THE DANIEL AND FLORENCE GUGGENHEIM MEMORIAL LECTURE

High Power Lasers in Space and Aeronautics

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HIGH POWER LASERS IN SPACE AND AERONAUTICS

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Abstract

Two applications of lasers to aerospace technology will be discussed. First is the development of laser metal fabrication which could have an impact in improving welding technology to the point where use of welding in aircraft structures could become much more widespread. Applications of high power lasers to surface heat treating and alloying will also be discussed.

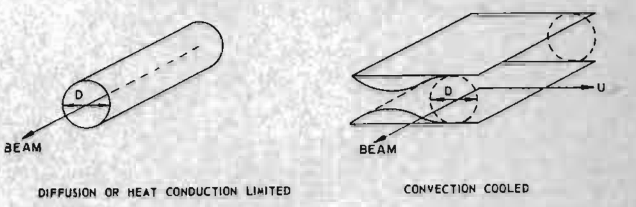
The second laser application is to the propulsion of objects from earth to low orbit. If the energy received from a 10^9 W ground based laser were efficiently converted into the kinetic energy of a propellent at suitable specific impulse (800 seconds) then propulsion to orbit seems a definite possibility with possible large savings in access to space.

The High Powered Laser

The first gas lasers were essentially Geissler tubes in which the mechanism for achieving an inverted population depended on the difference between the high electron temperature in the gas and the low gas temperature. The gas temperature in these lasers was kept low by contact with the walls. If one attempted with such a laser to increase the power by increasing the diameter or by raising the pressure, transition to an arc occurred in which the gas temperature became high destroying the difference between the electron and gas temperatures. I'd like to begin by describing the advances that have been made in the last few years which now have made many orders of magnitude improvements in the power capabilities of several kinds of gas lasers.

The first we call the waste disposal principle. We can make a great gain by the well known story of removing heat by convection instead of diffusion, which is illustrated in Figure 1. The gasdynamic laser, which is shown in Figure 2, is an illustration of the power potential of the convection cooled laser. In 1971 we(1) announced the achievement of 60 kW CW with a gasdynamic laser.

HIGH AVERAGE POWER LASERS



$\approx$ 1 KW M

IN A DIFFUSION CONTROLLED LASER, WASTE ENERGY IS REJECTED IN A CHARACTERISTIC TIME

$$\tau_{DIFF} = \left(\frac{D}{\lambda}\right)^2 \left(\frac{\lambda}{C}\right) = \frac{D^2}{\lambda C}$$

MOVING THE GAS AT A SPEED U, WASTE ENERGY IS REJECTED IN

$$\tau_{FLOW} = \frac{D}{U}$$

SO FOR SAME ACTIVE VOLUME, AND SAME DENSITY, THE RATIO OF POWER AVAILABLE IS

$$P_{FLOW}\, P_{DIFF} = \frac{\tau_{DIFF}}{\tau_{FLOW}} = \frac{D}{\lambda}\,\frac{U}{C} \sim \frac{D}{\lambda}\, M$$

$$\sim 10^3 \cdot 10^5$$

Figure 1

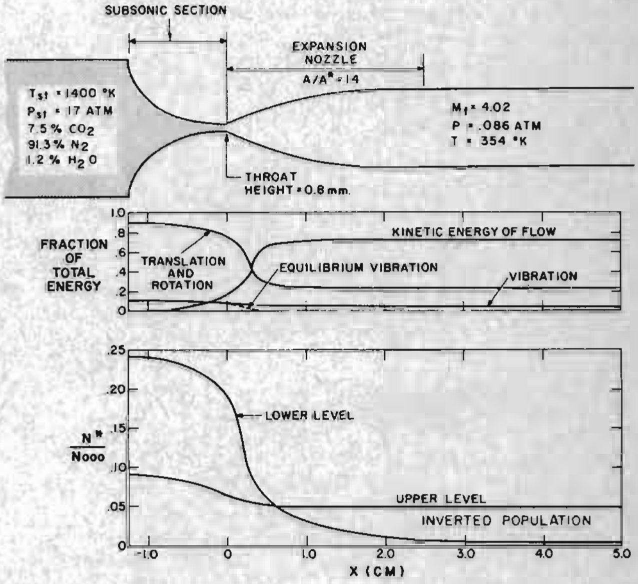


Figure 2. Illustrating the operation of a gasdynamic laser in which an inverted population is achieved by rapid cooling which freezes in an upper CO_2 level population. Simultaneously adequate water concentration to deactivate the lower level population is added. Thus, an inverted population is achieved in the supersonic region.

The second important principle was invented by James Reilly(2) of Avco Everett Research Laboratory. He pointed out that, as is well known, in large scale discharges the thermal instability, which produces the transition from a glow discharge to an arc, is an instability in the production of free electrons. If one had a highly uniform method of producing ionization throughout a gas volume and simultaneously arranged that electron temperatures were kept low enough so that the initial ionization would be the only ionization present then the transition from glow discharge to an arc could be prevented even for very large volumes and high pressures. This separation of these processes can be done cleanly for a CO_2 laser as is shown in Figure 3. If the electron temperature is kept below 1.3 volts then the ionization rate, due to the high temperature tail of the Maxwell distribution, will be negligible. On the other hand, for the CO_2

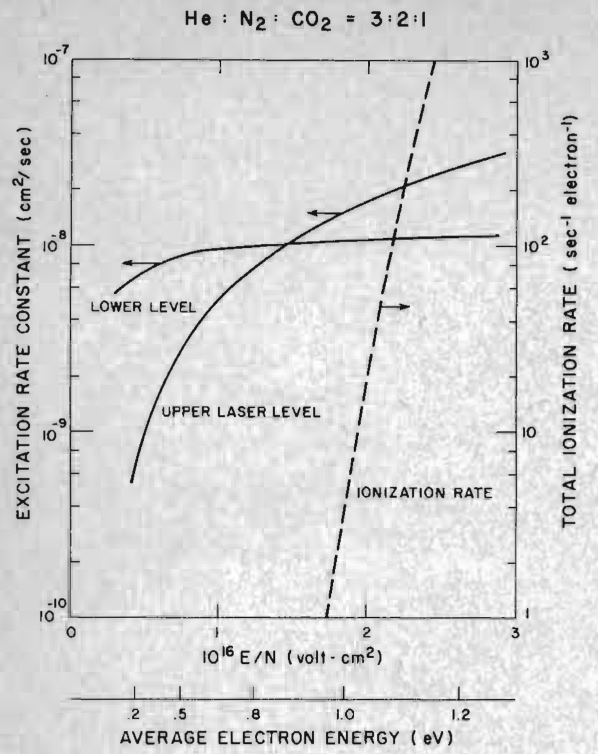


Figure 3. Illustrating the excitation and ionization rates for a 3:2:1 He:N_2:CO_2 mixture. For average electron energies greater than about .85 volts, the upper level is excited more rapidly than the lower level producing an inverted population. For electron average energies less than about 1.3 volts the ionization rate is still small enough so that very little ionization occurs while the gas is being excited to lase.

laser it is possible to excite the upper state laser level and the vibration of nitrogen (which transfers rapidly to upper state CO_2) without exceeding the field strength or the electron temperatures at which appreciable ionization rates will occur. If then the initial ionization is achieved, for example, with an electron beam accompanied by the application of a homogenous electric field (the sustainer field), a uniform large scale glow discharge can be attained. A schematic diagram of apparatus for achieving this type of discharge is shown in Figure 4. There will, of course, be a steady degradation of the electron energy to heat the gas and, thus, the process can only be continued for a finite time before fresh gas must be used. This, however, has allowed the production of about 50 joules of 10.6 micron laser energy per liter atmosphere of 3:2:1, He:N_2:CO_2 mixture.

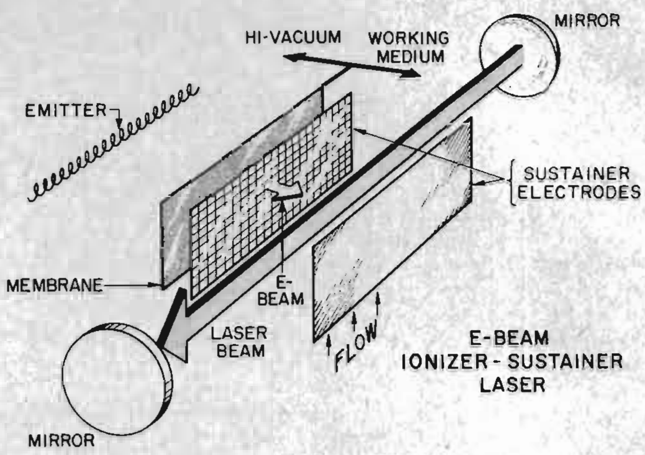


Figure 4. Illustrating the principle of the E-beam sustainer laser in which an electron beam is formed in high vacuum, passes through a metal foil membrane, and ionizes the laser gas uniformly to a controlled electron density. The application of the sustainer field then keeps the electron temperature high enough to excite the upper laser level and to achieve an inverted population, but not high enough to increase the ionization beyond that produced by the electron beam. Thus, a uniform glow discharge can be achieved in a large volume at a high pressure. This design has increased the power capabilities of electrically driven lasers by orders of magnitude.

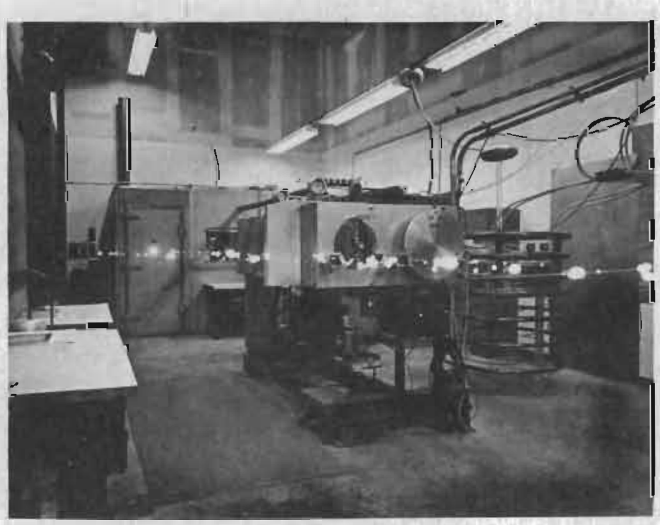


Figure 5. A practical realization of the E-beam sustainer laser. This laser produced 2,000 joules in 20 microseconds pulse with near diffraction limited performance. The hundred megawatt beam exploded dust particles in room air which produced the string of white beads in the photograph.

In what follows, I will be talking primarily about E-beam sustainer lasers which have been made to operate in both pulse and CW modes. A pulsed E-beam sustainer laser is shown in Figure 5.(3) This laser produced 2,000 joules of 10.6 micron radiation in 20 μsec. The white spots along the beam trajectory are plasma blobs produced by the explosion of dust particles in the room air. At the time of its construction it was by far the most powerful laser of its type. The principles enunciated above can also be used in a steady flow laser which produces CW power. The realization of this potential is shown in Figure 6. It is clear that both the pulse and the CW versions can be extended to much higher powers.

Figure 6. The Avco HPL-10 two station metal working laser. In this laser continuous operation at powers up to about 15 kW is achieved for industrial processing of metals. To facilitate more intensive use of the laser which is capable of operating continuously, two work stations are used so that set-ups can be made at one station while the other station is performing an operation. Lasers of this type have been sold to the Caterpillar Tractor Co. and the General Motors Corp.

It is one of my purposes this morning to exhibit to you the extraordinary range of roles that the high power laser will play in aeronautics and in space. I propose to do this by discussing two contrasting applications of high power lasers -- one is close enough to realization that the appropriate considerations are really detailed ones, whereas the second one can still be dismissed with laughter, perhaps for another few years. These two applications are extremes, and let us just say that we don't have time to discuss the array of intermediate applications which might exist.

Laser Metalworking

It has been appreciated for some time that the high power laser could offer exceptional opportunities in the working of metals because it would enable the application of heat to achieve a refinement which has hitherto been possible only in the vacuum electron beam. The vacuum electron beam has demonstrated its ability to perform superior welds, and to do other fine work involving the precise application of heat. However, in use outside the vacuum its performance is degraded and this has resulted in a restricted field of application. The high power laser offers similar facility as an extremely flexible and controllable heat source without the necessity for the vacuum enclosure. In the continuing search for fine fabrication techniques it is not surprising that laser fabrication techniques have attracted a certain amount of attention from aeronautical production people, as they have in other industries where high quality metal fabrication is important.

I want to tell you something this morning about some of the applications that are under development with the 15 kW laser we call the HPL-10.(4) First, let's consider deep penetration welding. In deep penetration welding one applies localized heat with an intensity so great that the pressure generated by boiling metal is sufficient to displace the molten liquid. This process requires powers of the orders of 10 kW (Figure 7). The penetration which can be achieved naturally is a function of the beam power and the speed with which the beam moves along the seam. Typical results are shown in Figure 8, and these are very similar to those attained with vacuum electron beams. A typical cross section of a weld is shown in Figure 8. Welds can be made in this way with quality comparable with vacuum electron beams. Laser cutting of materials is particularly interesting for those materials which resist machining, an example is in removing the flashing from a titanium forging (Figure 9). Another application of lasers is to the hardening of surfaces. This can be done by sweeping a beam across the surface in order to heat it and to rapidly quench the heated region by heat conduction to the substrate after the beam moves on. Case hardening achieved in this way is shown in Figure 10.

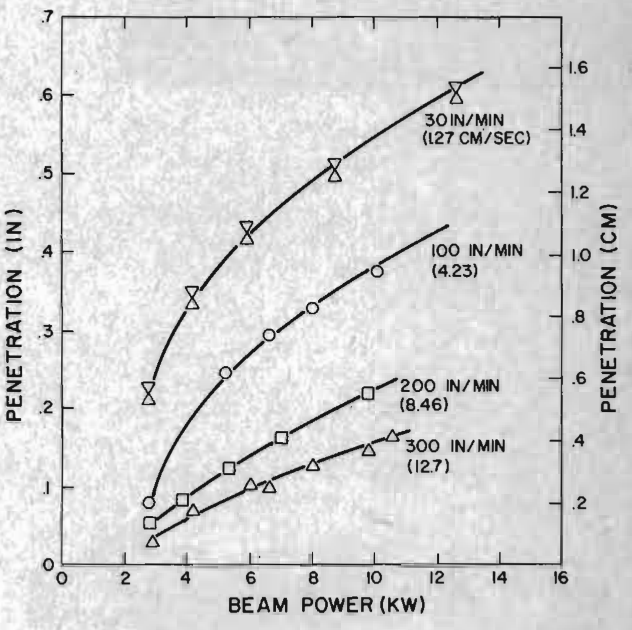


Figure 7. Maximum thickness of 304 stainless steel which can be fully penetrated by the Avco Laser Metalworker operating at various beam powers and various speeds.

Another similar application is in surface alloying metals to achieve extreme wear and corrosion resistant properties. Results achieved in this way are exhibited in Figure 11 and Figure 12.

Laser Propulsion

I would like now to turn to a very different application of lasers. For many decades before it was successfully accomplished, it was proposed that chemical rockets could be built to propel objects to earth orbit and beyond. It was always admitted that such rockets would be very much larger than the payloads they propelled because of our inability to attain jet velocities close to orbital velocities. Nevertheless, the drive to expand man's horizons, which is at the heart of the space effort, was so compelling that this operation was

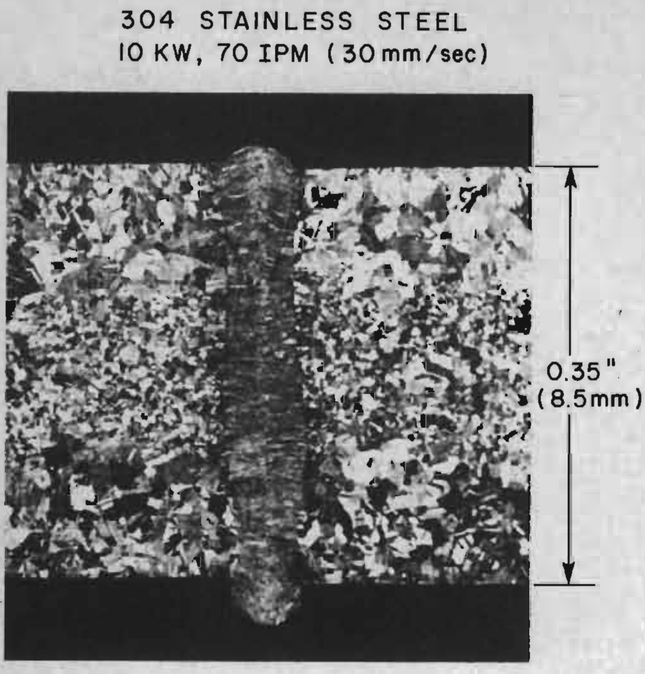


Figure 8. Butt weld between two sections 12" (30 cm) dia stainless steel pipe with 0. 35" (0. 9 cm) wall thickness. Weld was made in single pass from the inside by deflecting a laser beam, which entered pipe along pipe axis, to a radially outward direction.

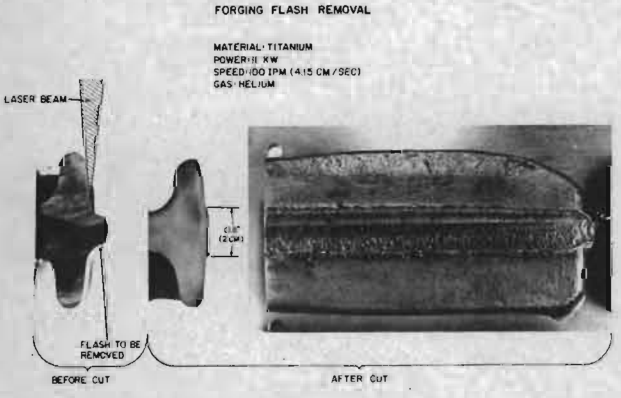


Figure 9. Laser cutting of flash from a titanium forging. Because no bulky cutting head is required for laser cutting, the cut edge can be located very close to the forging projections. The bandsaw quality 0. 8" (2 cm) deep cut has a very narrow heat affected zone because of the high cutting speed, and is relatively free of oxide formations due to the use of a helium assist gas.

undertaken in spite of its considerable costs. Indeed, several important applications for instrumented space vehicles have been found which clearly justify their cost even on very simple economic grounds. However, a great deal of uncertainty exists about the future of manned space

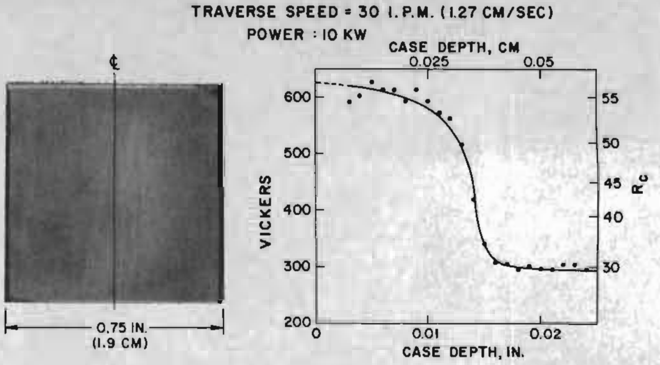


Figure 10. Cross section of 4140 shaft heat treated by ring source generated from annular laser beam focused onto the shaft surface by a toric mirror.

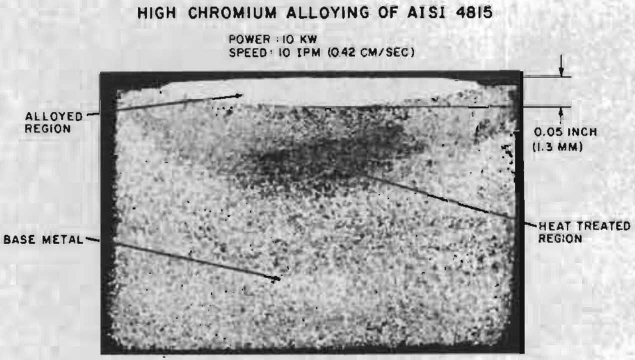


Figure 11. By adding chrome to a thin laser melted layer of this 4815 steel, a surface was generated by this on-line process which maintains its hardness at very high temperatures.

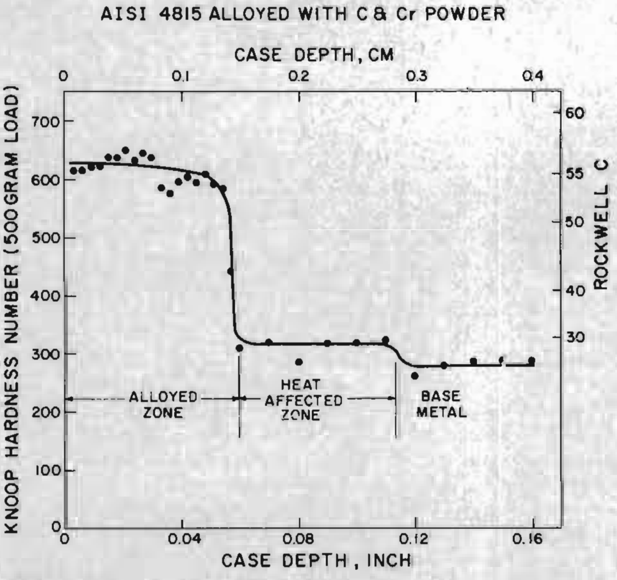


Figure 12. The alloyed region, with hardness values in excess of R_c55, is approximately 0. 050" (0. 125 cm) deep.

flight. Indeed, the high costs of manned space flight have resulted in a cliche terribly damaging to public support for space flight that goes -- "if you can afford to put a man on the moon why can't you. . . . " The key idea has been the enormous costs of these operations and this cost is undoubtedly related to the costs of boosters and the very large installations needed for their operation. It is true that the space vehicle costs themselves have been very large but this possibly was related to the necessity of preventing failure at almost any cost and to the necessity for heroic engineering efforts to make minute weight savings.

There has for many years been another possibility for going from earth to orbit, namely, the possibility of beaming power from the ground to the vehicle, of using this power to accelerate air or a propellant carried aboard to velocities much higher than those attained with chemical rockets. This possibility has been attractive for two reasons. First, almost all of the machinery is on the ground where repeated use offers a tremendous opportunity for cost saving. Second, the opportunities, as in electrically propelled jets, to achieve specific impulses as high as desired has, of course, also been very attractive. It has been proposed many times that transmission of radio waves or microwaves could some day implement an entirely different space program than that powered by rockets. This system has not been developed because radio waves and even microwaves would spread by diffraction to the point that they could not be concentrated on a vehicle's antennae. Nevertheless, this has been a very attractive idea. Consider how much it would cost to put a pound in orbit if you had an electric cord plugged in that could continuously supply the power. The kinetic energy of an object in low earth orbit is about 4 1/2 kW hours per pound which only amounts to a few cents worth of electricity. Transmitting power to accelerate a vehicle into orbit offers a major opportunity to reduce the costs of space operations.

The point of all this is that now we can begin to see a realistic way of accomplishing this dream. The high power laser provides us with an energy source which can be transmitted through the atmosphere without large loss either by diffraction or absorption and furthermore, it is well known that laser beams impinging on an object (Figure 13) can easily evaporate material and produce jets with specific impulses ranging into the thousands. Here then is a possibility that can lead to a completely different kind of space program. Let's do a few numbers to see if this whole idea makes sense.

Let us calculate the amount of power necessary to place a 1-ton payload in low Earth orbit. Let me review simplified calculations interrelating laser power absorbed by the vapor, P, thrust on the vehicle, T, vehicle mass loss rate, $\dot{m}$, and vehicle acceleration, $\dot{v}$. Assume that the vapor is heated enough so that the latent heat of evaporation can be neglected and that all the vapor enthalpy is efficiently converted to a jet of velocity, V. Then:

$$P = \frac{1}{2}\dot{m}V^2$$

And neglecting atmospheric drag and gravity:

$$T = \dot{m}V = m\dot{v}$$

The specific impulse can be varied over wide limits by suitable choice of propellant and by time variation of the laser power.

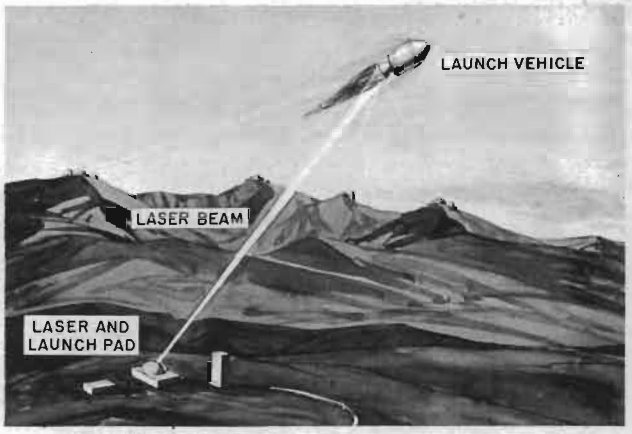


Figure 13. An artist's sketch to illustrate the use of ground based laser beam power to accelerate a vehicle. A number of lasers, say ten, are focused on the vehicle being accelerated into orbit. Note that no system for converting the laser energy into the thrust of a propellant is indicated here. This lack reflects the need for intensive work in this area.

An interesting and simple case to analyze is V = v: ejected mass just coming to rest in Earth coordinates. In this case the momentum of the vehicle stays constant since no momentum remains in the wake. If P is constant, then the vehicle acceleration $\dot{v}$ will be constant during the laser propulsion trajectory (from the equations above):

$$P = \frac{1}{2}\dot{m}v^2 = \frac{1}{2}m v \dot{v}$$

For a final orbital velocity of 8×10^5 cm/sec, assuming that we accelerate at 10 g (10^4 cm/sec^2):

$$P/m_0 = \frac{1}{2} 8 \times 10^9 \text{ ergs/sec gm}$$

$$= 400 \text{ watts/gm} = 400 \text{ MW/ton}$$

where m_0 is the mass reaching orbital velocity.

After making allowances (see below) for propagation losses, thrustor losses, etc. , it seems reasonable to suppose that the laser assembly required would have a power output of about 10^9 watts. In order to provide something like an "engine out" capability and also to reduce development costs, I would propose that we use ten 100 MW lasers as was indicated in Figure 13.

It is worth noting that the diffraction spreading of beamed power which defeated the microwave propulsion system is completely tolerable for the laser wavelengths. For example, at $\lambda = 10.6$ microns the diffraction spreading of a laser beam $\frac{2.4\,\lambda}{D}$ can be held to 10^{-5} radians with a mirror 2.4 meters in diameter D. The scattering of the laser beam by atmospheric disturbances is in the order of 10^{-5} radians for very good seeing from high mountains. With vehicle receiver optics of one or two meters in diameter at ranges of 100km the laser beam could be concentrated on the receiver optics.

Problems in Laser Propulsion

Before a project of this sort could be undertaken, a number of problems must receive a much fuller exploration. These problems will now be listed, but in most cases only speculative answers can now be given.

1. The first problem is undoubtedly the scaling of lasers from presently obtained powers to the order of 100 MW. The physical order of magnitude of a 100 MW laser can be estimated from the performance of existing CO_2 E-beam sustainer lasers which produce approximately 50 joules per liter atmosphere of laser medium. Thus, for 100 MW, 2 million liters per second will be required and if the gas flows at 10^5 cm per second at a pressure of .3 atm (room temperature), a flow area of about 7 square meters is required which will give some idea of the dimensions. The power required for such a laser might be like 500 MW since the efficiency obtainable is of the order of 20% (the power required to drive all ten lasers would be 5 GW). I do not want to minimize the problem of scaling up lasers to this order of magnitude. However, I know of no physical limitations which will prevent us from doing so.

I would like to illustrate the scaling up difficulties by considering what I believe to be the toughest problem in scaling up to this order of magnitude. This is the problem of obtaining the medium homogeneity necessary to achieve the high optical quality postulated. If we select a laser optical path length of say 10 meters and we ask that the beam brightness be within 10% of the theoretical maximum, this requires that the medium be homogeneous in optical path length to about .3 of a wave length (λ). This requires that the density variation averaged along the optical path length be less than 1/2%. The significance of this can be seen from the fact that in order to produce the laser energy (50 joules per liter) postulated, we must approximately double the temperature of the gas while it is flowing through the laser region. Thus, it is required that the heat disposition be controlled through the laser region to about 1/2% and that density variations due to other causes be held similarly small or be optically compensated. This, of course, is an engineering problem of considerable proportions. It is reminiscent of the difficulties in making large high quality optical mirrors. One needs a technique of iterative testing and adjustment to achieve this kind of precision.

2. The second problem is the problem of pointing the lasers at the proper part of the vehicle and this will require pointing accuracy similar to that which is obtained with present day astronomical telescopes (10^{-5} radians). There are two differences between the pointing of these lasers and the pointing of an astronomical telescope. First, the slewing rate is much more rapid with accompanying rigidity requirements. On the other hand, by utilizing a closed loop operation with the cooperative target vehicle in which pointing errors can be telemetered back to the lasers, it seems that this problem is soluble.

3. The problem of propagation through the atmosphere will also require a good deal of attention. The propagation of intense laser beams through the atmosphere will alter the translational temperature and this alteration can be positive or negative depending on the nature of the absorption. Thus, if the energy absorbed is quickly transferred to translational energy, it will produce an acoustic expansion, thus, eventually lowering the density. On the other hand, absorption by CO_2 of 10.6 micron radiation results in the removal of CO_2 molecules from the 100 state which is then refilled from translational energy resulting in a decreased translational energy and eventually in increased density. The problems involved are well understood in principle, but the achievement of a system adequate to compensate for them in practice will require a considerable research and development program.

A second propagation problem that might present even larger difficulties is atmospheric breakdown. As we illustrated in Figure 5, high intensity laser beams produce local gas breakdowns when they impinge on atmospheric dust particles. A typical result when an intense laser beam impinges on an alumina particle is shown in Figure 14. In this figure one can notice the particles being propelled in much the same manner as we have postulated for laser propulsion. One could hope that the results on the vehicle would not be quite as violent as those on these alumina particles. While these phenomena are not understood quantitatively, the following rules generally seem to offer some kind of a rough upper bound to the power than can be safely transmitted. In the CW 10.6 μ laser the power limit seems to be above 1 MW/cm^2. For pulsed lasers about 10 joules/cm^2 can apparently be transmitted without serious gas breakdown. If we have a beam of one square meter cross section, the propagation of 10^9 watts calls for an average power of 10^5 watts per square cm. Thus, it seems that at least for propagation, breakdown limits will not prevent the laser propulsion envisaged here.

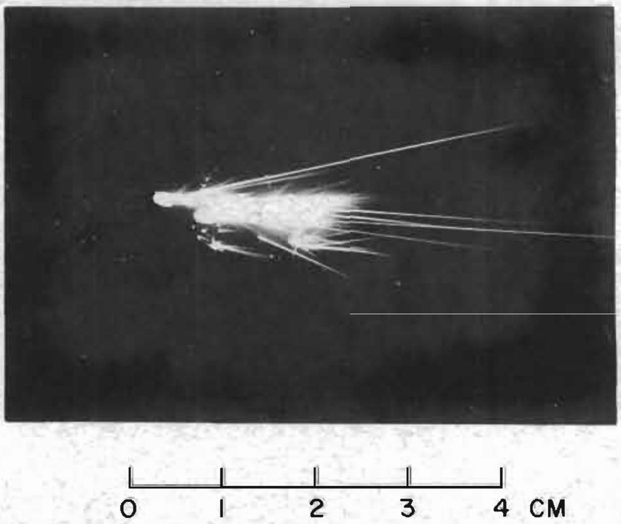


Figure 14. Impact of an intense laser beam 30 MW/cm^2 on 20 - 30 micron alumina particles. The evaporation of the particles produces a plasma which is heated intensely by the laser beam. The evaporation also propells the particles away from the laser rapidly accelerating them to very high speeds.

It is clear that more work is necessary on the propagation of high power laser beams. Very little information exists on their transmission through the upper atmosphere. These are problems that will require considerable research and development before laser propulsion can be realized.

4. Perhaps the most uncertainty exists in the area of converting laser energy into thrust at the proper specific impulse (about 800 seconds) and with high efficiency. There is, of course, lots of evidence(5) that high velocity jets can be produced by evaporating metal with lasers, but in general this has not been done with high efficiency. Efficiencies so obtained have generally been less than 20%. One reason for the low efficiency is that with small laser spots gas flows in to a solid angle of about 2π so that only a small fraction of the momentum is directed. This can be overcome for laser pulses by making the pulse duration short enough; however, it must be remembered that atmospheric breakdown limits may be a constraint here. Another source of loss will be the energy reradiated from material heated by an intense laser beam. An interesting possibility in thrustors is presented by the opportunity to use air as a propellant medium.(6) Figure 15 shows a laser powered ram jet. Since in this device neither the propellant nor the energy source need be carried on the vehicle, indefinitely large specific impulses should be attainable. This could be attractive for aeronautical as well as space application. It seems clear that a great deal of work must be done before it can be said that efficient laser thrustors exist. This work is just beginning at Avco Everett under NASA sponsorship.

LASER PROPELLED RAM JET

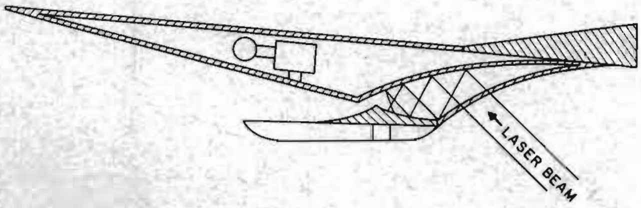


Figure 15. In this schematic drawing a proposed technique for a laser driven ram jet is suggested. Easily ionized seeding material, e.g., potassium vapor, is introduced upstream of the throat. A laser beam impinges on the aft end of the vehicle whence it is focused near the throat, thus, heating occurs due to the laser energy in a relatively high energy region producing thrust in the standard manner for a ram jet. Other opportunities for laser ray paths will be evident.

Concluding Remarks

I have attempted to exhibit that the development of the high power laser will have an important impact on aeronautics and perhaps will revolutionize the technology of the propulsion of vehicles to orbit. The load capacity of a laser propulsion system promises to be orders of magnitude greater than that achievable practically with rocket propulsion systems. It could be the fundamental supply system for massive earth orbit assembly projects. If developed it could provide the propulsion for modules from which large scale manned orbital stations could be assembled.

Projects of this sort are distinctly unfashionable in these pessimistic times, and it may well be that years will elapse before the serious R & D efforts to realize an advance of this kind can be begun. In the meantime, the development of high power lasers will hopefully continue for lesser objectives. The study of propagation through the atmosphere is continuing, and if sufficient research can be done on thrustor development, perhaps laser propulsion can be prepared as a realistic option when enthusiasm for taking the next step into space will be rekindled.

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