Concepts and Status of Laser-Supported Rocket Propulsion

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Laser propulsion, a unique new system in which thrust is produced by the absorption of remote laser energy, has several distinct advantages over existing forms of propulsion. This article is intended as an overview of the status of laser propulsion based on a review of the scientific literature. Included in the discussion is an evaluation of the advantages and limitations of laser propulsion, as well as the types of missions for which it can best be used. The various types of proposed thrusters are also discussed, focusing on operation, current research, and unresolved problems. Also included is a thorough list of references documenting the research in this relatively young field.

I. Introduction

CURRENTLY, there are a large number of advanced propulsion systems either available or under development but, with a few exceptions, all share a common disadvantage: the energy source must be carried onboard the spacecraft. Chemical rockets, for example, provide high thrust levels and low structural weight but, because of limits on the energy released from combustion, specific impulse (I_{sp}) tends to be relatively low. Conversely, electric propulsion produces high specific impulse but the inherent low thrust levels and heavy onboard equipment result in poor thrust-to-weight ratios. Even nuclear engines, with their high thrust and good I_{sp}, suffer because a massive nuclear reactor (with radiators and shields) must be carried onboard. Today, for the first time, it appears possible to obtain both high thrust and high specific impulse while eliminating the need for a heavy onboard power source.

The idea, first proposed over a decade ago,[1] is to use a high-power laser as a remote power source. Instead of using energy from nuclear or chemical reactions to heat a propellant, a powerful beam of laser energy is employed. And, since the laser energy can be used to heat the propellant to extremely high temperatures, specific impulses in excess of 1000 s appear practical. As will be seen, one of the main limitations is the amount of available laser power.

During the past decade, a large number of investigators have examined many diverse aspects of the laser propulsion question. Much progress has been made both in the understanding of the propulsion aspect and in the development of high-power lasers. Several different techniques have been devised to efficiently absorb and use the laser energy but, in general, these can be grouped into two distinct categories depending on the type of laser used.

One concept is to operate the laser in a steady-state mode known as continuous wave (cw) operation. The laser is focused into a small chamber in the engine where the laser energy is absorbed by a propellant, whose temperature is raised to many thousands of degrees. This absorption chamber functions much like the combustion chamber on a chemical rocket, and once the propellant has been heated, it exits via a conventional nozzle, producing thrust.

An alternative approach is to use a repetitively pulsed (RP) laser which operates by producing high-frequency pulses of intense laser radiation. Typically, a laser pulse is fired into the rear of the engine where the high-intensity radiation is sufficient to cause an electrical breakdown of a small amount of propellant, creating a high-temperature, rapidly expanding plasma. This plasma, which closely resembles a supersonic blast wave, quickly exits a supersonic nozzle to create its thrust.

Both devices rely on high temperatures and low molecular weight fuels to offer high specific impulse and high thrust. This unique capability enables laser propulsion to be used profitably in a wide range of mission applications. The most promising role now appears to be as an orbital transfer vehicle (OTV) where a laser-propelled vehicle can compete with traditional propulsion even at relatively low laser power levels. In the more distant future, when lasers capable of beaming gigawatts of power become available, a laser vehicle could conceivably serve as an Earth-launch vehicle.

The purpose of this article is to examine the current status of laser propulsion and discuss the potential and problems of such devices. Although this article is intended for readers not familiar with the field, a discussion of some of the more technical aspects is also included, as well as detailed descriptions of the operation of the various thruster designs. A large number of references are also included, covering the many diverse aspects of the field. Several of these in particular provide a broad coverage of laser propulsion.[2-11]

II. Specific Impulse

One of the most important parameters in rocket propulsion engine design is specific impulse, since it directlk affects the amount of payload delivered. Although other factors such as propellant density and storability have been given much consideration, specific impulse continues to be important, especially in systems designed for high-energy missions. As mentioned earlier, there are definite limits to the specific impulse that can be achieved by a chemical rocket. Consider the equation for I_{sp}, assuming an ideal frozen gas flow through an ideal nozzle.

$$I_{sp} = (1/g)\,[(2\gamma/\gamma-1)\;RT_c\phi]^{1/2} \tag{1}$$

where $\phi \equiv 1-(P_e/P_c)^{\gamma-1/\gamma}$, P_e is nozzle exit pressure, γ the ratio of specific heats, R the gas constant, T_c the chamber temperature, and ϕ a pressure ratio term that depends on the design of the nozzle. Also note that for an ideal gas, $R=\bar{R}/\mathrm{MW}$ where $\bar{R}$ is the universal gas constant and MW the molecular weight of the exhaust gas. It is important to realize that most of these factors are relatively constant. Both γ and

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ϕ vary only slightly between rocket designs. As a result, $I_{sp} \sim (T_c/\mathrm{MW})^{1/2}$.

Obviously, to maximize I_{sp}, we would like to use a low molecular weight exhaust gas and operate at high chamber temperatures; however, in a chemical rocket, both T_c and MW are inseparably linked to the choice of propellant. For example, in a hydrogen-oxygen system, maximum T_c is about 3500 K and the molecular weight of the products tends to be about 12. Neither quantity can be changed substantially and specific impulse will never rise much above the state-of-the-art value of about 500 s.

In a laser system, however, combustion is not necessary and any material can be selected as a propellant. As a result, hydrogen with its molecular weight of 2 (1, if fully dissociated) has been the leading propellant candidate. Another advantage of a laser system is that the maximum temperature is no longer a function of the energy released by combustion nor must it be held low to prevent damage to internal components as in a solid-core nuclear rocket. Instead, T_c can be raised to the metallurgical limits of the absorption chamber walls, allowing maximum chamber temperatures in excess of 10,000 K.[12] This means that the specific impulse of a laser thruster could easily be between 1000 and 2000 s, a substantial improvement over existing systems.

Specific impulse vs temperature for hydrogen is shown in Fig. 1.[7] Note that if other materials are used, specific impulse falls as $1/\mathrm{MW}^{1/2}$ and values above 1000 s are more difficult to achieve. A major disadvantage of hydrogen is its inherent low density as a liquid which directly affects tankage size and weight. Storability is also poor. Another difficulty is that hydrogen, once dissociated, does not completely recombine while in the nozzle. This nonequilibrium situation can produce a sizable penalty in specific impulse, and currently is being studied. For all of these reasons, many investigators have examined other fuels with better storability (such as water), or monatomic gases such as helium, despite the I_{sp} penalties.[5,10,13-17]

It must be pointed out that RP thrusters, which do not make use of ideal nozzle flow, do not obey the relations presented above. Instead, the flow represents a blast wave phenomenon. In an extensive analysis of this flow, Simons and Pirri showed that I_{sp} in an RP thruster is proportional to the inverse fourth root of the molecular weight.[18-20] This implies that in an RP device, low MW propellants are not as important as in a cw system and that alternate fuels could be used with less penalty. Nevertheless, the desire to operate at high temperatures with low molecular weight propellants is present for both types of laser propulsion.

III. Efficiency

In order to demonstrate the advantages and limitations of laser propulsion, it is useful to derive an expression relating thrust, specific impulse, and laser power. As a starting point, define the efficiency of the laser system η as the ratio of exhaust kinetic energy to laser power P.

$$\eta \equiv (\tfrac{1}{2}\dot{m}c^2)/P \tag{2}$$

where $\dot{m}$ is mass flow and c the exhaust velocity, assuming nozzle exhaust pressure equals ambient pressure. Two other general relations for rocket performance are $F = \dot{m}c$, where F is thrust and $I_{sp} = c/g$. By these definitions, Eq. (2) can be rearranged to show that

$$F = (2\eta P)/(I_{sp}g) \tag{3}$$

Immediately it is possible to see the tradeoff between thrust and specific impulse which are inversely related. It is fairly obvious why this is so. If laser power and efficiency are held fixed then the quantity $\dot{m}c^2$ is constant. If an increase in I_{sp} is now sought, the mass flow must fall considerably faster than c rises; thus, the thrust must fall. Similarly, if an increase in thrust is desired, then mass flow must increase and I_{sp} must necessarily fall.

Equation (3) is graphed in Fig. 2 for power levels ranging from 1 to 100 MW, assuming an overall efficiency of 50%. Notice that in order to achieve meaningful thrust levels (over 1000 N) at high I_{sp} (over 1000 s), it becomes necessary to use laser powers in the tens of megawatts. At the present time, such laser power levels are not yet available but are being developed.

Although 1000 N is a significantly higher thrust level than can be obtained using electric propulsion, it is still small

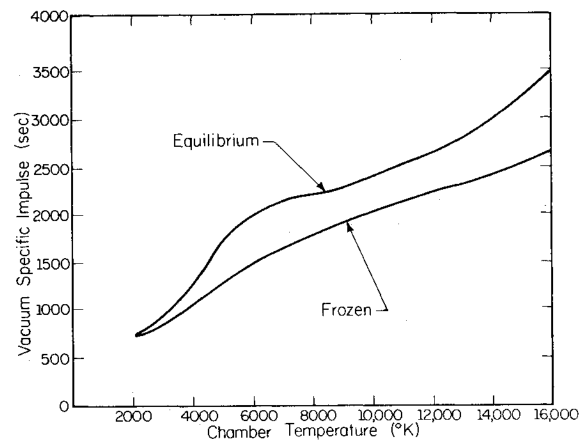

Fig. 1 Vacuum specific impulse vs chamber temperature for pure hydrogen.[7]

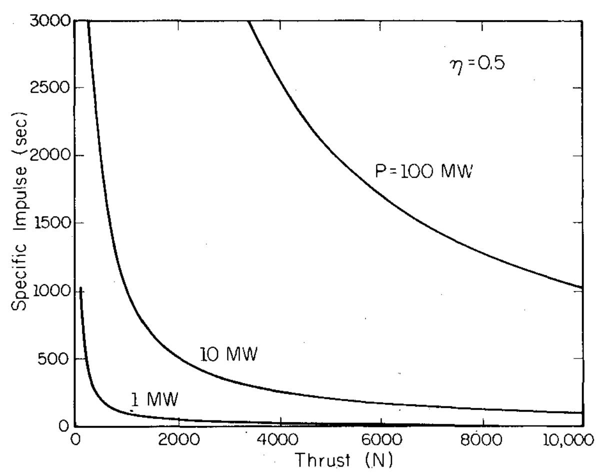

Fig. 2 Specific impulse vs thrust at various laser input power levels, based on the relation $F = (2\eta P)/(I_{sp}g)$. Efficiency η is 50%.

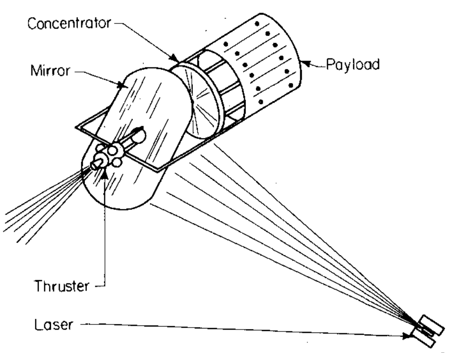

Fig. 3 Major components of a typical cw system, taken from Ref. 10. The collecting mirors refocus the beam into the thruster through a small window.

compared to chemical engines. For example, a proposed OTV engine would provide 65,000 N of thrust at an I_{sp} of 495 s. To duplicate this with a laser thruster (operating at 50% efficiency) would require over 300 MW of laser power. Fortunately, for most mission applications, such high thrust is not usually required. Thus, if this same 300 MW could be used to provide 20,000 N of thrust at an I_{sp} of 1500 s, it would be a clearly superior alternative.

A final important implication of Eq. (3) is that the efficiency of a laser thruster is very important. If a candidate device is found to have a higher efficiency than its competitors, the improvement translates directly into lower laser power requirements, greater performance, and lower cost. In evaluating laser thrusters, efficiency is of crucial importance.

IV. CW Laser Propulsion

The main idea of a cw laser thruster is the use of a continuous laser beam to steadily heat a fluid in the absorption chamber and then to expand this fluid out a conventional rocket nozzle. The preferred fluid is hydrogen, but other fuels with higher densities or better absorption characteristics also have been suggested.

One important feature of most cw systems is the need to introduce the laser upstream of the flow (Fig. 3), which is necessary to ensure stable heating of the propellant. Most gases tend to become opaque to laser radiation at higher temperatures, so if the laser were introduced through the nozzle, the gases in the nozzle would tend to be heated and would become opaque. This would block the heating in the absorption chamber and cause instability in the flow. Because of this requirement, several generic features of a cw thruster appear, as shown in Fig. 3.

First, the incoming laser energy must be collected and concentrated by a system of mirrors. This is to correct for the inevitable spreading of the beam, which can be spread to several meters in diameter over distances of hundreds or thousands of kilometers. After this the laser must pass through some type of window in order to enter the sealed absorption chamber. The main problem with both devices is that they must be able to transmit the enormous energy fluxes without absorbing a significant fraction.

The window is the major difficulty. In a typical 100 MW system with a window diameter of 20 cm, the laser flux through the window will be 3.2×10^5 W/cm^2, enough to melt most materials. The preferred approach is to use a high-transmittance crystalline material such as SrF_2, ZnSe, or KCl. Depending on the laser's wavelength and the window material selected, transmittance through the window will be about 99.98%.[10] Although good, this still means that 20,000 W is absorbed by the window. As a result, temperature gradients begin building in the crystal, and when these gradients reach a critical level, the window will crack. Thus, the window will hold up only for a few seconds at these high power levels.

Solutions to the window problem should come in several ways. First, continuing advances in crystalline technology will tend to increase transmittance to even higher levels. Also, it is possible to actively cool the window, especially if cryogenic hydrogen is used as the propellant. Both edge and face cooling are possible, but need to be proven in operation. Such active cooling slows the formation of temperature gradients in the crystal and significantly increases operating time. Another possible solution is to use a rotating system of mirrors, which would operate much like the frames of a motion picture. When one window begins to overheat, the system is rotated and the laser energy is allowed to pass through a new window. A final possibility is to use an aerodynamic window in which a high-velocity flow of a gas is used to separate the chamber from the low-pressure external environment.[5] Although this appears feasible for operation in the atmosphere, the large mass losses that would result make it undesirable for operation in space.

Problems with the concentrator mirror are not as critical. This is because the beam is much more diffuse when it contacts the mirror, and intensities are much lower. Also, coatings now exist for the infrared (i.r.) wavelengths with reflectivities of 99.8%.[10] This means that the intensity of radiation absorbed by the mirror should be less than the intensity of light incident on a surface in normal sunlight.

It seems likely that the major difficulties with the mirror will not be thermal, but rather structural and control

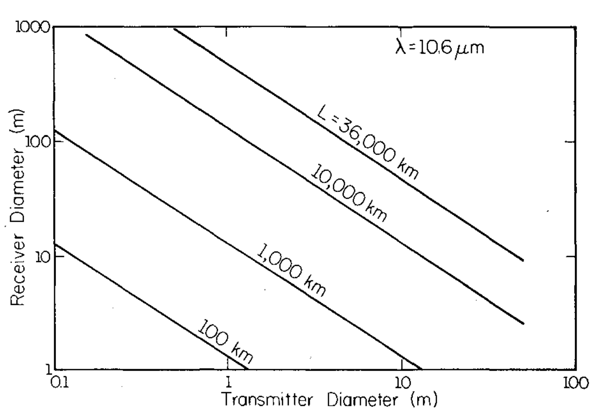

Fig. 4 Laser transmitter mirror diameter vs spacecraft receiving mirror diameter for ranges from 100 to 36,000 km (GEO). Results based on the relation $D_R = 2L\tan(1.22\gamma/D_T)$, assuming diffraction-limited optics (best case possible) and $\lambda = 10.6$ μm.

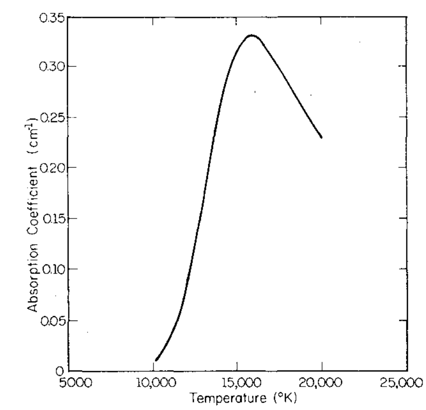

Fig. 5 Absorption coefficient of pure hydrogen at 1 atm for 10.6 μm radiation.[21,77]

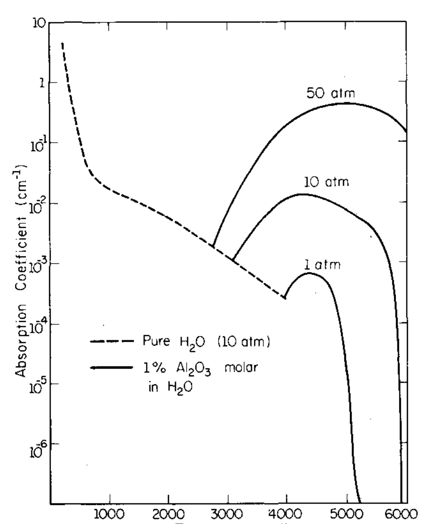

Fig. 6 Absorption coefficient vs temperature at 10.6 μm for water vapor with and without Al_2O_3 seedant at various chamber pressures.[5]

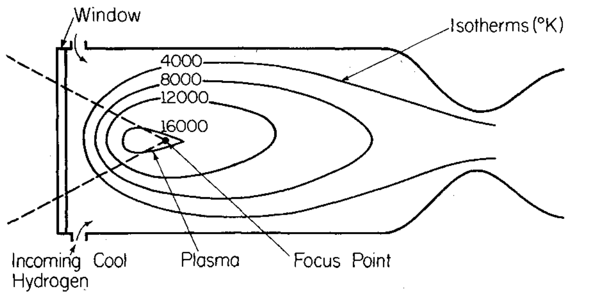

Fig. 7 Dual-flow thruster showing convergent laser entering through the window, annular flow around a central plasma, and downstream mixing. (Isotherms taken from Ref. 34.)

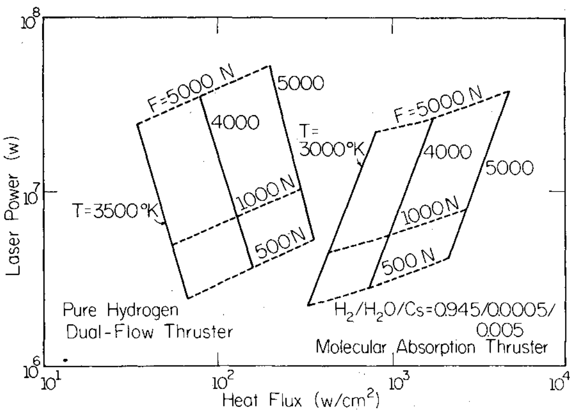

Fig. 8 Predicted heat flux vs laser power at various thrust levels and temperatures for both dual-flow and molecular absorption thrusters.[36]

problems. As seen in Fig. 4,[10] the receiver diameter becomes very large (tens of meters) as the transmitting distance approaches the radius to geostationary orbit (GEO). As a result, if such a system is to be used as an OTV, either these large and heavy mirrors must be used, or some other form of propulsion must be included for the apogee burn at GEO.

V. Absorption Processes

The success of laser propulsion hinges on the ability to couple the laser energy to a working fluid, quickly heating the fluid to high temperatures. The absorption must be complete and must occur in a relatively small volume to minimize chamber size and radiative losses.

In any gas there are several possible absorption mechanisms, the most important of which are inverse bremsstrahlung (IB) absorption, resonance absorption, photoionization, and photodissociation. IB absorption occurs when a photon is absorbed by a free electron during a collision with either a neutral atom (neutral-electron absorption) or an ion (ion-electron). The excited electron eventually transfers its energy to the surrounding gas through collisions, raising the bulk temperature of the gas. This process is continuous (with a strong wavelength dependence), but requires the presence of free electrons, which usually occurs only at high temperatures.

Resonance absorption, by contrast, occurs when the gas molecules directly absorb the incoming photons in one of their vibrational/rotational transitions. This is effective even at low temperatures, but the frequency of the laser photons must be matched carefully to the available transitions. Photoionization and photodissociation occur when a molecule absorbs a photon, causing the molecule to ionize or dissociate, respectively. In a gas, the relative contribution of each process depends on the properties of the gas, including its temperature and pressure, and the wavelength of the laser energy.

In gases that have available resonance transitions at the wavelength of the laser radiation, it is possible to simply heat the gas directly by passing the laser beam through the cold bulk gas. Although simple, this technique has the disadvantage of being highly wavelength dependent, and is useful only up to about 5000 K, at which point the absorbing molecules begin dissociating. Also, once the energy has been trapped in the vibrational/rotational modes of the molecule, the conversion of this into translational energy often is incomplete in the nozzle, resulting in inefficient thrust production.

There is also the problem that such transitions are most effective only in polyatomic molecules. In hydrogen and the noble gases, there are no such strong transitions at current laser wavelengths. In fact, as is seen in Fig. 5, the absorption coefficient of pure hydrogen at 1 atmosphere is virtually zero until about 10,000 K, at which point dissociation and then ionization begin. These processes are active up to about 15,000 K, at which point IB absorption becomes the dominant mechanism, its effect peaking near 20,000 K as neutral-electron IB ceases.[21] The further decrease in the absorption coefficient with increasing temperature is due to a decrease in number density as the pressure is held fixed.

The paradox is that hydrogen cannot absorb any laser radiation unless it is already hot. One way around this difficulty is to seed the hydrogen with molecular gases (such as H_2O or NH_3) that have the desired resonance transitions. This has the effect of boosting the hydrogen absorption coefficient at low temperatures and allows direct laser heating. It also has the undesirable effect of increasing the molecular weight of the propellant.

A different approach is to artificially inject a large number of free electrons into the hydrogen to boost the IB absorption contribution. This is usually done by focusing the laser beam to a small spot and jumping an electric arc across the spot. The free electrons from the spark cause a sharp rise in the absorption coefficient at the focal spot, which then causes the hydrogen at the spot to be instantaneously superheated to a plasma having peak temperatures near 20,000 K.

Once formed the plasma begins propagating back up the laser beam. This is caused by the plasma heating the fluid in front of it, which in turn begins absorbing and heating up. If the laser intensity is high ($>10^7$ W/cm^2 for air), this wave phenomenon propagates back up the beam at supersonic velocity. This is known as a laser-supported detonation (LSD) wave, used in RP devices.[22-24] At lower intensities, the plasma propagates subsonically, and is referred to as a laser-supported combustion (LSC) wave.

The LSC wave can be used as a stable heating zone for a thruster. By injecting the propellant stream opposite to the direction of propagation, the plasma is stabilized and steadily heats the flowing hydrogen. To ensure stability, the beam is usually tightly focused, with optics of focal number less than ten.[25] In this way, should an upstream perturbation occur, the plasma moves into a region of lower laser intensity where it cannot sustain itself, and the plasma tends to be returned to its stable location. The maintenance of stable laser-supported plasmas has been demonstrated in several gases by various investigators,[26-29] and numerous analyses have studied the stability questions.[5,30-33]

A final alternative which is similar in concept to adding molecular seedants involves the use of small particles suspended in the hydrogen. These particles absorb the incident laser energy, are rapidly heated, and transfer the energy to the surrounding gas by radiation and conduction. Although the wavelength used is relatively unimportant, the particles must not be reactive with hydrogen, and must have acceptable boiling points. They must also be small to enhance heat transfer. Unfortunately, small particles tend to scatter incoming radiation, resulting in a widely scattered beam which causes larger energy losses. Other problems include suspending the particles in the propellant and maintaining that suspension. Candidate particles include carbon, tungsten, and some ceramics.[10]

It should be noted that maximizing the absorption coefficient of a hydrogen plasma can be accomplished best by increasing the pressure within the absorption chamber. The absorption coefficient of hydrogen at high temperature tends to be proportional to the square of the electron density, a quantity largely dependent on pressure.[21] Thus, complete absorption can be ensured by tailoring the absorption coefficient through pressure variations.

So far this discussion has centered on hydrogen as the propellant, but other substances with better absorptivity have been examined also. One of these is water with its superb storability. When seeded with Al_2O_3, the absorption coefficient (Fig. 6) remains high up to about 5000 K.[5] Although there are penalties in specific impulse, other considerations may make its use desirable.

It is interesting to point out that at lower laser wavelengths (< 1 μm), the contribution from resonance absorption in pure hydrogen tends to become much more important. In fact, for lasers operating at 0.448 μm, resonance absorption from the H_β transition is expected to be significant.[21] At still lower laser wavelengths (<0.4 μm), photoionization becomes more and more important.

VI. CW Thrusters

Dual-Flow Plasma Thruster

Much of the research effort in laser propulsion has been directed toward the development of a thruster that absorbs the laser energy through the use of a stable hydrogen plasma. There is now a clearer understanding of the problems that must be considered when designing such a device.

Temperatures in the center of the hydrogen plasma can exceed 20,000 K, and if the plasma were allowed to fill the entire absorption chamber, heat losses through the chamber walls would be enormous and damage to these walls very likely. The preferred approach is to use a dual-flow arrangement, as shown in Fig. 7.[3,4] In this concept a plasma is maintained in the central core of the chamber and a cold flow of hydrogen flows annularly around the plasma, isolating it from the walls. Downstream from the plasma is the mixing region where the hot and cold flows combine to give a uniform temperature at the entrance to the throat. This temperature should be as high as possible without causing damage to the throat. The temperature isotherms are estimated from an analytical two-dimensional study by Keefer et al.[34,35]

The main reason for the two flows is to minimize heat losses to the chamber walls. The cold flow is designed both to prevent the plasma from contacting the walls and to absorb some of the radiation given off by the plasma. Heat losses in cw thrusters are considered to be a major problem, and it has been suggested that large devices could lose nearly one-half of the incident laser energy to the walls.[2,30] Kemp has recently developed a model of energy losses through the chamber walls of a dual-flow thruster, concluding that heat fluxes of 50-500 W/cm^2 will occur for laser powers of 10 MW (Fig. 8)[36] This results in a significant fraction of the incident power being lost, even when using the dual-flow arrangement.

Experiments currently being conducted by Jones and McCay at NASA Marshall are attempting to study the dual-flow concept.[4,37] Using a 30 kW cw CO_2 laser, the initial goal is to establish and maintain stable plasmas in hydrogen (as has been done previously by Conrad et al.).[29] Two-dimensional temperature profiles will be made of the plasma and mixing zone in an attempt to understand the absorption and flow behavior. In the future, the central plasma core region will be studied in more detail using a small-diameter quartz chamber. This central core is interesting because the flow in this zone is expected to have a complex three-dimensional convection-dominated nature.

Another important aspect of ongoing research involves an understanding of the mechanisms responsible for plasma initiation. As mentioned earlier, a spark gap has been widely used as the source of free electrons for initiation. Unfortunately, it is difficult to make a spark jump across the center of a very small focal spot, and this method has proven to be unreliable. An alternate approach is to strike the focal spot with an extremely intense pulse of laser energy from a secondary laser. The pulse causes the propellant to ionize, and a plasma is sustained by the main laser. Recent work by VanZandt and McCay[37] with a 6 kW CO_2 laser cofocused through the primary optics indicate that this can be a reliable method of initiation. For hydrogen, pulsed breakdown intensities are roughly 7×10^9 W/cm^2 with a slight pressure dependence.

A third technique is to rely on seed molecules or particles as the source of free electrons. Easily ionizable molecules, such as cesium, can be seeded into the hydrogen and will enhance absorption at low temperatures.[38-40] Although this helps absorption, it is not known if such suspended seedants are sufficient to reliably cause initiation. The effect of seeds on laser breakdown intensities is shown in Fig. 9, clearly showing that direct initiation may be possible with large seed particles and a small focal spot.[41] A similar approach is to use a retractable tungsten target placed at the focal point, since it has been shown that plasmas can be ignited quite easily off metal surfaces.[42-49] One problem with both this concept and the use of metal vapor seedants is that the vapors may coat and cause failure of the laser inlet window.

A large number of unanswered questions remain concerning the dual-flow device. Measurements need to be made of heat losses to the chamber walls, then used to estimate the overall efficiency of the device. In particular, the magnitude of the radiative losses should be measured. Unlike a chemical rocket, where only about 25% of heat losses are radiative,[50] the dominant loss in a laser thruster is expected to be caused by radiation to the walls.[23,30,33] To reduce this it may be possible to seed the cold annular flow with materials that will intercept this radiation. Another potential problem involves the mixing of the two flows. The fluid mechanics of the thruster needs to be examined to see if the two flows can be mixed thoroughly by the time they reach the throat, to find ways of facilitating this mixing, and to see if the plasma undergoes any instabilities under flow conditions. In ad-

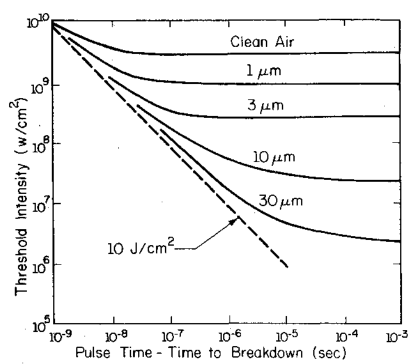

Fig. 9 Laser pulse time vs breakdown intensity in air containing particles of various sizes.

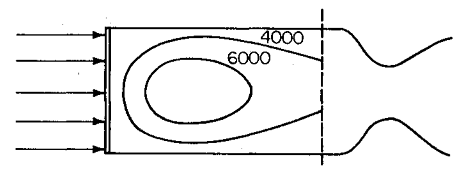

Fig. 10 Temperature profiles of a molecular absorption thruster. Peak temperatures are lower, but the beam can be applied uniformly, permitting nozzle entrance temperatures comparable to the dual-flow thruster (Fig. 7).

dition, since most of the mixing occurs in a temperature range of 2-10,000 K, a reliable means of quickly measuring these temperatures spectroscopically is needed.

Some attempts also have been made to analytically model what is occurring inside a cw device. An early effort by Raizer[51] assumed constant-pressure one-dimensional flow in air with heat addition by a laser. Thermal conduction was considered the dominant heat-transfer mechanism, neglecting radiation losses from the plasma. The solution was obtained analytically, and produced temperatures and ignition thresholds in reasonably good agreement with experiment, although the predicted values of wave velocity were considerably high. Kemp and Root[30] later extended this one-dimensional analysis to hydrogen and included the transport effect of thermal radiation. The formulation also included accurate hydrogen properties and was solved numerically by iterating on the mass flow until a finite downstream temperature was obtained.

The problem was extended to two dimensions by Keefer and Crowder,[34] but retained the simplifying assumption of one-dimensional steady flow. The ratio of specific heat to thermal conductivity was assumed constant, as was the laser beam radius, and radiation from the plasma was considered as a loss only. Most recently, Merkle[52] has attempted to model the very complicated flowfield in the plasma region by including the full set of Navier-Stokes equations in the problem.

Molecular Absorption Thruster

It is possible to avoid the extremely high temperatures, potential instabilities, and initiation problems of the pure hydrogen plasma by using instead a seeded hydrogen mixture and molecular resonance absorption. In this case, a plasma is no longer needed; rather, the laser beam broadly enters the chamber and uniformly heats the flowing propellant. Although peak temperatures are much lower, the uniform heating allows nozzle entrance temperatures that are comparable to the plasma thruster case. In addition, there should be no mixing problems and there are no startup difficulties because the mixture will usually begin absorbing at room temperature. A rough estimate of what the temperature profiles would be like is shown in Fig. 10. Peak temperatures would have to be selected to prevent dissociation of the seed molecules.

As discussed earlier, it is necessary to seed the hydrogen with materials that absorb through molecular absorption. In a series of experiments, Fowler et al.[15,16] measured the absorption coefficients of mixtures of hydrogen containing H_2O, D_2O, and NH_3. In each case, the absorption coefficient was large enough to allow near-complete absorption within a few tens of centimeters (although there has been some disagreement on the H_2O data[17]). Maximum temperatures tended to be 4000-6000 K (much lower than in a pure hydrogen plasma), but adequate for propulsion. In most cases, Fowler created a low-temperature plasma to measure absorption, but he also discovered that it was possible to heat the gas directly without a plasma, resulting in a glowing region of high-temperature gas. Data for D_2O are shown in Fig. 11.

Kemp applied his heat loss model to this device as well, and graphs showing the comparison between the two thrusters are shown in Fig. 8. Several important things can be discerned from the comparison. First, predicted energy losses are roughly a factor of ten greater for the molecular absorption thruster, since there is no buffer gas in this design. Also, since the molecular absorption device does not use pure hydrogen, specific impulse tends to be roughly 20% lower at the same chamber temperature. Finally, the slope of the heat-loss line for the second thruster is positive, indicating growing heat losses as the power is increased. These results have not been proven experimentally but, if true, would result in much lower efficiency for the molecular absorption device. A one-dimensional adiabatic model for flow in a molecular absorption thruster also has been developed by Legner and Douglas-Hamilton.[5]

VII. RP Laser Propulsion

The second major type of laser propulsion uses a rapidly pulsed laser instead of a continuous beam. As a result, the working fluid is not stably heated; rather, it is subjected to tremendous bursts of laser energy. Each pulse heats a small amount of propellant, which then is explosively driven out a rocket nozzle.

Operation of a typical RP thruster is shown in Fig. 12.[20,53,54] In this device there is no absorption chamber as such; only a complex parabolic nozzle whose interior is covered with a highly reflective coating. The function of this nozzle is to concentrate the laser pulse at the focus point, which is located just downstream of the propellant inlet. The intensity at this point is extremely high ($>10^7$ W/cm^2 for air), and when it strikes a small amount of propellant that has been injected into the nozzle, it causes the fluid to ionize and break down into a high-temperature, rapidly expanding plasma,

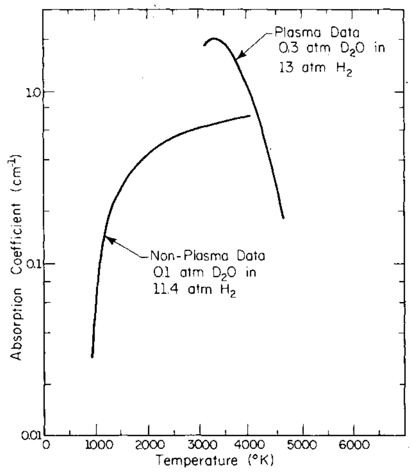

Fig. 11 Absorption data for D_2O-seeded hydrogen.[15] Data are shown for operation with a plasma and without.

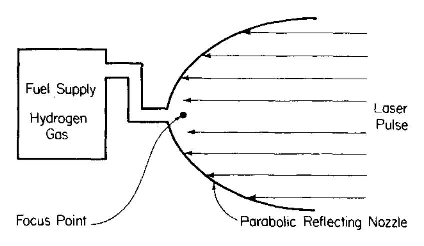

Fig. 12 Schematic operation of RP hydrogen thruster.[20] Hydrogen enters nozzle when pressure is low and then is struck by a laser pulse. This ionizes the gas and creates an LSD wave, which propagates out of the nozzle.

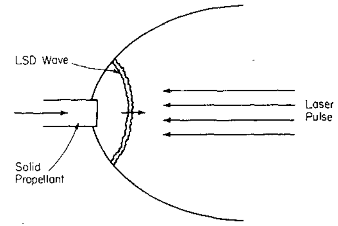

Fig. 13 Operation of a solid propellant RP thruster. A solid rod is advanced to the focus point, where the tip is struck by the pulse, ablating a small amount of solid and creating an LSD wave.

known as a laser-supported detonation (LSD) wave. As this wave, which resembles a supersonic blast wave, begins moving out of the nozzle, the laser pulse ends. Total duration of the pulse is typically about 1-5 μs and is followed by a pause sufficiently long to allow the LSD wave time to totally escape the nozzle. When this occurs, more fuel is injected into the nozzle and another pulse arrives, completing the cycle. An alternate approach is to use a rod of solid propellant as shown in Fig. 13.[13,55]

The operation of the RP thruster is dependent on the phenomenon of the LSD wave. This supersonic wave was first found to occur when metallic surfaces were irradiated with high-power laser pulses for the purpose of examining the potential of lasers as weapons.[22,24,42-49] Typically, when a pulse with a peak intensity of 10^7 W/cm^2 or higher was incident on the target, the air above the target would break down into a plasma, which then began propagating up the laser beam at supersonic velocity. If the intensity was slightly lower, subsonic LSC waves would develop.

The structure of the LSD wave is shown in Fig. 14.[45] It consists of a strong shock followed immediately by a thin absorption zone that travels with the shock. This zone is a high-temperature plasma region with peak temperatures of about 10,000 K. It was quickly discovered that the LSD wave would absorb most of the incident laser energy, thus shielding the target from any damage. This also means that an LSD wave, when used for propulsive purposes, could provide an efficient means of coupling the laser energy to a propellant.

Using the known properties of the LSD wave, it is possible to construct a model of the flow in an RP thruster. The theory behind RP operation is also very similar to studies done on detonation propulsion,[56-59] except that instead of using explosives in the nozzle, laser energy is used to create the blast wave. In 1977, Simons and Pirri constructed such a model,[18,19,60] analyzing the function of an RP thruster operating in a multiple-pulse mode with gaseous propellants. As mentioned earlier, one of the important findings was that specific impulse is proportional to the inverse fourth root of the molecular weight of the propellant, indicating that it is less essential to use low molecular weight propellants. It was also found that the flow in an RP thruster can be nearly as efficient as in a cw device. Another key result was an analytical relation between I_{sp} and the delay time between laser pulses. This is plotted as the solid lines in Fig. 15, where the shaded region represents delay times too short to allow the propellant to flow from the injector to the focus point.

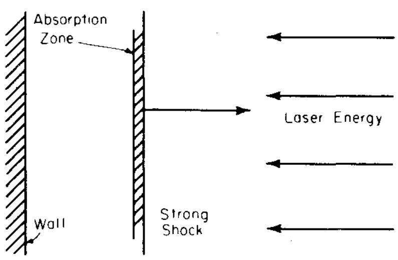

Fig. 14 Initiation and propagation of an LSD wave in air above a surface, first observed in early experiments. The high-intensity laser (>10^7 W/cm^2) creates a blast wave which moves up the laser beam at supersonic velocity. Absorption occurs in a narrow region behind the shock, which heats the ambient gas as it passes.

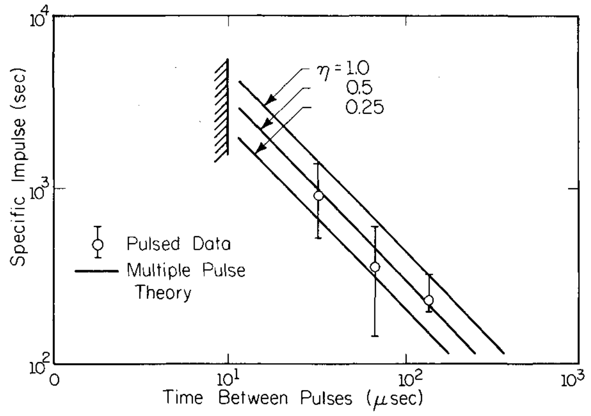

Fig. 15 Specific impulse vs delay time for an RP thruster using helium.[54] Data points indicate observed two-pulse performance with error bars included. Solid lines are predictions based on multiple-pulse theory and represent (from top to bottom) efficiencies of 100, 50, and 25%.

Also shown in Fig. 15 is some actual data from a series of tests conducted by Nebolsine et al.[20,54] The thruster used was a small device using both conical and parabolic reflecting nozzles and a self-regulating fuel feed system as shown in Fig. 12. The device uses gaseous propellants, stored in a plenum, which flow into the nozzle whenever the pressure in the nozzle is low (i.e., when the LSD wave has left the nozzle). Several propellants have been tested, including hydrogen and argon, but the data presented in Fig. 15 are for helium. Notice that not only are high values of I_{sp} indicated, but the values seem to be in good agreement with multiple-pulse theory. The data corresponds to a theoretical efficiency of about 50%, with a large uncertainty.

These experiments seem to verify that high specific impulse can be achieved in an RP thruster and with good efficiency. A major uncertainty, however, is what will happen when these laboratory devices are scaled up in size. Another problem area could be the nozzle, which must be strong enough to withstand the high-pressure, high-frequency blasts while maintaining its reflective coating. It is not known if the nozzle can be cooled sufficiently and strengthened without becoming prohibitively heavy and complex.[55] A third key problem is that the laser must enter the nozzle along the nozzle's axis and, since this design does not easily allow the use of mirrors for redirecting the beam, there may be limitations on the types of space missions that this device can be used for. There are also several potential problems, such as laser transmission through the rocket's exhaust plume,[61] the ability to supply adequate mass flows of propellant in a high-frequency pulsed inlet stream, and the effects of high-frequency vibrations caused by the repetitive blasts.

Still, there are a number of clear advantages to an RP thruster. The main factor is design simplicity. Since everything occurs in the nozzle, there is no need for an absorption chamber or the complicated series of windows and mirrors found in cw devices. This not only means that the RP design can be streamlined more, but, since there is no window, very high laser powers can be handled safely. Another advantage, as demonstrated by Back and Varsi,[57] is that rockets using detonation propulsion are superior to traditional rockets when operating in high-pressure environments near the surface of planets. Also, pulsed beams tend to propagate better through the atmosphere.[7] All of these factors indicate that an RP thruster would be much more suitable for launch from Earth.

Several important aspects of RP thruster operation still need to be investigated. As with cw systems, the basic absorption mechanisms that lead to gas breakdown and formation of the LSD wave are not yet fully understood. In particular, the effect of the presence of ionizable seed particles on wave initiation and breakdown intensity needs evaluation. Also needed is more complete modeling of the LSD wave and its behavior in the nozzle, including an estimate of heat loss to the nozzle walls and overall thruster efficiency.

It is still far too early to make a choice between the RP and cw systems, since little data are now available. However, two factors will be important when deciding—specific impulse and overall efficiency. Continuous wave systems could prove superior due to their ideal nozzle flow and long pressurized absorption chambers that ensure complete absorption. However, RP thrusters, which do not have chamber walls or throats that can be damaged, could operate at higher temperatures and peak pressures. In addition, cw thrusters will be plagued with large radiative energy losses through their walls, a problem that may also be critical in RP nozzles. Obviously much more information is needed before these uncertainties can be resolved adequately.

VIII. Alternate Laser Propulsion

There are also several forms of laser propulsion that have not been studied in as much detail. One of these is the so-called hybrid engine, which uses a modified chemical rocket. After combustion occurs, a laser is used to heat the products further before they enter the nozzle. This increases the chamber temperature and boosts specific impulse. Since a majority of the energy is provided by combustion, lower laser powers can be used. The drawback to this scheme is that high molecular weight fuels must be used, and the added cost and weight of the laser optics could easily offset the improved performance.

Another laser system has been suggested by Myrabo[62] and assumes the availability of a multigigawatt space-based laser. The main purpose of the system is to provide low-cost transportation between distant points on the Earth using small laser-powered shuttles. Such a shuttle would be propelled out of the Earth's atmosphere and allowed to free-fall to its destination. The design incorporates three main types of laser propulsion. At low altitudes the vehicle rotates and sequentially fires a series of radially placed pulse thrusters (rotary pulsejet). The thrusters use air as the propellant, which is picked up as each thruster enters the airstream during the rotation. Since no onboard fuel is required specific impulse is infinite. At higher altitudes the laser is used to create LSD waves in chambers containing hydrogen. The waves drive MHD generators which create a strong potential difference between different parts of the vehicle. When this potential is discharged, a strong shock is created in the ambient air, entraining the air and producing thrust. Once the vehicle leaves the atmosphere, the pulsed thrusters are again used, but now operate with an onboard hydrogen propellant.

A final alternative which has received some attention is the use of lasers to propel aircraft using air as the propellant. This eliminates the need for costly onboard fuels.[63,64]

IX. System Problems

The missions that can be performed by laser propulsion depend a great deal on the laser power available and the location of the laser. In general, however, possible missions can be divided into three groups: stationkeeping, orbit raising, and Earth launch.

Stationkeeping would use a relatively low-power laser in combination with a small thruster to maintain a spacecraft in a desired orbit and/or correct for satellite drift. This places very modest requirements on laser power and thus is certainly feasible, but the added cost and complexity of the laser optics and thrusters would undoubtedly offset the modest gain in performance. At the other extreme, launching from the Earth requires high thrust and therefore high laser power (in excess of 1 GW). Although it is possible to combine the outputs of many smaller lasers into a single beam, it is unlikely that such laser power levels will be available in the foreseeable future.

Laser propulsion appears to be best suited for orbit raising, a mission that demands high specific impulse (1000-2000 s) at moderate thrust levels (1,000-10,000 N). Neither chemical nor electric propulsion can provide this combination of high thrust/high I_{sp}. Such performance requires laser powers of 10-100 MW, which is high but not unreasonable.

A major constraint is the location of the laser. If it is placed on the Earth's surface it will have access to large amounts of electrical power at relatively low cost. And, since the weight of the laser is unimportant, power levels can be very high. But ground-based lasers face an important obstacle; distortion and scattering of the beam, both by turbulence in the atmosphere and from refraction caused by the inadvertent heating of the air in the beam's path (thermal blooming). Although the severity of these effects depends largely on the wavelength of the laser, the result tends to be a beam that is poorly focused, a problem which worsens as the angle from vertical increases. Although the use of adaptive optics will help reduce these problems, the end result will likely be that a ground-based laser only will be able to "see" a target in low-Earth orbit (LEO) for a few minutes per day.[10] It is possible to avoid much of this problem by placing a mirror in orbit that would redirect the ground-based beam. Other alternatives are to build the laser on a mountain top, or fly it on an aircraft to minimize atmospheric effects.[10]

By contrast, a laser located in LEO would have a much wider field of view, would remain within range of the target for a much longer time, and would not be affected by the Earth's atmosphere. This last point implies that beam spreading could be reduced close to the theoretical limit, resulting in lighter, smaller mirrors. One problem with this system is that, since the maximum practical range (using practical mirrors) is under 5000 km (see Fig. 4), the laser and thruster must either occupy similar orbits or a relay mirror must be used. However, the biggest problem is that the laser and a massive power source must first be lifted into orbit.

In the immediate future, it is clear that the lasers available for propulsion will be small; a few megawatts at best. Once larger, more efficient lasers become available, serious considerations can be given to using them for orbit raising, possibly from LEO to GEO (geosynchronous Earth orbit). A study[10] considered the ground-based laser case, comparing its cost to that of an advanced chemical tug (ACT). By assuming a 500 MW beam firing 50-s bursts once per day for 14 days, it was found that the laser system costs were competitive with the ACT, and would become significantly cheaper if shuttle costs continue to rise. Similar results were obtained in studies by Holloway and Garrett[65] and Lockheed.[66]

Obviously, the future of laser propulsion depends largely on the development of lasers producing tens or even hundreds of megawatts of power.[67-70] Current state-of-the-art lasers are producing continuous power levels in excess of 1 MW[67,71] in both pulsed and cw modes. The most highly advanced lasers today are chemical lasers operating in an open cycle. These are compact and efficient, and work at wavelengths that permit good transmission through the atmosphere. The other main type of laser is the electric-discharge laser, commonly used in industry today and capable of high-power output at relatively high efficiency (>20%).[70,72]

New types of lasers are now being developed that promise higher power with greater efficiency. Three of the most promising are the solar-pumped, nuclear-pumped, and free-electron lasers (FEL).[73,74] The FEL in particular offers the potential of very high closed-cycle efficiency while, in principle, being operated at almost any desired wavelength.

By the end of this decade lasers with power levels in the tens of megawatts should be available. And beyond this, there appears to be no fundamental obstacles preventing powers of hundreds of megawatts. The main uncertainty is the desire to develop such lasers and the funding to do so. But since high-power lasers have many potential users (military, laser fusion, power beaming, TELEC,[75,76] and propulsion), interest in these lasers will probably continue.

X. Summary

One of the objectives of this paper has been to demonstrate the proven viability of laser propulsion as an option for propulsion in the future. A large number of problem areas remain, but for each of the devices examined, an effort has been made to identify these problems and discuss possible solutions. There appear to be no fundamental obstacles preventing the eventual development of an operational thruster.

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