INVESTIGATION OF POSSIBILITIES FOR SOLAR POWERED HIGH ENERGY LASERS IN SPACE

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ABSTRACT

An investigation of the feasibility of solar powered high energy lasers in space has been undertaken under the sponsorship of the NASA/OAST Research Division. Preliminary analysis indicates that both direct and indirect pumping methods can lead to high energy lasers having interesting efficiencies and capabilities. Many topics for further research have been identified.

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I. INTRODUCTION

NASA is considering several future applications for high energy lasers based in space. Two of the most important concepts are laser propulsion and laser power transmission. Laser propulsion would make possible a very efficient means for orbit raising, launching heavy payloads to the moon and other parts of the solar system, and also long duration loiter of air-breathing craft in the upper atmosphere. Laser power transmission could provide a near-term, very viable alternative to the microwave-linked Space Power System (SPS) now being considered by NASA. Large amounts of solar power, converted and transmitted by laser beams, might be delivered to small collectors on the earth, on the moon, or in space at a fraction of the cost of microwave power, and a demonstration could be accomplished in the near term. These, and many other possibilities, have been described by one of the authors of the present report in a separate paper.[1]

While it is clear that many of the above concepts could be implemented with combinations and modifications of existing technology, it is very important to investigate whether the efficiencies, and thus the capabilities, of the postulated systems can be improved. In particular, it is necessary to seek methods for converting solar photons to laser photons with maximum efficiency. One of the earliest lasers ever built was powered by the sun. That device, built at the RCA labs in Princeton, N.J. in 1963, used crystalline Ca F_2 : Dy^{2+} at liquid Neon temperature (27^oK) as the lasing medium. Although it operated successfully, the efficiency was quite low. It seems strange that in the fourteen years since the RCA experiment very little further research has been undertaken to search for more efficient methods for producing solar-induced lasing. The present effort represents a new beginning in this important and promising area of laser science.

While intuition suggests that exploiting the sun is an obvious and desirable thing to do, it is important to realize at the outset that nature imposes some rather serious constraints upon the utilization of solar energy. There is an instinctive tendancy to think of the sun as the hottest, most intense, most boundless source of power available to mankind. While focussed sunlight is potentially available in enormous quantities from large reflectors, the focal spot is neither as intense nor as rich in ultraviolet radiation as the energy available from other pumping sources normally used in laboratory lasers. The main advantage of sunlight is that it is free and available in quantities limited only by the cost of the collector. Indeed, Figure 1 shows that a 300 meter diameter solar collector at the earth's distance from the sun (1 A.U.) intercepts approximately 100 megawatts of radient flux - - enough to satisfy the needs of a community of several thousand people if efficient conversion to electricity were possible. Generating this power with

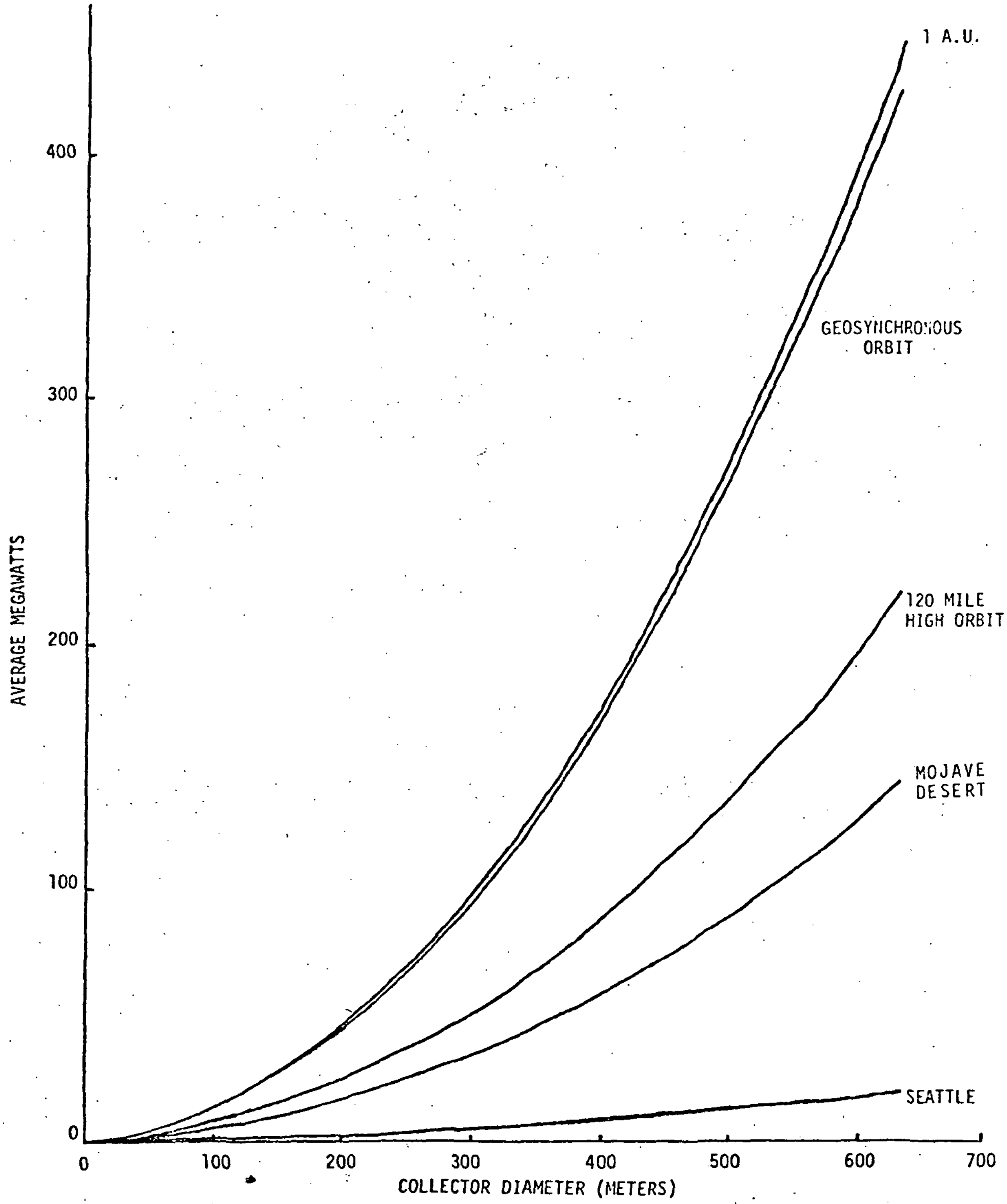

Figure 1: Total Solar Energy (Time Averaged) Available To Circular* Collectors At Various Locations. (To determine usefulness, reduce the available energy by the efficiency of the conversion process.)

* i.e. - Filled apertures normal to the incident solar flux.

petroleum requires combusting a one gallon of gasoline/second or eighty six thousand four hundred gallons/day (561,000 lbs). Moreover, a solar collector on the earth's surface or in low earth orbit suffers an immediate efficiency deficit of 50% because it spends half of its time in darkness! Hence, if lasers powered by the sun are going to be justifiable, they have to have high system efficiency, good cost effectiveness, and other uniquely advantageous capabilities.

In the present paper we shall not elaborate in detail upon the unique advantages and justifications of solar lasers in space. References 1 and 2 are devoted to this topic. Indeed, those reports show that there are numerous important functions that can be performed only by the sort of solar laser system under discussion. The cost effectiveness stems from the diversity of applications, the basic simplicity of the closed-cycle system, the long-duration amortization, and the economy of scale achieved by extensive proliferation of relatively modest individual units. Here we shall concentrate only upon physical issues and systems issues. These will be developed analytically in sections II and III.

For a candidate laser system to be of interest for space applications, it must be scalable to megawatt or gigawatt power levels and it must be as efficient and light-weight as possible. This tends to limit at the outset the usefulness of inefficient methods such as using solar cells to power electric lasers. More direct approaches are needed, the summum bonum being an efficient device in which the lasant is directly stimulated by sunlight. Thus, a major thrust of the present work has consisted of "brainstorming" for as many promising candidate methods as could be identified. Attention has been directed both to the types of materials which may lase efficiently with direct solar stimulation and to possibilities for synergistic combinations of other excitation methods which may work well in the space environment. Certain materials that were rejected in flash-lamp laser research because of low gain or other limitations have been re-investigated for possible usefulness in the solar/space situation. A lengthy literature search was undertaken to ferret out relevant experimental and theoretical data. Remarkably little information exists in the literature to support optical pumping calculations of the sort required, but a few useful publications were found. In this report we shall concentrate upon a small number of identified possibilities that appear to be genuinely promising, excluding a large number of unfruitful ideas that did not survive initial scrutiny.

II. SOLAR LASER SYSTEM CHARACTERISTICS

The most important physical limitations upon the use of the sun for direct laser pumping are imposed by its low specific intensity and by the dearth of ultraviolet radiation on the short wavelength side of the 6000^{o}K black body peak. Very few simple materials of interest for lasers have ionization potentials as low as 2 electron volts; hence, if large ion/electron densities are required, the ionization will have to be augmented by some external method.

A further problem area involves management of waste light (i.e. heat). The solar continuum spectrum is quite broad, extending principally over the 0.2 to 3 micron wavelength range. Typical lasing species absorb radiation in only a few bands that are usually no more than a few hundredths of a micron wide at most. All of the unused solar flux is superflous for direct laser stimulation. --It is true that many indirect laser processes may benefit from using solar heated gases or liquids to drive generators or other ancillary devices, but most gases and liquids are also poor absorbers in the visible range. Hence the gas would have to be either indirectly heated in a black plenum or seeded with an opaque material in order to make maximum use of the light at the focal point of the collector. --These dilemmas have led to an interesting concept: It is entirely possible to design the solar collector as an enormous filter so that it would focus only the parts of the spectrum which are useful, allowing most of the remaining radiation to simply pass on through. A very light-weight, deployable mylar "light-bucket" with narrow-band reflective coatings should be feasible. The gain in system efficiency afforded by this gambit should be very significant, because much weight can be eliminated in the form of radiators and other waste heat management equipment. This should be borne in mind later in this report when we argue that the efficiency of the lasing process itself is not as important as other factors affecting the system efficiency.

Let us turn now to a generalized characterization of a solar laser system. Figure 2 shows a conceptual design. The large, low-weight concentrator brings radiation to an approximate focus, where it is converted by some means to laser radiation. The laser beam is then expanded through an optical system to illuminate a large "adaptive" projection aperture. The adaptive optics of the projector permit full phase-front control so that the resulting nearly diffraction-limited beam can be delivered to the user with great precision and agility. The laser itself includes the laser cavity and optics, the lasant medium, ducting, energy storage medium, heat exchangers, pumps, auxilliary electrical supply, etc. Additionally, there must be a waste heat radiator, possibly located behind the concentrator. This sort of system has been named a "STAG" device. The name originally meant "Solar Tracking Adaptive Geometry."

The total power collected, P_c, by a circular concentrator normal to the sun's rays is given by

$$P_c = \frac{\pi}{4} I D_c^2 \quad , \qquad (1)$$

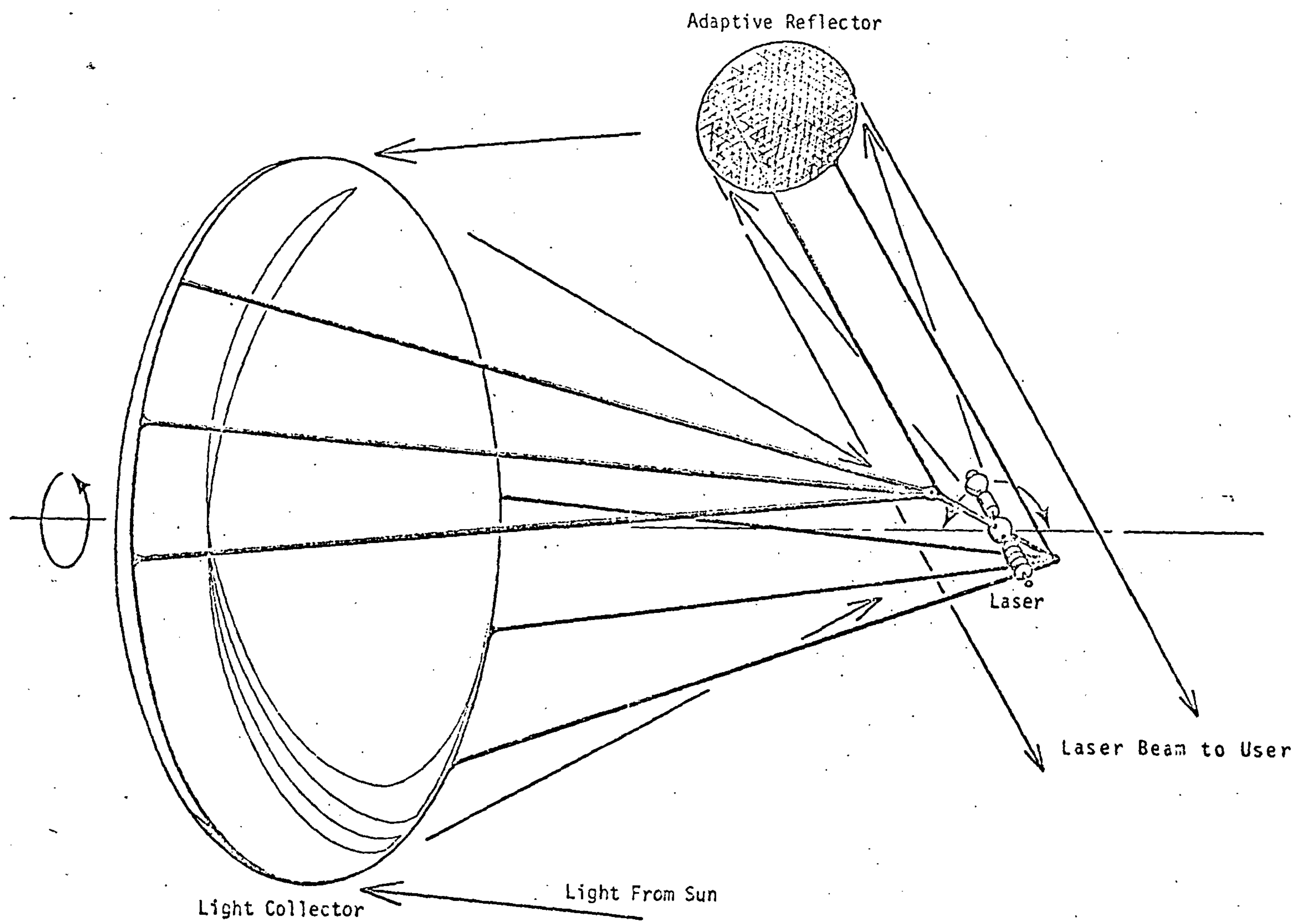

Figure 2: Conceptual View Of A STAG Device

where I is the "insolation," or flux density of solar radiation integrated over the entire spectrum (1380 watts/meter^2), and D_c is the diameter of the concentrator. Assuming that the focal spot is nearly diffraction limited, its diameter, d_s, will be

$$d_s = \frac{f}{r_o} \cdot (D_o) \tag{2}$$

where f is the focal length of the collector and r_o and D_o are, respectively, the range and diameter of the sun. The value of r_o is 1.50×10^{11} meters and D_o is 1.41×10^{9} meters. Then the flux of power through the focal spot, ϕ_f, will be simply

$$\phi_f = \frac{P_c}{\frac{\pi}{4} d_s^2} = \frac{I D_c^2}{f^2} \left(\frac{r_o}{D_o}\right)^2 \quad . \tag{3}$$

Noting that the "f-number" of any optical system is defined as

$$f_{\#} = \frac{f}{D} \tag{4}$$

and that the solid angle subtended by the sun is just

$$\Omega_o = \left(\frac{D_o}{r_o}\right)^2 = 8.84 \times 10^{-5} \text{ steradian,} \tag{5}$$

equation 3 simplifies to

$$\phi_f = \frac{I}{f_{\#}^2 \Omega_0} \qquad (6)$$

Substituting the values of I and Ω_0, we have

$$\phi_f = \frac{1.56 \times 10^4}{f_{\#}^2} \text{ kilowatts/meter}^2 \quad . \qquad (7)$$

So the available flux to drive a laser is simply a function of f-number. Since we have used the value of I for the entire spectrum, this is the maximum available thermal flux. It compares favorably with the flux available from a xenon flash tube in a laboratory. As previously noted, however, the portion of the total flux usable for direct pumping may be much smaller because of the small usable bandwidth; and the spectrum of a xenon tube is heavily weighted toward the ultraviolet compared with the solar spectrum. --From equation 7 it can be seen that an f/1 concentrator will give 1.56 kw/cm², while an f/0.4 concentrator will give 9.75 kw/cm². The latter (f/0.4) concentrator probably represents the smallest desirable f-number, since shorter f-numbers will result in a large increase in the surface area of the concentrator with an accompanying increase in weight.

In summary, the only limit to the total available energy is imposed by practical limits on the diameter of the concentrator.

But there is also a rather strong limit to the total brightness at the focus imposed by f-number. The only way to increase the brightness (or power flux) in the laser medium is to go through a conversion process, such as using solar energy to produce electricity to run the laser directly or drive a flash tube. A penalty will be paid in system efficiency for such conversions, however.

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Before elaborating the physics of the laser itself, it will be instructive for us to examine the relative importance of the various components in determining overall system feasibility. The key parameter in any space-based system is total weight. We may characterize the weight breakdown as follows:

$$W_s = \left(\frac{W_L}{P_L}\right) P_L + \left(\frac{W_p}{d_p^n}\right) D_p^n + \left(\frac{W_c}{a_c}\right) A_c + \left(\frac{W_R}{a_R}\right) A_R \qquad (8)$$

The quantities are defined thus:

W_s = Total system weight

$\frac{W_L}{P_L}$ = Laser weight per unit power

P_L = Laser power

$\frac{W_p}{d_p^n}$ = Adaptive projector weight per unit (diameter)^n

D_p^n = (Diameter of adaptive projector aperture)^n

$\frac{W_c}{a_c}$ = Light concentrator weight per unit area

A_c = Area of concentrator

$\frac{W_R}{a_R}$ = Heat radiator weight per unit area

A_R = Area of heat radiator

The adaptive projector diameter is shown raised to a power n because different scaling laws apply for different types of projectors. The most up-to-date scaling information[3] is shown in Figure 3.

In order to make use of equation 8, we must find reasonable values for the four terms in the summation. We shall keep the laser weight per unit power as a free parameter. The weight per unit diameter of the adaptive projector can be read from the line in Figure 3 for an advanced actively controlled structure. (Hence $W_p \cong 10^4$ kg for $D_p \cong 30$ meters). Assuming that the concentrator is an erectable structure made of 0.1 mil mylar and allowing this weight again for stimulating the weight per unit area, W_c/a_c, might be as low as 6×10^{-3} kg/m^2 which is twice the weight of the basic mylar surface. The required collector area, A_c, is related

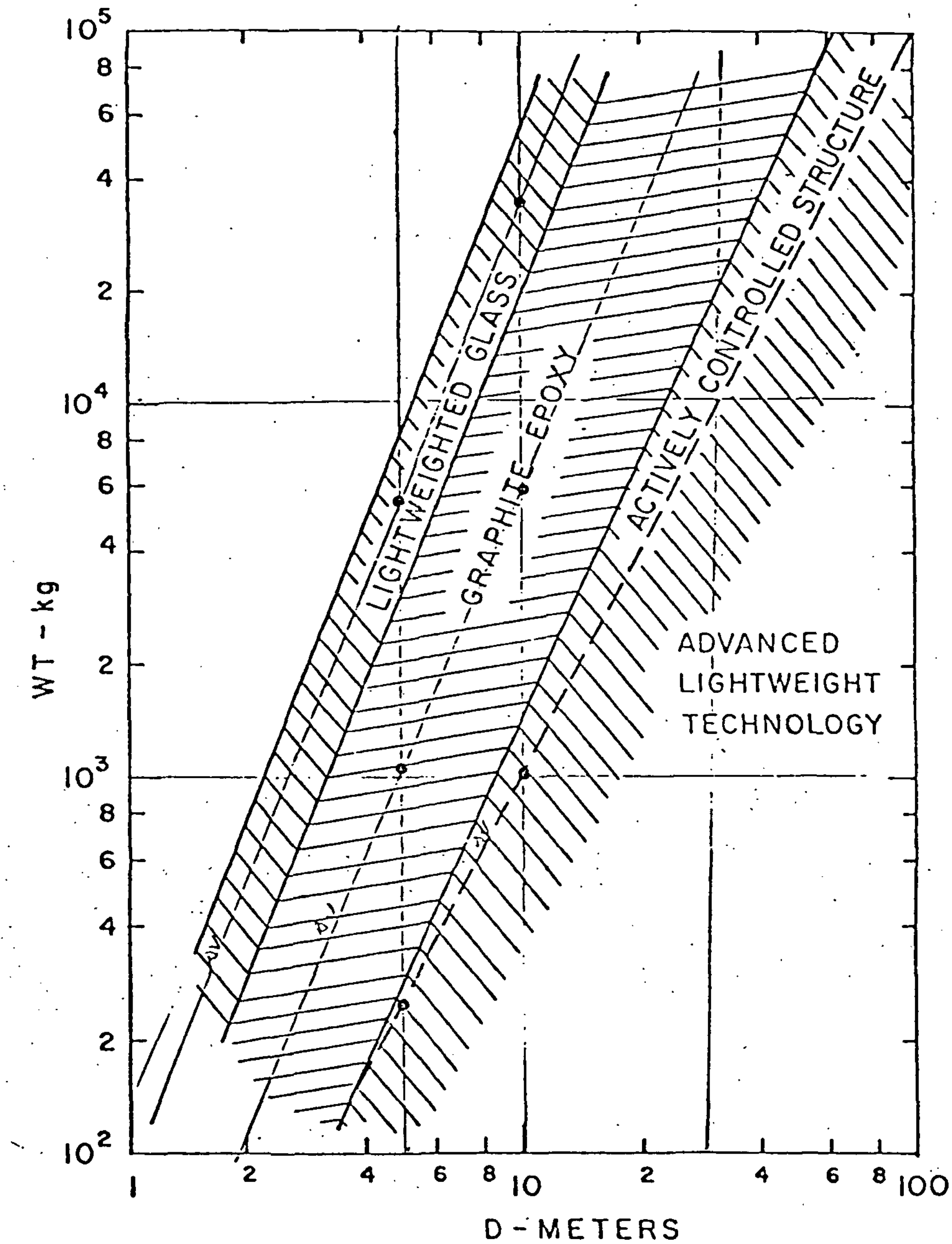


Figure 3: Weight Versus Aperture For Large, Diffraction-Limited Projector Apertures.

to the desired laser power, P_L, by

$$\frac{P_c}{I} = A_c = \frac{P_L}{\eta_T I} \quad , \tag{9}$$

where η_T is the overall efficiency of power conversion from solar radiation to laser radiation, being equal to the product of the efficiencies of all sub-cycles of the conversion process. Substituting $A_c = \pi/4 \times D_c^2$ and $I = 1380\ W/m^2$, we note that

$$D_c = 30.4\sqrt{\frac{P_{MW}}{\eta_T}} \quad . \tag{10}$$

One component of the total efficiency is the efficiency of the basic laser cycle itself, η_ℓ. This is a very important parameter in the optimization because the power wasted in the laser device, P_W, determines the minimum area, A_R, of the radiator, and hence its weight, W_R. The laser power is related to the total collected power by

$$P_L = \eta_T P_c \quad . \tag{11}$$

For the case of a directly solar pumped laser developed in more detail in section IIIB the total efficiency is the product of the laser cycle efficiency and the solar filter efficiency. Assuming that the filtering process can be lossless (e.g. energy not in the pump band reflected into space) then the only waste heat that must be rejected by the radiator is that associated with the inefficiency of the laser cycle itself. The power wasted is related to the collected power and the radiator area by

$$P_W = \eta_F (1 - \eta_\ell) P_c = A_r \sigma \varepsilon T_R^4 , \qquad (12)$$

where the total efficiency $\eta_t = \eta_f \eta_\ell$ and η_f and η_ℓ are the filter and laser cycle efficiencies respectively. σ is the Stefan-Boltzmann constant, ε is the emissivity and T_R is the temperature of the radiator. Eliminating P_c from equations 11 and 12, we see that

$$A_R = \frac{(1-\eta_\ell)}{\eta_\ell} \cdot \frac{P_L}{\sigma \varepsilon T_R^4} . \qquad (13)$$

This can now be utilized in equation 8, together with the value of A_c from equation 9. Finally we note that the best W_R/a_R thus far achieved in advanced space radiator design is $\cong$ 1.0 kg/m^2, and we therefore adopt this value.

At this juncture, it is interesting to compare the weights of the concentrator and radiator. Combining equations 9 and 13, we can write

$$\frac{A_R}{A_c} = \eta_F (1-\eta_\ell) \cdot \frac{I}{\sigma \varepsilon T_R^4} . \qquad (14)$$

Equation 14 can be restated in terms of weight by simply multiplying by the previously given values $W_C/a_C = 6\times10^{-3}$ kg/m^2 and $W_R/a_R = 1.0$ kg/m^2 and inserting the constants:

$$\frac{W_\ell}{W_R} = \frac{.17}{\eta_F(1-\eta_\ell)} \left(\frac{T_R}{1000^oK}\right)^4 . \qquad (15)$$

Equation 15 is plotted in Figure 4 with radiator temperature T_R as a parameter. The laser cycle efficiency is assumed to be 0.3 for this plot. Since it appears as $(1-\eta_\ell)$ lower values will not significantly affect the numerical results. It is important to note that for indirectly solar pumped lasers where $\eta_F = 1$ and all the waste heat must be radiated, the radiator weight dominates the collector weight for any reasonable radiator temperature. For a directly solar pumped laser with a reasonable pump bandwidth (as will be seen in IIIB) the maximum filter efficiency will in general be less than 0.1 so here the collector weight will dominate for radiator temperatures above 800^{o}K. Therefore, for indirectly pumped lasing such as the baseline case of electrically excited CO, improvement of waste heat management is a driving issue. We can clearly see that lasers dependent upon black-body radiation for the first stage of the energy conversion process will pay a penalty in system weight because there is no way to avoid the need for a large radiator. Clearly, maximum effort should be devoted to development of lasers utilizing filtered radiation or to better radiator technology. The latter may be more difficult than the former.

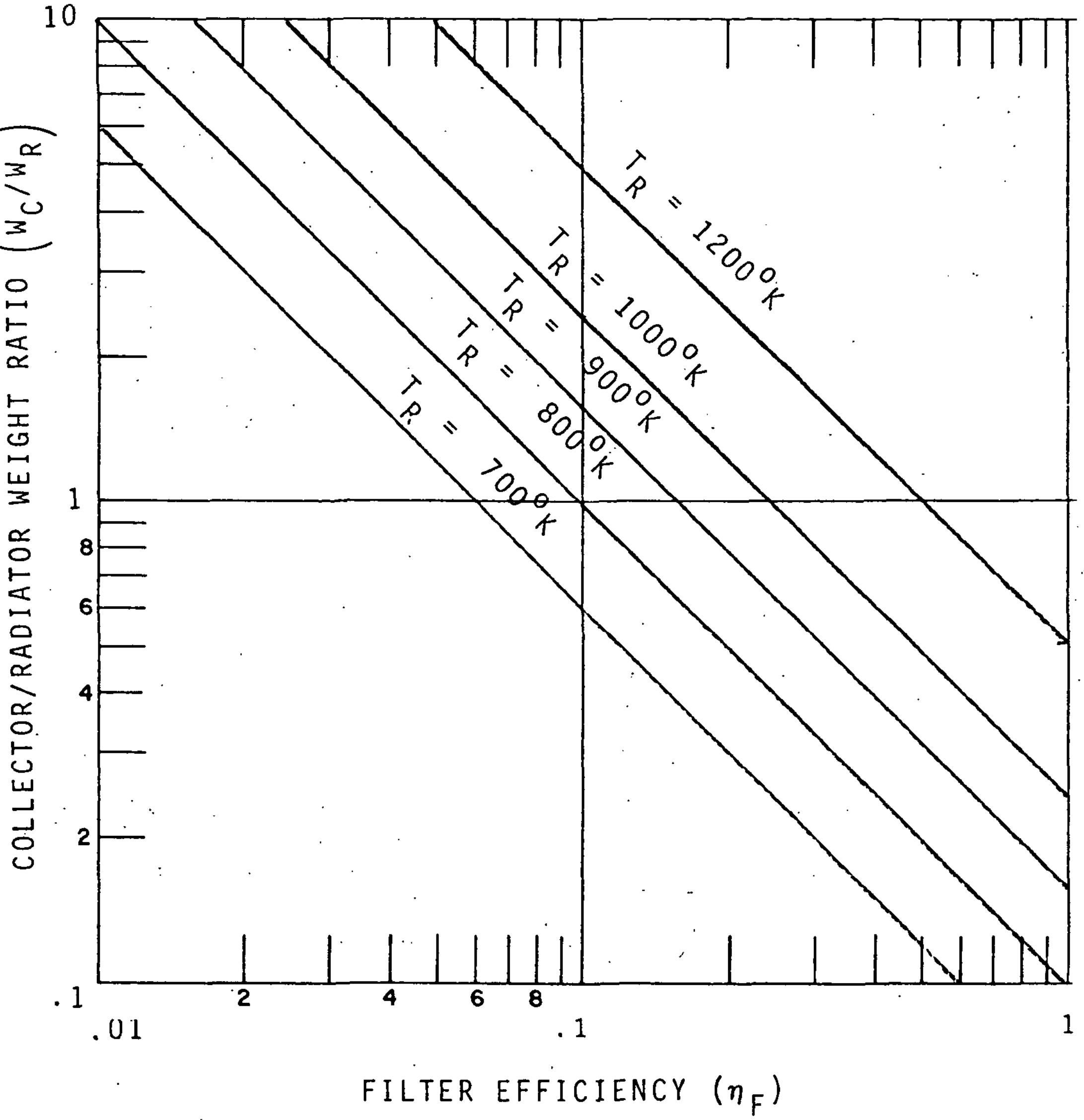


Figure 4: The ratio of collector weight to radiator weight as a function of filter efficiency with radiator temperature as a parameter. η_ℓ is assumed to be 0.3

Let us try out some reasonable numbers for a 100 megawatt space laser system using the relationships developed in the prior discussion.

$$P_L = 100 \text{ MW}$$

$$T_R = 1000^{o}\text{K}$$

$$\eta_\ell = 10\% \quad \Longrightarrow \quad \eta_T = 1\%$$

$$\eta_F = 10\%$$

$$\frac{W_R}{a_R} = 1.0 \text{ kg/m}^2$$

$$\frac{W_c}{a_c} = 6\text{x}10^{-3}/\text{m}^2$$

$$\frac{W_p}{d_p^n} = 11.1 \text{ kg/m}^2 \quad (n = 2)$$

$$\varepsilon = 0.7$$

$$D_p = 10 \text{ M}$$

We obtain a radiator weight of $2.3\text{x}10^4$ kilograms. The 10 M projection aperture weighs $1.1\text{x}10^3$kg, so it is clear that the laser itself will dominate the weight of the entire system if it exceeds ~$7\text{x}10^4$kg. This corresponds to ~700 kg/MW, which is very power intensive. Present chemical lasers (which are not suitable for long term power transmission use in space) being designed for aircraft use are estimated at 380 kg/MW dry weight. Our baseline CO laser design is estimated at 1000 kg/MW. Thus it appears that laser design is going to be very important in determining system weight. It does seem, however, that the present state-of-the-art is approaching the needed criterion; but this is not to say that still lighter lasers would not be better!

It is very interesting that the wavelength of the laser does not strongly enter the optimization (e.g., through projector aperture size). Wavelength seems to be important only in so far as it affects the type of laser and, hence, the laser weight. This conclusion will likely be modified when the user at the other end of the laser beam is also included in the system optimization.

III. CONVERSION OF SOLAR ENERGY TO LASER RADIATION

At the outset of the work reported here, we naively assumed that some sort of hybrid scheme for converting solar energy to laser energy would more likely provide optimum system efficiency than direct solar pumping of the lasant medium. Because of the findings reported in Section II, however, we have changed our viewpoint. Since the weight of the laser itself dominates the system weight so strongly, any extra step in the conversion process will very likely add significantly to the system weight, and hence to the cost of deploying the system in space. We have essentially shown that two or three space Shuttle sorties to low orbit can probably deploy the needed solar concentrator, adaptive projector and heat radiator for a 100 Megawatt laser. But how many more sorties will be needed to deliver the laser itself? Since we are not looking toward just one system, but toward many hundreds of them to achieve many gigawatts of power transmission capacity, it is essential that the laser be kept as simple and compact as possible.

In this chapter we shall outline several possible schemes for implementing solar to laser energy conversion. First, a "base-line case" will be described. This is a conservatively designed carbon monoxide electric-discharge laser that can almost certainly be built within the near term by scaling up from present technology. Then a prescription will be given for the physics of directly pumped solar lasers. An example of a workable directly pumped iodine laser will be elaborated. Finally, some other promising schemes for both directly pumped and hybrid lasers will be discussed. Some conclusions will then be drawn concerning relative cost-effectiveness and performance efficiency.

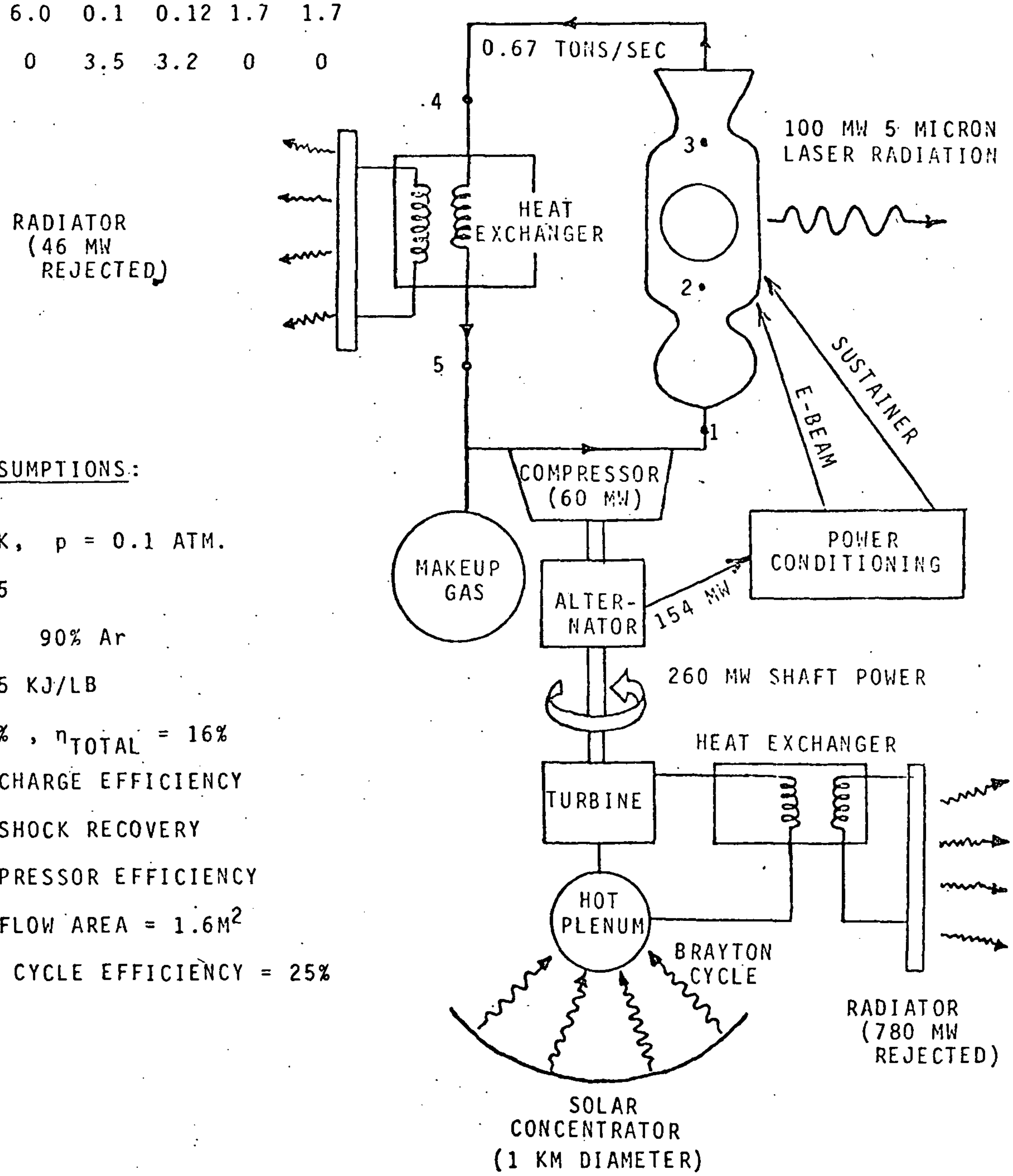
A. Baseline Case

Figure 5 shows a schematic representation of our proposed 100 megawatt CO EDL baseline solar laser system. The gross properties of the system are apparent from the figure and will not be further explained here. The efficiencies quoted are high, but not inconsistent with present experimental and theoretical findings. The overall conversion efficiency is ~11%.

While this concept is straightforward in design and might, indeed, be capable of performing many of the missions envisioned for high energy space lasers, it also has some liabilities that need to be considered. Foremost of these is that this CO EDL epitomizes the previously mentioned point that the "laser" term in equation 8 can include a multitude of complications: In the present case there would be at least four separate closed-loop fluid cycles plus pumps, ducting, etc. to handle the fluids. Also there would be the appreciable weight of the fluids themselves and their storage tanks. Additionally, a generator and power conditioning subsystem would have to produce megavolts of potential energy and kiloamperes of current. Insulation, busing and cooling for the power supply would add further weight. Moreover, heat exchangers and radiators for 826 MW of waste thermal energy would be required. Let us try to estimate the total weight of the principle elements of this melange:

CYCLE CONDITIONS:

STATE	1	2	3	4	5
T, ^{o}K	314	65	78	474	177
P, ATM	6.0	0.1	0.12	1.7	1.7
MACH #:	0	3.5	3.2	0	0



ASSUMPTIONS:

$T = 65^{o}K$, $p = 0.1$ ATM.

MACH 3.5

10%CO 90% Ar

P/m = 75 KJ/LB

$\eta_L = 65\%$, $\eta_{TOTAL} = 16\%$

95% DISCHARGE EFFICIENCY

NORMAL SHOCK RECOVERY

80% COMPRESSOR EFFICIENCY

CAVITY FLOW AREA = 1.6M^2

BRAYTON CYCLE EFFICIENCY = 25%

Figure 5: 100 Megawatt Supersonic Carbon Monoxide Electric Discharge Laser Powered By Solar Energy

The turbine in the primary Brayton cycle would have a specific mass of about 0.09 Kg/kw, yielding a total mass of ~19,800 Kg for 220 megawatts of delivered shaft power. (This is comparable to the propulsion turbine for a large ship.)

The alternator would probably resemble currently available cryogenically cooled devices, which weigh approximately 82 kg/MW. Hence, for 154 MW, the expected mass is 12,600 Kg.

The compressors and blowers used to move the CO gas in the primary loop and the coolant gas (freon?) in all of the secondary loops would require approximately 30% of the total excitation energy, or about 60 MW total. We believe 0.1 Kg/kw to be a reasonable number for the specific mass, but this value needs verification. This yields 6000 Kg for the compressors themselves. The fluids and ducting are also quite heavy. Rough estimates of the total required flow imply an index of about .05 Kg/kw, or 3000 Kg.

The heat exchanger would weigh 14,800 Kg, primarily because of the heat wasted in the first step conversion of solar energy to shaft horsepower. --The power conditioning equipment would be quite heavy if transformers and large numbers of rectifiers were used. Considerable weight savings may be possible using high vacuum insulation although this idea has not been fully exploited. A crude estimate puts the weight of the power conditioner at another 10,000 kg.

Finally, we come to the laser cavity itself. Various estimates have been made for the specific mass of the laser cavity of an advanced CO laser ranging from 100 to 1000 kg/MW.

A typical value is 400 kg/MW, giving a total of 40,000 kg for our 100 MW laser.

Summing all of the foregoing estimates, we obtain a total of just under 106,000 kg for the total laser system weight. To this we add ≈4,000 kg for the ~1km diameter collector ≈20,000 kg for the radiator and approximately 1,000 kg for a 10 meter projection, giving ≈131,000 kg total. This equates to at least five Space Shuttle flights to deploy each device in low orbit.

All things considered, the baseline case provides an option that is not too grim. It would be nice, however, to have a less complicated system. Moreover, while five Shuttle flights would not be prohibitive cost-wise, fewer would be better. Since the system needs to be moved to high orbit, some sort of propulsion system is necessary. This might be cleverly achieved by venting solar heated hydrogen from the hot plenum at the focus or by a solar-electric engine. The propulsion system and reaction mass would add to the weight of the system, of course, but it would be available thereafter for station-keeping, etc. Station-keeping should not provide any serious problems. The mass of the system would largely dominate the solar photon thrust upon the 1 km^2 concentrator.

B. Direct Solar Pumping

In section II, we have already discussed the physical constraints that nature imposes upon the direct use of solar radiation. Now we shall investigate whether we can live within those constraints and still devise a laser that is simpler and better than the baseline case. In particular, we shall inquire as to whether direct solar pumping of a continuously operating high energy laser is possible. To accomplish this, we need to write down the basic equations for an optically pumped laser, specialized to the fact that the pumping flux is not arbitrary but rather is tied directly to the available solar flux. This means that we need to state the kinetics of the pump and laser processes so that the laser medium can be scaled to conditions that are appropriate for use of solar energy at maximum efficiency.

Figure 6 shows schematically the operation of a typical optically pumped laser. The impinging radiation somehow pumps the electrons of the lasing species from the ground state into upper excitation levels, whence they cascade down to populate the upper laser state. Lasing occurs when the upper state is depopulated by stimulated transitions to the lower laser state. The equation giving the number-density of electrons in the upper laser state, N_U, as a function of time is

$$\frac{dN_U}{dt} = \alpha_A \frac{\phi}{h\nu} - \frac{N_U}{\tau_{loss}} \quad . \tag{17}$$

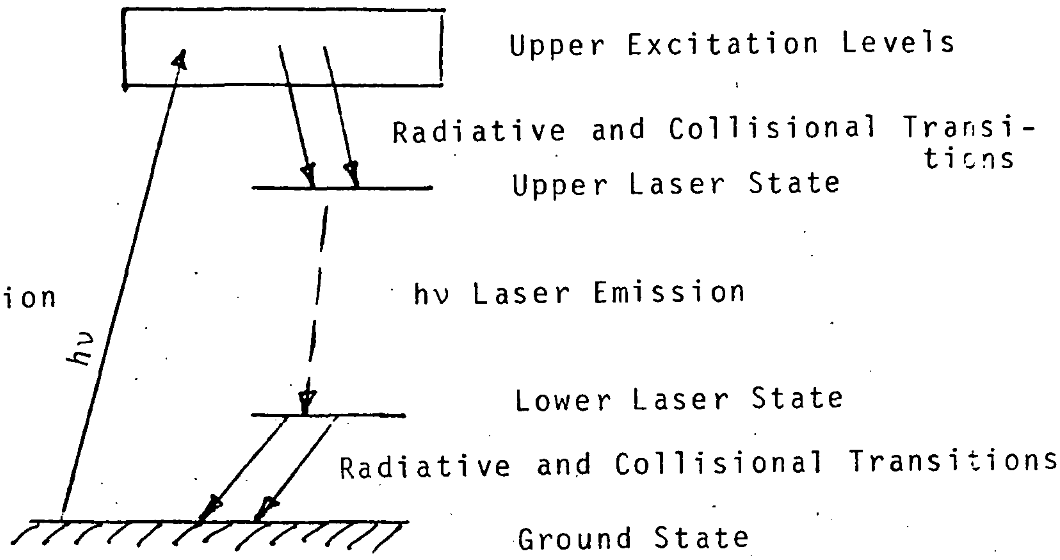


Figure 6: Schematic Representation Of Optically Pumped Laser Energy Levels.

In equation 17, ϕ is the impinging optical flux, $h\nu$ is the photon energy, α_A is the absorption coefficient, and τ_{loss} is the depopulation lifetime from the upper laser state. τ_{loss} may be either radiative or collisional. The absorption coefficient is expressed in units of cm^{-1}, giving the absorption per unit path length. We need to know the absorption as a function of wavelength so that we can integrate the total absorption over the solar spectrum. To achieve a useful form for the equations, let us first think back to the derivation of equation 7 and re-state the solar flux differentially. The Planck law for the sun at 6000^oK is :

$$\phi_\lambda = \frac{8142}{\lambda_\mu^5 \left(e^{2.439/\lambda_\mu} - 1\right)} \quad \text{Watts/m}^2\mu \quad , \qquad (18)$$

which can also be stated

$$F_\lambda = \frac{4.105\times10^{22}}{\lambda_\mu^4\left(e^{2.439/\lambda_\mu}-1\right)} \quad \text{Photons/m}^2\text{ sec } \mu \quad . \qquad (19)$$

By analogy with equations 1 through 7, we can now derive the flux available at the focal point, ϕ_f:

$$\phi_f = \frac{\phi_\lambda\left(\frac{\pi D_c{}^2}{4}\right)\Delta\lambda}{\pi\left(\frac{fr_o}{D_o}\right)^2} = 1.13\times10^4\ \frac{\phi_\lambda D_c^2\ \Delta\lambda}{f^2}$$

$$(20)$$

$$= \frac{9200\ \Delta\lambda}{\lambda_\mu^5\left(e^{2.439/\lambda_\mu}-1\right)} \cdot \frac{1}{f_\#^2} \quad \text{Watts/Cm}^2 \quad .$$

This is the flux that we now substitute for ϕ in equation 17. Dividing by $h\nu$ in the first term on the right of equation 17 gives us a photon flux, F, per unit bandwidth, since

$$F\Delta\lambda = \frac{\phi}{h^2} \qquad (21)$$

We therefore obtain an equation of the form

$$\frac{dN_U}{dt} = \frac{F\Delta\lambda}{L_A} - \frac{N_U}{\tau_{loss}} \quad , \qquad (22)$$

where we have identified the absorption length, L_A, as the reciprocal of the absorption coefficient, α_A. (The absorption length is the distance over which the impinging pumping flux decreases by one e-fold.)

In the steady state $\frac{dN_U}{dt} = 0$, so from equation 22:

$$\frac{F\Delta\lambda}{L_A} = \frac{N_U}{\tau_{loss}} \quad , \tag{23}$$

and thus

$$N_U = \frac{F(\lambda p)(\Delta\lambda)_p \, \tau_{loss}}{L_A} \quad . \tag{24}$$

Here we have indicated the functional dependance of F upon the pump wavelength, while also noting by the subscript p that $\Delta\lambda$ is the pumping bandwidth, which is actually the bandwidth of the absorbing transition.

This is directly related to the filter efficiency, η_F, introduced in Chapter II which simply represents the fraction of the total solar fluence (1380 W/M^2) that falls within the assumption band of the laser. η_F is plotted in Figure 7 as a function of the center wavelength of the absorption band. The parameter is the bandwidth of the absorbing transition expressed as a percentage of the center wavelength.

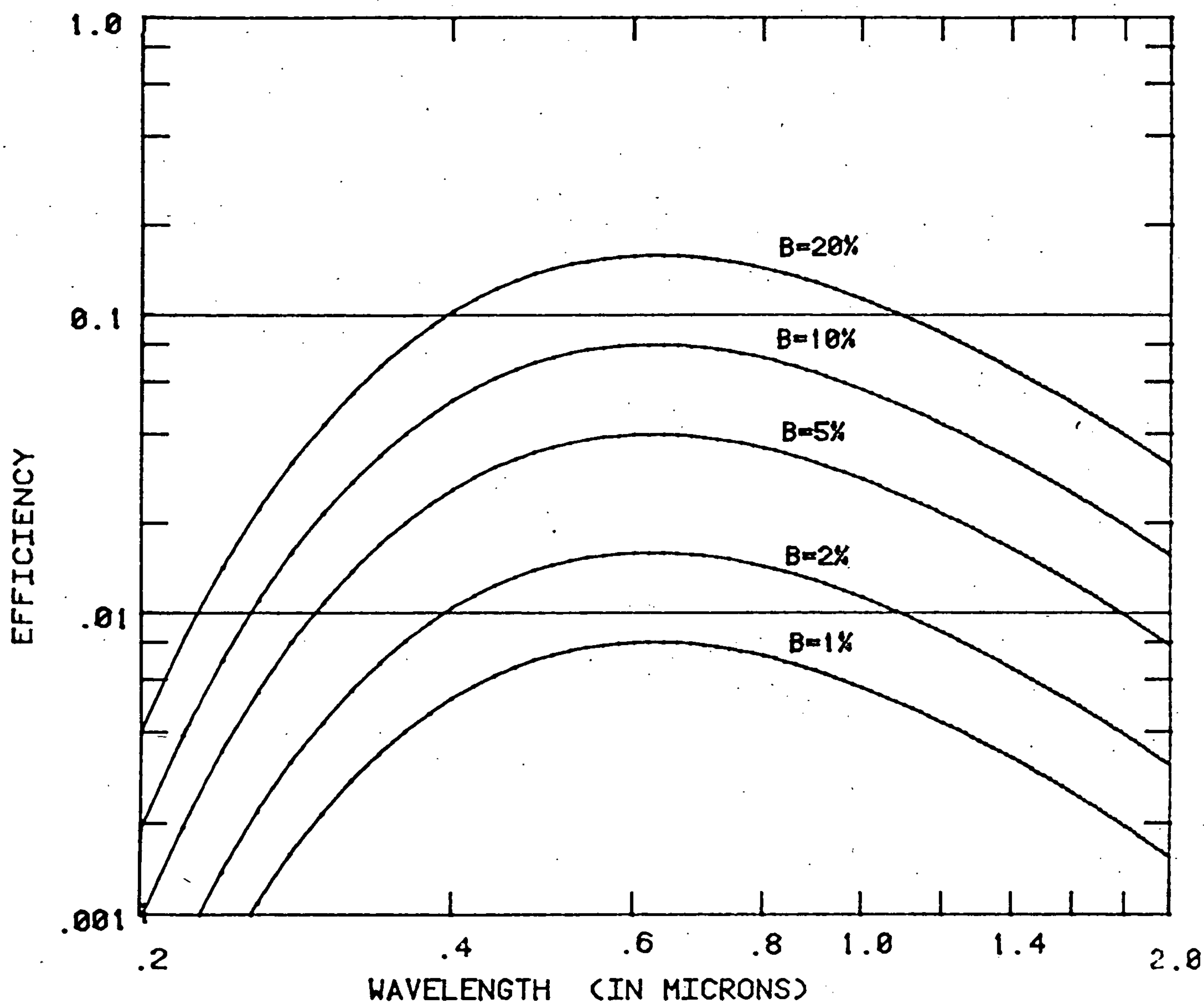


Figure 7: Pumping Efficiency Vs. Wavelength

Having N_U now in hand, we can use it in the gain equation. Since we know the pumping rate, we now know the population of the upper laser state; and we must proceed to find out what gain it will produce per unit distance along the laser. Accordingly we employ the gain coefficient, G, given by

$$G = \frac{\lambda_L^3}{8\pi c \tau_{loss}} \left(\frac{\lambda_L}{\Delta\lambda_L}\right) \cdot N_U \quad . \qquad (25)$$

The maximum useful gain length for a solar laser is related to the absorption length, L_A, by a factor ranging from 1 to a few depending on the detailed optical design. The so-called "laser equation" then results when we multiply the gain by the length over which gain can occur. Hence the emergent intensity, I_e, of a beam passing through the lasant medium is related to the impinging intensity, I_o, by

$$I_e = I_o e^{(GL_A)} \quad . \qquad (26)$$

For an efficient laser to be designed it is desirable to have $GL_A \simeq 1$.

Having gathered together the needed components from the foregoing discussion and having substituted the appropriate constants for the sun, we finally obtain for the solar laser equation

$$GL_A = \frac{0.24}{(e^{2.452/\lambda_p} - 1)} \cdot \frac{1}{f_{\#}^2} \cdot \left(\frac{\lambda_L}{\lambda_p}\right)^4 \cdot \frac{(\Delta\lambda)_L}{(\Delta\lambda)_L} \cdot \left(\frac{\tau_{loss}}{\tau_{21}}\right) \simeq 1 \quad . \qquad (27)$$

All wavelengths are stated in microns. Subscripts "L" refer to the laser and subscripts "p" refer to the pump (i.e., the fraction of the solar spectrum sampled by the absorption of the lasant). The fraction τ_{loss}/τ_{21} gives the ratio of the mean time for the upper laser state to depopulate by all loss processes to the mean time for it to depopulate only by radiative decay in the transition of interest (i.e. $1/\tau_{21}$ is equal to the Einstein A-Coefficient). The relation between all recombination times is given by

$$\frac{1}{\tau_{loss}} = \frac{1}{\tau_{21}} + \frac{1}{\tau_{collision}} + \cdots \quad . \tag{28}$$

Equation 27 tells whether a medium will lase when illuminated by sunlight. The other really crucial quantity needed to characterize the laser is its overall efficiency. This is simply found by taking the ratio of the total energy that actually emerges as laser energy to the total solar energy captured:

$$\eta_T \leq \frac{\lambda_p}{\lambda_\ell} \cdot \frac{\int_{\substack{pump\\band}} \phi_\lambda \, d\lambda}{\phi_f} \quad . \tag{29}$$

$$\eta_T = \eta_F \eta_\ell , \quad \eta_\ell \leq \frac{\lambda p}{\lambda_\ell}$$

In this context, it is interesting to recall the idea proposed at the beginning of section II that the solar concentrator itself can act as a filter. If only the portion of the solar spectrum needed for pumping is brought to the focal point, the amount of waste heat that must be discharged is minimized. Since radiators would be much heavier than solar concentrators even as large as several square kilometers in area, this gambit would have a marked effect upon the system efficiency. The really nice thing about directly pumped solar lasers is that cooling is required only in one primary fluid loop. Most of the other ancillary systems can be small and easily manageable if a good direct lasant can be identified.

The weight of a 100 MW solar pumped laser system is plotted in Figure 8 as a function of the solar filter efficiency and indicates clearly the effect of this approach. The nominal values for weight coefficients used in section II are used in this Figure (W_ℓ = 1000kg/MW, W_P = 11.1kg/m^2, W_c = 6x10^{-3}kg/m^2, W_R = 1kg/m^2, T_R = 1000^{o}K, D_P = 10M) because of the potential for a very light weight solar collector relative to a waste heat radiator, the figure indicates that for example, a directly pumped laser with an overall efficiency of only 1.5% and a filter efficiency of 7.5% can compete with an indirectly solar pumped laser with an overall efficiency of 10%. This leaves considerable margin for system improvement if a successful well matched direct solar pumped laser is found.

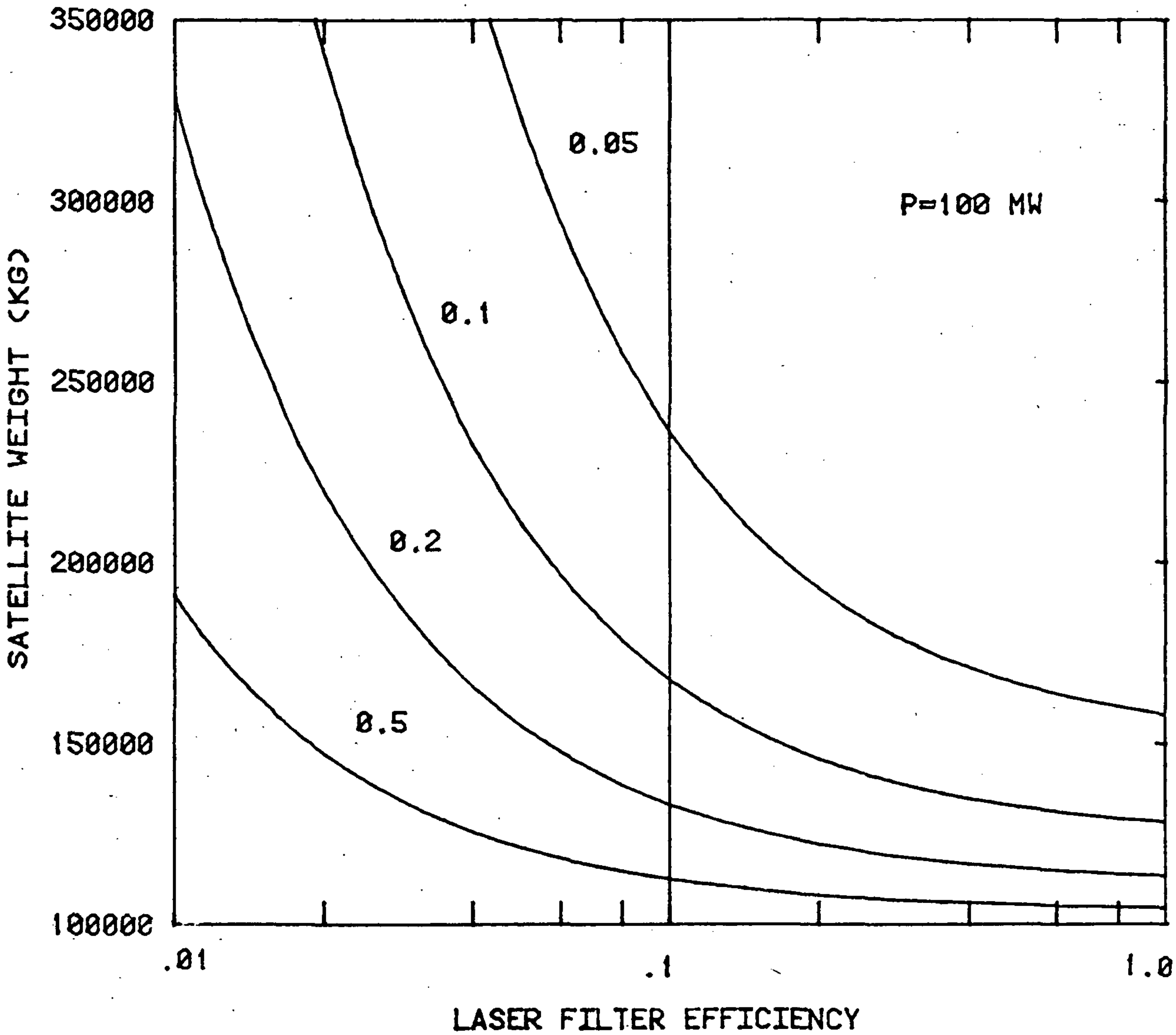


Figure 8: Direct Solar Pumped Laser

C. Iodine Lasers

A lengthy search of the literature in the Library of Congress for data on optically pumped lasers produced surprisingly little useful material. The objectives of the search were gain coefficients, absorption coefficients and cross sections, radiation lifetimes, collision lifetimes, and profiles of absorption and emission spectra. Most of the optical pumping information from the early "flash-lamp" days of laser physics seems to concern either wideband visible absorption in solid crystals, which are useless for very high energy lasers, or coincidences between narrow resonance-absorption lines of electrically excited gases and upper laser states of other admixed gases. The latter are also useless because narrow lines absorb so little energy from a black-body spectrum that the efficiency is very low. (This difficulty also eliminates many candidate lasers such as excimers from consideration. Although they may perform well when stimulated by other mechanisms, they do not respond to broadband optical pumping.)

One of the best documented materials that has interesting properties for our purposes is trifluoromethyl iodide, CF_3I. A laser based on this material was described first by Kasper and Pimentel in 1964.[4] Other more recent discussions are found in two papers by Hohla, et al.[5,6] The mode of operation is illustrated in Figure 9, adopted from reference 6: Electronically excited iodine atoms in the $5^2P_{1/2}$ state are generated by photodissociation of the CF_3I. Lasing occurs on the magnetic dipole transition at 1.315 μ wavelength as the upper state radiates to the ground state $5^2P_{3/2}$. Breaking the CF_3-I bond requires only about 2.5 eV, but the photolysis in the experiments described is accomplished principally by a molecular absorption band 0.05 μ wide centered at ~0.275 μ (hν≃4.75 eV). This leaves ample excess energy for the excitation of the photolysis products. Several other chemical processes affect the composition of the gas as indicated in Figure 9. An important contribution to basic research would be a laboratory study of the differences in behavior of the lasant in a 6000°K steady-state, closed cycle configuration from the pulsed flash tube configuration which was used for all of the data in the literature.

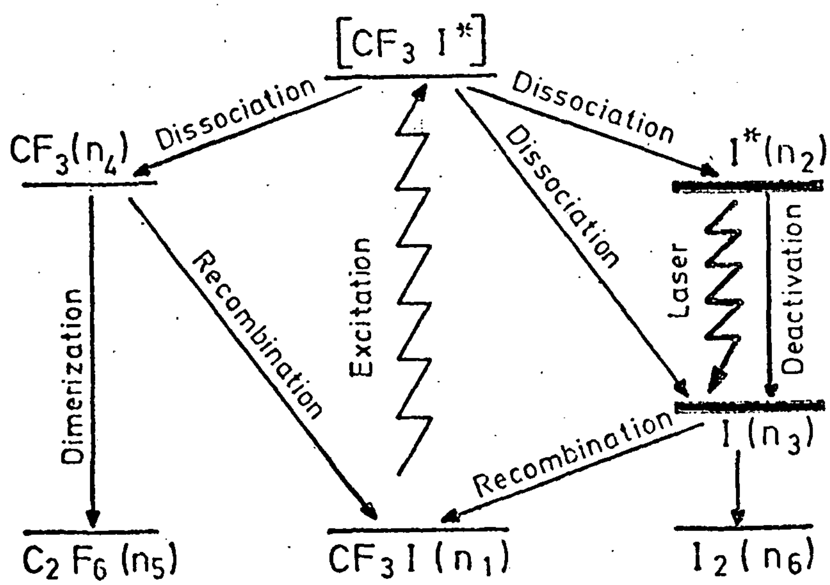


Figure 9: Level Scheme Of Photochemical Iodine Laser. Chemical Species N_1 Through N_6 Occur In The Laser (Ref. 6).

With the analytical tools that we have developed above, it is now an easy matter to use the available data from reference 6 to investigate the feasibility of a directly pumped solar laser. From equation 20 we obtain

$$\phi_f = \frac{41.8}{f_{\#}^2} \quad \text{watts/cm}^2 \quad , \tag{31}$$

for the solar flux in the 0.275 μ molecular absorption band. This is only 0.026 of the total solar flux. The photons are reemitted at 1.315 μ, so the overall efficiency from equation 29 is 0.0054 or ~½%. This sounds small, but, recalling the discussion of overall system efficiency and the idea of prefiltering the sunlight at the concentrator, this is probably an acceptable efficiency. (For example, the projector aperture would be only one-fourth of that required for the CO baseline case. Hence it would weigh less than one-sixteenth as much.)

Referring to equation 25, we identify

$$\sigma = \frac{\lambda_L^3}{8\pi c \tau_{loss}} \quad , \tag{32}$$

as the stimulated emission cross section. Reference 6 shows σ increasing from 2×10^{-19} Cm^2 to 1.8×10^{-18} Cm^2 as the pressure is reduced. We shall adopt the latter value. The mean value of τ_{loss} is ~1.3×10^{-3} second, and the radiative lifetime, τ_{21}, is

$\sim 10^{-1}$ second. Putting everything together, we obtain from equation 27

$$GL_A = \frac{0.13}{f_\#^2} \quad . \qquad (33)$$

Adopting $f_\# = 0.4$ gives $GL_A = 0.81$. Therefore iodine will work as a moderately good lasant! By making the laser in several independently pumped sections to increase the length, GL could be increased to well in excess of 1.

Thinking back to our treatment of the baseline system, we can make a very rough estimate of the weight of a 100 MW iodine system. For iodine the filter efficiency is low (≈3%) due to the 10% bandwidth combined with the U.V. pump band ($\lambda p = .275\mu$) which does not match the solar spectrum at all well. (Refer to Figure 7.) In addition even assuming that each absorbed photon yields one laser photon the laser cycle efficiency cannot exceed the ratio of quantum energies $\frac{\lambda p}{\lambda} = \frac{0.275}{1.315} = 0.21$. Using the nominal values for specific weights employed in conjunction with Figure 8, we obtain a weight estimate of approximately 180,000 kg which compares with 130,000 kg for the baseline case. The 180,000 kg estimate uses a specific laser weight of 1000kg/MW. It is conceivable that a directly pumped system such as iodine which is much simpler could weigh half that, 500kg/MW. In this case even iodine, which is far from the ideal solar pumped laser would compare favorably with the baseline CO system.

Hence, in spite of the fact that the system weight is still too high, we find numerous encouraging aspects in the fact that this crude conception can be made to work at all and that it can compete with the baseline case.

D. Other Directly Pumped Lasers

Two other possible candidates for direct pumping have been considered in some detail:

Liquid dye lasers at first seemed to hold some promise, but were rejected because of low efficiency. Better data is actually needed to support this conclusion, however. Our best reference material on dye lasers is due to Dienes.[7]

A very promising class of materials is concealed in obscure literature which we discovered late in this study. Liquid inorganic chlorides such as $POCl_3$ - $ZrCl_4$, $POCl_3$ - $SnCl_4$. $SeOCl_3$ and other similar compounds can be doped with Nd^{3+} to produce wide absorption bands in the visible. The band structure is very similar to that of neodymium doped glass, but the liquid is capable of handling much higher average powers than the glass. References 8 through 15 contain considerable useful information, but time has not permitted us to fully explore this important possibility. These materials are sufficiently promising to prompt much more experimental and theoretical research.

E. Hybrid Schemes

In addition to turbo-electric schemes such as the CO baseline system, there are other possible hybrid solar approaches that should receive further scrutiny. We list a few here:

A hot, partially ionized gas, possibly seeded with low ionization material, might be expanded through a magnetic field to create an MHD laser. Alternately, an MHD generator driven by solar heated gas might power an electric laser.

An interesting variation on the iodine laser has been proposed to us by Gary Russell of Jet Propulsion Laboratory. Xenon gas, partially ionized and heated by sunlight, would be expanded supersonically into a plenum. The resulting non-equilibrium distribution of electrons and ions would then be "tickled" by high voltage, causing an electron cascade. The resulting flash of light, rich in ultraviolet, would then pump the iodine. In other words, it may be possible to build a "transformer" to convert the 6000^{o}K black body spectrum to an ultraviolet peak that would improve the pumping efficiency.

Such ideas, together with a continuing search for better lasant materials will no doubt converge eventually to a high efficiency system.

IV. CONCLUSIONS AND RECOMMENDATIONS

Our studies have shown beyond reasonable doubt that 100 megawatt high energy lasers in space can be energized by the sun. Even within the very limited scope of the present contract work, it has become clear that at least two different types of laser systems could be developed within the near future and launched by a few Space Shuttle flights. We have high confidence that the efficiency of such devices can be improved considerably and that the weight in orbit can be reduced accordingly. The various principle components of the system have been discussed separately, and the nature of the needed system optimizations has been indicated.

There is a clear need for more research in many areas. The nature of the needed laser medium is sufficiently well understood that much work can be done toward its realization.

--System optimization should be done for every plausible candidate system to establish which is truly the best. Ideally, the user should also be included in the system optimization because the application may have strong impact on the required characteristics of the system. Individual components such as the large adaptive projector, the deployable solar concentrator, and the waste heat radiators all require further development and improvement. Above all, the laser itself provides a challenging and fascinating technological problem.

The payoffs that will accrue from the deployment of a solar laser system in space will have enormous consequences for the future of the United States. We hope that this report will provide some modest but significant incentives toward that end.

LIST OF REFERENCES

1. Rather, J. D. G., "Space Transportation, Solar Power from Space, and Space Industrialization: A Better Way."--White Paper submitted to NASA headquarters, January, 1977.

2. Rather, J. D. G., "A Study to Recommend to NASA High Power Laser Technology and Research Programs"--Final Report for NASA/OAST, Contract #NASW-2866, July, 1976.

3. "Large Erectable Apertures," (Unclassified title), W. J. Schafer and Associates, Inc., Technical Report Number - 76-65, 20 January, 1976, (Secret).

4. J. V. V. Kasper, G. C. Pimentel, Appl. Phys. Lett. 5, 231, 1964.

5. K. Hohla, P. Gensel, K. L. Kompa, "Photochemical Iodine Laser, A High Power Gas Laser," Laser Interaction and Related Plasma Phenomena, Vol. 2, Ed., J. Schwarz and H. Hora, Plenum Press, N.Y.; London, 1972.

6. K. Hohla, K. L. Kompa, "The Photochemical Iodine Laser," Handbook of Chemical Lasars, Ed. R. W. F. Gross and J. F. Bott, J. Wiley and Sons, New York.

7. Dienes, A., "Dye Lasers"; Laser Applications to Optics and Spectroscopy, Ed., S. Jacobs et al, Addison-Wesley Pub. Co., Reading, Mass., 1975.

8. Yu. K. Voron'Ko, L. V. Krotova, V. A. Sychugor and G. P. Shipulo, "Lasers with Liquid Active Materials Based on $POCl_3$: Nd^{3+}," Translated from Zhurnal Prikladnoi Spektroskopii, Vol. 10, No. 2, pp. 244-247, Feb., 1969.

9. C. Brecher, K. W. French, "Comparison of Aprotic Solvents for Nd^{3+} Liquid Laser Systems: Selenium Oxychloride and Phosphorus Oxychloride," J. Phys. Chem., Vol. 73, No. 6, June, 1969.

10. F. Collier, G. Girard, M. Michon, J. P. Pocholle, "Amplification Cross Section of the 1.052-μ Transition of Nd^{3+} in $POCl_3$ - $SnCl_4$ - (H_2O) System by Three Different Methods," IEEE J. Quantum Electron., Vol. QE-7, No. 11, November, 1971.

11. E. J. Schmitschek, "Laser Emission of a Neodymium Salt Dissolved in $POCl_3$," J. Appl. Phys., Vol. 39, 6120, 1968.

12. M. Itongyo, T. Sasaki, Y. Nagao, K. Ueda, C. Yamanaka, "High-Power Nd^{3+} $POCl_3$ Liquid Laser System," IEEE J. Quantum Electron., Vol. QE-8, No. 2, February, 1972.

13. V. V. Griforyants, M. E. Zhabotinski, V. M. Markushev, "Lasing and Spectral Line Characteristics in Phosphate Glasses and Inorganic Liquids with Neodymium," IEEE Journal Electron., Vol. QE-8, No. 2, February, 1972.

14. A. I. Zaretskii, S. I. Vladimirova, G. A. Kirollov, S. B. Kormer, V. R. Negina, S. A. Sukharev, "Some Characteristics of a $POCl_3$ + $SnCl_4$ + Nd^{3+} Inorganic Liquid Laser," Sov. J. Quant. Electron., Vol. 4, No. 5, November, 1974.

15. M. E. Zhabotinskii, N. M. Zhavoronkov, V. G. Lebedev, B. N. Malyshev, Yu. P. Rudnitskii, G. V. Ellert, Vestn. Akad. Nauk SSSR, No. 2, p. 52, 1969. (Russian, untranslated)