NASA TECHNICAL MEMORANDUM

NASA TM X-62,142

NASA TM X-62,142

APPLICATIONS ANALYSIS OF HIGH ENERGY LASERS

By R. D. Arno, J. S. MacKay, and K. Nishioka

Office of Aeronautics & Space Technology
Advanced Concepts & Missions Division
Moffett Field, California 94035

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON, D. C. MARCH 1972

ACKNOWLEDGEMENT

This paper was assembled with the help, guidance, and cooperation of a large number of individuals both within and outside of NASA. It would be impossible to name all of those who have had some influence, but at minimum the authors must extend thanks to: F. Carl Schwenk, NASA-SNSO; C. Fredrick Hansen and Bob McKenzie, NASA-ARC; Frank Rom and Lloyd Shure, NASA-LeRC; Larry Edsinger, NASA-ACMD; and personnel of United Aircraft Corporation, AVCO, and the USAF.

TABLE OF CONTENTS

SUMMARY AND CONCLUSIONS

Laser systems open an entirely new option for performing some functions of conventional power, propulsion, and energy transfer systems. Whether they are technically competitive or economically viable is much less certain. More than a dozen aerospace applications of high power laser systems were examined in varying degrees of detail. The results were likewise tempered with varying degrees of promise.

Although laser system applications displayed some unique characteristics and capabilities, it became obvious that any large scale replacement of existing systems and methods by lasers would require many simultaneous advances in laser and associated systems states-of-the-art. It became immediately apparent that the high power and long duration operating requirements of most of the applications would require closed cycle flowing gas systems--a major advance from the present open-cycle, short-burst capability. It was also apparent that current low laser efficiency would make the closed cycle systems heavy relative to other techniques of power handling. Furthermore, the theoretical advantages of focusability and high power density rest heavily on advanced methods and materials in optics and pointing systems. Three to ten meter diameter optics near the diffraction limit and one-tenth micro radian or better pointing will be required. Laser receivers and power converters with 20 to 40 percent efficiency will be necessary but are considered reasonable objectives.

Some of the laser system drawbacks can be countered, however, and several applications appear very interesting. For example, low orbit drag make-up, orbit changing, communications, aircraft power, launch vehicle power, and illumination applications all have promising implications; promising, that is, if the laser generator remains on the ground where its weight is not so important, or if it can be used many times in space so as to amortize its launch costs.

INTRODUCTION

In the last ten years lasers have progressed from laboratory curiosities to profitable industrial tools. This has led to rather ambitious extrapolations of potential laser capabilities and much speculation about future applications. There is little doubt that progress in laser technology and the unique properties of coherent electromagnetic radiation will insure an important future role for lasers. However, much of the application conjecture thus far is not based on systematic analysis or objective comparison with competing technologies. It is the purpose of this document to make at least a preliminary attempt at such an analysis and comparison, i.e., determine where laser systems are competitive and/or find what characteristics they must attain to become competitive.

The analysis was undertaken in the following manner: (1) Possible applications were listed and categorized; (2) required components were enumerated and the characteristics of these components were extrapolated; (3) complete system characteristics were calculated parametrically for selected applications using the postulated component characteristics; (4) and finally, where possible and appropriate, comparisons were made with competing systems. The applications examined include energy transfer for electric power and energy transfer for various aeronautic and spacecraft propulsion schemes as well as communications, illumination, and others. Emphasis was placed on high power systems rather than low power commercial or industrial applications and includes some qualitative assessments in addition to the quantitative analyses.

Most of the applications proposed to date do not take advantage of the unique coherent and single frequency properties of the laser light which ultimately may be the most useful. Instead, the laser is used primarily as a source of heat producing energy. Whether the ultimate use be the application of heat or some more sophisticated utilization, the unique characteristics of the laser beam do permit its use where other methods are inoperable. It is the coherence and single frequency nature of the radiation that offers the ability to concentrate a great deal of energy into a narrowly focused beam. Distance, therefore, is not the barrier it has been, and it now becomes more reasonable to consider the transmission of power, data, or light between the Earth, spacecraft, the moon, and even the planets.

LASER CHARACTERISTICS

Lasers are sources of coherent electromagnetic radiation in or near the visible region of the spectrum. The single frequency (or limited number of frequencies) and coherence of the radiation permits energy densities and focusability previously unachievable. In terms of propagating energy over large distances and/or with great precision, the advantages are obvious.

Lasing is caused by an avalanche of coordinated, stimulated photon emissions and attendant electron or vibrational energy transition. The three most common techniques of raising electron energy ("population inversion") for high power lasing involve chemical reaction, gas expansion, and electric arc discharge. These techniques are simply referred to as chemical, gas-dynamic, and electric discharge respectively. Although it is not necessary, all three use a flowing gas mode for heat removal. Each technique carries with it certain advantages and disadvantages. To date the chemical system has demonstrated the lowest mass flow requirement, the gas dynamic the highest power, and the electric discharge the highest efficiency. The chemical system is not readily amenable to closed cycle operation and hence is less appropriate for most of the applications discussed here where continuous or long term operation is required.

The most reasonable method of making a closed cycle gas dynamic laser may be to incorporate the laser cavity directly into a nuclear reactor powered Brayton cycle. Brayton cycle technology is generally advanced or at least well understood on a component basis. Figure 1 shows schematically how a nozzle, laser cavity, and diffuser might be included in a closed cycle Brayton system.

Another closed cycle possibility, which seems amenable to the electric laser scheme, is to employ an advanced but conventional power system--perhaps Brayton again--to mechanically drive and electrically charge a separate laser loop. This configuration appears in Figure 2. Most varieties of this configuration will not require the direct addition of heat to the laser loop as shown. Since efficiencies, mass flows,

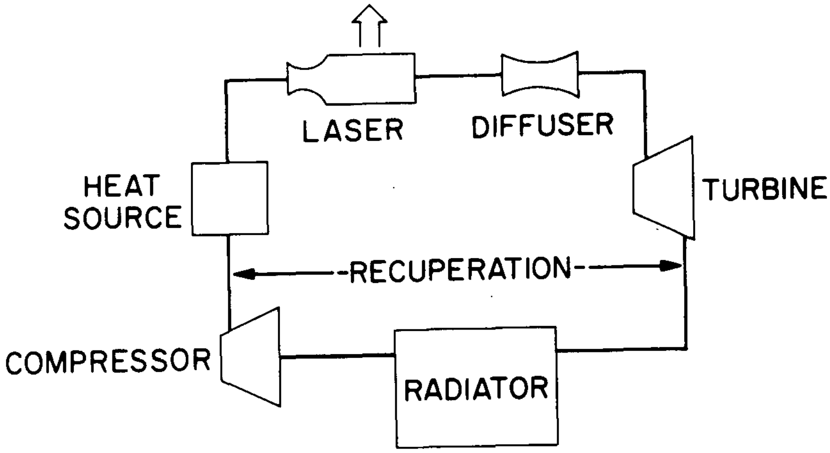

Figure 1 Closed Cycle (Brayton) Laser Generator

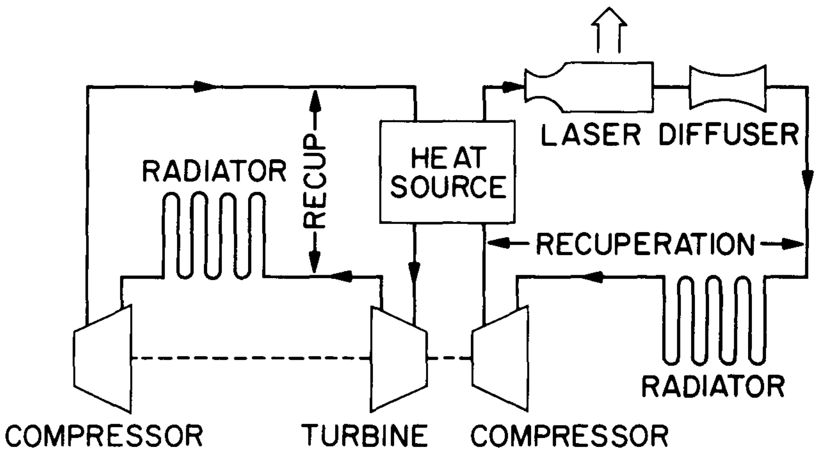

Figure 2 Separate Loop Laser Generator

etc., are as yet unknown, it is impossible to define the system characteristics precisely. Some general conclusions, however, can be drawn which are consistent with studies at Lewis Research Center and elsewhere. The single loop system is very difficult to analyze, but in the case of the two loop system (Figure 2) it is clear that the power and hence weight of the primary system is greater than that of a conventional electric power generator by the reciprocal of the laser efficiency. If an overall efficiency of 20 percent is assumed (optimistic by today's standards), then the power source must be five times larger than if it were merely generating electrical or mechanical power. Thus, if power system technology can deliver a generator at 20 kg/kW electric (20 kg/kW_e), then the laser generator weight will be 100 kg/kW lased (100 kg/kW_L) plus the weight of the laser loop. A specific weight of 100 kg/kW_L is considered optimistic, and anything better must be considered a technological breakthrough. Examining the single loop system of Figure 1 it is evident that the efficiency with which energy is drawn off at the laser cavity is the main determiner of the gas flow rate which in turn sizes many of the cycle components. Because the laser efficiency is low and the diffuser tends to be inefficient, 100 kg/kW_L again appears to be an optimistic number. More pessimistic estimates are one to two orders magnitude higher.

LASER SYSTEMS ANALYSIS

A list of more than thirty possible applications was developed and divided into five categories: (1) Electric power transmission; (2) energy transmission for propulsion; (3) communications; (4) photon transmission and illumination; and (5) heat transfer (for commercial and military applications). Ten to fifteen of the applications were examined in some detail. The last category was not pursued. The complete list of applications considered appears in Table 1.

Requirements and Constraints

The possible uses of electromagnetic radiation in the laser spectrum are many, and energy flux requirements vary considerably, ranging over 30 or more orders of magnitude as shown in Figure 3. Most common energy conversion devices operate at the upper middle part of the scale, between one and a thousand kW/m^2. (Solar flux is 1.4 kW/m^2 at 1 AU.) Figure 4 shows the energy fluxes and attendant temperatures associated with energy conversion requirements.

The principal factors affecting the flux level that can be achieved are discussed below:

Optics Quality. It should be safe to assume that optics quality near the diffraction limit is possible, i.e., the beam spread angle (θ) should be near 1.22 times the radiation wavelength (λ) divided by the optics diameter (D). A value of $\theta = 2\lambda/D$ was used in this analysis.

Wavelength. Lasers presently operate at or near the visible region of the spectrum. Most of those of interest are between about 0.1 and 10 micron wavelength, although x-ray and other frequencies may be possible. Both atmospheric attenuation and atmospheric dispersion of the beam are functions of the wavelength.

Table 1 Laser System Applications

Electric Power Transmission
- Orbit to Earth
- Earth to satellite/spacecraft
- Spacecraft to spacecraft
- Ground to ground

Energy Transfer for Propulsion
- Launch vehicle - ablative propellant
- Launch vehicle - H_2 propellant
- Aircraft takeoff/takeoff assist
- Aircraft flight sustaining
- Orbit keeping/drag make-up/attitude control
- Orbit changing
- Interplanetary electric propulsion
- Laser detonated fusion propulsion
- Laser powered sail spacecraft

Communications
- Interplanetary
- Terrestrial
- Between orbit and ground

Photon Transmission/Illumination
- Remote area illumination
- Atmospheric probe from ground
- Atmospheric probe from orbit
- Night scan of clouds, Earth resources
- Planet/comet/asteroid illumination
- Beacon/signal/transit
- Planet atmospheric analysis
- Chemistry/gas & materials properties
- Interferometry
- Chemical processing

Heat Transfer
- Cutting, drilling, punching
- Welding
- Data recording (punching)
- Tunneling, mining
- Material analysis (ionization, vaporization)
- Chemical processing
- Weapons
- Nuclear fusion

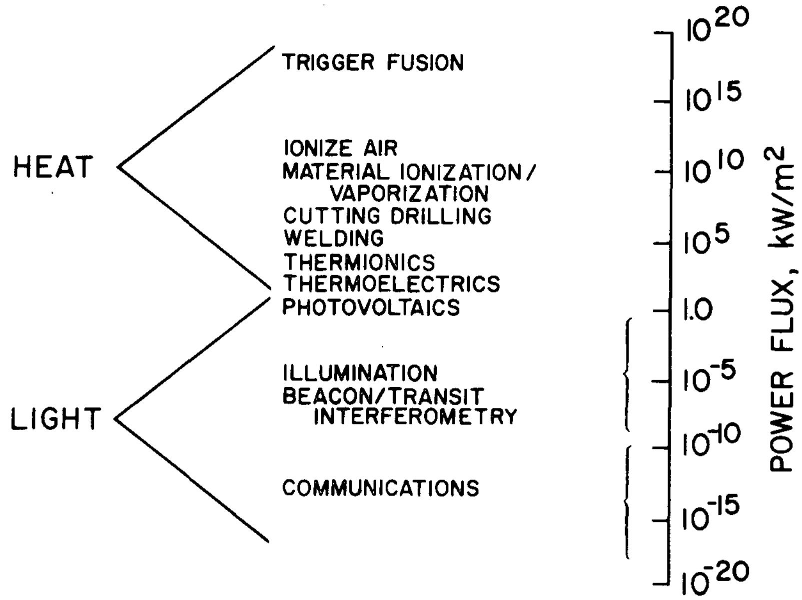

Figure 3 Possible Uses of Laser Flux

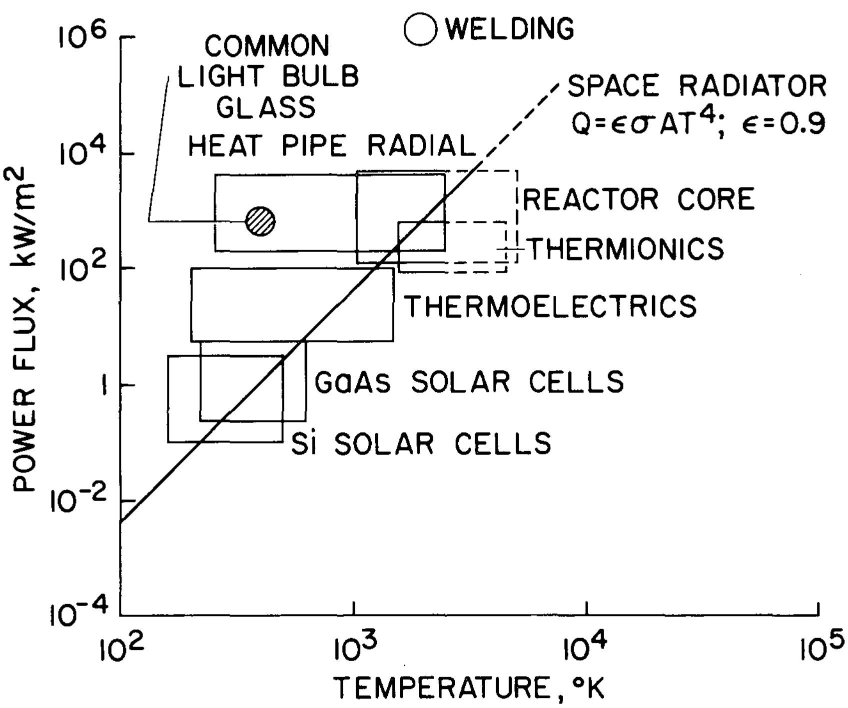

Figure 4 Operating Regimes of Some Power Converters

Optics Size. Visible wavelength optical mirrors on the order of 5m have been built. Optics of 10m size are certainly within reason. Larger optics size and greater wavelength accuracy may require phased arrays.

Pointing Accuracy. Current pointing system accuracies are close to one micro-radian. An order of magnitude improvement will be close to limits imposed by material rigidity, thermal flexing, etc.

Beam Attenuation/Dispersion. Laser beam attenuation and dispersion by the atmosphere is a significant unknown. Laser wavelength, power level, wind velocity, entrained solids, and distance all play a role.

Distance. Despite good focusability, as with most propogation problems, flux level varies inversely with the square of the distance from the source.

Power Level. Flux deteriorating factors can be countered by increasing the power output of the laser. This solution is viable only if the high power levels can be tolerated by the generating system and the power loss in a wide beam is acceptable.

A visualization of the effects of optics quality and pointing error is given in Figure 5. As long as θ, the beam spread, and ϕ, the pointing error, remain small, the angles can be added and then multiplied by the target distance to determine the resultant spot size, i.e., $d = (\theta + \phi)R$. Although not rigorous, it is a convenient simplification to assume that the beam energy is distributed uniformly over the spot, hence flux = 4(power lased)/πd^2.

Figure 6 shows the effect of θ and ϕ on the spot diameter at various distances. With this data it becomes clear, for example, that with a 10^{-7} radian pointing and optics performance, receiving devices on the order of 100m in diameter will be required at 10^6 km or power will be wasted. A reasonable conclusion seems to be that efficient propagation of laser energy must be restricted to synchronous orbit distances and that pointing and optics must be capable of achieving

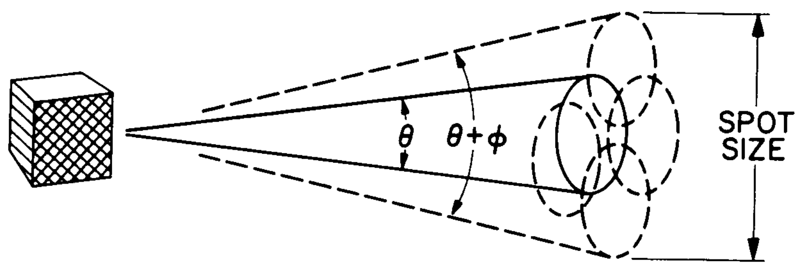

Figure 5 Laser Beam Spread and Pointing Error

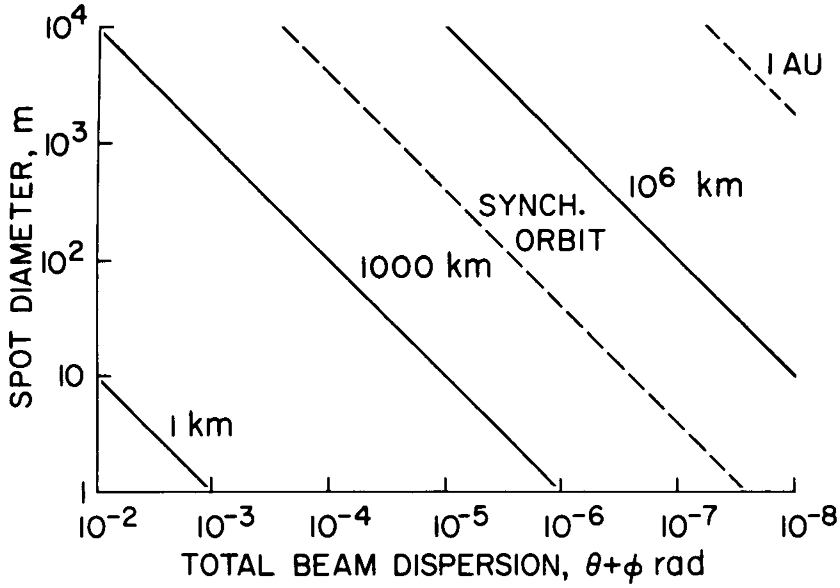

Figure 6 Spot Size - As Affected by Optics and Pointing

10^{-7} radians each. The availability of large and accurately pointed phased arrays may at some future date ease the distance constraint. In the case of power transmission, it is intuitively clear that defocusing (or deterioration of θ) is preferred to poor pointing, since a small wandering spot would be hard to utilize in most applications. Since the larger of the two angles θ and ϕ will have the dominant effect on spot size, in an optimum solution they should be near the same magnitude.

A pointing accuracy of 10^{-7} radians is a relatively easy conceptualization. The beam angle, on the other hand, involves more variables, as shown in Figure 7. If θ is to be 10^{-7} radians, radiation of 5 micron wavelength will require 100 meter optics, or 10 meter optics will require wavelengths of less than a micron. The advantage of an operational high power laser with a wavelength shorter than the currently most advanced CO^2 lasers operating at 10.6μ is obvious.

The flux requirements and capabilities then dictate what can be accomplished with laser and related technology. It is evident from Figure 8, for example, that power requirements become unrealistically high for doing materials effects or even power transmission beyond synchronous orbit distances. This figure shows distances of interest and flux requirements for various applications using θ and ϕ values of 10^{-7} radians.

Energy Conversion With a Laser Beam

Many of the applications investigated require a subsystem which receives the laser beam and converts it to electricity. The conversion schemes that have been proposed for electrical power systems are: photovoltaics, thermodynamic cycles, thermoelectrics, and thermionics. Although the flux requirements for the various conversion methods vary widely, the incoming flux level is not critical since the laser beam can be focused or defocused by mirrors as required. Receiver size restrictions (and hence sending requirements) must be determined by the user.

Photovoltaics is the most direct and most commonly used method of converting light energy into electricity. Solar cells have been used

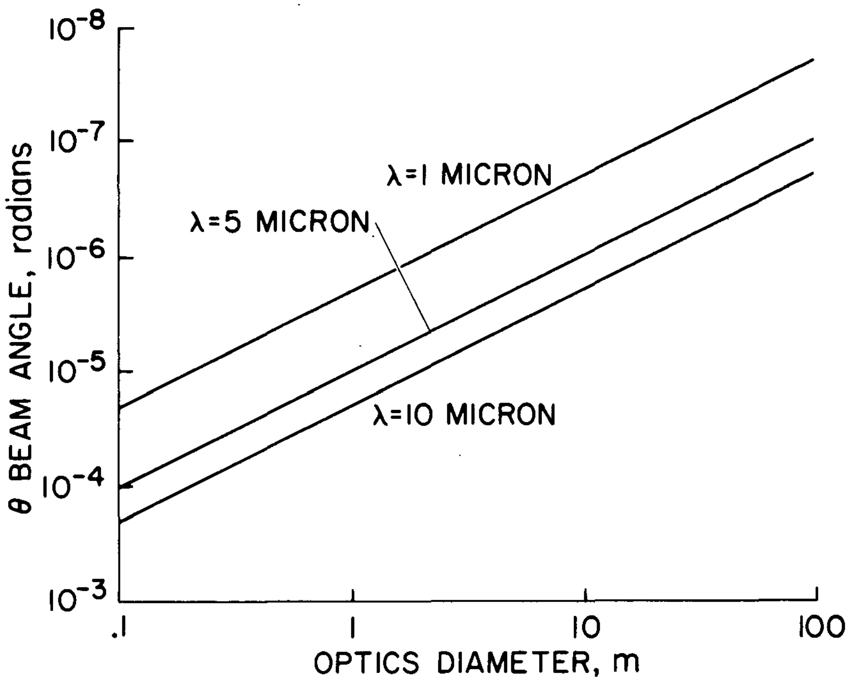

Figure 7 Effect of Optics Diameter & Wavelength on Beam Angle

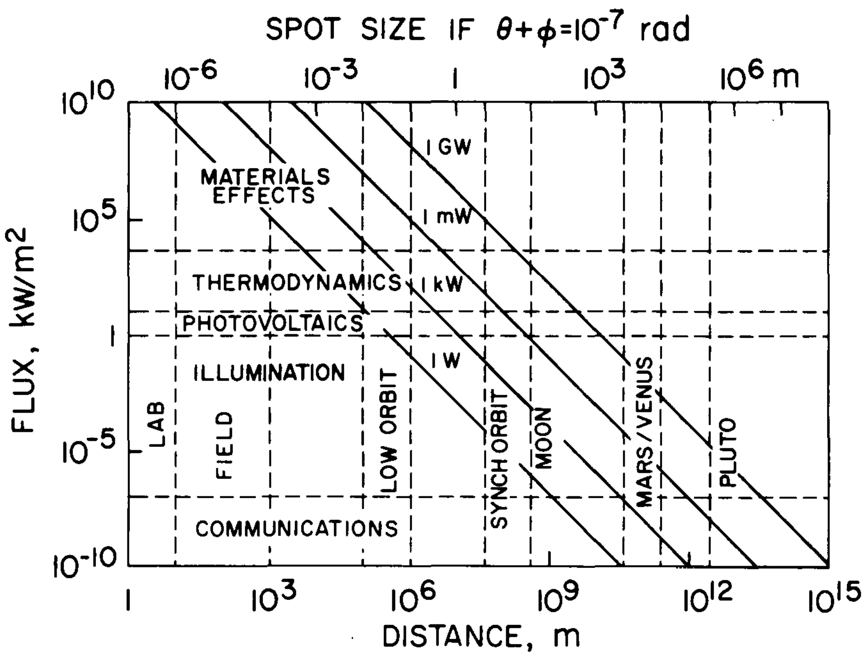

Figure 8 Application Regimes

many times on spacecraft as the primary source of electric power. Solar cells could be used for laser application almost without change from their present configuration. Additional advantage, however, can be gained in conversion efficiency by optimizing the photodiode for a single wavelength as exists with a laser. A number of photodiodes have been optimized for use with lasers and have achieved quantum efficiencies of up to 90 percent. Thus far the optimizations have been for communications applications requiring high responsivity, and hence involve low power and low temperature. Nevertheless, it is reasonable to expect that with the use of anti-reflective coatings, composition adjustments, etc., laser--photovoltaic conversion efficiency will someday reach 30 or 40 percent as contrasted with the multispectral solar cell application at 10 percent. The quantum efficiencies of some photodiodes are shown in Figure 9, adapted from Reference 1, to illustrate the fact that there are a number of possibilities for matching high efficiency converters to specific laser wavelengths.

In addition to the prospect of higher conversion efficiency, laser systems can also take advantage of the fact that the laser flux can be much higher than solar flux. Without active cooling an increase in incident flux on the array brings about higher temperatures and consequently lower conversion efficiency. But the maximum product of flux level and conversion efficiency (the point at which the specific area and weight of the receiving array are minimized) can yield higher power output than possible at one solar flux. Figure 10 illustrates the effect of temperature on typical solar cells (Reference 2). The solid lines show state-of-the-art Silicon (Si) and galium assenide (GaAs) performance.

If, in fact, improvements of the type mentioned earlier can be made and efficiencies can be increased by a factor of two or three, then performance curves corresponding to the dotted lines might be achieved, represented by the equation $\eta = \eta o - 0.00046(T-300)$. A heat balance of the solar panel can be made and the equilibrium temperature of the array can be determined (in free space) under any assumed flux level. Thus an optimum flux level can be found which is primarily a

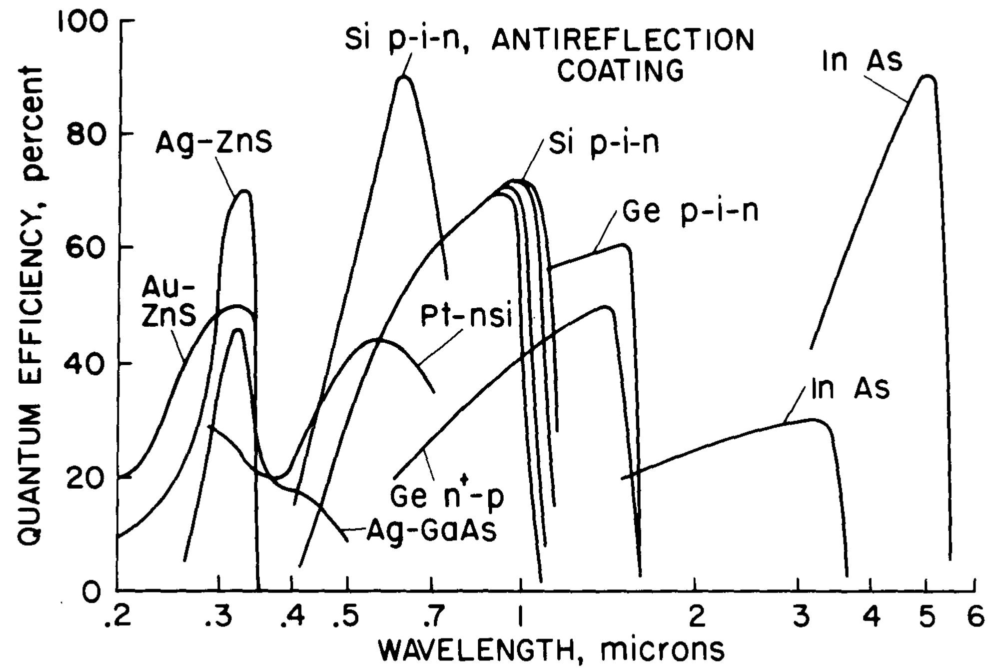

Figure 9 Wavelength Dependence of Quantum Efficiency for Several Photodiodes

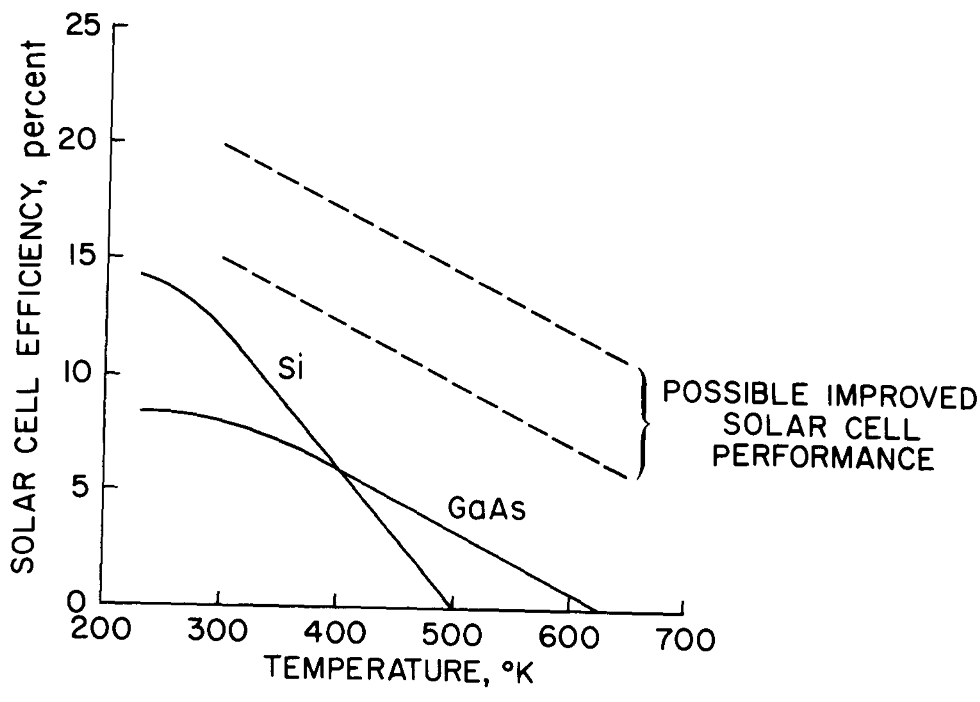

Figure 10 Detector Performance

function of the baseline efficiency (at 300°K). The temperature at the best flux level has been derived from the temperature-flux-efficiency relationships (assuming an equal front and back side emissivity and a packing factor near unity) and is given by:

$$T = \frac{-\left[\frac{5}{8} - \eta_{oo}\right] \pm \sqrt{\left(\frac{5}{8} - \eta_{oo}\right)^2 + \eta_{oo}\left(1 - \eta_{oo}\right)}}{b} \qquad (1)$$

where

$\eta_{oo} = \eta_o + b\,T_o$

$\eta = \eta_o - b(T - T_o)$

$b = 0.00046\ (K°)^{-1}$ (Silicon)

$T_o = 300°K$

$\eta_o = \eta\ @\ T = T_o$

The optimum flux level is then found from:

$$I = \frac{\eta\ 8 \varepsilon \sigma T^3}{b}$$

where

ε = emissivity of array

σ = Stephan-Boltzman constant

The corresponding effect of the increased cell performance on specific weight and specific area is shown in Figure 11. Lines which relate available and used power are drawn and labeled at 5, 10, 20, and 40 percent conversion efficiency. As the flux on the cell is increased, there is a decrease in conversion efficiency, but the specific area and weight improve nevertheless due to increase in available energy. It becomes apparent that a possible application exists wherever solar cells are currently attractive, and may even imply applications where solar cells were previously not competitive since the receiver specific weight potentially has an order of magnitude advantage over solar cells.

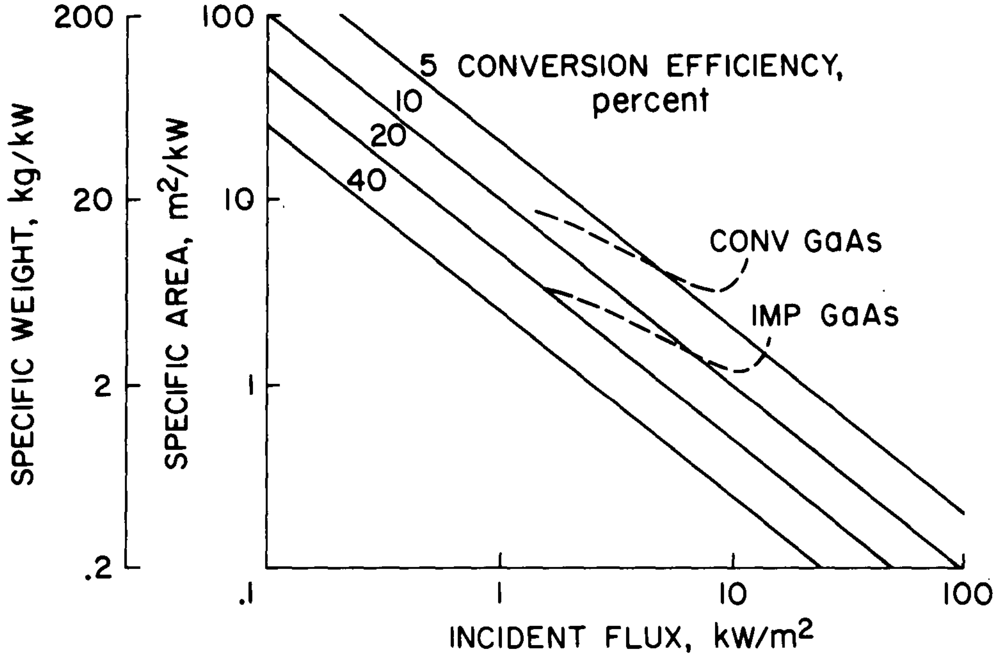

Figure 11 Photovoltaic Array Optimization

Turbomachinery or other heat operated energy conversion devices also reap certain advantages from a laser energy source by virtue of the fact that the high incoming energy flux reduces the required energy collector size or corresponding heat source size. No extended discussion of such devices is carried out here since the weight advantages are not likely to be any greater than those of the photodiode method. The photovoltaic method is merely taken to be a representative case, or pessimistically, a best case. A pictorial representation of a thermodynamic type laser energy converter is shown in Figure 12.

The development of more sophisticated energy conversion techniques (such as a "reverse laser" or light rectifier) remains as one of the most challenging problems of advanced laser application. The characteristics of such devices are not predicted here.

Subsystem Interactions

A general discussion of devices which receive laser energy and convert it to electricity has already been made. No mention, however, was made of the possible location of sender or receiver since atmospheric attenuation of high power laser beams is largely unknown currently, and hence was not included in this analysis. Distance rather than actual location of the subsystems is the criteria considered.

Figure 13 shows a schematic of a laser power transmission system. The diagram is appropriate to most of the applications. The effect of distance between the sender and receiver was illustrated in Figures 6 through 8. Obviously distance compromises performance, hence the tradeoffs with conventional systems are strongly affected by this parameter. The specific weight of the receiving device (say photovoltaics) is dependent on the incident flux (Figure 11) and the total weight of the sending device depends on its power output. If the sum of θ and ϕ (the beam spread and pointing accuracy) is 10^{-7} radians then the target spot size is approximately $10^{-7}R$, where R is the range. If the receiver is designed to accept the entire laser beam, its diameter, d, will be $10^{-7}R$ and the flux for a given power output will diminish as the square

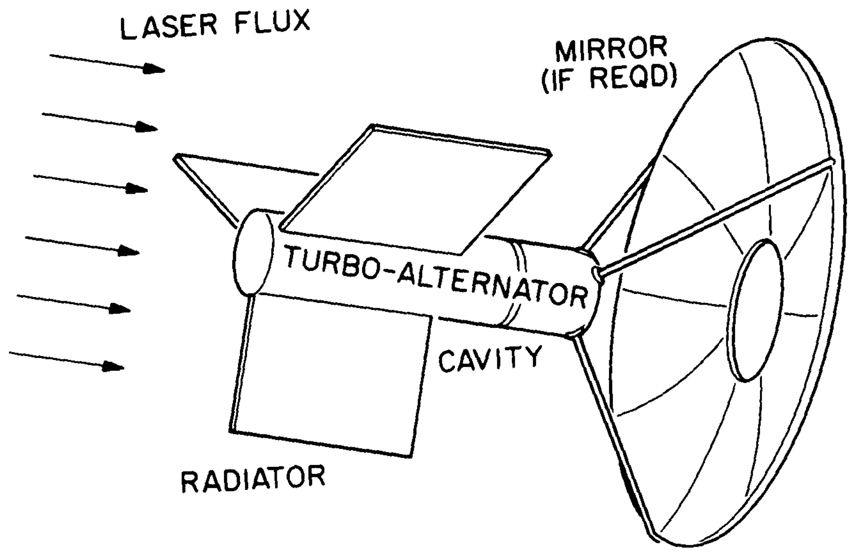

Figure 12 Thermodynamic Receiver

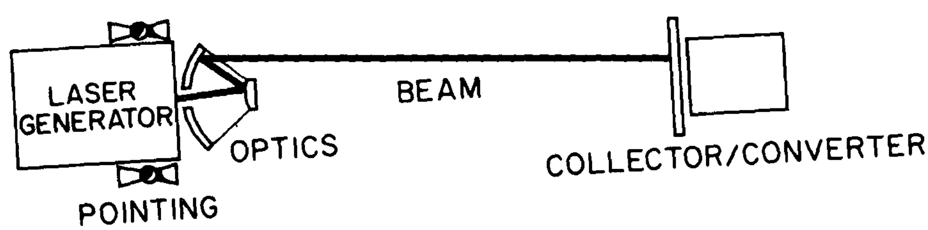

Figure 13 Laser System Schematic

of the distance from the source. The receiver specific weight is mini - mum when operating at only the optimum flux level. This receiver minimum weight can be maintained if the power at the source is increased to cancel R^2 losses. For a given receiver power, however, as the distance increases the power loss due to an overly large spot also increases. Figure 14 shows how the power required to maintain the optimum flux on an array increased with distance based on Figure 11. The specific weight and area of the array are better than that of conventional solar cells by a substantial margin (also illustrated in the figure) as long as the proper flux level is maintained. Of course, the receiver can be designed to accept the entire beam in order to conserve sender power but it will be at the sacrifice of receiver performance.

LASER APPLICATIONS

In the applications described below, calculations were made of system weights, laser receiver areas and weights, fuel and/or power consumption, thermal pollution, as well as trip time and payload capability for propulsion schemes. Not all of these characteristics are appropriate or of interest in all applications, but the procedure is similar in all cases. First, user power requirements were estimated based on existing methods, extrapolations, or standard calculations. In a few cases the requirements stated were more or less arbitrary or were influenced by laser capability. Once a power requirement was established, the receiver size could be determined, based either on the assumption of 10^2 - 10^3 kilowatts per square meter for heat absorbers or 1-10 kilowatts per square meter for photovoltaics (Figure 4), and their specific weights could be found accordingly (Figure 11). Receiver efficiencies could be postulated, but were frequently handled parametrically. Then the laser generator could be sized using 100 kg/kW_L or described by parametric range.

One result was inevitable--since most of the system performance characteristics are really unknown, no concrete answer to any application question could be given. It seems fairly certain that laser receivers can be made smaller and lighter than solar cell arrays, hence

POINTING & DISPERSION ANGLE, $\theta+\phi=10^{-7}$ radians

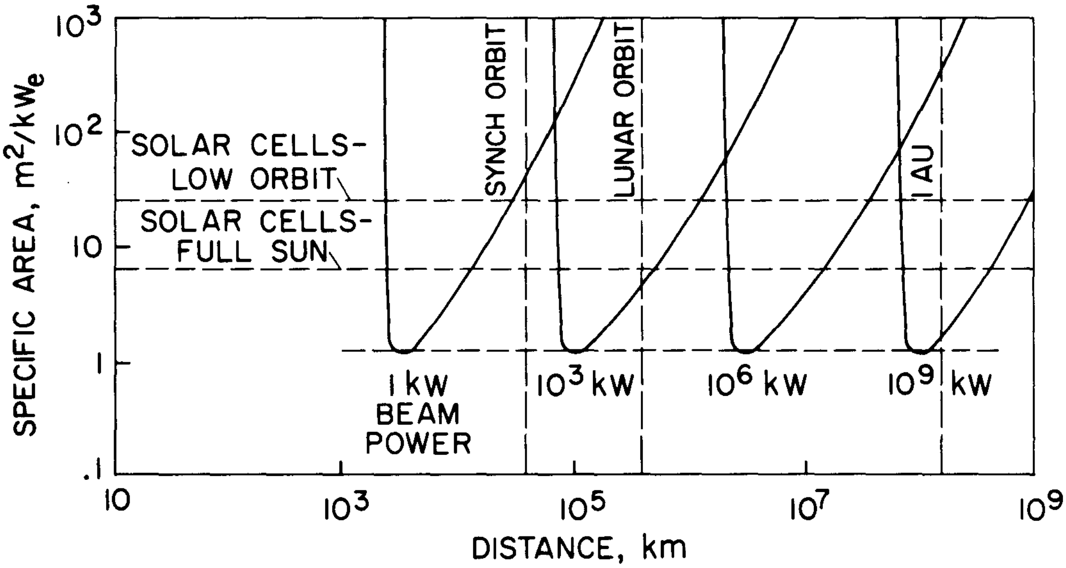

Figure 14 Laser Receiver Specific Area

yielding an advantage, but the question remains as to what penalty one would be willing to pay in terms of power wasted, pointing mechanism complexity, optics size, and cost in order to achieve this gain. The sacrifices (in all but cost) are outlined in the earlier discussion and in Figures 6, 7, 8, and 14. The applications analysis described below is predicated on the gain in receiver performance, leaving the disadvantages to be evaluated by the reader.

Stand-off Power System

It has been proposed that the laser beam is uniquely suited as a power transmission device which can save reactor shield weight in high power applications by allowing large separation distances without power transmission wires. Typical of such an application would be an Earth orbital space station where the power generation system would be removed by a kilometer or so, such that only a shield compatible with natural radiation would be required. The result, however, is that any wire weight savings is more than cancelled by the higher generator and receiver weights. The weight and area advantage of a laser receiver over conventional systems has been already described. If, however, the generator is dedicated to only the one application its weight too must be charged to space station power system. In a technology era when Brayton cycle power systems weigh 20 kg/kW_e, laser generators will weigh 100 kg/kW_L or more. The final laser generator specific weight is then found by dividing this generator weight by the receiver efficiency. If, for example, the laser receiver is 10 percent efficient and the generator specific power is 100 kg/kW_L, the generator will weigh 1,000 kg/kW_e, far more than the system weight of a 20 kg/kW_e Brayton system with its shield at optimum separation (typically less than 100 meters). Such is the inescapable consequence of so many energy conversions: first reactor thermal to electrical, then electrical to laser, and finally laser back to electrical

Drag Make-up

For low orbit altitude drag make-up with laser power, like other electric propulsion missions, a low system specific weight is required. For systems using photovoltaic cells, typical array specific masses are 17 kg/kW$_e$ when illuminated by the sun. (As noted earlier, laser power can drastically reduce this part of the system mass.) The remainder of the propulsion system mass is also about 17 kg/kW$_e$ and will remain an irreducible mass with or without laser illumination. Typical system masses can be found in documents such as Reference 3.

For nuclear electric systems, there tends to be a minimum mass (usually consisting of reactor and associated shielding) which is approached as the power is reduced. An example of such a system is given in Reference 4. In this case, the following expression for specific mass of the nuclear electric propulsion system is used:

$$\alpha = 1600 \text{ kg} + 8P \qquad \text{kg/kW}_e$$

where P is the power in kilowatts.

For the thruster subsystem (which will be used in either the nuclear or photovoltaic systems) the thruster efficiency (which is a function of the average ion exhaust velocity was taken as:

$$\eta = \frac{0.842}{1+\left(\frac{16000}{V_{ex}}\right)^2} \tag{2}$$

This is typical of mercury electron bombardment thrusters such as described in Reference 5.

In order to estimate drag make-up requirements, some assumption must be made about the thrust duration. For the nuclear electric and chemical rocket cases, the whole orbital period was assumed available and used in this analysis. In the laser or solar electric case, it was assumed that the sun or laser beam would be seen by the satellite only half the orbital period.

The drag data, as a function of altitude, was taken from Ref. 6, which assumes an average drag coefficient of 1.31. This was then applied to a typical orbiting space station (SIVB, 80 metric tons, 82 m^2 area, and 10 KW of auxiliary power). The results are shown in Figure 15, which does not include the laser option.

One of the main difficulties with the electric propulsion systems is that there exists an altitude below which an increase in power (and, hence, deployed area) adds more drag than can be made up by the power available. This results from the fact that the thrust/unit power has a minimum due to the loss of thrustor efficiency with reduced Isp, as indicated in Equation (2). Similarly, there are difficulties of excessive propellant consumption for the chemical rocket systems which limit operation to very short duration if the total mass in orbit is to be limited. Thus, there exists a lower limit to the orbit altitude for which drag make-up is applicable.

The addition of laser power leads to the results depicted in Figure 16. Here the reduced mass of the photovoltaic system is the chief factor in the success of the laser system which completely supplants the heavier solar electric and nuclear electric systems as well as much of the chemical system. Unfortunately, this curve reflects only the "at target" system mass and not the total system mass or cost, which may be far more important factors.

Orbit Changing

Another possible electric propulsion application is orbit changing. One of the most difficult missions involves raising a payload from low Earth orbit to geosynchronous orbit and then returning it to low orbit. In order to make a comparison between laser and conventional systems, assumptions similar to those used in previous sections were used, and energy requirement estimates were taken from Reference 7, where the velocity increment needed for changing both altitude and inclination is:

$$\Delta V = \left(V_o^2 - 2V_f\, V_o \cos \frac{\pi}{2} \Delta i + V_f^2\right)^{1/2} \qquad (4)$$

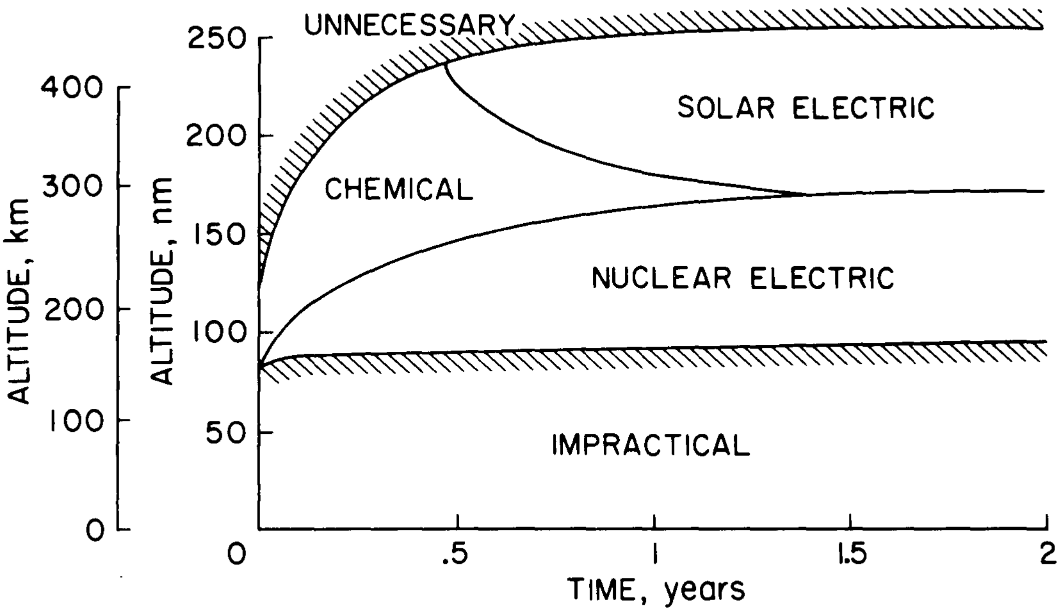

Figure 15 Drag Make-up - SIVB Conventional

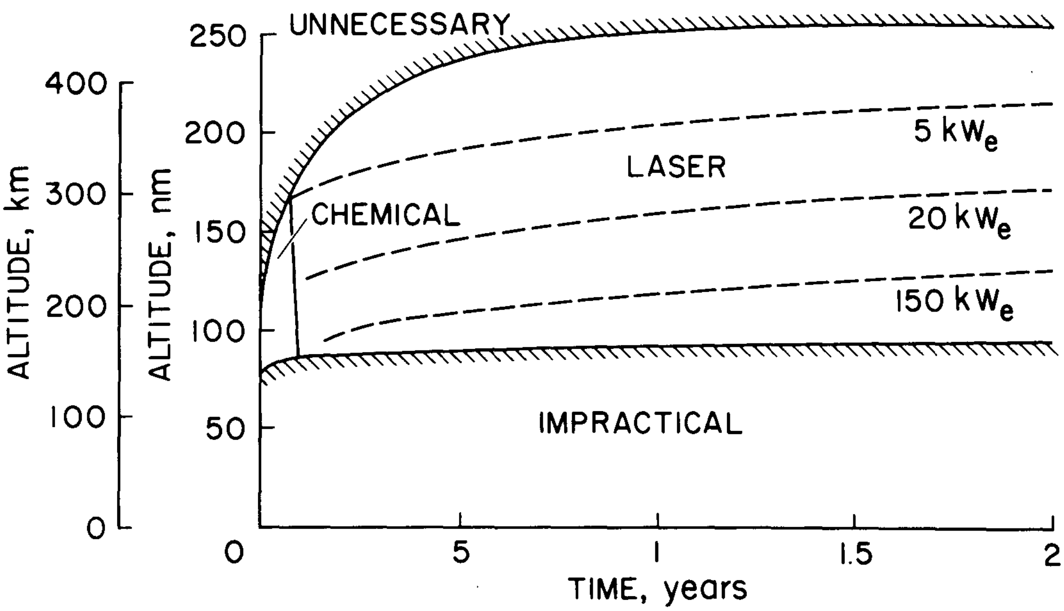

Figure 16 Drag Make-up - SIVB Laser

where

V_o = initial velocity
V_f = final velocity
Δi = change in inclination

Again the major impact here is the ability to reduce the array mass to very low values. Under such circumstances, the receiver mass of the laser-electric system can be much lower than any nuclear electric system. Also, there will exist a value of ion engine specific impulse which will give a minimum mass for the total propulsion system, including both propellant and power supply mass. However, in this case there does not exist the relation between orbit altitude and thrust requirements, as was the case for drag make-up.

Figure 17 shows a comparison of the payload weights that can be thus transferred as a function of total weight launched to low Earth orbit. (The mass in Earth orbit is measured in numbers of launches of a representative space shuttle whose payload is assumed here to be 27 metric tons per launch.) The figure shows that significant payload advantages can be realized with the laser system. However, the payloads would have to be of a type which could tolerate much longer transit times. The distinction between the two laser systems is that the lower curve includes a weight penalty in the form of a chemical stage used to ferry the photovoltaic laser detector through the lower Van Allen belts, i.e., to about 13,000 km. This method does, however, profit by affecting a reduced trip time and smaller power requirement. The upper curve merely assumes that cell design can avoid degradation and circumvent the ferry requirement.

An examination of the use of a solar sail type device with laser illumination was also investigated. For this case, data for the sail mass and mass per unit area were obtained from Reference 8. In this case, high accelerations (and associated shorter trip times) could only be attained at the expense of very high laser power values. It became apparent that the sun was an unequaled competitor in spite of its tremendous distance from the Earth.

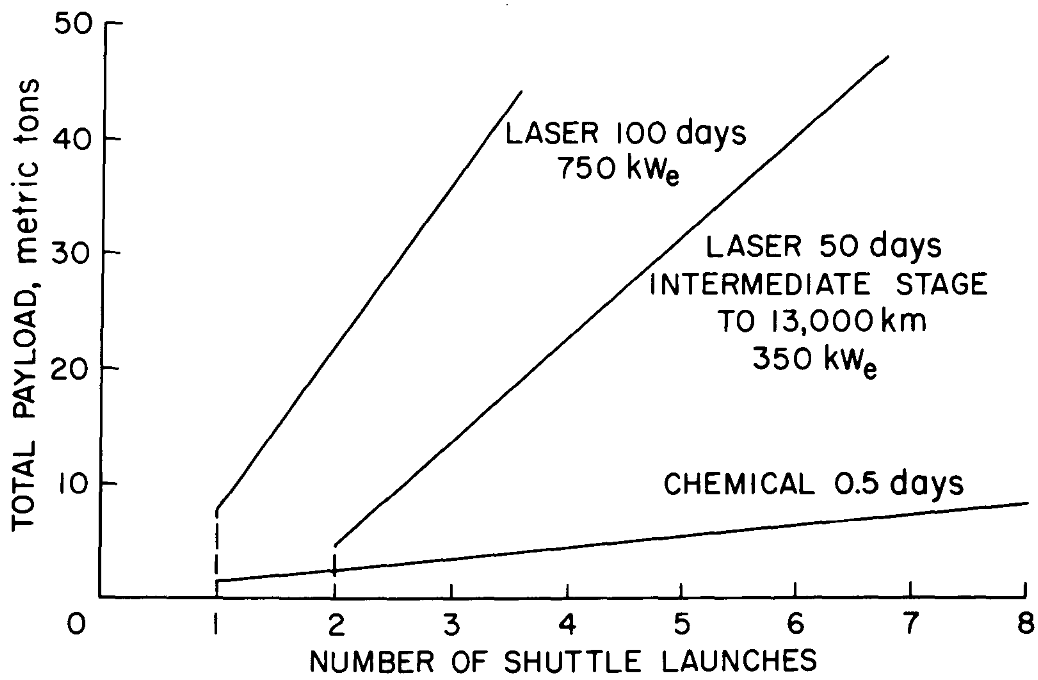

Figure 17 Geosnychronous Round Trip Missions

Interplanetary Laser Propulsion

Three schemes of interplanetary laser propulsion have been proposed. They are:

Laser Electric Propulsion. This is exactly the same method that has been described for drag make-up and orbit keeping. Laser power is converted to electric power and subsequently converted to thrust through electric thrustors. It became apparent upon initial investigation of this scheme that R^2 losses would render it noncompetitive with other systems beyond lunar/terrestrial distances without phased arrays. For example, if θ plus ϕ is 10^{-7} radians the power required to equal solar flux at Mars orbit would be more than 10 GW. (See Figure 8.)

Laser Sail. A photon engine with small mass can be configured by placing a reflector on a spacecraft and remotely positioning the photon source--a laser generator. The method, however, suffers the same fate as the previous scheme. Unreasonable pointing and focusing angles are needed beyond lunar distances.

Laser Detonated Fusion Propulsion. This is one way of avoiding the distance barrier. The laser, which actually only plays a subservient role in the propulsion system, is aboard the spacecraft. The laser is used to trigger a fusion reaction and consequently an explosive thrust--in much the same way the high flux capability of the laser might be used to initiate fusion for terrestrial purposes. If such a scheme survives the engineering problems to live up to its theoretical performance, the potential gains are tremendous. An examination of this approach has been made in Reference 9. A comparison is made here with a nuclear electric system--the most likely competitor--since its total system mass is of the same order of magnitude (i.e., compatible with a single shuttle launch). Chemical systems may be competitors, and may be more economical, but they are much heavier and involve complex operational problems. The characteristics of the nuclear device are taken from Reference 10. Figure 18 shows the significant payload and/or trip time advantages of fusion propulsion over nuclear electric for an initial mass in Earth orbit equivalent to one shuttle launch.

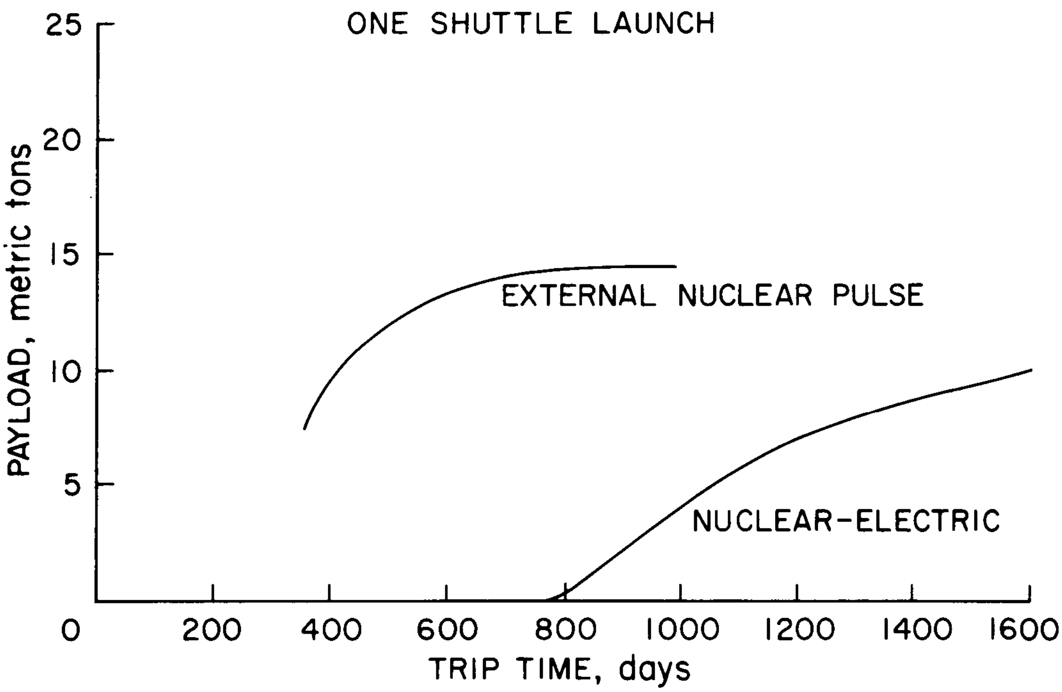

Figure 18 Laser Nuclear Pulse - Jupiter Orbiter

Laser Launch Vehicle

Based on the theoretical possibility that a high power density laser beam could be used to heat a propellant to a higher temperature (and therefore a higher specific impulse) than obtained in conventional boosters, two launch vehicle schemes have been proposed. One would use liquid hydrogen; the other would use a solid ablative material.

The specific impulse of a fuel is approximately equal to the square root of the absolute temperature of the fuel divided by its molecular weight, i.e., $Isp \approx \sqrt{T/M}$. Making some assumptions about the absorbtivity of the propellant plasma it is possible to calculate the power requirement needed to achieve a given Isp and thrust. For seeded hydrogen the power requirement in kilowatts is about 1/30th of the product of thrust and Isp, i.e., $P = F \times Isp/30$ where the thrust is in pounds. Since the Isp affects the quantity of fuel required, it is appropriate to examine the effect of Isp and thrust to weight ratio on payload mass fraction for a total velocity change, ΔV, of 9 km/sec. Payload mass fractions as high as 0.4 can be achieved. Subsequently, the optimum Isp is found to be between 1,000 and 3,000 sec for minimizing the electric power per payload mass in orbit. The last value represents between 500 and 1,000 kilowatts per pound of payload for thrust to weight ratios between 1.2 and 4.0.

Since each launch sequence takes only a few minutes this would seem to be a natural application for the simpler open cycle laser. At a laser specific power output of 100 kW per pound of fuel per second (an approximate projected performance) the amount of fuel needed is greater than the propellant required to launch the same payload by conventional chemical boosters. For example, 500 kW per pound of payload and 200 seconds flight time means 1,000 pounds of laser fuel for each pound of payload launched, at best. Fuel requirements are illustrated in Figure 19. Because of these high requirements, the only real argument for laser powered launch vehicles can be made with closed cycle systems. And this scheme in turn is justifiable only with the prospect of a cheap source of power to run the closed cycle. Fortunately such a

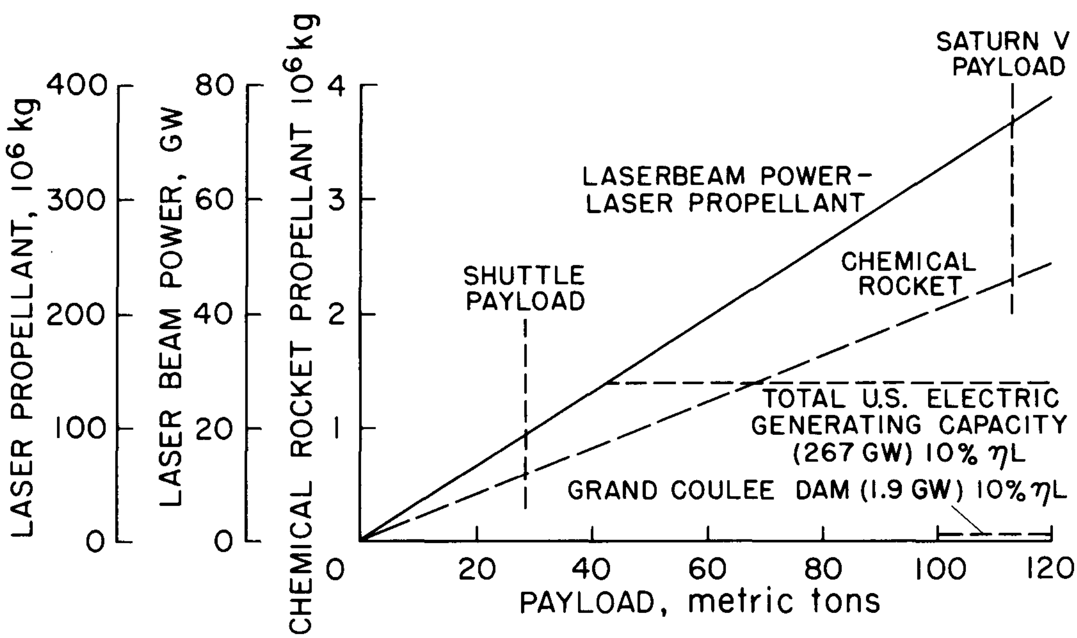

Figure 19 Laser Powered Launch Vehicle

source of power exists in the form of terrestrial power stations. In order to avoid the discrepancy of fuel consumptions again, only nuclear stations are considered. With the promise of electric power at, say, 5 mil per kilowatt-hour even a very inefficient laser generator could be used economically in launch vehicle applications.

Since approximately one gigawatt would be required to launch 1,000 kg to low Earth orbit using a laser rocket, this would seem to indicate that only small payloads could be accommodated easily. If, with inexpensive electric power, launch costs could be lowered to the vicinity of $10/lb (a figure based on the projected cost of hydrogen and a reusable vehicle) it is possible to determine how many launches would be required before the laser and electric power plant costs could be amortized. As can be seen in Figure 20, the trade-off between conventional launch systems and a laser system which involved $3 billion for development would come between one and ten million pounds launched--a weight which implies one laser launch each day (at 1,000 kg each) for ten years. At first glance such a total weight seems rather high, although lower launch costs would decrease the incentive for payload weight reduction and consequently tend to raise the total weight launched. The key question may be whether or not a viable space program can be built around one or two ton payloads.

Aircraft Take-off

The high frequency of aircraft flights may make laser aircraft take-off a more economically viable system than space booster applications. It is possible that the same propulsive techniques just described for launch vehicles could be used for take-off, i.e., separate from the cruise propulsion. It is also conceivable that the take-off propulsion could be combined with the cruise propulsion, for example, by employing heat driven gas turbines.

Although this technique was not investigated in any detail, it is possible to state that such a concept is technically feasible when taken in the same context as the other applications investigated. It would

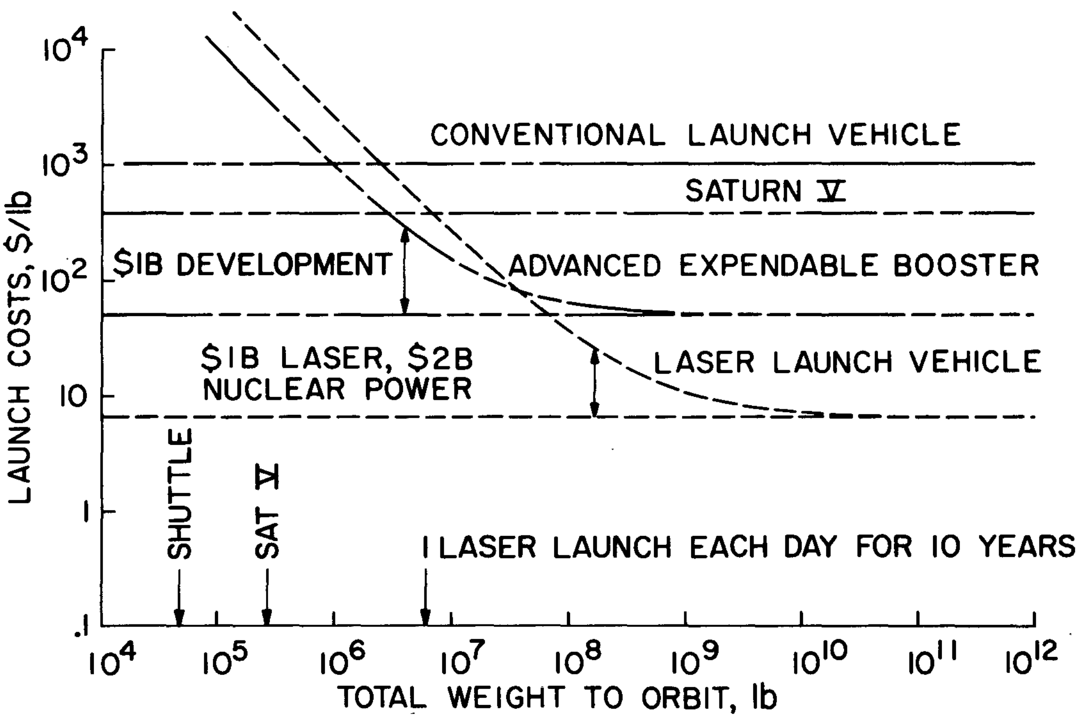

Figure 20 Launch Cost Implications

depend on a cheap source of electric power--as in the case of the boosters, and it would probably be located near the airport to minimize pointing problems.

Aircraft Cruise

The use of lasers to supply aircraft cruise power is of potential economic benefit. Moreover, if the laser system were located in space, atmospheric pollution could be reduced. Putting the energy source in space would also alleviate some of the multi-acquisition and tracking problems attendant a ground based system. Also there is apt to be less atmospheric attenuation from a space borne system for aircraft at 40,000 feet altitude or higher.

The aircraft system would likely employ a gas turbine with heat supplied by heat exchanger (and heat sink reservoir) rather than combustion. Some calculations were made for a Boeing 747 size airplane as representative of a large stable platform. The aircraft weighs about 700,000 lb with fuel or perhaps 450,000 lb in a laser utilization configuration. With a lift to drag ratio of fifteen, the thrust required for cruise would be 30,000 lb, which translates to about 40 MW of power required at 600 mph. Since the overall utilization efficiency of the aircraft is difficult to predict with this preliminary analysis, the actual power requirements and necessary receiver area are plotted as a function of this efficiency factor in Figure 21. The nominal power requirement of 100 MW is high but not inconceivable and the area requirements seem feasible. Some potential difficulties lie in the high flux required to develop adequate temperatures. A miss-aimed beam of 1,000 solar fluxes is certainly a potential hazard. The large number of aircraft in service at any one time also implies a difficult logistics problem, not to mention the cost of 1,000 or more systems in orbit.

Communications

The focusability of the optical wavelengths can be interpreted as high antenna gain in a communications sense, which means power requirements or antenna (aperture) size can be reduced over conventional

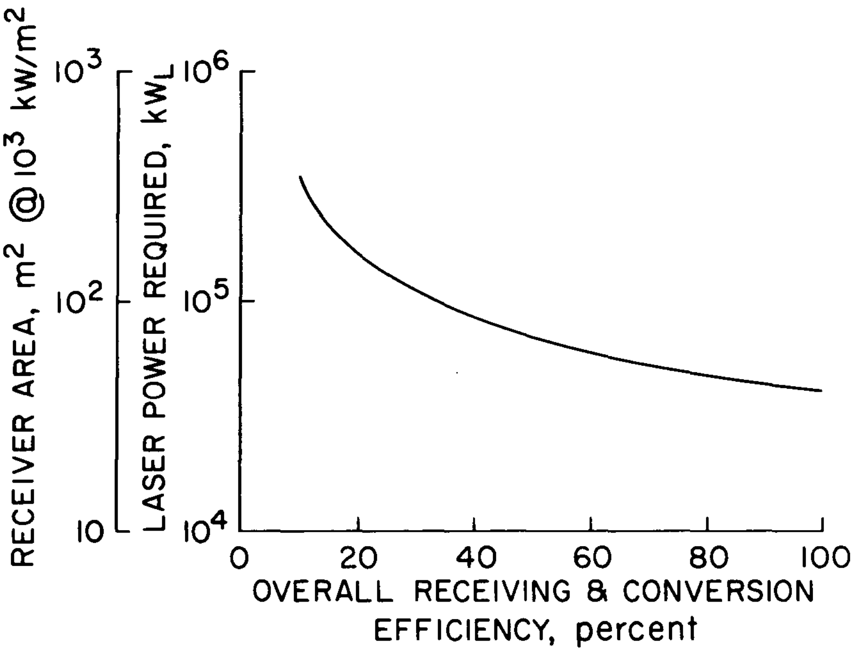

Figure 21 Aircraft Sustained Flight - 747

systems at no sacrifice to data rate. Or, conversely, data rates can be increased for equivalent power levels and antenna sizes. Figure 22 (Reference 11) shows power requirements for various bit rates at Venus, Jupiter, and Pluto. A cross hatched section indicates the data regime for typical orbital experiments. Real time color TV may require more than 10^6; a manned vehicle could require 10^8. It is evident in the diagram that X band and S band require much larger antennas by one and two orders of magnitude if power and bit rates are held constant. The question is whether this apparent advantage is negated by development problems and/or system cost. The answers must come from continued basic laser research.

Ground Station Power

The growing concern over environmental problems of thermal pollution and nuclear safety, together with the advent of laser systems has brought to light some of the new possibilities in laser power transmission. Consequently, much interest has been expressed in placing energy sources in space rather than on the ground. Such an undertaking is, however, extremely ambitious in view of the tremendous size of terrestrial power plants--not untypically 1,000 MW--and the current small size of laser systems. Figure 23 shows some of the characteristics of a laser system needed to replace a small 10 MW ground system. The array characteristics are based on data from Figure 11. It was assumed that a ground array of photovoltaic devices would be used, and that flux levels would be limited to a maximum of 2 solar constants to avoid safety hazards. (Obviously the actual limits are as yet unknown.) In terms of thermal pollution, it is apparent that no advantage is gained from laser applications unless the ground conversion system is more efficient than conventional power stations, i.e., about 30 percent for nuclear systems, and this has yet to be demonstrated. In terms of ground area, the scheme does not look unreasonable; there is probably no more ground area required than would be needed for a standard power station. The area requirement is smaller by an order of magnitude than a ground array depending solely on solar flux--solar flux, however, does not pollute.

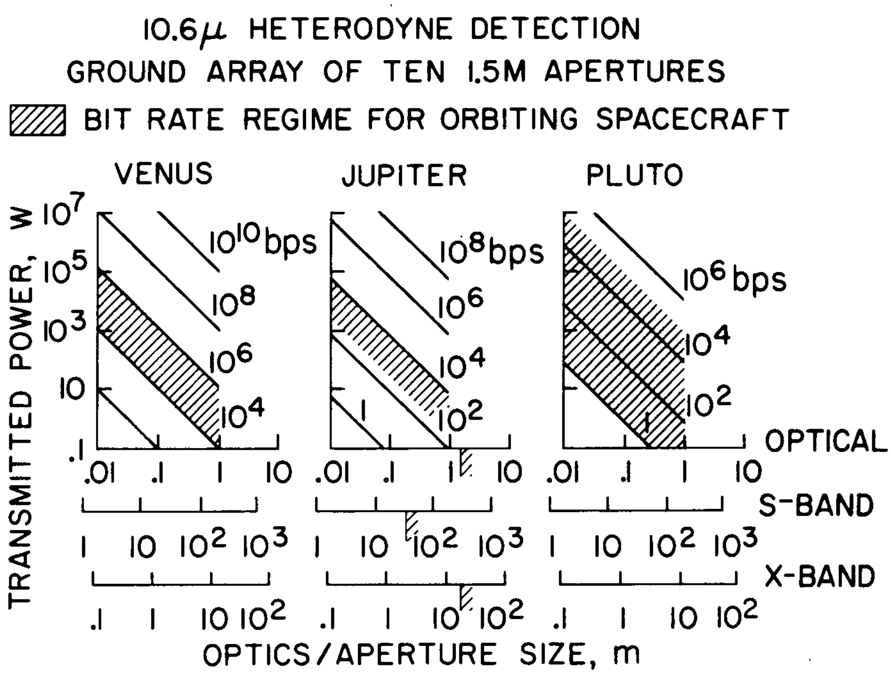

Figure 22 Transmitter Power Requirements

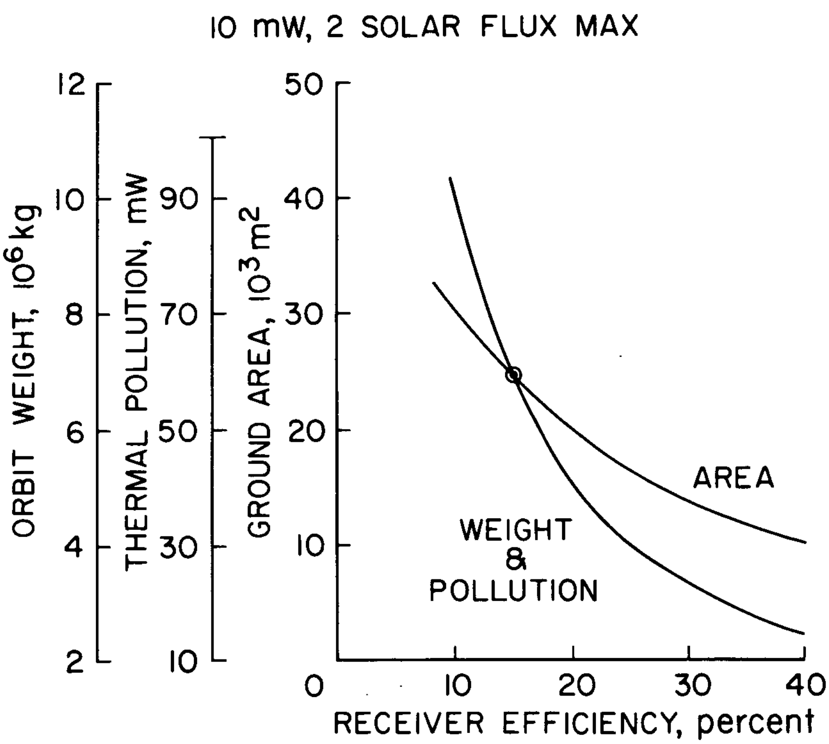

Figure 23 Orbit to Ground Power

Perhaps the biggest problem associated with the power station in the sky concept is its weight. A ten MW laser system could weigh between 5 and 10 million kilograms--equivalent to one or two hundred Saturn V launches to synchronous orbit. At present costs it could be as expensive to launch a laser system as it would be to completely build a conventional ground power station.

There are far more laser application possibilities than can be quantitatively analyzed in this report. A few additional are examined qualitatively below.

Ground Illumination

It is a simple matter to determine flux requirements for ground illumination to enhance vision. It is yet to be shown whether or not laser illumination is psychologically acceptable considering its single wavelength and dancing interference patterns. Conceptually, the idea is simple enough to warrant consideration, and as Figure 8 shows, modest powers can illuminate useful areas--such as a battle scene, city streets, or a disaster area. The trade-off must be made on usefulness, cloud interference, duty cycle, competing systems, etc.

Fog Dispersal

The exact requirements for fog dispersal are as yet unknown because of our lack of understanding of phenomena such as beam and water droplet interaction, rates of fog flow, and the meteorological interactions. It is probably safe to assume that at least one solar flux and probably no more than ten would be used for fog dispersal. Under such assumptions, it can be determined that a GW or so would be required, for example, to keep an airport clear. Such a device would probably be located near the airport to eliminate pointing and focusing problems from orbit. It is possible, of course, that waste heat from the inefficient generator may have more effect on clearing fog than the laser itself.

Terrestrial Power Transmission

The idea of transmitting power from one spot to another on the ground without the necessity of power transmission lines is attractive. Conventional lines are, however, very efficient (typically 90 percent), while laser systems will probably be limited to less than 10 percent. Such a technique, therefore, does not appear attractive except in those cases where land lines are impossible to install or where such lines would be used only for a short time.

OVERALL SYSTEMS IMPLICATIONS

It is evident from laser system application studies that the well established existing systems are strong competitors. Even where lasers appear to show decided advantage, the broader picture--which includes the transmitter and not just the receiver--is much less attractive. The weight advantage gained at the receiving spacecraft (or whatever) is far overshadowed by the weight of the transmitting system. Total system mass, therefore, cannot compete with that of conventional systems. Any apparent optimization of the receiver is only a suboptimization. This is not to say that the advantages gained in drag make-up or orbit changing, etc., should be ignored, but it does imply one of two things: Either the generator should be on the ground where its weight is not so important; or the generator weight must be amortized over a large number of uses. Figure 24 illustrates the trade-off that exists in the second case between laser systems and conventional power systems in terms of total mass launched to Earth orbit. Assuming a receiver specific weight of between one and ten kg/kW_e and 10 percent efficiency, the diagram shows how many times the generator must be used before the total mass of the laser system can equal the weight of conventional systems. The trade-off is a function of both the laser generator weight--plotted on the ordinate--and the competing conventional system weight. As the conventional system becomes lighter it can be seen that the breakeven line moves to the right, i.e., the laser must be used more times to remain attractive. At the very minimum it appears that the laser generator will have to be used for five separate applications if total weight is the deciding criteria.

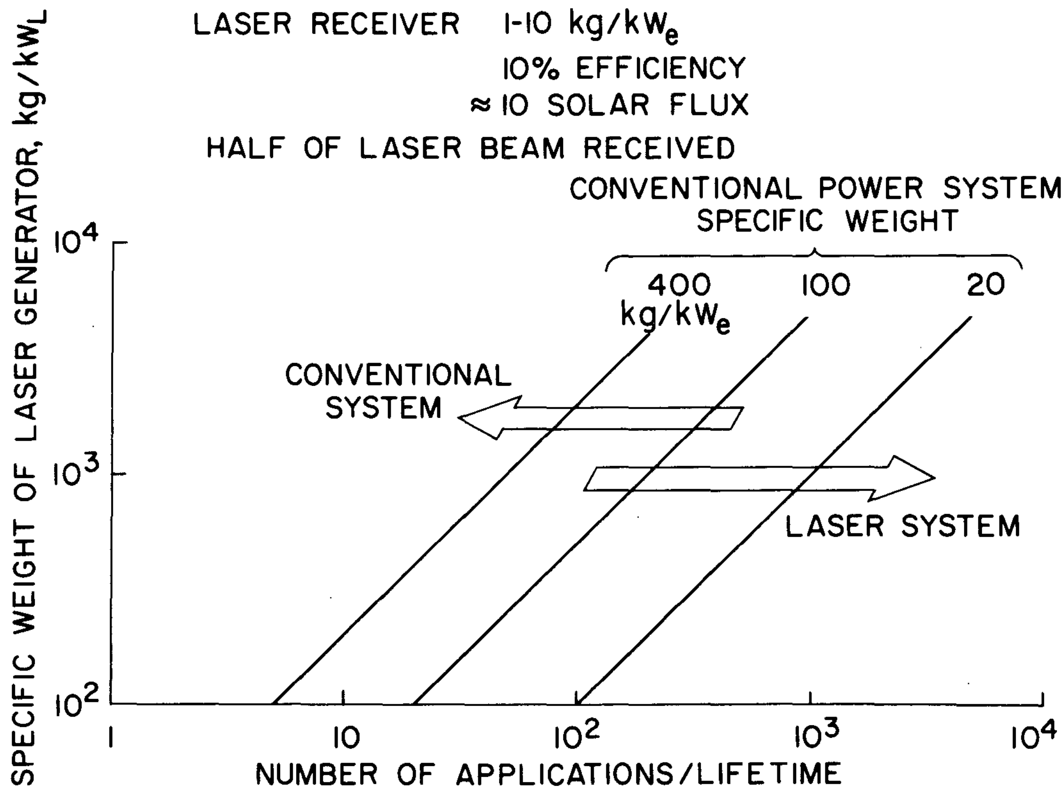

Figure 24 Minimization of Power System Weight Launched

CONCLUDING REMARKS

Few, if any, of the laser applications investigated display unique capability. There are, nevertheless, situations that warrant continued development effort in the emerging field of high power lasers. There is yet much to be learned in the investigation of closed cycle lasers, optics, receivers and energy converters, atmospheric interaction, etc. Thus conclusions about particular laser applications would be premature. Any questions of cost, safety, reliability, environmental pollution, technology transfer, and actual future performance prohibit explicit determination of profitable applications. Based on the foregoing discussion, it is at least possible to state that a spacecraft's power system weight and/or specific area (hence spacecraft weight and/or specific area) can be reduced by the application of lasers where conventional power systems are currently used.

REFERENCES

1. Hans Melchior, Mahlon B. Fisher, Frank R. Arams; "Photodetectors for Optical Communication Systems," Proceedings of the IEEE, October 1970.

2. Gross, Sidney; "Photovoltaic Electric Power System Concepts for Solar Probes," Journal of Spacecraft & Rockets, Vol. 4, No. 9, September 1967.

3. "Study of a Common Solar-Electric Propulsion Upper Stage for High-Energy Unmanned Missions," TRW Systems Group; Under Contract to NASA/OART/ACMD, Contract NAS2-6040; 14 July 1971.

4. Brown, H. and Taylor, J.; "Navigation Study of Electric Propulsion for Unmanned Scientific Missions," CR-565, 1966, NASA.

5. Richley, E. A. and Kerslake, W. R., "Bombardment Thrustor Investigations of Lewis Research Center," Journal of Spacecraft & Rockets; Vol. 6, No. 3, March 1969, pp 289-295.

6. Lauderback, P. W.; "An Analysis of Low Orbital Drag Constraints of Orbit and Sun-Oriented Arrays," 1967 Intersociety Energy Conversion Engineering Conference, Miami Beach, Florida, August 1967.

7. Edelbaum, T. N.; Propulsion Requirements for Controllable Satellites. ARS Journal, Vol. 31, No. 8, August 1961, pp 1079, 1089.

8. MacNeal, Richard H.; "The Heliogyro, an Interplanetary Flying Machine, NASA Contract NAS7-427.

9. Keith Boyer and J. D. Balcomb; "System Studies of Fusion Powered Pulsed Propulsion Systems," AIAA/SAE 7th Propulsion Joint Specialist Conference, Salt Lake City, Utah, June 14-18, 1971.

10. Schaupp, R. W. and Sawyer, C. D.; "Applications of Nuclear Reactor Power Systems to Electric Propulsion Missions," Thermionic Propulsion Specialists Conference, 1971.

11. K. F. Sinclair; "Communications Implications of Future Unmanned Planetary Missions," L"ESPACE ET LA COMMUNICATION, Paris, March 29-April 2, 1971.

NASA--ARC- Coml., Calif.