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Review of Laser-Solid Interaction and Its Possibilities for Space Propulsion

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PREFACE

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

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ABSTRACT

The literature on laser-solid matter interaction is surveyed and the important regimes of this process are delineated. This information is used to discuss the possibility of a laser induced ablation thruster. It is concluded that such a thruster may be feasible if a sufficiently high intensity, high frequency laser beam is available and that further study of interaction is needed.

I. INTRODUCTION

The major purpose of this report is to determine (1) if it is at all reasonable to use laser induced ablation as a method of providing thrust for a space vehicle and (2), if so, what can be said of desirable properties of the laser beam and the ablation solid. The study concentrates on the laser-solid interaction itself and no attempt is made to consider problems of beam generation and control. The report is divided into two parts: the first is a brief description of the interaction based on a review of papers in the field, and the second deals with the questions posed. Due to the many diverse problems of and approaches to the complicated process of interaction, it was felt that an overall look at this process is necessary to set the proper stage for discussion of the intended application.

II. REVIEW OF LASER-SOLID INTERACTION

A bibliography on laser-matter interaction is presented at the end of this report. Many of the references published in the last few years are given directly; those of earlier work in the field along with discussion are given in [9, 17, 26, 42]. In total there are several hundred papers available.

The interaction of a laser beam and a solid surface depends greatly on the beam intensity* I and pulse time t_p. For Q-switched pulses of 30-50 nsec on metal, emission or surface damage is apparent for $I \geqslant 10^7$ W/cm^2 [9]. Even for long times (such as that for free-running modes) low intensities ($I \leqslant 10^5$ W/cm^2) give surface melting only [38]. For vaporization to occur it is necessary that the heat deposited by absorption reaches the specific heat of evaporation E_v before it can diffuse away. Assuming nearly complete absorption, this requires $I > I_v \approx \rho E_v \sqrt{K/t_p}$ where ρ is the density of the solid and K its thermal diffusivity [2]. For a nominal pulse time of 1 sec, $I_v \approx 10^4$ W/cm^2 for metals within one order of magnitude. Materials with smaller diffusivities may have I_v one or two orders of magnitude smaller. (Also, melting latent heats and thresholds are one to two orders of magnitude less.) With CW laser operation, t_p should be associated with the thermal equilibration time (size) of the material. It is readily seen that for plasma and/or impulse generation, interest is in intensities described by units MW/cm^2 or greater. See [24]. A description of possible physical processes at such intensities is given here, along with a review of work on interaction.

At lowest intensities and/or very short times after pulse initiation the beam impinges directly on the surface, being partially (in most cases to a large extent) reflected and partially absorbed. For metals the classical formula for absorption (characterized by the skin depth based on electrical conductivity) does not apply at high frequencies; the process is quite complicated [9]. A simple exponential

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*Flux density would be the more proper term.

absorption law is used in [9,52]; this simplification is shown in [9] to have little effect on results for times such that the thermal diffusion length is much greater than an anomalous skin depth. (This means for metals times much greater than about one psec.) It is also assumed in [9,52] that the absorbed energy is immediately thermalized; this is reasonable since the electronic relaxation time is small [9]. For very high intensities, direct ionization of the material (tunnel effect) can occur within a time of several wave periods [15,34,56]. A layer of ionized matter with the same (uniform) number density as the solid forms - an overdense layer, i.e., one where the plasma frequency is greater than the laser frequency. If the pulse ends before expansion of this layer can take place (and if nonlinear absorption is negligible), then in essence it may be totally reflected [4,56].

Assuming that significant initial absorption (with thermalization) does take place, the short time behavior (before expansion of any vapor or plasma formed) of the material is governed by any further heating and thermal diffusion. Since phase transitions are taking place and since the vapor formed may partially or wholly absorb the laser radiation due to excitation and ionization (direct or thermal with subsequent coupling of the laser fields with free electrons), the heating and diffusion process takes place with multiphase effects. Diffusion in the limit of an ionized (plasma) material is considered in [13,26,34]. This limit is used to qualitatively describe the case of a high intensity ultrashort pulse that can produce direct ionization and/or rapid thermal ionization so that most of the medium affected by thermal diffusion is an overdense plasma rather than a solid [34]. Heating of a plasma without diffusion (at times shorter than a diffusion time) is considered in [13,21]; classical collisional absorption (inverse bremsstrahlung) in an underdense medium is assumed. The results could be of interest in cases of sequential pulsing when a beam interacts with plasma formed by a prior pulse. If the plasma optical depth is small, nearly uniform heating results along with large reflection at the solid or overdense surface. A large optical depth can give complete absorption in a heating wave that propagates toward the surface [13,21,54]. Surface heating and vaporization (low intensities, nearly transparent vapor, longer times with vapor removal) with thermal diffusion of heat into the solid phase is considered in [9,52]. Evaporative surface cooling can lead to subsurface temperature maximums, superheating of underlying material, and its subsequent vaporization giving explosive removal of a solid surface layer [52].

As the (overdense) vapor forms at high intensities it will expand; the expansion wave at sonic velocity will overtake the thermal diffusion wave at a time t_f. This is the time scale for which consideration of fluid dynamics becomes important. If $t_p > t_f$, then $t_f \approx K\ (\rho/I)^{2/3}$ using solid properties [2]. Considering diffusion in the plasma limit gives a similar result except that K is the electron thermal diffusivity and is a function of the density and temperature (energy input). The result for $t_p > t_f$ is $t_f \approx \text{const.} \times A^{7/2}\ I/\rho^2$, see [26]. Here A is the mass number of the material and the constant equals $\dfrac{m_p^{7/2}}{\sqrt{m_e}\, e^4 \ln\Lambda}$ where $m_{e,p}$ are the electron and proton masses, e the electron charge, and $\ln\Lambda$ the Coulomb logarithm. For $t_p < t_f$ (very short pulses), then using the solid limit $t_f \approx K^3 \left(\dfrac{\rho}{It_p}\right)^2$ and using the plasma limit $t_f \approx \sqrt{\text{const.}} \times A^{7/4}\ \sqrt{It_p}/\rho$ where the same constant applies [34]. The constant solid diffusivity gives smaller t_f at high intensities, vice versa for the plasma. Inclusion of plasma ion heating by electron-ion collisional relaxation would give further complications but not change the qualitative results [34]. It is seen that the determination of t_f for a given situation requires solution of the laser heating-thermal diffusion problem unless the limiting cases discussed give similar results. Typically for long pulses on metal, t_f is in the nsec range for high intensities ($\sim 10^7$ MW/cm^2) using the plasma limit. For intermediate intensities ($\sim 10^4$-10^5 MW/cm^2), t_f drops to the 1-10 psec range (either limit). Pulse times much greater than one nsec are "long" ($t_p > t_f$). It is also to be noted that for lower intensities ($I \leqslant 10^3$ MW/cm^2) the metal vaporization time equals or exceeds t_f and immediate vapor removal takes place. It is only at high intensities ($I \geqslant 10^6$ MW/cm^2) that metals have significant static heating of a nonsolid phase.

For many cases of interest, absorption and heating during the fluid dynamic portion of the interaction are important. Possible absorption mechanisms for a vapor or plasma will be discussed later; the dynamics is treated here. Let ℓ_a denote a typical absorption length (inverse of the absorption coefficient), C the specific heat capacity, and T the temperature of either a solid or vapor (plasma). The heating time (that required to double the thermal energy) $t_h \approx \rho C T \ell_a / I$ with complete absorption and the corresponding acoustic signal propagation time $t_s \approx \ell_a / v_s$ where v_s is the acoustic velocity. If $t_s \ll t_h$, heating is slow and for ℓ_a small the heating wave (which may be diffusive) is a small perturbation. Strong heating ($t_s \gg t_h$) on the other hand would induce shock propagation. The critical intensity ($t_s \approx t_h$) is $I_h \approx \rho v_s C T$. See [13]. If an overdense plasma resides next to the solid surface, then absorption takes place elsewhere and I_h for the solid should be compared to the thermal heat flux at the surface. Partial absorption in the vapor phase can further complicate the task of trying to develop strong heating criteria for the solid phase. Nevertheless, estimates of I_h for a solid are of interest. For metals, $I_h \approx 0.05$ to 0.5 GW/cm^2 for $T = 300^\circ$K. For metal vapors I_h is roughly the same at $T = 2000^\circ$K and varies as $T^{3/2}$. Formation of shocks in both vapor and solid phases can be expected for intermediate or high intensity pulses.

At high intensities, an expanding underdense plasma forms. Absorption of the laser beam occurs in a region near to where the plasma becomes overdense. Heat is conducted from the absorption region to the solid phase. As the expansion first starts, gradients are large and the absorption length ℓ_a is small. Three regions form: the solid phase, then a dense phase separated from the solid by a shock propagating inward (away from direction of laser incidence and absorption), and finally the expanding plasma separated from the dense phase by a deflagration wave also propagating inward and where the absorption takes place. A detailed study of the regions and of the deflagration wave jump conditions and structure is given in [25]. The dense phase has constant temperature and density, both higher than that of the solid. The deflagration wave is weak in that the pressure drops by only a factor of about two. However, the temperature rise and density drop can be two orders of magnitude large. Temperature at the inner edge of the expansion region (next to the wave) varies as $I^{2/3}$, see [25]. The deflagration wave thickness is governed by the electron thermal conductivity, the wave being overdense with absorption at its outer edge only and the Prandtl number being very small. As time increases, the continued expansion means gradients will fall and ℓ_a increase. At the onset of the wave, this means that the absorption efficiency will increase [25,54]; later the absorption will change to primarily a volume effect with a secondary amount in a surface evaporation zone. The dynamic structure changes. Self-similar gas dynamic models as given in [2,5,23] should be valid for these longer times. See also the discussion in [26]. The similarity solutions are 'self-consistent' [5] in that the optical depth of the plasma layer is constant and of order unity. Any decrease in density beyond that at this condition of optical depth would result in more laser beam penetration to the solid surface, increased vaporization, and consequent increased plasma absorption and optical depth - the process is self-regulating. As the plasma layer thickness increases to a dimension like that of the interaction area on the surface, multidimensional effects must be considered [3]. (It is possible that for sharply focused beams a self-consistent state does not form [5].) Lateral spreading of the plasma gives a drop in the vapor density and higher intensity at the surface.* A quasi-steady state vaporization process ensues in contrast to the similar planar case wherein the vaporization rate decreases with time. The spreading also allows the vapor to be accelerated to hypersonic velocities. Details are given in [3], see also [5]. In [23] the effects of nonequilibrium ionization in self-consistent and quasi-steady state heating are explored for intensities $I \geq 10^6$ MW/cm^2. These longer time theories are somewhat limited in that electronic heat conduction is not considered. Structure of the vaporization process is not examined but instead synthesized as an evaporation wave with jump conditions corresponding to complete absorption of the beam. Nevertheless, they are valuable in giving a qualitative view of fluid dynamic processes and in some cases should also be quantitatively accurate. Another model problem of similar feature is that of [10,11] dealing with long time nonstationary wave effects; this is briefly described next.

The model concerns the case of heating at intermediate to low intensities where initially the vapor is essentially not ionized and hence poorly absorbing. Effects of possible beam reflection at the evaporation wave and condensation during expansion are considered. As time increases, the amount of vapor also increases, pressure gradients decrease, and the cooling effect of expansion decreases. Due to the exponential dependence of ionization on temperature, ionization of and absorption by the vapor suddenly increases near the evaporation wave. The vapor heating and

*The optical depth of the plasma outside of the evaporation zone remains of order unity.

attendant pressure rise leads to creation of a shock propagating outward. The absorption length in the vapor becomes small as the ionization increases sharply; absorption takes place in a narrow region behind the shock and it becomes a detonation wave. Vaporization at the surface ceases (thermal conduction is neglected). A plasma forms behind the detonation and the surface pressure drops. As the wave emerges at the vapor-vacuum interface, a rarefaction-heating wave forms and travels inward, preceded by a shock wave. (Instead of a vacuum, a low pressure transparent vapor may be present. In this case a shock propagates ahead of the expansion into this ambient vapor.) This is somewhat similar to the deflagration structure discussed previously and to the heating-shock wave in [13]. Due to the large internal energy of the plasma, the heating wave is much slower (relatively weak) than the original evaporation wave. The preceding shock is reflected from the surface, raising its pressure, and eventually merges with the low density very hot plasma. After this time, the pressure will start to drop again. The heating wave reaches the surface and vaporization resumes. The relatively cold vapors from the (new) evaporation wave drive away the plasma. The entire process then repeats. Several of these plasmas 'flares' can occur during a long pulse (several μsec) such as that from a free-running laser. Despite the rapid and wide surface pressure variations in such a process, the impulse generated changes smoothly with pulse time (total energy at constant intensity) [10,11]. The impulse shows qualitative agreement with that found by self-similar theory but is somewhat larger. This is partly due to the fact that comparisons were made using nonsimilar results which include the adiabatic regime of expansion after pulse termination. It is shown in [10] that the characteristic time for flare initiation (beginning of vapor absorption) and for the pressure pulsations decreases with increasing intensity. It is also shown that lateral spreading increases this time and that if the flare starts in the planar stage before spreading, subsequent spreading will yield a quasi-steady vaporization mode. For high enough intensities with very strong heating, the transparent vapor stage ceases to exist and the evaporation process is continuous rather than intermittent. The discussion of the preceding paragraph then holds. Further details on wave parameters and generation for the recurrent flares are given in [10].

For long times after pulse termination, the dynamics of the vapor is that of a free expansion [44,48]. Continued vaporization after the pulse with heat supplied by the vapor adjacent to the solid surface can make a major contribution to both material yield and the impulse [48].

Results of experimental investigation of the distribution of ion emission over charge, energy, and solid angle at the Moscow Engineering Physics Institute are given in [39,46,49,50]. Other measurements are given in [42]. The former deals with the interaction of a neodynium glass laser with metals at $t_p \approx 15$ nsec and $I \approx 10^2 - 10^7$ MW/cm^2. The pulse time is sufficient for establishment of quasi-steady vaporization [50]. The latter reference uses a ruby laser on aluminum and copper at $t_p \approx 30$ nsec and $I \approx 10^5$ MW/cm^2. Diameter of the area of interaction at high intensities (both cases) is on the order of 10^{-2} cm and is about 10^{-1} cm for $I < 10^4$ MW/cm^2. The average directed kinetic energy of ions of charge Z is found to increase monotonically with Z at a weakly varying rate. The energy is nearly independent of the intensity. Emission tends to concentrate in the normal direction as Z increases. Typically the ion energy is of the order of 10^{-16} J/unit charge. The effect of increasing intensity mainly is to increase the maximum charge of the emitted ions. Single ionization only occurs for $I \approx 10^2$ MW/cm^2, $Z \leq 5$ for $I \approx 10^5$ MW/cm^2, and $Z \leq 20$ for $I \approx 10^7$ MW/cm^2. The total number of ions produced with charge $Z \gg 1$ is several orders of magnitude smaller than the number with charge $Z \approx 1$; the decrease is roughly exponential. Average charge is $Z \approx 2$ to 3 for the higher intensities. These results are consistent with the quasi-steady vaporization theory where equilibrium conditions are assumed for the plasma composition in the one dimensional absorbing region (at least for $I \leqslant 10^6$ MW/cm^2) and a nearly adiabatic expansion with recombination occurs in the outer spreading region [39,46,50]. The importance of recombination is pointed out in [42,49,50]. Ions of large charge ($Z \geqslant 7$) tend to have frozen composition in the expansion due to their large velocities [50]. Rate processes are considered theoretically in [23] for $I \geqslant 10^6$ MW/cm^2. The mechanism for producing such large ion energies is that of a quasi-neutral collisionless expansion [1,42,50]. The electrons receive energy from the laser beam and attain large velocities. They have a tendency to expand quickly, but the heavy ions set up a restraining electric field with the charge separation and slow down the electrons. The ions experience an acceleration proportional to their charge. The energy transferred per electron is small but the process is effectively repeated many times (the electrons fall back) until the ion current (velocity) matches the electron current (velocity) in the outer part of the expansion. It is to be noted that the ion yield may be a small fraction of the total mass removal by the beam [42]. This can be explained by recombination and especially by post pulse evaporation [48].

Experiments at low intensity ($I \approx 10^1 - 10^3$ MW/cm^2) indicate large liquid yields [38,43]. This can be explained by crater formation with attendant gas dynamic blowing of surface liquid off the crater walls. Liquid drops can also form by condensation in the vapor and by vapor formation in superheated surface liquid, giving another blow-off effect. See [24]. Droplets can act to shield the surface from radiation. At high intensities of laser radiation, heating and vaporization rates are sufficiently high so that droplet formation need not be considered. For given energy, the total yield at first increases with intensity, then drops [9]. The change (for metals) occurs at $I \approx 10^3 - 10^4$ MW/cm^2 [9,29]. The increasing yield can be attributed to increasing vaporization (and melting) rates. When the stage of vapor ionization is reached, the plasma absorbs the energy and shields the surface, vaporization drops [9] and crater formation may not occur [29]. Microscopic splinter formation has been observed after pulses of intensity $I \approx 10^4$ MW/cm^2 [35]. The hypothesis made to explain this is that of compressional relaxation. The laser pulse forms a high pressure vapor at the surface and a compression wave travels in the solid. When the pulse ends, surface pressure drops, and a rapid expansion of the compressed solid gives fracturing and explosive particle removal. A surface pressure as large as 10^{11} N/m^2 (10^6 times standard atmospheric pressure) is deduced in [51] from experimental measurements involving a beam of roughly 10^5 MW/cm^2 intensity on a carbon target. This is as large as the elastic. modulus of metals. At a low intensity of 300 MW/cm^2, a pressure of only the order of 10^8 N/m^2 can be expected [11]. Stresses are considered in [31,32,36,37].

Finally, this review of processes in laser-solid interaction will close with a discussion on vapor or plasma absorption. While radiation emission from the vapor is certainly measurable [17,20], it can usually be considered negligible compared to the input energy of the beam [4,17,38,48]. Scattering of the beam is also unimportant [4]. Thus absorption and reflection or refraction of the beam are the important radiative effects. Efficient absorption may be expected upon plasma formation; this is brought out by experimental results [26,28,38,42,48,68]. Changes in the absorption by a vapor as intensity increases are described in [59] and will be briefly given next. A cold vapor (without electronic excitation) is transparent. A partially ionized vapor will exhibit an absorption coefficient independent of intensity at very low intensities. Absorption is by bound-free or free-free electronic transitions (assuming no resonant bound-bound transition). For radiation at optical frequencies, the former can occur only with highly excited atoms, the binding energy of lower states being too large. If the heating and absorption are very weak, the temperature and kinetics of the vapor are not changed and neither is the absorption. As the intensity increases beyond a certain value, increases in temperature and absorption promote ionization, especially of the highly excited atoms for short times. A decrease in absorption can result since the excited atoms absorb most of the light. As even stronger heating at larger intensities takes place, excitation and ionization from the lower states become important and as a plasma forms strong absorption occurs.

Consider an electromagnetic wave propagating in a situation where travel is from a transparent medium (such as a vacuum) to a plasma where the charge density builds up from near zero to an eventual overdense condition (plasma frequency ω_p greater than wave frequency ω). The wave induces periodic charge motion (essentially electronic) in the plasma, i.e., it becomes a plasma wave. The wave group velocity decreases as the charge density increases until the critical density ($\omega = \omega_p$) is reached and reflection occurs. Absorption can take place by damping the plasma wave directly or by transformation of the transverse wave into a longitudinal wave with subsequent damping. In the former case collisions of the oscillating electrons with ions can damp the wave and this is known as classical collisional absorption. It corresponds to absorption by free-free transitions (inverse bremsstrahlung), taken in the high temperature limit where the thermal energy greatly exceeds the photon energy [4]. This is the mechanism of overriding importance in many cases of gas dynamic interaction and is discussed in [53,54].

Let ℓ_d denote the characteristic electron density gradient length near the critical density. Nearly complete collisional absorption requires $\ell_d > c\tau_{ei}$ where c is the velocity of light and τ_{ei} is the electron-ion collision time based on critical density [54]. This is simply a requirement that a collision (damping) takes place in the time the light takes to travel through the underdense region that is near to being overdense. (In the very underdense region, little of the wave energy is carried by the electrons.)

In a narrow density region near critical ($\omega \approx \omega_p$), generation of longitudinal plasma oscillations is possible by either a resonant coupling to the beam electric field in a case of incidence at an angle to the density gradient [54,63,69] or a coupling due to the presence of ion density fluctuations [53,54,55,66]. Maximum coupling for inclined incidence results if the polarization (electric field vector) is in the plane of incidence; the (driving) field component along the gradient direction is then for a given incidence angle greatest. Increasing the angle also increases this component but gives reflection at lower densities (lower ω_p) - a deleterious effect for large angles. Optimum incidence angle θ is about $\theta \approx (\omega\ell_d/c)^{-1/3} \ll 1$ [63,69]. The velocity characteristic of the electron oscillation in the plasma wave is $v_e = \frac{eE}{m_e\omega}$ where E is the electric field amplitude. The plasma is 'cold' if its electron thermal velocity is much less than v_e, 'hot' if it is much greater. In a cold plasma, damping of the inclined incidence longitudinal oscillations can be by collisions [63] or if the plasma is collisionless, by breaking of the plasma wave [69]. As the temperature increases, Landau damping can be expected to become important [54,63,69].

Efficient coupling through ion fluctuations requires that they be larger than thermal, hence some form of instability is needed [54]. Such an instability requires a minimum (high) intensity for formation [54,55]. Many types of instabilities have been postulated [54,55,66]; perhaps the most important are the modified two stream [55,64] and parametric [54,55,64,66]. This anomalous absorption has not been verified experimentally [26].

A summary of the salient features of the processes of interaction is in order. At the lowest intensities of interest, surface absorption, melting, and evaporation with diffusion of heat into the solid phase are the important phenomena. The vapor is effectively transparent and expands freely. The processes of beam absorption-reflection and phase change at the surface are quite complex. Liquid blow-off may occur. As the intensity increases with concomitant increase in the evaporation rate and vapor temperature, the ionization-enhanced absorption threshold is obtainable and a quasi-periodic system of wave 'discontinuities' may propagate in the vapor phase. The vapor then absorbs much of the laser energy and becomes a plasma. Further increase in the intensity gives plasma formation from the solid with much or all of the absorption occurring in the expanding plasma after an initial short time. The interaction is then principally gas dynamic. Collisional damping of plasma waves becomes a major absorption mechanism. Excitation and damping of longitudinal oscillations can also be important in deflagration, detonation, or evaporation waves. The initial static heating can be important for ultrashort high intensity pulses. The dimensional effect of lateral spreading results in a quasi-steady process for long times of gas dynamic interaction.

III. POSSIBILITIES FOR SPACE PROPULSION

It is seen from the review in the first part that a laser impinging on a solid can produce ablation particles of high energy and large surface pressures. Utilization of this effect of impulse generation for a propulsion system is discussed here. It is common to speak in terms of a 'coupling coefficient' which is the impulse per unit energy for a given laser pulse. Experimental values for intermediate intensities (10^4 - 10^5 MW/cm^2) are in the range 10^1 - 10^2 μN-sec/J [9,48,51]. Experiments with free-running lasers at low intensities (10^2 - 10^3 MW/cm^2) give a higher coefficient [43], even lower intensities [1] give a similar or lower coefficient. In [1] a systematic investigation of the use of various metals as an ablative material for propulsion is reported. A maximum specific impulse of 660 sec was determined. Relatively low ion energies were measured. The specific impulse is about equal to 0.1 η/β where η is the efficiency of conversion of the laser energy into directed kinetic energy (including absorption efficiency) and β is the coupling coefficient in N-sec/J. Since η is potentially high [48], a specific impulse of 10^3 to 10^4 sec appears feasible. This agrees with the ion energies discussed in the first part. It is seen that the low intensity results correspond to low conversion efficiencies η, particularly those of [1]. This can easily be explained by large beam reflection and inefficient particle acceleration mechanisms (surface vaporization and heating with free expansion and also liquid blow-off for [43]). Interaction in the quasi-steady gas dynamic (plasma) mode provides efficient absorption and also the related collisionless expansion produces large ion energies. The ion energy and directionality increase with charge (intensity). Provided that efficient absorption is maintained, it seems reasonable to try to utilize the highest intensity possible. Minimum intensity (ionization threshold) is about

10^4 MW/cm^2 for metals (see Sec. II). The threshold depends mostly on the ionization potential and thus this minimum intensity should approximately hold for other materials too. The best ablation material would probably be one of low potentials for multiple ionization. Time for establishment of the quasi-steady mode is shortest for material of small mass number (Sec. II and [5]). This may be of importance at higher intensities, especially if the pulse energy is limited.

It is assumed that the laser beam is generated at a fixed station (earth, moon, or orbiter) and sent through space to the vehicle. The elimination of an on-board power supply is one of the main attractions of the present proposed application. Assuming beam divergence in the diffraction limit [70], the intensity at the vehicle I_{veh} in relation to the generation station intensity I_o is $I_{veh} \approx I_o d^4/(\lambda^2 L^2)$ where d is the beam diameter at the station, λ the wavelength, and L the distance traveled. Taking d = 1 m, $\lambda = 10^{-6}$ m, and $L = 10^4$ km, $I_{veh} \approx 10^{-2} I_o$. Laser energy transmission is seen to be a valid procedure for near space application provided a high frequency (visible or UV light) is used to minimize divergence. The laser ablation thruster must be compared to a laser absorption (solar) cell - power conditioner - ion engine system [71]. Since the specific impulse is probably comparable, efficiency is an important consideration. Complete collisional absorption requires that $\ell_d > c\tau_{ei}$ where $\tau_{ei} \sim \omega^{-2} T^{3/2}$ since $\omega_p^2 \sim$ electron density. Efficient absorption is thus favored by high frequencies. This is also true for inclined incidence absorption where the effective "collision time" is $\tau_{eff} \approx \left(\frac{m_e \ell_d^2}{\omega k T}\right)^{1/3}$ [54]. In the quasi-steady vaporization mode, $\ell_d \approx r$ where r characterizes the interaction area radius and plasma thickness. The requirement $r > c\tau_{ei}$ is equivalent to the condition that the electron density outside the evaporation zone be less than critical. The minimum radius can be determined as $r_{min} \approx 10^{-15} A^{1/2} \lambda^4$ I where r_{min} is in cm, λ in μm, and I in W/cm^2. Using A = 10 and $I = 10^4$ MW/cm^2, $r_{min} \approx .32$ cm for $\lambda = 10$ μm and

$r_{min} \approx 3.2 \times 10^{-5}$ cm for $\lambda = 1\ \mu m$ (near infrared). For visible or UV light, r_{min} is very small even for high intensities. This means that complete absorption can be expected. (It also implies that the density change across the evaporation wave is large.) The overall need for high frequency is quite clear.

Assuming a pulse time equal to the time for establishment of the quasi-steady mode [5] and using nominal values $I = 10^4$ MW/cm^2, $A = 10$ and $r = 1$ mm, the minimum pulse energy can be estimated. It is equal to about 6 J at $\lambda = 1\ \mu m$ and scales as $\lambda^{-2/9} A^{7/18} r^{26/9} I^{7/9}$. For the intended application, pulses with energy of several thousand joules would be desirable.

The shape of the pulse with respect to time may have to be tailored to avoid fragmentation by either subsurface superheating or compression relaxation.

To examine the possibilities of a laser ablation thruster a little further, consider a laser producing 100J pulses at $\lambda = 1\ \mu m$ and focused on the ablation material with an intensity of 10^4 MW/cm^2 and spot radius 1 mm. The pulsing frequency is 10^5 sec^{-1} and the space vehicle mass is 500 kg. Assume that the thrust force during the pulse is given by quasi-steady theory [5], it scales as $\lambda^{-2/9} r^{17/9} I^{7/9}$ and produces a time average acceleration in this situation of approximately 0.2 m/sec^2. The time average power input is 10 MW. Note that this estimate of acceleration cannot be considered as being accurate in that post pulse evaporation and the possible effects of rapid pulsing are not considered. The actual acceleration may be near the value given above and could possibly be considerably greater.

It can be concluded that it is reasonable to consider laser ablation for near space propulsion. It is clear that fairly high intensity beams at high frequencies are needed. The actual feasibility of such a system can only be determined by a more detailed analysis and/or experimental studies. The latter is not presently possible due to limitations of available lasers with regard to pulse energy and frequency. An attempt at analysis would involve difficulties due to the complicated nature of the interaction and ignorance of some aspects of the problem. For example, to model the structure of the evaporation zone, it is necessary to know the thermodynamic and transport properties of high temperature multiphase mixtures and their absorption and reflection properties. Details of such processes are not presently known [9,25]. Also, it cannot be said that excitation, ionization and recombination rates are well known. Non-Maxwellian velocity distributions (see [23,69]) introduce further difficulty. Analytical modeling without experimental verification of results may be somewhat dangerous.

NOTE: A recent book on laser-matter interaction [72] came to the author's attention after completion of this review and study. The book contains a comprehensive view of the process and is certainly recommended reading. However, the most recent references are understandably not used and the discussion of gas dynamic interaction and plasma abs ption is not thorough. Some of the conclusions are at variance with the results presented here. The author feels the present review to be more pertinent to the problem of laser ablation thrusters.

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As a matter of convenience, papers are split into three groups and listed chronologically in each group.

General

(Review papers, plasma dynamics, overall modeling.)

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