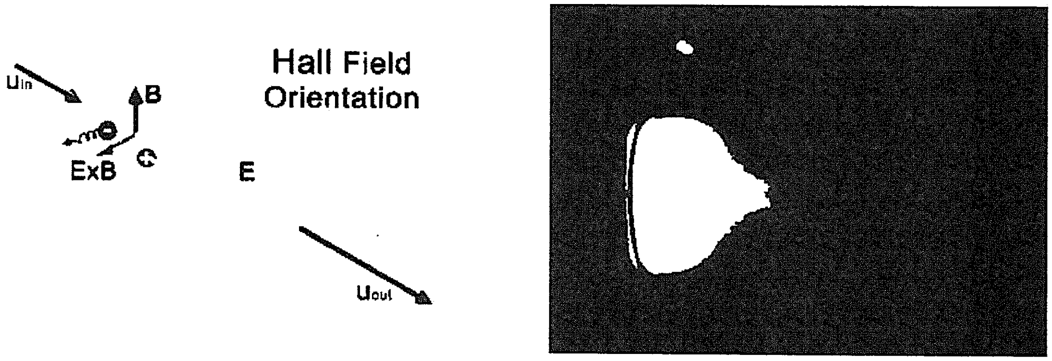

Figure 3. Field Orientation for Hall Field Systems and P5 Hall Thruster. Left: Figure shows the Hall field orientation. Right: P5 Hall Effect thruster being tested at the University of Michigan.

Electromagnetic thrusters use electromagnetic body forces (**ExB**) of Lorentz force to accelerate a propellant plasma as shown in Figure 4.[16, 17] The electric field is applied using electrodes within the thruster. The Lorentz or **ExB** force accelerates both positively charged ions and negatively charged electrons or negative ions in the same direction. The magnetic field can either be applied externally (applied field thruster) or generated by a very high current (typically thousands of amps) plasma discharge (self-field thruster). The current also serves to ionize the propellant. It is the interaction of the electric and magnetic fields that pushes the plasma out of the thruster at high velocity via the Lorentz force that acts mutually perpendicular to the electric and magnetic fields. Spacecraft electromagnetic thrusters are capable of processing much higher power densities (50 kW to tens of MW) and much higher thrust densities than electrostatic thrusters (hundreds to thousands of N/m^2).

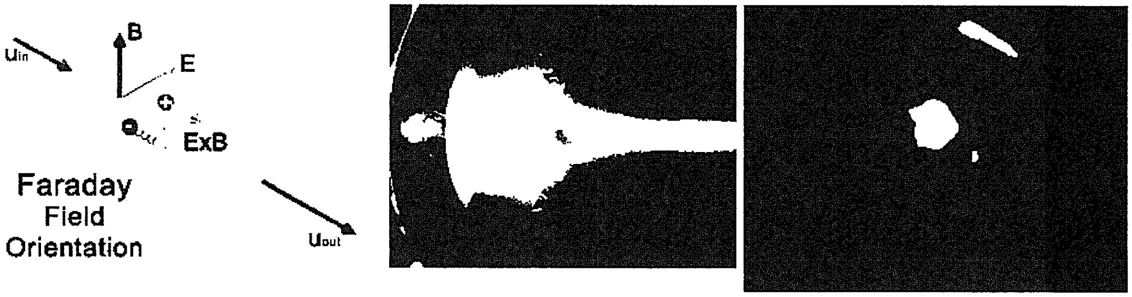

Figure 4. Electromagnetic Accelerator Field Configuration and Self-Field Electromagnetic Spacecraft Thrusters. Left: Illustration of the electric and magnetic field configuration. Center: Photograph of a MW-class pulsed magnetoplasmadynamic (MPD) thruster being tested at Princeton University. Right: Photograph of a 50-kW steady-state MPD thruster being tested at Princeton University.

An example of an air-breathing electromagnetic accelerator system for high-speed and high-altitude flight is shown in Figure 5. Air enters through the inlet on the left. The center section both accelerates the flow via electromagnetic body forces and heats the gas through Ohmic heating. The gas is then further accelerated using a diverging gas-dynamic nozzle.

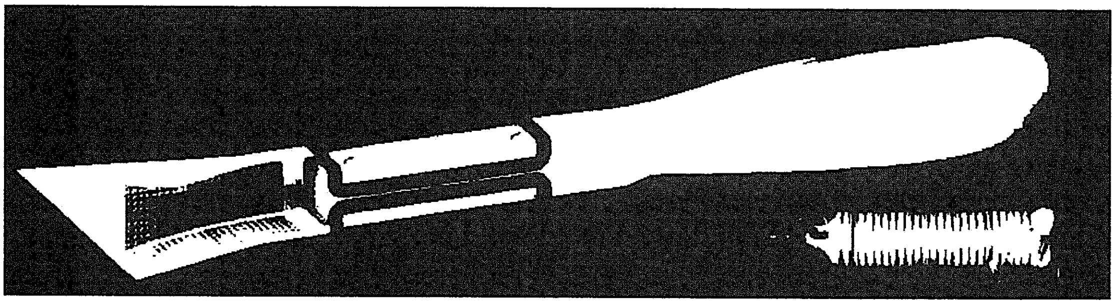

Figure 5. Air-Breathing MHD Engine. An illustration of a conceptual high-speed air-breathing MHD engine and (insert) a photograph of the operating proof-of-concept experiment being investigated by Lockheed Martin Aeronautics.

We note here that in its first-ever list of top 10 emerging aerospace technologies, released in 2009, the American Institute of Aeronautics and Astronautics (AIAA) included two plasma technologies: plasma actuators for active flow control and plasma-based advanced space propulsion technologies.

Chapter 2: Aeronautical Applications – Concepts and System Issues

In this section we will review the following issues and concepts:

- Basic principles and problems of MHD propulsion, power generation, and flow control.
- MHD inlet control.
- MHD power generation in scramjet flowpath.
- Plasma-generated virtual surfaces for drag reduction, steering, and virtual cowl.
- MHD energy bypass: the Ajax concept.
- The reverse energy bypass concept.
- MHD power generation and aerodynamic control for reentry vehicles.

BASIC PRINCIPLES OF MAGNETOHYDRODYNAMICS AND REQUIREMENTS FOR MHD PERFORMANCE

The basic principles of magnetohydrodynamics (MHD) are understood very well. When an electrically conducting fluid crosses magnetic field lines, an electromotive force (Faraday e.m.f., equal to the product of flow velocity *u* and the strength of magnetic field *B*, *uB*, multiplied by the channel width) is induced across the fluid and the B field. If then a pair of electrodes is positioned on either side of the fluid flow and connected via a ballast resistor on the outside, an electric current will be induced in the circuit, and power will be generated on the external load. This electric power will represent partial conversion of the flow enthalpy (consisting of thermal and kinetic energy of the flow) into electricity. At the same time, the current flowing through the finite-conductivity fluid will produce Joule heating[a] of the fluid that will increase both static temperature and entropy of the fluid.

The ratio of the extracted electrical power to the Joule dissipation rate is determined by the ratio of the load resistance to the sum of load and fluid resistances; this ratio is called the "load factor," k, $0<k<1$.

The current (current density **j**) induced in the fluid, being normal to both the magnetic field **B** and the flow direction, results in the body force per unit volume equal to **j×B** and directed against the flow. This body force, commonly called the "Lorentz force" (it should be properly called the ampere force or the ponderomotive force), is directed against the flow in MHD generators, acting to slow the flow down and reduce its total energy, which is in line with the electricity extraction.

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[a] Joule heating, given by the expression, $Q=I^2Rt$, (Q is the heat generated by a constant current, I, flowing through a conductor of electrical resistance, R, for a time, t), is the process by which the passage of an electric current through a conductor releases heat. If current, resistance, and time are expressed in amperes, ohms, and seconds respectively, the unit of Q is the joule. The increase in the kinetic or vibrational collisional energy of the ions and electrons manifests itself as heat and a rise in the temperature of the conductor. Rather than a wire, the conductor in this application is an ionized fluid.

Similarly, if a voltage source (e.g., a battery) is connected to the electrodes placed on either side of the flow in such a way that the applied e.m.f. acts against the induced Faraday e.m.f., then the current will flow in the direction opposite to the Faraday current, and the **j×B** force will be in the direction of the flow. This will be an MHD accelerator that converts the battery-supplied electrical energy partially into enthalpy of the flow and partially into Joule dissipation in the circuit. The corresponding load factor, *k,* defined as the ratio of the applied electric field *E* and the product *uB*, *k=E/uB*, is greater than 1 in this accelerator configuration.

In generator and accelerator devices, the interaction between the induced motion of electric charges across the B field and that field results in an e.m.f. induced along the flow. This secondary e.m.f. is called the "Hall e.m.f.," and the magnitude of Hall effect increases with the ratio of electron-cyclotron frequency, ω_B=eB/m, and the electron collision frequency, ν. This ratio is called the electron Hall parameter, Ω_e. As the Hall parameter approaches 1, the Hall current directed along the flow increases at the expense of the transverse Faraday current, resulting in reduction of the **j×B** force. To reduce or eliminate the Hall current, the electrodes placed on either side of the flow are normally segmented and thus form multiple pairs. Each electrode pair has a proper resistor and/or battery in its circuit. Theoretically, this segmented-electrode Faraday configuration enables the performance equal to that without the parasitic Hall effect. However, as the Hall parameter increases, so does the voltage fall between the adjacent electrode segments, so that eventually arcing between the segments starts, effectively negating the advantage of segmenting.

A better (and more "natural") MHD configuration at high values of the Hall parameter is the one where each electrode pair (with the electrodes on either sides of the flow and right across each other) is shorted, and the voltage is either extracted (in the generator case) or applied (in the accelerator case) along the flow, between the first and the last electrode pair. This is called the "Hall configuration."

A useful dimensionless parameter reflecting the strength of MHD interaction is called the MHD interaction parameter, or the Stuart number, and it represents the ampere body force effect relative to the flow momentum flux:

$$S = \frac{\sigma BL}{\rho u}$$

In this equation, σ is the electrical conductivity of the fluid, *B* is the magnetic field strength, *L* is the characteristic linear dimension, ρ is the fluid density, and *u* is the velocity.

Therefore, for a significant MHD effect in high-speed, high dynamic pressure flow (e.g., in hypersonics), the conductivity and the B field strength must be high. Herein lies the principal problem for aeronautical MHD applications. Indeed, normal air is not an electrical conductor. Air does become ionized and thus electrically conducting as it is heated to very high temperatures (3,000–10,000K or higher), such as those achieved in shock and boundary layers around reentry vehicles, at Mach numbers M=12-25 or so. The ionization fraction then reaches 10^{-5}-10^{-2}, and the conductivity from 100 to about 3,000 mho/m ensues. Seeding the shock or boundary layer with a modest amount of alkali metal vapor helps in getting the conductivity close to the maximum achievable level of ~3,000 mho/m. At this level of conductivity, a modest magnetic field, B~0.1-0.3 Tesla, is sufficient for substantial MHD effects (power generation, flow acceleration, or aerodynamic control). However, at gas temperatures of "only" 1,500-2,000K or so typical for scramjet combustors, even seeding the flow with alkali vapor results in conductivities no higher than 10-30 mho/m, in which case the strength of magnetic field required for substantial MHD performance at L=1 meter or less is quite high: B=3-10 Tesla. The weight, volume, and complexity associated with such a strong magnetic field that must be created in such a large volume make this application very problematic.

NONEQUILIBRIUM MHD IN COLD AIR FLOWS

The situation becomes worse in relatively cold air. Indeed, static gas temperatures at Mach number less than about 12 are quite low (<1,500K) even in shock and boundary layers. At these temperatures, the electrical conductivity of air, even if seeded with alkali metals, is negligible. For MHD devices to operate in such conditions, conductivity (ionization) has to be created in a nonthermal (nonequilibrium) way. Nonequilibrium (i.e., with cold gas and hot electrons) plasmas are routinely sustained in glow and RF discharges such as those in fluorescent light tubes and devices used in microchip fabrication. The principal differences between those devices and the MHD systems for aeronautics follow:

- Pressures of interest in aeronautics (>10-100 Torr) are much higher than those in typical glow discharges (1 Torr or less) resulting in much higher power required to sustain plasmas and to severe problems with arcing instabilities.
- The ionization fraction needed for a good electrical conductivity and acceptable MHD performance is much higher than that required for a fluorescent light, again resulting in high power budget and overheating.

For cold nonequilibrium plasmas, the power budget is determined by the average energy cost (usually expressed in eV), W_i, of ionization (i.e., of producing an electron-ion pair), and the rate at which the electron-ion pairs must be generated in order to compensate for electron losses in recombination, attachment, and other processes. The recombination is the dominant loss mechanism at reasonably high electron densities, and its rate is proportional to the product of electron and ion number densities. Since in quasineutral plasmas the number densities of electrons and ions are close to each other, the recombination rate (per unit volume) is equal to $k_{dr}n_e^2$, where k_{dr} is the dissociative recombination rate coefficient and n_e is the electron number density. Note that the characteristic plasma decay time due to recombination is almost always very short, typically ~1-10 microseconds, so that the flow moves only a very short (~1 cm) distance during the decay time. This is why schemes with pre-ionization upstream of the MHD region with no ionization in the MHD region itself are not viable; the ionization must be done continuously throughout the MHD region.

The average energy cost, W_i, of ionization varies greatly depending on the ionization method. For example, in conventional glow-like discharges of large volume at moderate or high pressure, the ionization cost is ~10,000 eV (i.e., three orders of magnitude higher than the minimum ionization energy [10-15 eV]). This is due to the low average electron energy (~1 eV) and to the dominant losses of electron energy in inelastic collisions with air molecules. This is why a highly efficient ionization technique must be used in order to give cold-air MHD devices a chance to be viable. High-energy electron beams represent such a technique. Generated in vacuum electron guns and injected into air through either thin foil or a differentially pumped window, energetic (>1-50 keV) electrons produce many more low-energy plasma electrons, so that the average ionization cost is only $W_i = 34$ eV. This ionization efficiency is theoretically the best.

Of course, electron beam systems are quite difficult to work with due to fragile foils or massive differential pumping facilities; X-ray generation is also not helpful for flight applications. But even putting these important practical problems aside, and even with the lowest possible cost per electron, the requirement that a cold-air nonequilibrium MHD device uses significantly less power for ionization than it extracts from (in the generator case) or adds to (in the accelerator case) the flow imposes a severe constraint on the maximum level of ionization and conductivity. Calculations show that the maximum ionization fraction is on the order of 10^{-6} and the maximum conductivity is on the order of 1 mho/m. With this low conductivity, substantial ($S \sim 0.1$ or higher) MHD interaction parameters can only be reached with magnetic fields higher than several Tesla (i.e., 10-20 Tesla). The weight and volume of a magnet then makes such flight devices quite impractical, unless a breakthrough in magnet and materials technologies occurs resulting in ultralightweight magnets with $B \sim 10$ Tesla.

As an example of potential use of nonequilibrium cold-air MHD devices with ionization by e-beams, we note the studies of MHD scramjet inlet control performed by one of the authors of this survey and his Princeton University colleagues. These theoretical/computational studies showed that indeed, with proper optimization, MHD interaction at the compression ramp upstream of the scramjet inlet can restore the shock-on-lip (SOL) condition at Mach numbers higher than the design Mach number for a given fixed-geometry inlet (Figure 6). During the MHD operation, the generated electrical power would be enough for ionizing e-beams, with a significant percentage of the power left to be stored onboard and used for other purposes. The advantage of MHD inlet control is that it eliminates the need for a variable-geometry (movable) cowl that would be associated with a large weight and complexity; the disadvantage is that the weight and complexity associated with magnets and e-beam systems may negate the advantages. Systems studies are needed to fully assess the practicality of this MHD inlet control, and results of such studies would strongly depend on the state-of-the-art and future advances in lightweight magnet and e-beam technology. [18, 19, 20, 21, 22]

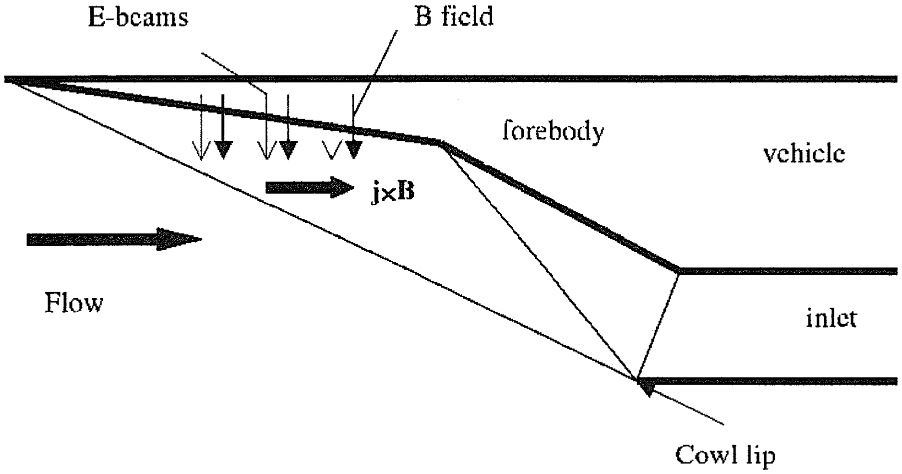

Figure 6. MHD Control of Scramjet Inlet Using E-Beam Ionization. The retarding ampere force restores the shock-on-lip condition at Mach numbers higher than the design value.

THE AJAX CONCEPT: MHD BYPASS

An MHD-assisted propulsion concept that has attracted perhaps the most attention over the last decade or two is known as the Ajax, or Ayaks. The concept, illustrated in Figure 7, originated in the 1980s at Leninetz Scientific & Production Enterprise (now Leninetz Holding Co.) in Leningrad, USSR (now St. Petersburg, Russia). A good overview of the concept and its present status and problems can be found in the recent article[23] included in the Special Section of the Journal of Propulsion and Power devoted to weakly ionized gases for propulsion enhancement, with one of the authors of this survey serving as special guest editor.

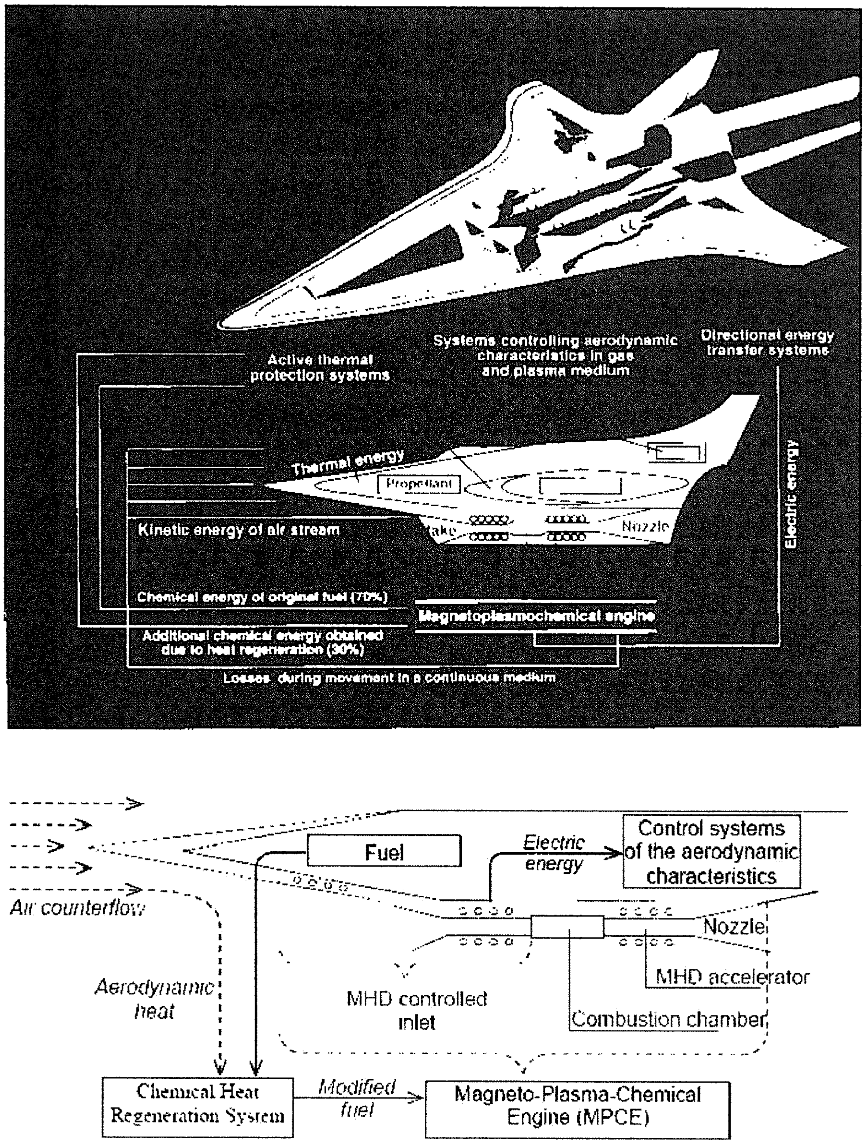

Figure 7. Schematic of Ajax Hypersonic Vehicle Concept. The upper and lower pictures represent the same concept, but were published by the authors (A. Kuranov et al.) at different times.

The key idea of the Ajax is that, with propulsion, aerodynamic, and heat protection system for hypersonic vehicles hitting their theoretical and practical limits, the only way beyond these limits is smart management of energy (i.e., taking energy from the surrounding flow and putting that energy where it is needed for propulsion benefits). The following three major concepts/systems are included in Ajax:[24]

- **Endothermic fuel conversion.** A mixture of hydrocarbon fuel (similar to kerosene) and water initially stored on board is used to cool the external surfaces and engine walls, and the heat transferred to the mixture is used in

a thermocatalytic "cracking" process that makes a syngas (i.e., CO – H_2 gaseous mixture) from the original kerosene-water liquid mixture. The syngas made onboard is a much better fuel from the I_{sp} standpoint than liquid hydrocarbons, and with the onboard thermocatalytic conversion there is no need to carry hydrogen from the takeoff. This part of Ajax is certainly very meaningful and probably viable.
- **MHD energy bypass.** This is perhaps the most controversial part of Ajax. An MHD generator extracts energy from the airflow upstream of the scramjet combustor; this energy bypasses the combustor and is put back into the flow via MHD accelerator placed downstream of the combustor. We will discuss this concept below.
- **Plasma for drag reduction.** A part of the MHD-generated power can, in principle, be used to generate a plasma in air upstream of the vehicle nose. This plasma would weaken the bow shock and reduce the wave drag on the hypersonic vehicle. Although there were claims by some Russian groups about 10-15 years ago that weakly ionized plasmas can reduce shock strength via some unknown physical mechanism, extensive research in the United States, Europe, and Russia has conclusively shown that the effects are purely thermal. However, even with purely thermal action, plasma drag reduction can be quite meaningful and useful for high-speed flight (see below).

Perhaps the most basic problem with the MHD bypass, as pointed out by D. Riggins,[25] is that as a propulsion power cycle, it runs in the direction opposite to that dictated by thermodynamics. Indeed, any thermodynamically correct heat-into-power conversion cycle has work addition (e.g., compression) prior to heat addition (e.g., in the form of combustion), and work extraction follows the heat addition. This is why air is compressed (work added) upstream of the combustor in all normal propulsion cycles, whether by compressor in a turbojet or a compression ramp upstream of a scramjet combustor. In this sense, MHD power (work) extraction before air enters the scramjet combustor, followed by MHD power addition after the combustor, constitutes a thermodynamically "wrong" and thus inherently inferior, propulsion system.

However, in criticizing the Ajax power cycle and arguing that the I_{sp} of Ajax is always less than that of a system without MHD bypass, D. Riggins[26] makes a significant mistake. In his derivations, he assumes that combustion-generated heat addition in the combustor occurs at a gas temperature equal to the stagnation temperature of the flow (i.e., that the flow is fully stagnant in the combustor). This assumption is in direct contradiction to the very idea of a scramjet, where combustion occurs in supersonic flow. Heat addition in the combustor thus occurs at a static, not stagnation, temperature. It is this fact that at least gives MHD bypass a chance to increase I_{sp}.

Indeed, calculations described in the above-referenced paper[27] by the Ajax group do result, in some conditions and with careful optimization, in an I_{sp} increase. Our analysis of their calculations shows that increase in static temperature caused by flow deceleration and Joule dissipation in the MHD generator upstream of the combustor is the reason for higher I_{sp}. Indeed, since the entropy increase in the combustor is equal to Q/T, where Q is the heat added and T is the static temperature at which this heat is added, any increase would lead to lower entropy increase and thus, as can be easily shown, to higher I_{sp}. The I_{sp} increase due to the increase in combustor temperature is made smaller by negative factors such as irreversibilities due to Joule dissipation in both MHD generator and accelerator and by the thermodynamically "wrong" work extraction before the combustor.

The I_{sp} increase, however, even in optimal cases, is only several percent. Given the crude assumptions in the paper[28] (1D flow, no boundary layer and heat losses, uniform plasma, no e-beam energy losses, no losses in electric circuitry), this gain of several percent would turn into a loss of I_{sp} in more realistic analysis. Additionally, the weight and complexity associated with magnet and e-beam systems should be kept in mind. Therefore, one can state with certainty that MHD energy bypass at Mach<12 (where nonequilibrium ionization of air is required) is not a meaningful technology.

Where the MHD bypass could be useful is at very high Mach numbers (Mach>12). First, stagnation temperatures at these Mach numbers are high enough for significant thermal ionization with reasonable amount of alkali seed (0.01–1% by volume), thus eliminating the need for a heavy, complex, and entropy-generating nonequilibrium ionization system. Second, at static temperatures (>2,000K) reached in the combustor at these Mach numbers, there is no combustion per se, just dissociation of fuel and air molecules followed by full or partial recombination into other molecules that releases heat into the flow downstream of the combustor in the expansion nozzle. For such a regime, the group at NASA Ames showed[29, 30] through modeling that MHD bypass can indeed increase the I_{sp}. Note, however, that materials and structures, as well as fuel development, are currently such that air-breathing flight at Mach>12 is not realistic. In the future, if air-breathing propulsion at Mach>12 becomes possible in principle, reexamination of MHD bypass benefits and flaws will be warranted, especially if lightweight magnets also become available by that time.

THE REVERSE ENERGY BYPASS

Returning to Mach<12, one of the authors of this survey, together with his colleagues, has proposed a very different bypass concept, dubbed the reverse energy bypass (Figure 8).[31, 32] The energy (in the form of electricity) is extracted from the flow in an MHD generator placed just downstream of the combustor (or collocated with the combustor). This at least avoids the need for e-beam ionization, since the air mixed with combustion products is sufficiently hot right after the combustor that an acceptable electrical conductivity (on the order of 10 mho/m or higher) can be generated thermally, provided alkali metals are seeded into the fuel and are thus present in the combustor and downstream of it.

A part of the electrical energy generated downstream of the combustor could be used upstream of the MHD generator, which is why this is called the reverse energy bypass (the energy being bypassed is moved in the upstream direction). Plasma-assisted combustion (such as ignition, flameholding, and mixing) would benefit from this electrical energy. Plasma heat addition, in steady or transient modes, enabled by this electrical power, would be beneficial for control of shock interaction at the inlet and for drag reduction and/or steering and pitch or yaw control when used in front of the vehicle's nose.

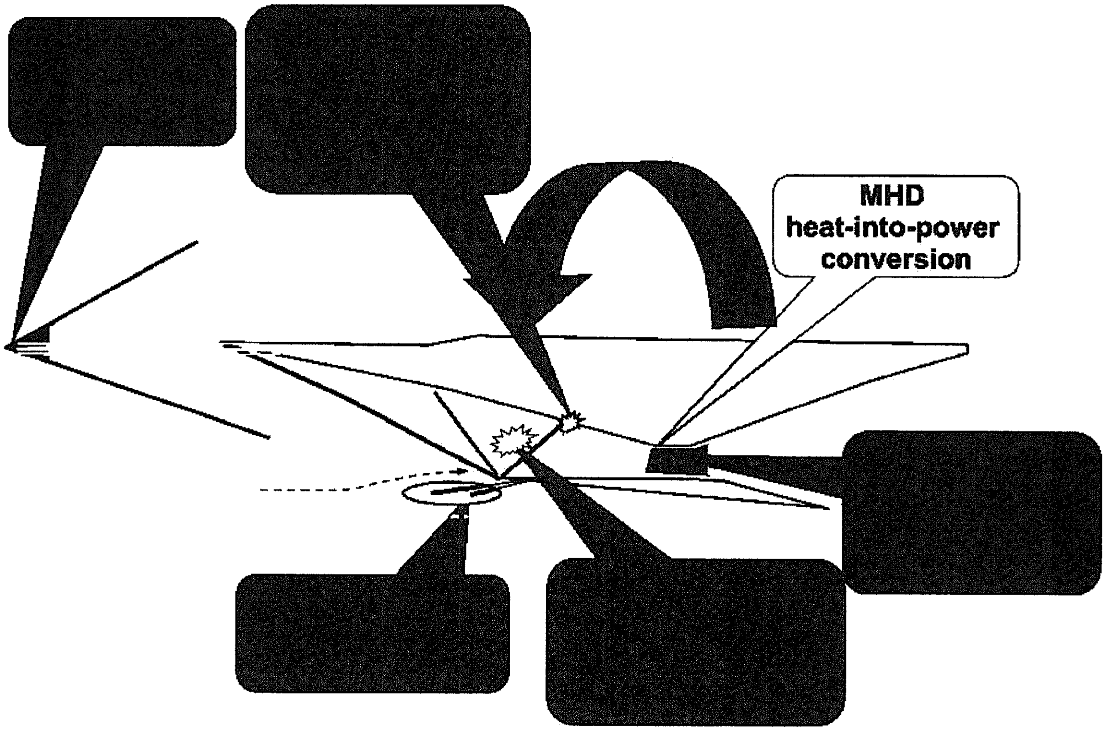

Figure 8. The Reverse Energy Bypass Concept. The red arrow symbolically depicts the general direction of energy bypass – upstream.

A promising version of the reverse energy bypass concept uses the electric power extracted from the flow in the MHD generator to increase the air mass flow rate through the combustor in off-design conditions. If the inlet is designed for shock-on-lip condition at a certain high Mach number (e.g., Mach 8), then at Mach numbers lower than the design value (e.g., Mach 6) the inlet does not completely capture the compressed flow, which is associated with the so-called spillage drag, effectively reducing the thrust. This undesirable effect can be prevented by the so-called virtual cowl—a heated region upstream of the cowl lip (Figure 9).[33, 34] This heated (e.g., plasma) region deflects the flow and helps with scooping more air into the inlet. Moreover, with proper positioning, only cold (unheated) air is scooped into the inlet, thus avoiding reduction in total pressure and thrust that would have occurred if heated air were scooped into the propulsion system.

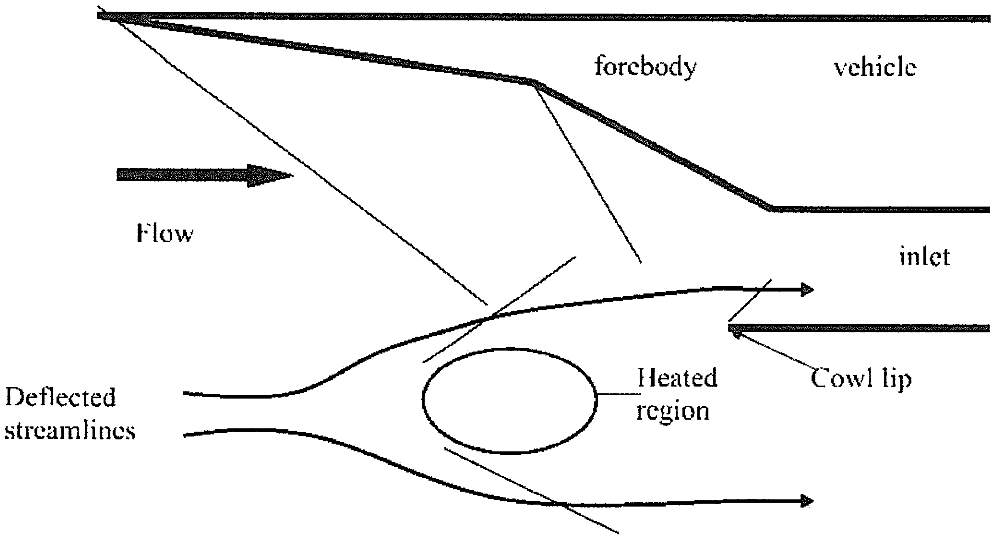

Figure 9. Schematic of the Virtual Cowl Concept. Plasma-generated heated region upstream of the cowl lip deflects the flow and scoops more air into the inlet.

Analysis of the reverse energy bypass involving MHD generator downstream of the scramjet combustor and an optimized virtual cowl revealed that, although enthalpy extraction and entropy production in the MHD generator substantially reduce the thrust, the combined system with virtual cowl can actually increase thrust by as much as 20-30%.[35, 36]

From the system standpoint, this concept, with all its associated weight and complexity, should be compared with that involving a movable (variable geometry) cowl that is associated with a heavy and complex electrohydraulic system and also requires power. An attractive feature of the reverse bypass concept that might make it a winner is its multifunctional nature. Indeed, MHD power generation downstream of the combustor can be an attractive power-production option for hypersonic vehicles. Alternatives (batteries, fuel cells, and the like) are not very competitive for generation of large amounts (hundreds of kW to 1-10 MW) of power onboard. Thus, if an MHD generator in the propulsion flowpath is accepted as the power source, its operation in conjunction with a virtual cowl that significantly increases thrust in off-design conditions, and also enables aerodynamic control and maneuvering, would become quite practical.

Note also that if another source of high (MW-scale) power, such as a nuclear reactor, is onboard, its use for virtual cowl, drag reduction, and aerodynamic control would be straightforward and would greatly increase performance of the hypersonic vehicle.

MHD APPLICATIONS TO REENTRY AND NEAR-ORBITAL FLIGHT

We now turn to MHD application to reentry and near-orbital flight. Due to the high velocities and enthalpies involved, the gas temperature in shock and boundary layers is very high, from several thousand to 10,000–20,000K. At these temperatures, thermal ionization is very substantial, and at the low end of the temperature range, a moderate seeding with NaK (sodium-potassium) mixture would be sufficient to produce an electrical conductivity from >100 mho/m to as high as 1,000–3,000 mho/m. With this level of conductivity, very modest magnetic field B~0.1-0.2 Tesla would suffice for a strong MHD performance (Figure 10).

Modeling shows that MW-scale power can be generated in these conditions by a surface-integrated MHD system from 1 square meter of vehicle surface. Interestingly, calculations show that the additional weight of the system, assuming a 1,000-second mission, is determined mostly by the water required to cool the copper-wire electromagnet and that the additional weight is quite acceptable, increasing the practicality of the system.[37, 38, 39, 40]

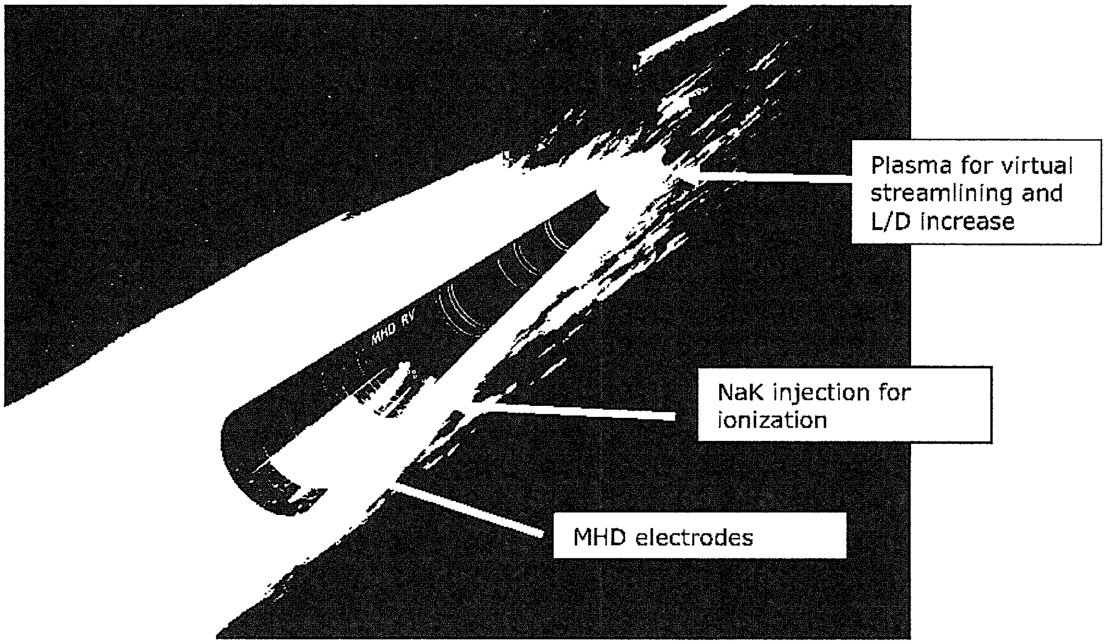

Figure 10. Reentry Vehicle With Surface-Integrated MHD Device and Plasma-Enabled Virtual Streamlining and L/D Increase.

One good use of such high power would be to create a plasma in front of the vehicle in order to reduce drag (Figure 10). Nonoptimized analysis shows that the "return" (i.e., the drag power saved divided by the power spent on creating the plasma) can easily be as high as 40-50 (i.e., the drag power saved is 40-50 times greater than the power spent on the plasma).[41] There are theoretical and experimental indications that with proper shaping of the plasma region (specifically, making it long and thin), the "return" can be >100. Thus, this "reverse energy bypass" would result in substantial reduction in drag and increase in L/D (lift-to-drag ratio) by tens of percent. The increase in L/D would directly translate in increased downrange for an unpowered hypersonic global "glider" and in increased cross-range for a de-orbiting space asset. Note that off-axis positioning of the plasma region would create steering or pitch/yaw control moments.[42]

An attractive application that utilizes this plasma/MHD-enabled increase in L/D is orbit inclination changes for space assets. Even a modest (a few degrees) orbit inclination change requires a very large amount of delta-velocity and energy and thus a very large amount of fuel to be burned. If the space asset dives into the upper atmosphere (to altitudes of 200-300 kft), it can use aerodynamic turning (similar to airplanes), provided the L/D ratio is high enough. Unfortunately, hypersonic L/D, especially in rarefied air at high altitudes, is not much higher than 1. Plasma and MHD technologies hold substantial and realistic promise to achieve hypersonic L/D of 3-10, which would be a game-changer and enable, among other missions, aerodynamically assisted, on-demand orbital inclination changes.

We now briefly consider another MHD application: a hybrid chemical/MHD propulsion. The nozzle exit velocity of chemical systems (air-breathing and rockets) is limited by the chemical energy available from the fuels/propellants and the temperature limits of the system materials. One method to increase the exit velocity of the system is to add an MHD accelerator system to the nozzle. The flow is first accelerated using a conventional gas dynamic converging-diverging nozzle and then the MHD system further accelerates the supersonic flow in the diverging portion of the nozzle. Many ground-based systems have been developed and tested to accelerate flows using MHD systems. These have been primarily either proof-of-concept systems or for hypersonic wind tunnels.[43, 44] Systems have been proposed for both small in-space systems[45, 46] and for large engines for launch vehicles.[47] While this concept has great potential and the accelerator physics are well established, it has several practical limitations. To be efficient, the energy added to the flow from the MHD system should be on the order of or greater than the energy added by the chemical stage. This requires power levels that are not available on either type of vehicles. For example, for launch vehicles the jet power levels would be in the hundreds of MW to tens of GW range. The low ionization fractions in the flows also severely limit the thrust efficiency of the MHD systems to a few percent. This combined with the large jet powers requires enormous launch-vehicle powers. Similarly for space systems, a better solution would be to use the available power in a more efficient electric thruster. The large powers also require large masses for the MHD system components for reasonable specific mass (kg/kW). To be comparable to pure electric systems on spacecraft, the MHD augmentation system specific mass would need to be improved by a factor of 1,000 over state-of-the-art technologies.[48] One potential solution around the power issue is to beam the power to the vehicle.[49] Another serious issue is the magnets needed to provide the 2- to 40-Tesla fields required. In many cases, the weight of the magnet and magnet power supply would exceed the vehicle mass using existing technology. The magnet system mass will need to be reduced by several orders of magnitude to make flight systems practical.

Chapter 3: Space Applications

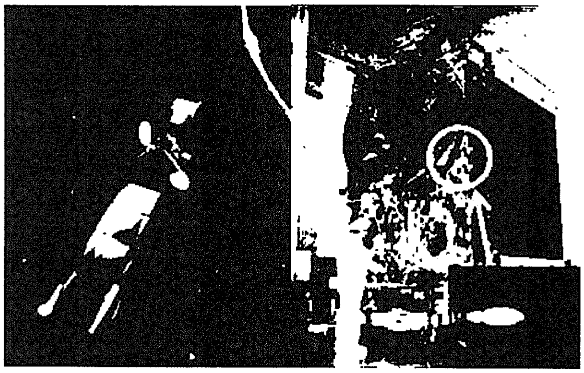

Figure 11. Electrothermal Arcjet Thruster on Satellite. Lockheed Martin Series 7000 Comsat with Aerojet 1.8-kW Arcjet thrusters (insert photo) for north-south station keeping.

Electric propulsion systems are currently being used for attitude control, positioning, and primary propulsion. The use of electric propulsion systems on spacecraft was limited by the amount of power available. The thrusters were developed decades before the power systems. Early applications were the replacement of hydrazine monopropellant thrusters with hydrazine resistojet and arcjet thrusters (increasing I_{sp} from 200 seconds to 300 seconds for resistojet thrusters and to 600 seconds for arcjet thrusters). An example is shown in Figure 11. This keeps most spacecraft the same, just changing the thrusters (lower risk and cost). Newer spacecraft are being designed specifically for use with electric thrusters. These are primarily gridded ion engines and Hall-effect thrusters operating on xenon propellant. Xenon is a unique noble gas that can be stored with densities close to liquids at pressures above 800 psia. As the available electric power has increased, the transition to all electric spacecraft has increased, as well as the sizes of the electric propulsion systems. Hall thrusters are used for station keeping as well as apogee insertion maneuvers. This trend will continue for decades to come.[50]

The high I_{sp} available from electric systems enables new operation concepts for what a spacecraft can do. The amount of propellant that can be stored onboard limits the number and types of maneuvers the spacecraft can perform. Electric systems enable enhanced ability to relocate assets, fly nontraditional or non-Kelplerian orbits, and keep spacecraft on station for much longer periods. Although the I_{sp} of electric systems are much higher than chemical systems, the thrust levels are much lower. This results in much lower spacecraft accelerations and longer repositioning times. The availability of higher power levels will allow for higher power thrusters to be used and, therefore, the repositioning times to be lower. For a given power, the I_{sp} and thrust can be traded ($P_{elect} = \frac{1}{2} g_o I_{sp} F_{th} / \eta$). High-power Hall-effect thrusters are being designed to operate in both a high-thrust (lower I_{sp}) mode for obit insertion and repositioning and high-I_{sp} (low thrust) for propellant-efficient maneuvers and station keeping. This adds significant flexibility to how the spacecraft is operated and the missions it can perform.

Very fine spacecraft positioning and pointing can be accomplished using the low thrust levels associated with some electric systems. For example, field emission electric propulsion (FEEP) and colloid thrusters are capable of thrust levels in the micro-Newton range and can be used to offset small spacecraft perturbations such as solar wind.

Another operational option enabled with electric systems is to fly at much lower obits where drag forces would normally cause the spacecraft to reenter in a short period of time. An air-breathing electric thruster can be used for drag make-up without the need for additional propellant.[51]

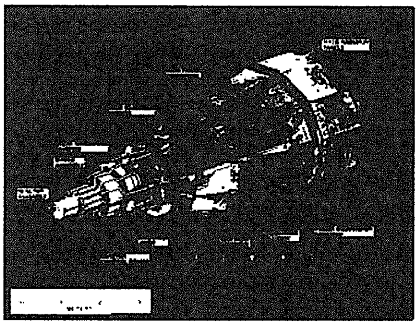

Figure 12. SP-100 Space Nuclear Power System. Illustration of the 100 kWe SP-100 nuclear reactor.

Nuclear fission power systems coupled with electric thrusters enable new capabilities. Nuclear space reactors have been flown in space (SNAP-10A by the United States and TOPAZ reactors by the former Soviet Union).[52] The SP-100 system shown in Figure 12[53] was being developed in the 1990s as a tug to move spacecraft from LEO to GEO orbits. Even higher powered systems have been proposed to planetary missions such as those shown in Figure 13.[54, 55] Having a nuclear vehicle in orbit also enables the beaming of power to air or ground vehicles from orbit or the use of laser and microwave weapons.

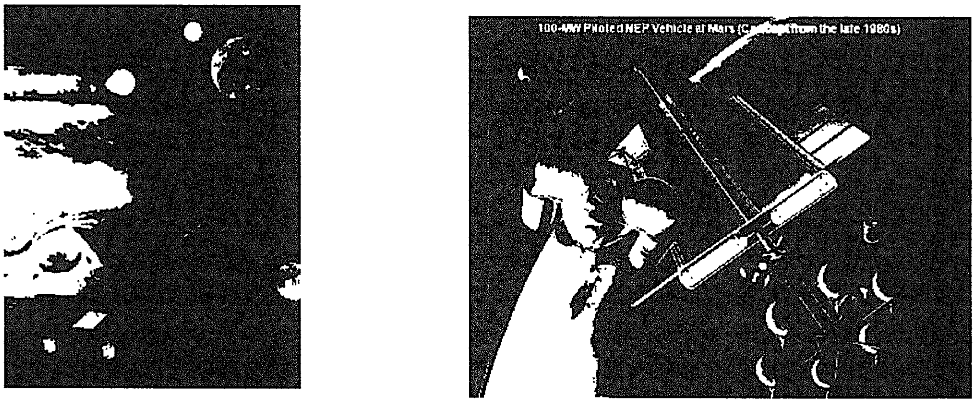

Figure 13. Nuclear Electric Propulsion (NEP) Concept Vehicles. Left is the 100-kWe Jupiter Icy Moons (JIMO) planetary spacecraft. Right is a 100-MWe-class piloted Mars vehicle.

Chapter 4: Summary and Predictions

The principal reason for attractiveness of plasma/MHD propulsion concepts is that they could in principle reach beyond the limits of conventional propulsion, power, and aerodynamic technologies. It is thus near or beyond those limits that novel plasma technologies will likely find their application.

The principal difficulties or flaws associated with the plasma and MHD technologies are as follows:

- Weight and complexity, especially if there is a need for a strong (>1 Tesla) magnetic field in large volumes, and if electron beams are needed for ionization.
- For MHD accelerator/thruster, power requirements could be overwhelming.
- MHD operation is accompanied not only by the work of ampere forces, but also by irreversibilities and entropy generation due to Joule dissipation. This reduces thrust and I_{sp} of propulsion systems.
- In the absence of thermal ionization (i.e., at Mach<12), complexity and power budget associated with nonequilibrium ionization all but make MHD propulsion systems impossible.

In contrast, applications to reentry, global-strike hypersonic gliders, and aeroassisted orbital maneuvering look very promising in the near future. The "free" thermal ionization enables MHD devices with very modest B field and the ability of plasma/MHD system to provide L/D far beyond that possible conventionally; together, it makes these applications both feasible and desirable for national defense. However, these types of applications are also likely to attract attention of other nations, including (but not limited to) Russia, China, and Japan, that have proven knowledge and experience required to accomplish such missions and technologies. These nations have the capability to develop such novel technologies within several years and deploying those technologies perhaps within 10 years.

The fortunes of MHD propulsion could increase dramatically if high-speed (hypersonic) vehicles begin to carry powerful onboard electricity sources, such as nuclear (fission or fusion) reactors. Since deployment of onboard nuclear power is mostly a political rather than a technological issue, it is difficult to predict if this going to occur and, if yes, when.

For spacecraft, the current trend of replacing chemical rockets with electric propulsion systems will continue and probably will become the standard. Electric systems can provide a much wider range of operation (e.g., low-thrust fine positioning/pointing, more frequent or nontraditional maneuvers, and longer times on station) than chemical systems can. The trend to larger spacecraft power levels will further accelerate this trend. Ultimately, the high power levels required (hundreds of kW to multi-megawatts) for certain missions will lead to revisiting the use of nuclear fission reactors in space.

Chapter 5: Endnotes

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