# Laser-Powered MHD Generators for Space Application

N. W. Jalufka

*Langley Research Center
Hampton, Virginia*

# Contents

## Introduction

The rapid development and utilization of space will require a readily available and relatively inexpensive source of abundant power. In the past, spacecraft have relied on chemical, nuclear, or solar-generated power to provide onboard power, communication, and propulsion. While these methods have proven adequate for past missions, studies (refs. 1 to 14) over the past several years have identified space-power transmission as a potential solution to the problem of on-site power generation in space. Lasers are being considered for space-power transmission because of the relatively small transmitting and receiving systems required when compared with those required by longer wavelength systems. Other applications of the transmitted laser power include propulsion systems for spacecraft and deep-space communications. These various application studies also conclude that the use of lasers in space can reduce the cost of space power and propulsion.

One concept for a space-power transmission system has received considerable attention: a large central power station in geosynchronous orbit which would beam power to remote users (ref. 1). The overall efficiency of such a system would depend not only on the efficiency with which the laser beam could be generated but also on the efficiency with which the beam could be converted to a useful form of energy at the receiver. Some research on laser-plasma interaction has been carried out and was primarily directed toward mathematical model development to study the absorption of laser radiation and the formation of a laser-supported plasma for laser propulsion systems (refs. 9 to 11). An experimental study (ref. 15) has been conducted on the coupling of a $CO_2$ laser beam with hydrogen gas. Laser-to-electrical power conversion has received some attention and one can readily define the requirements for a space-based laser-to-electrical power converter:

1. Energy conversion efficiency should be high.
2. Efficiency should be independent of the laser wavelength.
3. Power-to-weight ratio should be high.
4. Operation should be reliable and maintenance free.
5. System should not be excessively expensive.

Ideally, the converter should be wavelength independent to avoid the problems associated with matching the wavelength of the laser to that at which the converter is most efficient. High conversion efficiency is a major (and obvious) requirement, since laser energy not converted to electrical power may be converted to heat. One would then have the additional problem of rejecting heat in space which would require large radiators, thereby increasing the system mass. Four concepts have been identified that may satisfy these requirements:

1. Optical rectification
2. Reverse free-electron laser
3. Laser-driven magnetohydrodynamics (MHD)
4. Laser photovoltaics

Although optical rectification, the reverse free-electron laser, and laser photovoltaics are potentially high-efficiency systems, this paper examines only the laser-driven magnetohydrodynamic system.

## MHD Theory

MHD concepts have existed since the time of Faraday, and considerable research and development have been carried out in this area, resulting in several large systems in operation around the world (ref. 16). The concept of a laser-driven MHD generator, however, is conceivable only in a space-based laser energy-conversion system, since one must consider both power transmission as well as conversion. The laser-driven MHD converter offers high system efficiency, high power density, and closed-cycle operation. Furthermore, such a closed-cycle system can be built with few (or no) moving mechanical parts; thus it would be highly reliable and require little maintenance. A high overall system efficiency is expected because of the high conversion efficiency of the MHD generator (approximately 70 percent) and the high absorption (approximately 100 percent) of the laser beam in the working fluid (refs. 17 to 19). One may also adjust the working fluid characteristics (in some cases) of such a system to maximize absorption at a given wavelength so that the system could be designed for any transmitting laser wavelength. An MHD generator consists of a conductor moving through a fixed magnetic field. In these systems the conductor is a high-temperature ionized gas (or plasma) or a liquid metal. Electrical current $\vec{J}$ is extracted from the flowing plasma or liquid metal by electrodes. Figure 1 is a schematic of a simplified MHD generator.

Plasma system MHD generators are often classified according to the method employed to produce the plasma. These methods include shock waves, combustion, arcs, chemical processes, and explosives. More recently, the extensive research carried out in the area of laser-driven thermonuclear fusion has shown that plasmas may be efficiently produced and heated by lasers. This suggests that laser-produced and/or laser-heated plasmas or laser-heated liquid metals in conjunction with an MHD generator system might efficiently convert laser energy to electrical
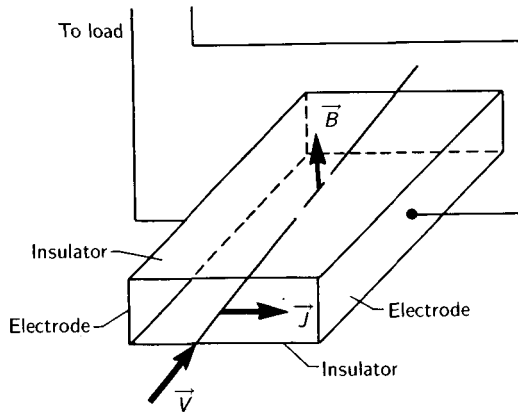
Figure 1. MHD generator geometry.

power. The most advanced linear-type generator is called a Hall generator since it utilizes the Hall current component, which is in the gas flow direction. The power equation for a Hall generator is given by (ref. 20)

$$P = \frac{\beta^2}{1 + \beta^2}\sigma \vec{V}^2 \vec{B}^2 K(1 - K) \qquad (1)$$

where $\beta$ is the ratio of the electron mean free path to the Larmor radius, $\sigma$ is the plasma conductivity, $\vec{V}$ is the flow velocity, $\vec{B}$ is the magnetic field, and $K$ is the ratio of load to open circuit voltage. If the plasma is in the Coulomb-dominated regime, then $\sigma$ is proportional to $T^{3/2}$ (ref. 21), so that increasing the temperature (with a laser) increases the power output of the generator (for those systems that operate with a plasma). If the laser energy is deposited in a short time (i.e., pulsed mode), the rapidly heated gas also expands, increasing $\vec{V}$ and, consequently, the generator output.

Magnetohydrodynamic systems were first proposed for space-power applications as a means of converting nuclear energy (heat) to electrical power (ref. 22). This first investigation was based on a two-fluid magnetohydrodynamic cycle and concluded that the efficiency of such a system (based on the existing technology) would be less than that of a turboelectric or thermionic system of approximately the same specific weight. The study did point out two potential advantages of the two-fluid MHD conversion system:

1. Long lifetime and high reliability, relative to turboelectric systems, afforded by the absence of moving parts
2. Ease of development, relative to thermionic and gaseous MHD systems, permitted by the relatively low temperatures

Because of the low efficiency of the two-fluid MHD system, no effort was made to develop MHD as a space-power system. However, research at Argonne National Laboratory initiated in the 1960's was aimed at minimizing the high energy loss of MHD systems. This research resulted in the two-phase-generator liquid-metal MHD (LMMHD) system which exhibits a much higher cycle efficiency. This high-efficiency LMMHD concept may now be considered for space application, which would utilize the unique combination of high efficiency and high-temperature capability.

## Laser-Plasma Interaction

Some of the candidate systems involve laser-plasma interaction, which may be broken down into two categories:

1. Plasma production by lasers
2. Plasma heating by lasers

### Plasma Production

Production of a plasma (ionized gas) by laser irradiation requires a minimum (threshold) intensity which depends on the type of gas, gas density, laser beam size, laser pulse width, and laser wavelength (ref. 23). This threshold is typically of the order of $10^9 \text{W/cm}^2$ for a variety of gases at atmospheric pressure.

Production of the plasma then proceeds in two steps. The first step is initial ionization, which can be accomplished in a gas by multi-photon absorption. After free electrons are produced, they are further heated by inverse bremsstrahlung resulting in a cascade process in which the energetic electrons produce further ionization by collision with the neutral atoms and ions. Once this stage is reached, the laser intensity required to maintain the plasma drops to a value equal to the loss rate from the plasma. This is typically of the order of a few kilowatts (ref. 24). The absorption coefficient (in $\text{cm}^{-1}$) for inverse bremsstrahlung is given by (ref. 25)

$$\alpha = \frac{(7.8 \times 10^{-9})Z n_e^2 \ln \Lambda(\nu)}{\nu^2 T_e^{3/2}(1 - \nu_p^2/\nu^2)^{1/2}} \qquad (2)$$

where $Z$ is the ionic charge, $n_e$ is the electron density in $\text{cm}^{-3}$, $\Lambda$ is the high-frequency screening parameter, $T_e$ is the electron temperature in eV, $\nu$ is the laser frequency, and $\nu_p$ is the plasma frequency. Coupling of the laser energy into the plasma is most efficient if the electron density of the plasma is such that $\nu_p$ is close to $\nu$. The absorption depth (i.e., the distance the laser radiation penetrates into the plasma)

is given by $\alpha^{-1}$. Because of the strong dependence of $\alpha$ on the electron density and electron temperature, the plasma parameters may be varied to achieve maximum absorption of any laser radiation in a fixed distance. If the electron density of the plasma reaches the critical density given by (ref. 26)

$$n_c = (1.24 \times 10^{-8})\nu^2 \tag{3}$$

then the laser beam does not penetrate into the plasma but is reflected instead. This situation results in a laser-supported detonation (LSD) wave propagating from the plasma surface along the laser beam toward the laser. These waves move at supersonic speeds and ionize and heat the medium through which they are propagating.

### Plasma Heating

The energy absorbed by the free electrons can be dissipated in several ways: (1) expansion of the plasma volume, (2) heating of the electrons, ions, and atoms, (3) inelastic collisions resulting in excitation and ionization of the ions and atoms, (4) diffusion of electrons out of the plasma, (5) attachment of electrons to atoms to form negative ions, and (6) radiative losses such as bremsstrahlung and radiative recombination. The relative importance of several of these processes depends on plasma parameters, and, in many cases, some processes are negligible. Expansion of the plasma volume and heating of the electrons are the most important processes for MHD power generation, as the other mechanisms represent energy losses. At the pressures and temperatures applicable to MHD power generation, the dominating processes appear to be expansion and heating, with radiative recombination being the major loss mechanism (ref. 27). The increase in electron temperature is given by (ref. 28)

$$\frac{\Delta T_e}{T_e} = (1.42 \times 10^{25})\frac{n_i Z^2 g_{ff}}{(T_e)^{3/2}\nu^3}$$
$$\times \left[1 - \exp\left(-\frac{h\nu}{T_e}\right)\right]\frac{1}{q}\int_0^{t_L} L\,dt \tag{4}$$

where $n_i$ is the ion density in cm$^{-3}$, $g_{ff}$ is the free-free gaunt factor, $T_e$ is in eV, $h$ is Planck's constant, $q$ is the cross section of the laser beam in cm$^2$, $t_L$ is the laser pulse length in seconds, and $L$ is the laser intensity. The integral

$$\frac{1}{q}\int_0^{t_L} L\,dt$$

is in joules/cm$^2$.

If the plasma exists for an adequate length of time, the electrons transfer energy to the ions by collision, and equilibrium is reached in a time given, in seconds, by (ref. 29)

$$t_{eq} = (7.34 \times 10^6)\frac{AA_f}{n_f Z^2 Z_f^2 \ln \Lambda}\left(\frac{T}{A} + \frac{T_f}{A_f}\right)^{3/2} \tag{5}$$

where $A$ is the atomic weight of the particle and the subscript $f$ refers to the field (heavier) particle.

These various properties of the laser-plasma interaction phenomena provide several options in the design of an MHD generator to be powered by laser radiation.

## Candidate MHD Systems

Among the MHD systems considered for space-power application are

1. Pulsed systems in which gas breakdown, heating, and flow depend on the initiation of an LSD wave
2. Plasma systems (pulsed or continuous wave (CW)) where the laser radiation is used to heat an existing plasma either prior to its introduction into the MHD generator or during its flow through the generator
3. Liquid-metal systems (pulsed or CW) in which the laser radiation heats the liquid metal or the carrier medium (or both) prior to mixing and introduction into the MHD generator

### Pulsed LSD Systems

Maxwell and Myrabo (ref. 30) have considered in detail pulsed laser MHD systems based on LSD wave generation. Figure 2 is a schematic of a pulsed LSD MHD generator. Two modes of power generation are possible in this configuration. In mode 1, power is generated as the LSD wave passes through the generator at a high velocity. In mode 2, power is generated when the high-temperature plasma remaining in the plenum chamber is vented through the generator.

Figure 3 shows the physical process of the power cycle for mode 1. The cycle is started with an LSD wave being ignited at the exhaust port of the MHD generator and propagating at a high velocity through the generator. The high-temperature, high-conductivity "slug" immediately behind the LSD wave provides the working fluid for MHD power generation. This mode is unique in laser MHD power generation since electrical power is generated nearly simultaneously with the deposition of energy in the working fluid.
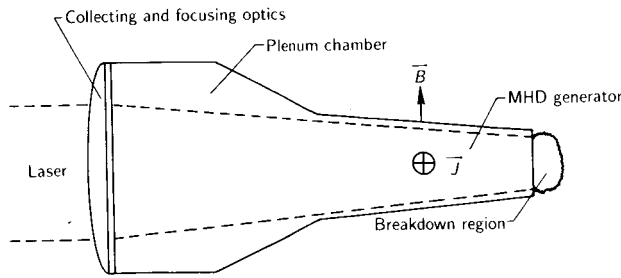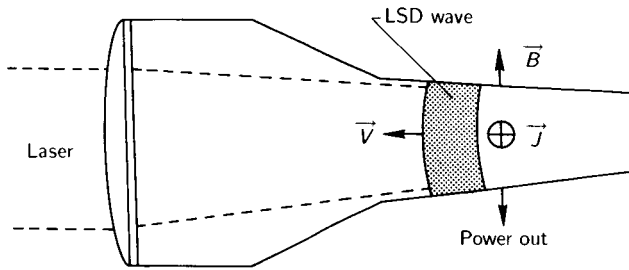
Figure 2. Pulsed LSD MHD generator.



Figure 3. Mode 1 power cycle for pulsed LSD generator.

The velocity of the LSD wave is given by (ref. 31)

$$V_{\text{LSD}} = \left[\frac{2(\gamma^2 - 1)I_0}{\rho_0}\right]^{1/3} \qquad (6)$$

where $\gamma$ is the ratio of the specific heats of the gas, $I_0$ is the incident laser flux, and $\rho_0$ is the ambient gas density in front of the wave. The pressure behind the detonation wave is given by (ref. 31)

$$P_{\text{LSD}} = \rho_0 V_{\text{LSD}}^2 (\gamma + 1) \qquad (7)$$

For practical values of incident laser flux and ambient gas pressure, LSD wave velocities greater than 1 km/sec and pressures behind the LSD wave of several atmospheres are possible. For these conditions, the electron temperature of the LSD wave can be driven to very high values and the electrical conductivity of the medium may reach the Coulomb-dominated limit (in the range of $10^3$ mho/m or greater). These conditions are suitable for very high electrical power densities.

To achieve a high extraction efficiency in this mode requires a conducting region of reasonable length (several centimeters). This has not been achieved experimentally because the short thermalization times at the pressures and temperatures expected cause the plasma to reach equilibrium a very short distance behind the LSD wave. Two possibilities might provide adequate slug thicknesses:

1. Deposit energy in the electron "gas" by ohmic heating in order to sustain nonequilibrium immediately behind the LSD wave absorption region.
2. Decrease the absorption coefficient so that the laser energy is absorbed over a length equal to the desired slug thickness.

Neither of these methods has been investigated experimentally. If either of these possibilities can be proven to be adequate, then high conversion efficiencies would be expected in this mode.

Figure 4 shows the physical process of the mode 2 power cycle. In this mode of operation, the LSD wave serves only to process the plenum chamber working fluid to high temperatures and pressures. Because of the short electron-ion thermalization times, this mode of operation must generate power under equilibrium conditions. The mode 2 cycle begins with the LSD wave being reflected at the optical window, that is, at the termination of the mode 1 cycle. Passage of this wave through the plenum chamber creates a dense, high-temperature plasma. The reflected wave helps to drive all of the working fluid through the MHD generator and acts much like a piston. Electrical power is generated as the high-pressure plasma expands through the generator. In this mode, the system is rather similar to a shock-driven MHD generator, which to date has achieved a generation extraction efficiency near 25 percent (ref. 32).

A space-based laser converter system based on the above concepts would use a noble gas (argon perhaps) as the working fluid with the addition of a seed material having a low ionization potential (cesium is a good candidate). Such a system would have to be closed cycle to avoid the problem of replenishing the gas supplies.

While little experimental data are available on this type of system, the feasibility study by Maxwell and Myrabo (ref. 30) assumes that the present state of the art has not reached its limit and that efficiencies approaching 50 percent might be achievable. This potentially high conversion efficiency as well as the simplicity of the system are two major advantages which make the system attractive. The disadvantages of the system include

1. Exposure to the LSD wave and high-temperature plasma might damage optical surfaces.
2. The system must operate at high power levels because of the high laser intensity required to achieve breakdown.
3. The system operates at high pressures and is closed cycle, so that a minor leak would render the system inoperable.
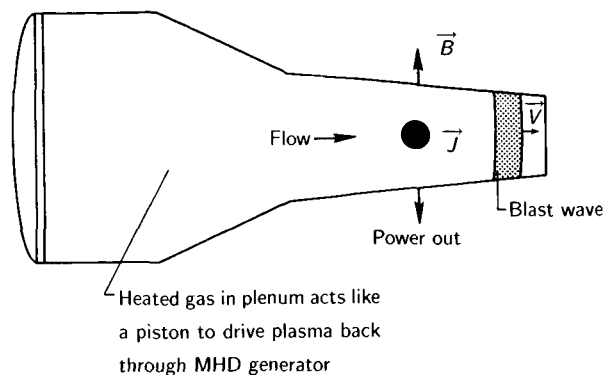
4

Figure 4. Mode 2 power cycle for pulsed LSD generator.



Figure 5. Laser plasma-flow MHD system.

## Plasma System

A second option for space-based laser-driven MHD generators is to use the incoming laser beam to heat an existing low-temperature plasma to higher temperatures before it flows into the MHD channel. In this system, the laser radiation is absorbed by the free electrons through inverse bremsstrahlung. Electron-ion thermalization occurs rapidly, so that the plasma flowing through the generator is in equilibrium. The intensity of the laser beam must be maintained below the breakdown threshold in order to prevent LSD wave formation and propagation back along the laser beam.

Figure 5 is a schematic of a laser-driven plasma MHD system. This is a closed-cycle system which employs a noble gas (argon) as the working medium. The working medium is seeded with a low-ionization element (cesium) to increase the electron density and thereby the electrical conductivity of the working medium. This procedure requires the separation of the two elements after passage through the MHD generator and before compression of the gas.

This system also offers the possibility of heating the plasma by absorption of laser radiation while the plasma is in the MHD channel. The length of the channel would be such that the laser beam is completely absorbed in the channel. This would keep the plasma electron temperature at a higher value and could possibly improve the efficiency of the MHD generator. Plasma temperatures achieved in CW laser-produced plasmas depend on the type of gas and pressure in the system and generally range from 15 000 K to 20 000 K. This temperature would drop rapidly outside of the interaction region because of radiative cooling and diffusion. This system has the advantage of having been studied extensively both experimentally and theoretically, so that the efficiencies and characteristics of the various components are well known (ref. 21). With an auxiliary means of achieving plasma ignition, the system would have the
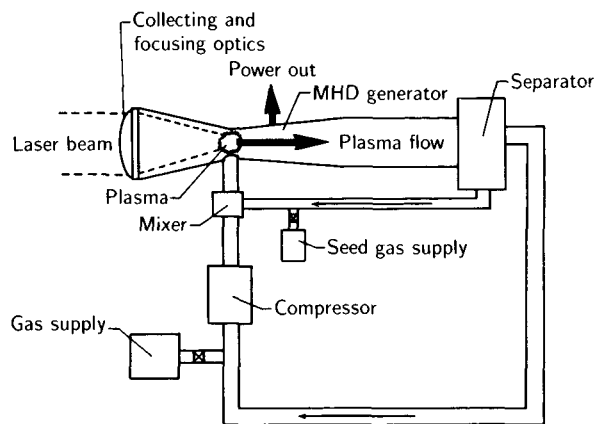
advantage of operation at lower power levels than if ignition by laser breakdown were required. A disadvantage of this system would be the exposure of the collecting and focusing optics to the plasma, which could result in long-term damage to this part of the system.

Performance of a Hall MHD generator has been calculated by Choi (ref. 33), assuming an unsteady turbulent flow in the channel. This model assumes an 80-percent efficiency for the absorption of the laser beam, which is somewhat conservative. Laboratory measurements of the absorption of $CO_2$ laser radiation by a shock-heated plasma show that absorption close to 100 percent is achievable (refs. 17 and 18). Based on the above assumptions, the model predicts a generator efficiency of greater than 40 percent, which agrees well with experimentally measured values of about 50 percent for a simplified generator design (ref. 34).

The efficiencies of the various system components are listed in table I for the plasma-flow system shown in figure 5. The efficiencies are the best values available in the literature (refs. 35 and 36). The overall system efficiency is defined as the electrical energy extracted minus the energy used to operate the system components divided by the laser power into the system. This expression is derived in the appendix. Using the efficiencies listed in table I, an overall system efficiency of 30.6 percent is obtained. This does not include the energy consumed by the magnet (negligible if a superconducting magnet is used), energy losses associated with the gas flow through the connecting piping (small if flow rates are not excessive), or radiative energy losses. Consequently, this figure is considered an upper limit for the efficiency of this system.

5

## TABLE I. EFFICIENCIES OF COMPONENTS OF PLASMA MHD SYSTEM (FIG. 5)

[Values from refs. 35 and 36]

Efficiency of—

| Absorption of laser, $\varepsilon_a$ | 0.80 |
|---|---|
| MHD generator, $\varepsilon_g$ | 0.50 |
| Separator, $\varepsilon_s$ | 0.85 |
| Compressor, $\varepsilon_c$ | 0.85 |
| Mixer, $\varepsilon_m$ | 0.90 |



Figure 6. Brayton cycle LMMHD system.

## Liquid-Metal Systems

The two-phase-generator liquid-metal magneto-hydrodynamic (LMMHD) concept was developed at Argonne National Laboratory in 1969–1970 (ref. 35). This concept demonstrated that LMMHD systems can be made with rather attractive efficiencies (40 to 90 percent). The two-phase-generator LMMHD system—which uses two working fluids, a thermodynamic fluid (gas or vapor) and an electrodynamic fluid (liquid metal)—is more flexible in coupling to different heat-source temperatures than the plasma MHD system. Unlike the plasma MHD system, which requires a high temperature, LMMHD systems can efficiently utilize heat-source temperatures as low as 450 K (ref. 35) because the liquid metal provides the conductivity in the generator and ionization is not required. Another difference between the LMMHD and the plasma MHD system is that the LMMHD system does not require the liquid metal to be in the atomic state (i.e., existing in the flow as single atoms). The liquid metal can be mixed into the flow in the form of an aerosol. The liquid metal acts as a heat source for the gas phase so that the expansion through the MHD generator takes place at practically a constant temperature.

There are two LMMHD cycles of interest for space applications:

1. Brayton cycle
2. Rankine cycle

***Brayton cycle.*** Figure 6 is a schematic of a Brayton cycle LMMHD system. At temperatures above approximately 800 K, this system becomes attractive because of its efficiencies, inherent simplicity, and low sensitivity of efficiency to design power level. An inert gas (e.g., helium) is the thermodynamic working fluid and a liquid metal (e.g., sodium or lithium) is the electrodynamic fluid in the MHD generator. The actual working fluid and liquid metal used in a space-based system would be determined by a number of factors. These include the operating temperature of the system and the maximum
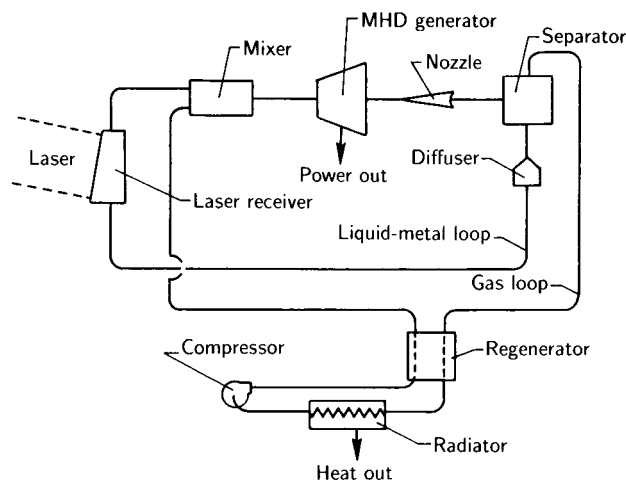
power generated. At typical flow velocities of approximately 150 m/sec and temperatures greater than 1000 K, the helium and sodium (or lithium) system is adequate. At higher flow rates and temperatures, liquid-metal carryover with the gas from the separator can become a problem. In a laser-powered application the laser energy is absorbed by the gas, the liquid metal, or both. The laser energy can be coupled into the gas in the same manner as in the plasma MHD system, with the heated gas collisionally transferring energy to the liquid metal. Since these MHD systems operate at pressures of several atmospheres, the absorption length would be of the order of a few centimeters. Heating of the liquid metal directly has not been studied in great detail, although absorption of radiation by high-temperature metals has been observed. The gas and the liquid metal are combined in the mixer, and the two-phase mixture flows through the MHD generator. The gas phase in this mixture is about 80 percent of the total volume. In the generator the gas expands, drives the liquid across the magnetic field, and generates electrical power. Since the liquid has a high heat content, this expansion occurs at almost constant temperature, and considerable available energy remains in the gas exiting the MHD generator. This energy may be used by transferring it to the carrier gas prior to mixing with the liquid metal. During the expansion through the generator, thermal energy is continuously transferred from the liquid to the gas, so that most of the enthalpy change in the generator comes from the liquid. This almost constant temperature expansion is the source of the potentially higher thermodynamic efficiency of the two-phase LMMHD system. After exiting the generator, the mixture flows through a nozzle where the liquid is accelerated. The resulting high-speed flow is separated and the liquid pressure required to

6

return the liquid through the absorption cell and to the mixer is obtained in the diffuser. The nozzle and diffuser could be replaced by a liquid-metal pump.

Blumenberg (ref. 36) has conducted optimization studies of space-power systems consisting of a Brayton cycle MHD system powered by a nuclear reactor. The mass-to-power ratio for this system varied from 9 kg/kW$_E$ for a 100 kW$_E$ system to 6 kg/kW$_E$ for a 10 MW$_E$ system. Since the system envisioned here has an external power source (the laser), these values should be reduced by 0.2 kg/kW$_E$ (specific mass of the reactor). This gives 8.8 kg/kW$_E$ for the approximate specific mass of the 100 kW$_E$ MHD system.

Brayton cycle LMMHD systems have a well-established technology base, at least for terrestrial applications, and for the most part this information is directly applicable in space. One problem area that may arise in the conventional LMMHD cycle is operation of the separator. In terrestrial applications, gravity plays an important role in the operation of this device, so that in the zero-gravity environment of space some other method of separating the liquid metal from the gas may have to be found.

Another problem area for this system is the requirement of the optical system to receive the laser beam and focus it to the proper spot size. This requires that a window transparent to the laser wavelength be sealed into the high-pressure gas-flow system. At the operational pressures envisioned for this system (several atmospheres), even small leaks could be detrimental. The possibility of damage to the window also exists if it comes in contact with the high-temperature liquid metal. This could be particularly detrimental to optical coatings on the window surface (if they are required).

Efficiencies for the various components of the Brayton cycle LMMHD are listed in table II (refs. 35 and 36). These values are typical of those quoted in the literature. Using these values and the procedure of the appendix, an overall system efficiency of 55.8 percent is obtained. Energy losses such as radiation loss, magnet power, and losses due to flow are not included but are assumed to be small. The calculated efficiency is therefore an upper limit for the overall system efficiency.

*Rankine cycle.* The Rankine cycle is shown in figure 7. This cycle is of interest at temperatures below 800 K. This cycle differs from the Brayton cycle only in the use of a condensable fluid as the thermodynamic working fluid. Since the thermodynamic fluid is in a liquid phase for part of the cycle, the reject heat exchanger and the compressor of the Brayton cycle are replaced, respectively, by a condenser

## TABLE II. EFFICIENCIES OF COMPONENTS OF BRAYTON CYCLE LMMHD SYSTEM (FIG. 6)

[Values from refs. 35 and 36]

Efficiency of—

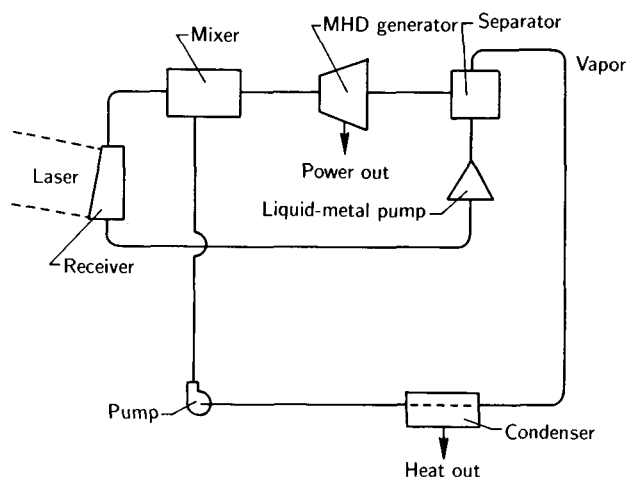| | |
|---|---|
| Absorption of laser, $\varepsilon_a$ | 0.80 |
| Mixer, $\varepsilon_m$ | 0.90 |
| MHD generator, $\varepsilon_g$ | 0.80 |
| Separator, $\varepsilon_s$ | 0.85 |
| Compressor, $\varepsilon_c$ | 0.85 |



Figure 7. Rankine cycle LMMHD system.

and a pump. Since the Rankine cycle is identical to the Brayton cycle in several respects, such as operating pressure, flow rate, absorption length, materials, windows, and laser coupling, the advantages of the Brayton cycle as well as its disadvantages apply to this system. In addition, the use of a condensable fluid would add some difficulty in a space-based system because the liquid phase is more complicated to control in zero gravity than the gas phase. The operating temperatures of the Rankine cycle are considerably lower than those of the Brayton cycle and are much lower than those anticipated in a laser-powered MHD converter system. Consequently, the Rankine cycle is not the best choice for a laser MHD converter system even though the overall system efficiency is about equal for the two systems.

## Summary and Recommendations

Laser-driven magnetohydrodynamic (MHD) systems for laser-to-electrical energy conversion have several advantages for space-based operation, including closed-cycle operation, high-temperature operation (which minimizes waste heat management problems), high conversion efficiency, and simplicity of design. Since these systems have few (if any) moving

7

mechanical parts, they should exhibit high reliability and low maintenance.

The pulsed laser-supported detonation (LSD) system discussed in this report offers the potential of high conversion efficiency and simple design. Since this system can be built with no moving mechanical parts, high reliability should be assured. This system would probably have the best power-to-weight ratio because auxiliary equipment is not required. Unfortunately, there has been little experimental research that is applicable to this system, so that the full potential of the system cannot be accurately assessed.

The plasma MHD system also offers a reasonably high conversion efficiency, closed-cycle operation, and simplicity of design, although the requirement of flowing the carrier gas does increase the complexity of the system over that of the pulsed LSD system. Thus the overall system efficiency would be lower than the efficiency of the pulsed LSD system. However, because of the large amount of research that has been conducted on this plasma MHD system, a much broader in-depth technology base exists which would reduce development cost.

Of the two liquid-metal magnetohydrodynamic (LMMHD) systems, the Brayton cycle appears to be the most attractive for space applications because of its higher operating temperature. In either case, however, the overall system efficiencies are quite high and both offer closed-cycle operation as well as simplicity of design.

All of the systems discussed here would require high-pressure operation (greater than 1 atm) in order to achieve high conversion efficiency. There are some problems inherent in this requirement. In particular, the adequate sealing of optical windows into a high-pressure system so that no leakage occurs may present some technical difficulties, but these do not appear to be insurmountable. Of more concern is damage to the optical windows because of possible contact with the high-temperature plasma. This problem could become particularly difficult if optical coatings are required on the windows. Care must be taken in the design of the system to eliminate (or at least minimize) this problem.

Since MHD systems meet many of the requirements for a space-based laser-to-electrical energy converter, the following recommendations are made:

1. Additional research on pulsed LSD MHD generator systems is required to determine their full potential.
2. Additional research on LMMHD systems is desirable to determine the best method of coupling laser energy into the system (i.e., into the liquid metal, the carrier gas, or both).
3. Research on laser-plasma interaction and system design should continue in order to minimize problem areas.

In addition, a more extensive and in-depth system study should be conducted to ensure the best system designs for particular space applications.

# Appendix

## Calculation of Overall System Efficiency

The energy input to the system is the energy in the laser beam $E_0$. If the absorption efficiency is $\varepsilon_a$, then the energy available for conversion to electricity is

$$E_0 \varepsilon_a \tag{A1}$$

The energy in the system after passing through the mixer with efficiency $\varepsilon_m$ is

$$E_0 \varepsilon_a \varepsilon_m \tag{A2}$$

and the energy extracted by the MHD generator having an efficiency $\varepsilon_g$ is

$$E_0 \varepsilon_a \varepsilon_m \varepsilon_g \tag{A3}$$

The energy remaining in the system,

$$E_0 \varepsilon_a \varepsilon_m (1 - \varepsilon_g) \tag{A4}$$

is the energy input to the separator which has an efficiency $\varepsilon_s$. The energy remaining in the system after passage through the separator is then

$$E_0 \varepsilon_a \varepsilon_m (1 - \varepsilon_g) \varepsilon_s \tag{A5}$$

and the energy in the system after passing through the compressor (efficiency $\varepsilon_c$) would be

$$E_0 \varepsilon_a \varepsilon_m (1 - \varepsilon_g) \varepsilon_s \varepsilon_c \tag{A6}$$

if the compressor were extracting energy from the system. The energy "extracted" would be the difference of these last two expressions, that is,

$$E_0 \varepsilon_a \varepsilon_m (1 - \varepsilon_g) \varepsilon_s (1 - \varepsilon_c) \tag{A7}$$

This was assumed to be the energy added back into the system by the compressor. The amount of energy required by the compressor to add this amount of energy to the system is

$$\frac{E_0 \varepsilon_a \varepsilon_m (1 - \varepsilon_g) \varepsilon_s (1 - \varepsilon_c)}{\varepsilon_c} \tag{A8}$$

The efficiency of the system is defined to be the net electrical power generated (i.e., the total power produced by the MHD generator, eq. (A3), minus the power required to operate the compressor, eq. (A8)) divided by the input energy (ref. 22), that is,

$$\eta = \varepsilon_a \varepsilon_m \left[ \varepsilon_g - \frac{(1 - \varepsilon_g) \varepsilon_s (1 - \varepsilon_c)}{\varepsilon_c} \right] \tag{A9}$$

Using the efficiencies from table I for the plasma-flow system gives

$$\eta = 30.6 \text{ percent} \tag{A10}$$

For the Brayton cycle LMMHD system (using the efficiencies from table II),

$$\eta = 55.8 \text{ percent} \tag{A11}$$

# References

1. Holloway, Paul F.; and Garrett, L. Bernard: Utility of and Technology for a Space Central Power Station. AIAA-81-0449, Feb. 1981.

2. Rather, John D. G.: *Final Report—A Study To Recommend NASA High Power Laser Technology and Research Programs.* WJSA-76-17 (Contract no. NASW-2866), W. J. Schafer Assoc., Inc., July 1976. (Available as NASA CR-155398.)

3. Rather, John D. G.; Gerry, Edward T.; and Zeiders, Glen W.: *Investigation of Possibilities for Solar Powered High Energy Lasers in Space.* NASA CR-153271, 1977.

4. Garrett, L. B.; and Hook, W. R.: Future Large Space Systems Opportunities—A Case for Space-to-Space Power? *Large Space Systems Technology,* NASA CP-2035, Volume I, 1978, pp. 507–531.

5. Kantrowitz, Arthur: The Relevance of Space. *Astronaut. & Aeronaut.,* vol. 9, no. 3, Mar. 1971, pp. 34–35.

6. Coneybear, J. Frank: The Use of Lasers for the Transmission of Power. *Radiation Energy Conversion in Space,* Kenneth W. Billman, ed., American Inst. Aeronaut. & Astronaut., c.1978, pp. 279–310.

7. *Future Orbital Power Systems Technology Requirements.* NASA CP-2058, 1978.

8. Rather, John D. G.; Gerry, Edward T.; and Zeiders, Glenn W.: *A Study To Survey NASA Laser Applications and Identify Suitable Lasers for Specific NASA Needs.* WJSA 77-14 TR1 (Subcontract under Contract NAS7-100), W. J. Schafer Assoc., Inc., Feb. 1978.

9. Hertzberg, Abraham; and Sun, Kenneth: Laser Aircraft Propulsion. *Radiation Energy Conversion in Space,* Kenneth W. Billman, ed., American Inst. Aeronaut. & Astronaut., c.1978, pp. 243–263.

10. Minovitch, M. A.: *Performance Analysis of a Laser Propelled Interorbital Transfer Vehicle.* NASA CR-134966, 1976.

11. Rather, J. D. G.; and Myrabo, L.: *Laser Propulsion Support Program.* NASA CR-170708, 1980.

12. W. J. Schafer Assoc., Inc.: *NASA Technology Workshop on High Power Lasers.* Purchase Order No. 709-78-1, 1979. (Available as NASA CR-168751.)

13. Bain, Claud N.: *Potential of Laser for SPS Power Transmission.* HCP/R-4024-07 (Contract No. EG-77-C-01-4024), PRC Energy Analysis Co., Oct. 1978. (Available as NASA CR-157432.)

14. Jones, W. S.; Forsyth, J. B.; and Skratt, J. P.: *Laser Rocket System Analysis.* NASA CR-159521, 1978.

15. Kemp, N. H.; and Krech, R. H.: *Laser-Heated Thruster— Final Report.* NASA CR-161666, 1980.

16. Grundy, Robert F., ed.: *Magnetohydrodynamic Energy for Electric Power Generation.* Noyes Data Corp., 1978.

17. Jalufka, N. W.; and Kloc, Barbara J.: Interaction of $CO_2$ Laser Radiation With a Shock-Heated Hydrogen Plasma. *Bull. American Phys. Soc.,* vol. 30, no. 2, Feb. 1985, p. 138.

18. Lee, Ja H.; McFarland, Donald R.; and Hohl, Frank: Production of Dense Plasmas in a Hypocycloidal Pinch Apparatus. *Phys. Fluids,* vol. 20, no. 2, Feb. 1977, pp. 313–321.

19. Box, S. J. C.; John, P. K.; and Byszewski, W. W.: Interaction of a $CO_2$ Laser Beam With a Shock-Tube Plasma. *J. Appl. Phys.,* vol. 48, no. 5, May 1977, pp. 1946–1952.

20. Sutton, George W.; and Gloersen, Per: Magnetohydrodynamic Power and Propulsion. *Magnetohydrodynamics,* Ali Bulent Cambel, Thomas P. Anderson, and Milton M. Slawsky, eds., Northwestern Univ. Press (Evanston, Ill.), c.1962, pp. 243–268.

21. Sutton, George W.; and Sherman, Arthur: *Engineering Magnetohydrodynamics.* McGraw-Hill Book Co., Inc., c.1965.

22. Elliott, David G.: *A Two-Fluid Magnetohydrodynamic Cycle for Nuclear-Electric Power Conversion.* Tech. Rep. No. 32-116 (Contract No. NASw-6), Jet Propulsion Lab., California Inst. Technol., June 30, 1961.

23. Morgan, F.; Evans, L. R.; and Morgan, C. Grey: Laser Beam Induced Breakdown in Helium and Argon. *J. Phys. D: Appl. Phys.,* vol. 4, no. 2, Feb. 1971, pp. 225–235.

24. Smith, David C.; and Fowler, Michael C.: Ignition and Maintenance of a CW Plasma in Atmospheric-Pressure Air With $CO_2$ Laser Radiation. *Appl. Phys. Lett.,* vol. 22, no. 10, May 15, 1973, pp. 500–502.

25. Johnston, Tudor Wyatt; and Dawson, John M.: Correct Values for High-Frequency Power Absorption by Inverse Bremsstrahlung in Plasmas. *Phys. Fluids,* vol. 16, no. 5, May 1973, p. 722.

26. Key, M. H.: Interactions of Intense Laser Radiation With Plasma. *Philos. Trans. R. Soc. London,* vol. A300, no. 1456, Apr. 23, 1981, pp. 599–612.

27. DeCoste, R.; Englehardt, A. G.; Fuchs, V.; and Neufeld, C. R.: Transverse Heating of a Cold Dense Helium Plasma by a Pulsed $CO_2$ Laser Beam. *J. Appl. Phys.,* vol. 45, no. 3, Mar. 1974, pp. 1127–1134.

28. Kunze, H. J.: The Laser as a Tool for Plasma Diagnostics. *Plasma Diagnostics,* W. Lochte-Holtgreven, ed., North-Holland Publ. Co., 1968, pp. 550–616.

29. Spitzer, Lyman Jr.: *Physics of Fully Ionized Gases,* Second rev. ed. Interscience Publ., c.1962.

30. Maxwell, Craig D.; and Myrabo, Leik N.: Feasibility of Laser-Driven Repetitively-Pulsed MHD Generators. AIAA-83-1442, June 1983.

31. Raĭzer, Yu. P.: Subsonic Propagation of a Light Spark and Threshold Conditions for the Maintenance of Plasma by Radiation. *Soviet Phys.—JETP,* vol. 31, no. 6, Dec. 1970, pp. 1148–1154.

32. Tate, E.; Marston, C. H.; and Zauderer, B.: *Large Enthalpy Extraction Experiments in a Non-Equilibrium Magnetohydrodynamic Generator.* Doc. 74SD226, General Electric Co., July 29, 1974.

33. Choi, Sang H.: *Space-Based Laser-Driven MHD Generator: Feasibility Study.* Final Rep. 681104 (Purchase Order No. L28161B), Information and Control Systems, Inc., Nov. 1981. (Available as NASA CR-178184.)

34. Jalufka, N. W.: Laser Heating of Low Temperature Plasmas With Application to Energy Conversion. *Bull. American Phys, Soc.,* vol. 31, no. 2, Feb. 1986, p. 158.

35. Pierson, E. S.; Branover, H.; Fabris, G.; and Reed, C. B.: Solar-Powered Liquid-Metal MHD Power Systems. *Mech. Eng.*, vol. 102, no. 10, Oct. 1980, pp. 32–37.

36. Blumenberg, Jurgen: Optimisation of Powerful Energy Supply Systems for Application in Space. IAF Paper 79-169, Sept. 1979.

Standard Bibliographic Page

| 1. Report No.<br>NASA TP-2621 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br>Laser-Powered MHD Generators for Space Application | | 5. Report Date<br>October 1986 |
| | | 6. Performing Organization Code<br>506-41-41-01 |
| 7. Author(s)<br>N. W. Jalufka | | 8. Performing Organization Report No.<br>L-16144 |
| 9. Performing Organization Name and Address<br>NASA Langley Research Center<br>Hampton, VA 23665-5225 | | 10. Work Unit No. |
| | | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, DC 20546-0001 | | 13. Type of Report and Period Covered<br>Technical Paper |
| | | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract

Magnetohydrodynamic (MHD) energy conversion systems of the pulsed laser-supported detonation (LSD) wave, plasma MHD, and liquid-metal MHD (LMMHD) types are assessed for their potential as space-based laser-to-electrical power converters. These systems offer several advantages as energy converters relative to the present chemical, nuclear, and solar devices, including high conversion efficiency, simple design, high-temperature operation, high power density, and high reliability. Of these systems, the Brayton cycle liquid-metal MHD system appears to be the most attractive. The LMMHD technology base is well established for terrestrial applications, particularly with regard to the generator, mixer, and other system components. However, further research is required to extend this technology base to space applications and to establish the technology required to couple the laser energy into the system most efficiently. Continued research on each of the three system types is recommended.

| 17. Key Words (Suggested by Authors(s))<br>Magnetohydrodynamics<br>Laser-plasma interaction<br>Space power transmission | 18. Distribution Statement<br>Unclassified—Unlimited<br><br>Subject Category 75 | | |
|---|---|---|---|
| 19. Security Classif.(of this report)<br>Unclassified | 20. Security Classif.(of this page)<br>Unclassified | 21. No. of Pages<br>14 | 22. Price<br>A02 |