APPLICATION OF HIGH POWER LASERS TO SPACE POWER AND PROPULSION

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INTRODUCTION

The National Aeronautics and Space Administration (NASA) is engaged in a high-power laser research program. The objective of this effort is to define the potential of high-power lasers for space missions of the future. The Lewis Research Center is responsible for the systems portion of the overall effort. Of necessity, the areas of investigation for system evaluations cover a broad range of technologies. Key areas in the Lewis effort are indicated in table 1.

Of particular interest to NASA is the transmission of power over long distances for applications such as direct conversion to propulsive thrust or electrical power. A key area of work pertains to problems inherent in transmitting, propagating, and receiving the laser beam over long ranges. The space-oriented applications of interest to NASA suggest that long duration and closed-cycle operation, with high efficiencies and reliabilities, are important technical goals for the laser. In addition, continuous wave (CW) operation is deemed of primary importance, at least for space operation, since such operation requires no high voltage switching components and reduces the peak intensities placed on the mirrors. Currently, only CO_2 lasers satisfy these criteria.

Accordingly, a major area of investigation is to advance CO_2 laser technology relative to these goals. However, wavelengths shorter than that of CO_2 (10.6 μ) are desirable (e.g., providing smaller transmitter and receiver mirrors); hence, efforts are also underway to explore other possible lasing media. Particular emphasis is being placed on visible portions of the spectrum due to possibly better compatibility with photovoltaic power conversion devices and possibly better atmospheric propagation. Here again, the goals are high efficiency, closed-cycle, CW operation. In this paper, the laser application to electrical power conversion and propulsion, and the associated problems of transmission of the laser beam, will be summarized.

POWER CONVERSION

The electrical power requirements of current Earth orbital satellites are typically less than 10 kW, and quite often in the 1-2 kW range. Solar cells are the primary power conversion source for these requirements. In the future, larger amounts of power may be required for applications such as direct broadcast satellites or manned space stations. Power conversion systems, other than solar cells, that may be considered include nuclear heated Brayton-cycle or Rankine-cycle systems, or solar-heated Brayton systems. A concept of a solar-Brayton system (ref. 1) is shown in figure 1. The large mirror at the bottom concentrates the solar energy into a receiver/heat exchanger system located at the top. The large ring surrounding the receiver is the radiator.

With the advent of the laser, and the possibility of transmission of high power beams over long ranges to a receiver of relatively small diameter, the solar-Brayton system of figure 1 can also be envisioned as a laser-Brayton system. The mirror concentrator, for a laser beam, would then no longer be a variable with power output. Instead, its size would only be a function of distance from the laser beam transmitter and size of the transmitter. Figure 2 is an example of a low-Earth requirement. The mass of solar cells, solar-Brayton, and laser-Brayton systems (based on weight assumptions for the solar-Brayton, ref. 2) are compared for a range of power outputs. In all cases, energy storage is included to account for night power or power required when out of sight of the laser transmitter. As can be seen, the laser-Brayton is competitive with the other two systems because of the small mirror required for a low-Earth orbit. In this example, the laser beam generator is assumed to be on the Earth, hence, the mirror is only 2 m in diameter for the 185-km range with a CO_2 laser having a 2 meter transmitter mirror. The receiver mirror mass is estimated to be about 7-9 kg.

Figure 3 is a similar comparison for the geostationary orbit case. Here the laser-Brayton system is at a decided disadvantage at less than 100 kW due to the very large (30-m diameter) and heavy (1725 kg) mirror required for a CO_2 laser beam. Obviously, this case could be improved by using a shorter wavelength laser, thus permitting use of a smaller mirror size.

The above two examples are for laser-Brayton engine systems of about 25-30 percent efficiency, systems that are compatible with state-of-the-art CO_2 laser (or, for that matter, with a laser of almost any wavelength) because the beam is only used as a heat source. Photovoltaic cells, similar to solar cells, are predicted to be capable of about 40 percent efficiency when illuminated by laser radiation in the visible wavelengths (ref. 3). Use of such cells would improve the comparisons. (Currently however, high-power visible wavelength lasers, capable of closed-cycle CW operation, are only in the conceptual feasibility stage.) Indeed, the mirror weight line on figure 3 would potentially become the power conversion system mass, if a photovoltaic cell system or similar such device became available and if the cell could withstand the higher laser beam flux levels (that is, watts per square centimeter as contrasted to solar cell technology of tenths of watts per square centimeter). For low-Earth orbit (fig. 2), the comparison would then be even more favorable to the laser system.

Other types of laser energy conversion devices are now only in the conceptual and discovery stages. It appears, however, that any system for conversion of laser beam energy to electrical power must not only have the general desired attributes of high efficiency, low mass, and low cost, but also must have the capability to operate at high laser beam flux levels. Of course, the required wavelength for conversion must be compatible with efficient laser beam generators. Other factors, such as altitude, total power, total mass, launch vehicle constraints, location or locations of the laser beam generator, and total cost, also will enter into the final power system selection process.

LASER PROPULSION

Another use of laser energy is for propulsion. The concept involves transmission of power from a remote laser station to a rocket vehicle where the laser radiation is used to heat a propellant, thus providing thrust. The laser could be located on the ground, in an airplane, or on a space station.

This concept is unique compared with other forms of propulsion in that it separates the energy source from the vehicle and also permits independent control of specific impulse, thrust, and choice of propellant. A schematic drawing of the concept showing the laser, in this case on the ground, and the rocket vehicle is illustrated in figure 4.

A number of technical areas must be considered in evaluating this concept. The major areas are:

1. Mission (trajectory constraints)
2. Laser power (scale-up to high power levels)
3. Transmitter (pointing stability, adaptive phased array design)
4. Atmospheric propagation (if operating within the atmosphere)
5. Receiver (vehicle constraints; lightweight design)
6. Engine (heat transfer; laser beam coupling)

Missions envisioned for this concept include orbit-to-orbit transfer, interplanetary injection, orbit drag make-up, and vehicle launch.

For a laser powered launch vehicle, perhaps 10^9 W of laser power would be required on target over a period of a few minutes, and even then the payload would only be about 1000 kg or less (ref. 4). At the present, launch vehicles using laser power appear to be quite remote. One mission of importance with lower power requirements, and therefore a more feasible application of the laser, is the one of delivering a payload from low-Earth orbit to geostationary orbit.

Figure 5 is a plot of payload mass delivered to geostationary orbit from low-Earth orbit as a function of trip time for an initial vehicle, propellant, and payload mass of 28,200 kg (the payload capability of the Space Shuttle). In this case, the trip time is the total round trip time required for the vehicle to go to geostationary orbit, drop off its payload, and return empty to low-Earth orbit. Parametrically presented are calculated values of specific impulse and laser power. Values of specific impulse of 1000 sec or greater offer significant improvements over a chemical rocket vehicle and require laser power levels possibly achievable in the near future. For instance, delivery of a 15,450 kg payload to geostationary orbit in less than 10 days would require a laser input of only 4 MW. This represents a fourfold improvement in payload capability over a chemical tug, which is currently under study for use with the Space Shuttle. For this example, the laser powered rocket engine operates continuously. This requires that the vehicle receiver be in continuous view of a laser transmitter. One way of accomplishing this would be to place laser beam generators on two or more space stations.

Other mission profiles for delivery of a payload from one orbit to a higher orbit are also possible. A concept for one such trajectory, which requires only one laser station located on the ground, is shown in figure 6. This concept is called perigee propulsion (ref. 5). Starting with the vehicle in low-Earth orbit, power is beamed to the vehicle via a ground-based laser for only a brief period of time as the vehicle passes overhead. This point corresponds to the perigee of the trajectory. The orbit is increased as a result of the rocket thrust, but thrust time is controlled so that upon completion of each orbit, the vehicle trajectory returns to the same perigee, which in all cases is directly over the laser station. Upon reaching the desired altitude, the orbit is circularized either by the laser rocket engine or by use of an auxiliary chemical rocket engine. The primary advantages of this concept are that only one laser is required for the mission, and, because the vehicle always returns to the same location relative to the laser station, pointing and tracking requirements are simplified compared to other techniques where continuous power is required. This concept, however, because of atmospheric propagation losses and trajectory constraints, does require higher laser power than the space-based laser concept shown previously in figure 5.

Other techniques for using the laser to supply power to a rocket vehicle, in addition to the two discussed, are also possible. Multiple laser stations on the ground, or airborne lasers having greater maneuverability and operating above a large portion of the Earth's atmosphere, are other approaches of interest.

LASER-POWERED ROCKET ENGINE

Relatively high values of specific impulse, hence high temperatures, are required to achieve the high levels of performance shown on figure 5. Figure 7 shows the specific impulse in space for hydrogen propellant as a function of temperature. Two curves are presented, one in which the thermodynamic state of the hydrogen is assumed to be frozen throughout the expansion process, and one in which the thermodynamic state is in local equilibrium during expansion.

This figure shows the temperature requirements likely to be imposed upon the rocket engine. For example, specific impulse values of 1000 and 2000 sec, for frozen expansion, require average chamber temperatures of about 3200° K and 10,000° K, respectively. It can be seen that at 3200° K the specific impulse of hydrogen greatly exceeds the deliverable specific impulse of the high-energy chemical bipropellant combination of hydrogen and oxygen operating at this temperature. For laser rocket engines at the lower specific impulse level, energy from the laser could conceivably be transferred to the hydrogen propellant by conduction from a laser heated plug. Such development would probably not require significant advances in technology. The engine with a specific impulse of 2000 sec, however, would be well beyond current technology.

A possible schematic for such an engine is shown in figure 8. In concept, laser energy would be beamed through a window and absorbed directly in the propellant, creating a sustained plasma. Either the heated plasma would exhaust directly through the nozzle, or coolant gas would be heated from the stable plasma core and act as the propellant (similar to the nuclear gas-core rocket concept). Some of the research areas associated with this laser rocket engine concept are:

1. Plasma initiation – This entails techniques for absorbing the radiation by the cold gas, causing it to ionize sufficiently so that inverse bremsstrahlung absorption can be initiated. Cesium particles, carbon particles, molecular gases, or starting arcs have been proposed as possible techniques.

2. Plasma stability – After initiation, subsequent changes in absorption may occur; these would result in an instability which might be detrimental to performance and operating life.

3. Energy transfer – Techniques for transfer of plasma radiation to the propellant are required. Seeding the propellant gas with micron-sized tungsten or carbon particles might be a possible approach. These would also protect the chamber walls.

4. Window technology – The window must pass a high-power laser beam for long periods of time. And, in addition, it may receive radiation from the very hot plasma. Cooling problems may be severe and require further evaluation.

Figure 9 shows an experimental test device to be used at Lewis for preliminary laser-heated flow visualization studies. These studies should help us to better understand the phenomena and problems associated with a laser beam interacting with a flowing seeded gas. Contracted efforts are also underway to evaluate both analytically and experimentally laser-plasma phenomena in rocket-type devices.

LASER TRANSMISSION

Most of the laser power and propulsion applications of interest to NASA will involve transmission of the laser beam over long distances. Such transmission may be in space (vacuum) or through the atmosphere. Current lasers provide different intensity distributions at the output aperture, depending on the type of optical resonator used for the cavity. Uniform illumination, Gaussian-type profiles with varying degrees of truncation, and annular modes are some more common profiles. From a systems point of view, it is important to know the propagation characteristics of the various beam shapes and, more importantly, to know the optimum intensity profile to place at the transmitting aperture to achieve a desired result at the receiver. (In some cases, maximum intensity might be desired; in other cases, maximum power in a given receiver diameter might be the desired result.) An analysis is underway at Lewis to evaluate these characteristics in a vacuum (that is, space).

Figure 10 shows some of the types of transmitter profiles we have considered to date. These profiles, emanating from a circular aperture (comprised of a single mirror or multiple segments) all have the same total integrated transmitting power. The scale at the left of the figure provides an indication of the relative intensities. The distribution with the lowest intensity is the uniformly illuminated case. Intermediate in intensity is a Gaussian beam truncated at its $1/e^2$ radius. To achieve the same total power on the transmitting aperture as the uniform distribution, the truncated Gaussian central intensity must be larger by a factor of 2.3. The third profile shown is that of a Gaussian with only a very slight truncation, in this instance at twice its $1/e^2$ radius. Here the central intensity is eight times as large as for the uniformly illuminated case to achieve the same total transmitter power. One can also see that the thermal gradient and thermal loading on the transmitting optics will be much more severe for the Gaussian-type beams.

Figure 11 shows the shape of the same beams when they reach the receiver in the far field. In this figure, relative intensity is plotted against receiver radius, which is expressed in terms of $\lambda L/D_T$, where λ is laser wavelength, L is range to the receiver from the transmitter, and D_T is diameter of the transmitter. For all beams, diffraction limited propagation (e.g., in a vacuum) is assumed. Notice that the beam from the uniformly illuminated aperture now has the highest central intensity, the one leaving as a $1/e^2$ truncated Gaussian becomes about 92 percent as great, and the Gaussian with only a slight truncation at the transmitting aperture becomes only 48 percent as great. For applications requiring maximum intensity, the uniformly illuminated beam would be the best choice of the three considered. These results are only valid, of course, for the case considered, that of equal power beams at the transmitter.

For those applications involving optimization or maximization of delivered power within the smallest spot, the uniformly illuminated beam may not be the most desirable. This is illustrated in figure 12. Power is shown as a percentage of transmitted power versus the receiver radius, again in terms of $\lambda L/D_T$. The uniformly illuminated beam, at the "classic" value of $1.22\ \lambda L/D_T$ (that is, radius of the Airy disk), is seen to give 84 percent of the total transmitted power. The $1/e^2$ truncated Gaussian beam provides the same amount of power in a smaller radius, or, at the same radius, will give an increase to 94 percent transmitted power. It appears that the $1/e^2$ truncated Gaussian is the most efficient for the cases considered. Obviously, trade-offs are required for each specific application depending on weight of receiver, cost of receiver relative to the transmitter, and intensity limits of the receiver and transmitter.

Using the truncated Gaussian profile on the transmitter, receiver diameter is plotted versus transmitter diameter in figure 13, for transmission distances of 160 km (low-Earth orbit) and 36,000 km (corresponding to geostationary orbit altitude) and for the case of 86 percent transmitted power. Again, diffraction limited propagation is assumed, as would be the case for laser beam transmission from a space station to another satellite or space vehicle. Also, the wavelength is assumed to be $10.6\ \mu$, as from a CO_2 laser. For the general case of equal diameter receiver and transmitter, it can be seen that the diameter would correspond to only 1.7 m for the 160 km range, a value well within the state of the art. For 36,000 km, however, the diameter is 25.7 m, a size well beyond the current capabilities of fabrication for the precise transmitter mirror that would be required.

For the receiver, however, large diameter, lightweight structures are most likely feasible. Figure 14 is a picture of a prototype solar mirror for the solar-Brayton power system (ref. 1). This mirror is fabricated from sections machined from magnesium and then formed to shape. The mass of this prototype is 4.9 kg/m^2. Figure 15 shows a more recent solar mirror fabricated at Lewis. This mirror is made of thin aluminum sheet material, including the supporting rib structure. The mass of this mirror is 1.5 kg/m^2. Based on this technology, laser receivers of quite large size appear feasible.

Since large transmitters appear necessary for most space applications, we have initiated efforts to evaluate techniques for fabrication of such mirrors. A current contracted effort is investigating the feasibility of several concepts for a 30-m diameter space-based laser transmitter. One of the concepts is schematically shown in figure 16. A composite base structure is used to provide stiffness and low mass. The mirror itself is segmented, with each segment (which could be either circular or hexagonal in shape) being limited to a diameter such that the mirror is within current state-of-the-art fabrication capability. To control the figure, or shape, of the mirror, each segment is individually controlled by precision actuators. In operation, a separate detection scheme would sense the figure (surface contour) and signal the appropriate actuators if corrections were required. In another concept, not shown, the segmented mirrors would be replaced with a thin deformable membrane surface.

The use of either thin membranes of uncooled segments appears feasible since only 0.6 W/cm^2 would be incident on the 30-m diameter mirror surface for a 4000 kW laser beam. And, of this amount, only 6 mW/cm^2 would be absorbed. The large size of a transmitter, as required for the CO_2 laser wavelength, thus might become an advantage under certain circumstances due to heat transfer considerations.

Another approach to active control is the use of coherent optical adaptive techniques (COAT) (ref. 6) with a multiple mirror system. The advantage of such phased array control is shown in figure 17. As indicated by the sketch on the left, diffraction-limited focusing is possible in a vacuum. In the atmosphere, however, turbulence cells cause defocusing, as shown in the center schematic, due to phase changes in the waves as they pass through the cells. In the adaptive phased array, a return wave is detected at the transmitter.

The detection system provides a means to obtain an error signal resulting from atmospheric aberrations, transmitter jitter, and optical misalignment. Active control of the high power transmitter mirror system can then be accomplished to tailor the phase of the wavefront, thus providing maximum power on target. COAT systems are highly versatile and applicable to either high power, master oscillator-power amplifier (MOPA) configuration lasers or to high power, unstable oscillator lasers. Indeed, with the MOPA configuration, adaptive control can be applied to the low-power master oscillator prior to amplification, thus correcting for perturbations in the amplifier gain medium. Another advantage to a COAT system is that it allows automatic acquisition and tracking of the target, thus easing the pointing and tracking requirements for the mirror mount system. Overall, it now appears that adaptive phased arrays may be the only feasible technique for near-diffraction limited transmission of power over long distances, and we have initiated contract effort in this area.

SUMMARY

The general objective of defining the potential of high power lasers for future space missions, forces our research program into consideration of all elements of the total system. The laser beam generator, its associated power supply, and the transmitter optical system will generally comprise a complete unit, which will be remote to the end use application. Such a unit may be located on the ground or in space. Limitations in beam propagation must be considered if the beam passes through the atmosphere. Typically, the receiver will be located in the space environment and will have unique characteristics, depending on whether electrical power is desired or whether beam energy is used to heat propellants for rocket thrust. Perhaps the greatest unknown area is that of highly efficient conversion of laser beam energy into electricity. In all cases, detailed trade-offs between the various components, their efficiencies, and their characteristics will be required to optimize the system.

Technology is not available today to undertake many of the applications discussed in this paper. On-going efforts in this area give promise, however, that such technology will become available in the future, thus providing an advancement in space capabilities and offering a choice among future mission options.

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TABLE 1.– NASA/LEWIS RESEARCH CENTER HIGH-POWER LASER SYSTEMS RESEARCH PROGRAM

Key areas	Potential requirements
Application concepts	Power; propulsion
Transmission	Long ranges; high beam quality
CO_2 lasers	High reliability; closed cycle operation
New lasing media	Short wavelengths; high efficiency; closed cycle operation

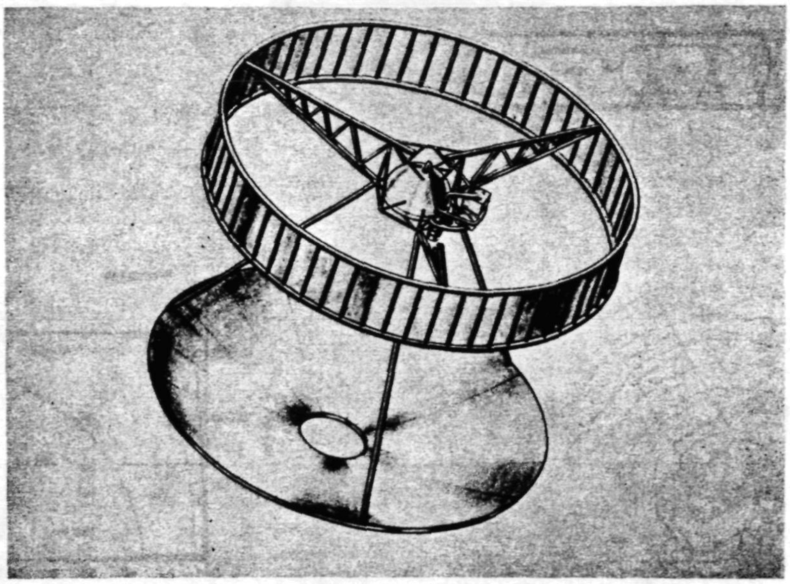

Figure 1.– Solar Brayton cycle space power system.

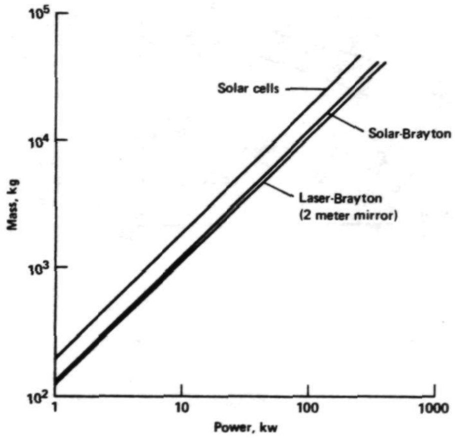

Figure 2.– Weight comparison – low orbit.

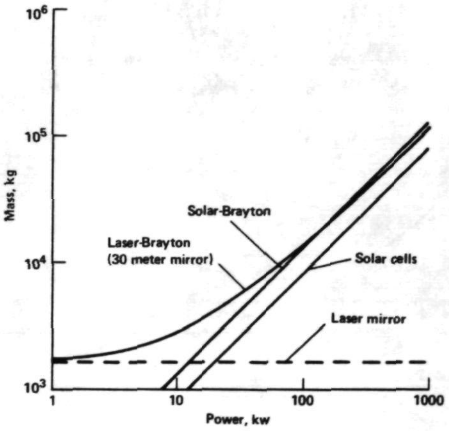

Figure 3.– Weight comparison – synchronous orbit.

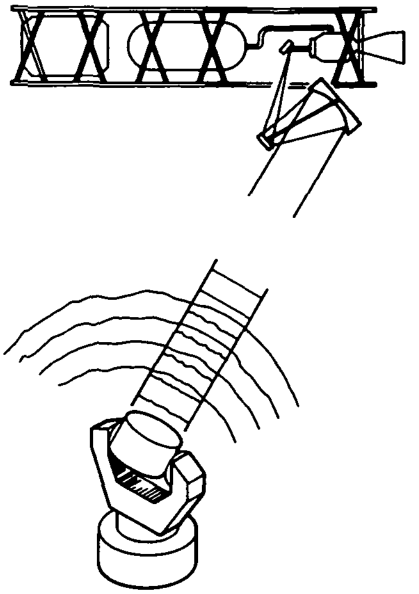

Figure 4.– Laser rocket space vehicle employing a ground-based adaptive transmitter.

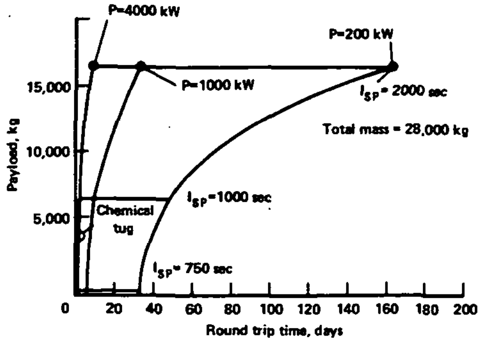

Figure 5.– Laser propulsion potential – payload to geostationary orbit.

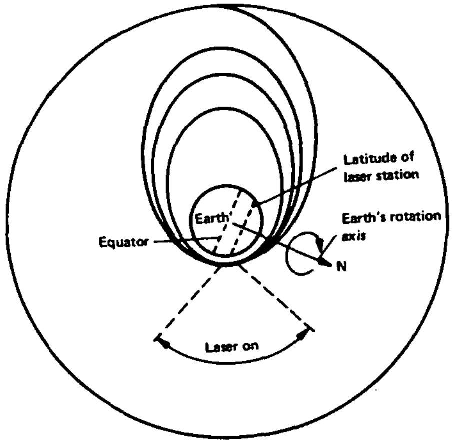

Figure 6.– Orbit raising with single Earth-based laser.

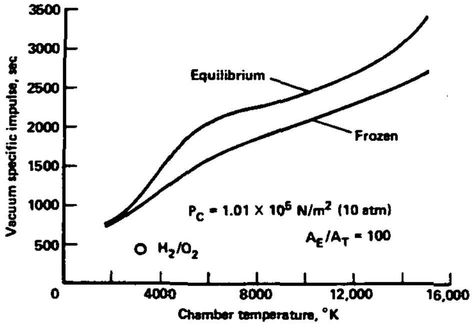

Figure 7.– Propulsion performance of hydrogen.

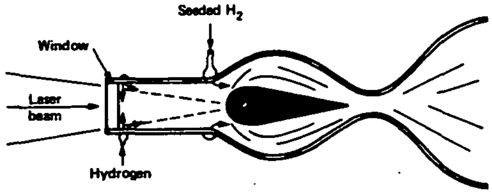

Figure 8.– Laser rocket thruster concept.

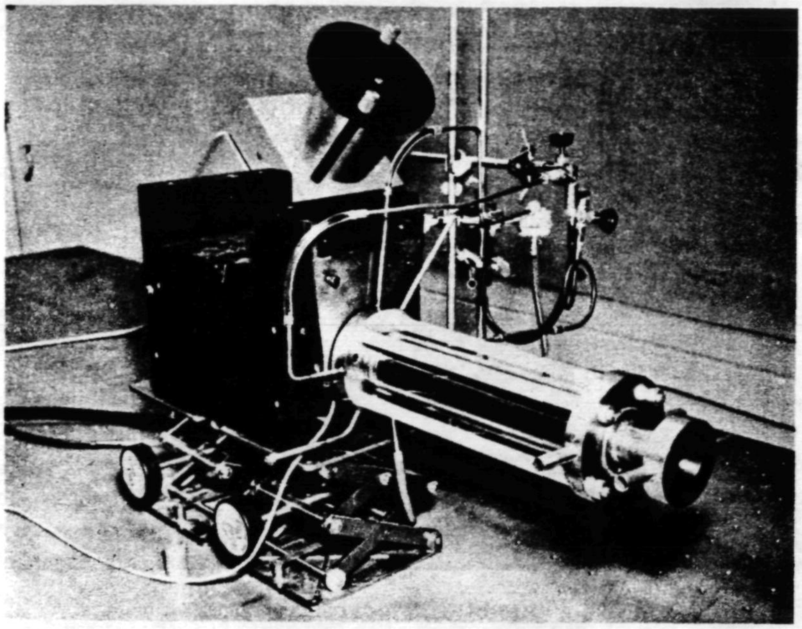

Figure 9.– Laser plasma flow visualization device.

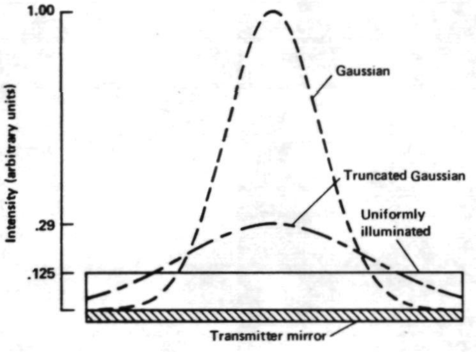

Figure 10.– Transmitter intensity profiles for equal total power.

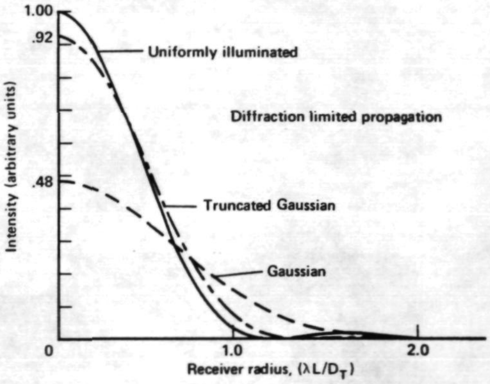

Figure 11.– Receiver intensity profile for equal power beams at transmitter.

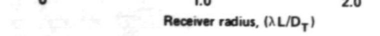

Figure 12.– Receiver power for equal power beams at transmitter.

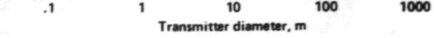

Figure 13.– Laser transmitter/receiver sizes.

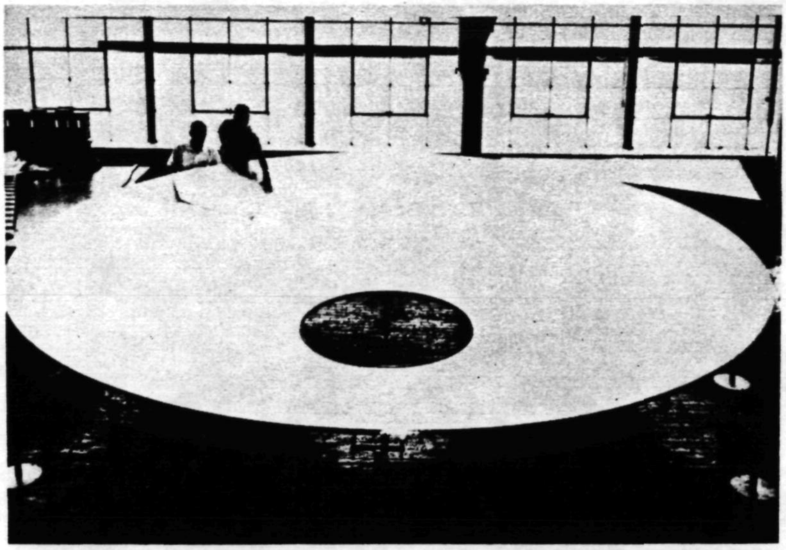

Figure 14.– 20-foot concentrator.

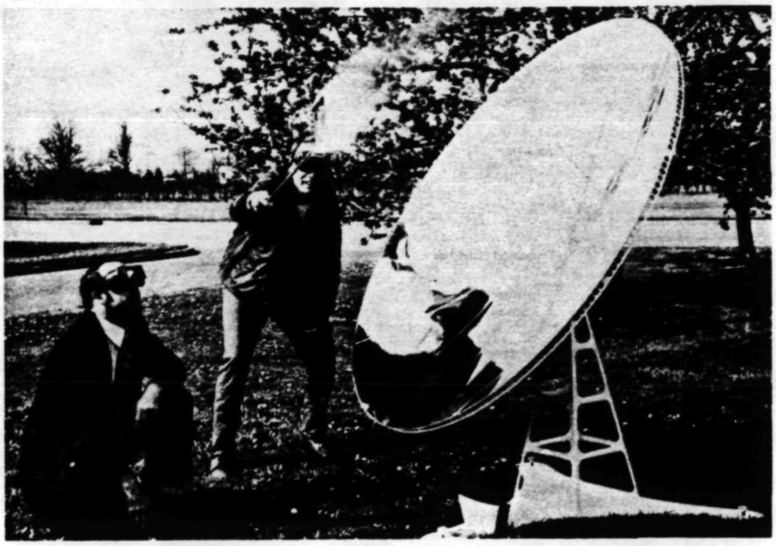

Figure 15.– Lightweight solar mirror.

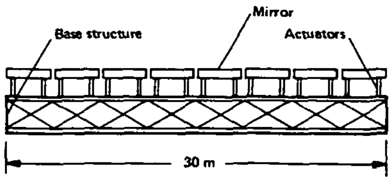

Figure 16.– Transmitter mirror with active segments.

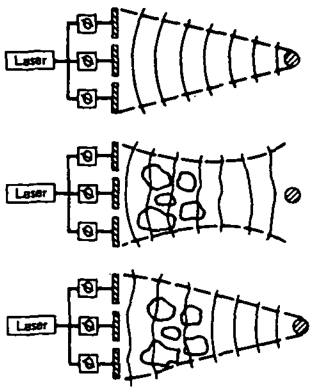

Figure 17.– Adaptive optics for atmospheric propatation.

DISCUSSION

George Sutton, AVCO Everett Research Laboratory – I have three comments. First, I think it is misleading to discuss truncated Gaussian beams from high power lasers. You must run saturated if you want high efficiency. If you run saturated then the beam possibly will not come out Gaussian. In fact, for all high power lasers built in the United States, none have even near-Gaussian profile. So the attributes of the Gaussian should not be incorporated into your systematic thinking about this application. Secondly, in your view of the atmosphere you omitted two very important propagation problems. One, for ground transmission, is thermal blooming and the other one is propagation through clouds. In the case of blooming, Hughes Labs. has reported, in December, on experiments and theory of the use of adaptive optics and the results of those are, for either uniform or Gaussian illuminated apertures, the adaptive optics provides no correction for thermal blooming for a CW focused beam. Their results indicate that if you go pulsed, however, you can get back almost to diffraction limited operation. So these results look a little dismal for the CW case. I should mention that at the same meeting, however, others discussed a possible way to beat this and that is by apodization or beam intensity shaping.

Don Nored: The phased array technique allows a way to shape the beam. I am aware that, from current lasers, you don't get a truncated Gaussian beam profile. But we have looked at a phased array, putting a uniform illumination on each of the phasor mirrors and then we could simulate the truncated Gaussian.

George Sutton, AVCO – But are you suggesting building a separate laser for each of the phasors?

Don Nored: Yes, that's one proposition. There are a number of ways of doing this. We are looking at them. Similarly, we are aware of thermal blooming and it would seem that high power CW beams have a problem. But we can break them up in to smaller beams. It may be that we will be forced, with CO_2, to ultimately go pulsed. Now on the pulsed copper vapor laser, that *is* quasi-CW, and the relaxation time in air may be all right.

Walter Schafer, Schafer Associates – You of course realize you are talking about pointing and tracking accuracies of about 0.3 μrad and therefore have to have this in your system.

Don Nored: Yes, one of the things we are trying to do is let the adaptive system help us because we can expand the beam, lock on it, contract it, and do it electronically to alleviate a lot of the requirements back on the transmitter base structure.