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POWER BEAMING OPTIONS

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John D. G. Rather
Vice President for Research and Technology Innovation
Kaman Aerospace Corporation

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Successful taming of beamed power would be a monumental jump in technological capabilities. I think history provides some lessons about such transformations that are worth pondering as we begin this workshop.

When we examine major technological revolutions, they all have a common thread. I think there have been four outstanding examples in the last 50 years. The first was the Manhattan project. The second was the development of the nuclear submarine/nuclear missile fleet. The third was the ICBMs. And the fourth was the Apollo program. Every one of these major revolutions in technology had the common thread that, at the outset, an important mission or application was recognized, but there was no existing technology base or master plan for getting to the desired operational capability. First, the people in charge of the government decision-making process had to be convinced that the new effort was worth doing. They, in turn, convinced the President, Congress, and the public. Having done that, enough organized support was mustered so that the programs could be launched. Then, the engineers were challenged to find the best way to reach the desired goals. Challenged with the question of how to get to the required performance criteria in the shortest time and most economical way, engineers have a wonderful record for coming up with workable solutions.

It's remarkable how little was known at the outset of these programs. Just think of Apollo: (1) no one had ever thought of rendezvous in lunar orbit; (2) hydrogen propulsion hadn't been harnessed except for a few Centaur experiments which were scaled far below what was needed for Apollo; (3) the required computer technology was not even on the drawing boards. Given the challenge, NASA achieved all the needed innovations successfully in eight years. You can go through the same ritual for the other examples, and the story is the same: You can't take existing technologies and expand them to serve some mission; what you must do first is to define the mission and then create the technology to do the job.

What we have to do here at Langley in order to make this conference yield high payoffs is to seek uniquely important missions and applications that justify power beaming: things that can't be done well by any other method, or that become cheaper, better, or quicker through this revolutionary technology. So the primary question becomes; "Does power beaming make sense when compared to other options?" The second question is, "If it does make sense, <u>what kind</u> of power beaming? Microwave? Laser?" The third question is, "How do we get there from here?"

To stimulate discussion, I will propose some large scale power beaming applications, bearing in mind all three of these foregoing questions. Let's start with really large-scale stuff in the tradition of the hugh microwave power satellites considered in the 1970s.

The United States would like to reverse the balance of trade. We do have an asset we can export: One thing we have that isn't being capitalized upon is 1.7 billion kilowatt hours per day of unused electrical capacity. At night, it isn't efficient to cool down the steam power plants or necessary to stop the flow of water in the dams. There is a large amount of existing generating capacity that just isn't used. Figure 1 shows the typical day to night electrical load swing for the United States as a whole. Most of it is in the Central and Eastern time zones because, even though there's a large population on the Pacific coast, they have more benign weather. There are eight or ten hours in the middle of the night when the U.S. has a lot of power available, and there are a few hours in the middle of a summer afternoon when there's a great demand that almost exceeds our abilities to supply it. For the latter demand, we build huge power resources that often are not used.

People started thinking about the microwave power source in orbit back when there was a perceived energy crisis. I would suggest that, since we are no longer building new power plants with such frequency, maybe we should think about using in better ways what we already have. One approach that could undoubtedly be realized more quickly than a major power satellite in orbit might be a large microwave phased array on the ground near our own power resources or near other countries' resources on the other side of the ocean, as shown in Figure 2. A passive reflector a kilometer in diameter up in geostationary orbit could be used to reflect the power back down to the earth near to places where there is a demand. This could work both ways, giving us the ability to import power across eight or ten time zones when needed. A single-dish, relatively low power transmitter at the receiving end would provide the phase reference for the transmitter and would enable controlling all the beam steering electronically, making the link fail-safe by constantly controlling the phase at the transmitter. But, in order for this to make any sense, the overall efficiency must be reasonably high, and the cost must be competitive with other methods of energy export.

At the bottom of Figure 2, it can be seen that nearly 50% transfer efficiency (electric to electric) could be achieved by a microwave relay system. This raises further interesting possibilities because, if inexpensive amorphous solar cell arrays can be built, why not deploy them on the earth's surface in Nevada, the Australian desert and the Sahara desert, and beam the energy around the world without bothering with the great difficulties of assembling a power plant 10 kilometers long in geostationary orbit? At least, this may be a first step to eventual power plants in orbit.

The fundamental question that should be addressed first is, "Is there a cheaper way to do it?" It's easy to see from Figure 3 that, on land, transferring power over distances of a thousand miles gets quite expensive. It's expensive to acquire real estate and to build power lines. The cheapest way of shipping energy across land turns out to be by natural gas pipelines. This motivated me years ago to look at some estimates for a laser relay system; and, of course, the microwave one just proposed might be even cheaper.

So we need to look at the questions of a) feasibility, and b) cost, in order to see whether the concept of power beaming makes any sense. The one thing that isn't on the chart shown in Figure 3 is the cost of moving oil in tanker ships, which is so cheap that it probably falls off the bottom of the chart. The arguments against fossil fuels must be couched in different areas such as (1) exhaustion of limited resources, (2) environmental pollution, and (3) vulnerability to supply-side blackmail. These matters are extremely important and have their own costs which must be added to the cost of cheap oil.

Now let's shift the discussion to lasers. A lot of attention was given in the 70s to microwave solar power. I would like to look at the laser alternative in some depth. I contend that it can be shown to be environmentally very acceptable. I believe that a near-term demonstration of considerable note can be achieved more easily with lasers than with microwaves. Also, possibilities do exist for direct conversion of solar photons to laser photons; and it's been proven that efficient re-conversion to useful energy can be achieved.

Lasers can perform two principal functions: propulsion and space power beaming. I think that, since we have to walk before we can run, the earliest reasonable opportunities that should be considered involve beaming power from the ground to space. Some examples of ground to space power beaming are shown in Table 1. Some of the associated applications include K-band wide coverage radar for air traffic monitoring and identification, which even gains current significance in the international attempt to control drugs. Then there is ship traffic monitoring, the same thing that the Soviets are doing with their unpopular nuclear reactor powered RORSATS except more so. Even clear air turbulence mapping can be done with millimeter wave radar; and then, of course, there are many defense applications. Electric propulsion for economical orbit raising from LEO to GEO, and direct broadcast TV transmission from GEO are other important applications that, I think, have definite merit. Then there are many other active remote sensing applications that we might consider in this workshop, plus industrial processes and life support.

Back in the 70s, the chart shown in Figure 4 was prepared by NASA as an index of some of the applications that they were considering at the time. Propulsion applications are shown in the shaded envelope, but the most interesting things for us at this workshop are the arrows that I have added to indicate 10 kilowatts per year and 1 megawatt per year. These show that even modest amounts of beamed power from lasers currently available can lead to a plethora of applications, including propulsion applications. So, even extrapolating from things that were being considered a decade ago, we begin to see the utility of power beaming.

Let's look at some possibilities augmenting the Space Shuttle usefulness with laser propulsion from LEO to GEO using ground-based lasers. Leik Myrabo, whom some of you know, has authored a book called "The Future of Flight", which expresses boundless zeal for laser propulsion. I worked with Leik for several years back in the late '70s and early '80s. We looked at several possibilities, particularly with regard to saving and using the Shuttle main tank by making use of the ullage fuel that's contained in it upon reaching orbit as a laser-heated monopropellant. We examined three possibilities in detail: (1) an autonomous tugboat taken up in the Shuttle bay, which had its own monopropellant; (2) a rendezvous of the Shuttle with a permanent tugboat in orbit where the tug is refueled with the residual ullage fuel from the Shuttle main tank and then used to boost the main tank or a large Shuttle payload up to GEO and; (3) raising the entire Shuttle to GEO and returning personnel.

I don't have time to go through all the details of this. The summary (see Table 2) is that, for that analysis, the typical amount of ullage fuel was taken to be 520 kg of hydrogen, and 3000 kg of oxygen. The total required energy to perform a typical mission is 4,500 gigajoules. That translates to 10 megawatts of laser power for 5.2 days, which isn't too bad!

The details of this mission were worked out in considerable depth by Leik Myrabo in a study contract supported by NASA Marshall Space Flight Center, from which several points in the present talk originated. Figures 5 and 6 show two walk-around charts which parameterize the various tradeoffs. Explanations of each chart are given on the page following. There are many factors that have to be looked at carefully to really appreciate the pros and cons of this sort of mission.

One possible motivation to consider for laser propulsion as we contemplate expanding major space activities from LEO to GEO and beyond is the fact that the radiation dose in the inner and outer Van Allen belts is quite considerable. As you traverse the belts, you integrate a large dose particularly in the outer belt if you don't make a fast trip. So if you consider solar-thermal or ion propulsion as alternatives, the payload had better be pretty immune to radiation because it will take ten or more days to get across the belt. This implies a dose of about

10^4 rad, as can be seen in Figure 7. So, depending on what you're trying to do, you might not want to expose even unmanned vehicles to radiation fluences like that, and this provides a persuasive reason supporting what we're trying to do at this meeting.

Now some thoughts about large mass in orbit. First, I want to affirm my belief that the real payoffs from many commerical endeavors -- even building power stations on the surface of the earth -- come when you scale to large size. The economies of large engineering efforts can become very significant, and this provides a challenge for us to find out how the scaling goes and where the payoffs come for the things we're considering at this meeting. Looking at the question of how we get large mass into high orbit, an old mnemonic that goes back to Professor Kantrowitz in the '60s is that approximately a gigawatt of laser power on the ground should be able to deliver a ton of payload to low earth orbit every four minutes. Even if the Shuttle were flying once a week, as people said it would at the beginning of the program, one ton per four minutes would equal the entire Shuttle fleet payload every three days. Of course, the way things are now, it would take a small fraction of one day. But the thing that interests me is that, if you look at the integrated amount of mass that you can get into orbit, piecemeal, 2000 lbs at a time, by a continuous stream going up from the surface, you find that you can do monumental works in very reasonable times. Figure 8 shows the estimated total electrical energy consumption in the United States to the year 2000 and beyond. At the bottom of the chart, it can be seen that a very small fraction of the total electrical energy of the United States would be required to build the first space colony for a few thousand people (e.g. the so-called Bernal Sphere).

Now let's come back to the same sort of picture that I showed earlier for microwave power beaming, but this time for huge lasers (Figure 9). Assuming we can build propulsion class lasers, then isn't it reasonable to think in terms of what else we can do with them -- like intercontinental power transfer? An early application could utilize a ground-based transmitter with a relay mirror in orbit sending power back to airplanes. (Abe Hertzberg will delight us with some details of laser air flight later in this session.)

The efficiencies of a laser relay scheme will probably be lower than those of a microwave scheme for the foreseeable future, but efficiency in not the whole story. Since the wavelength is about 10,000 times shorter for lasers than microwaves, the transmitter and receiver apertures can be 10,000 times smaller in diameter. Even with a realistic assessment of what the laser conversion efficiency will be, the numbers are not too daunting. I believe strongly in the free electron laser, which I'll discuss later, and it appears that 35% "wallplug" conversion efficiency is not unreasonable for the FEL*. So if we go through all of the losses associated with the full relay process to the user by this method, we'd probably be down to 15% instead of the 50% overall efficiency that we found for microwaves. However, the laser

*Free Electron Laser

relay may still render possible things that can't be done otherwise, and therefore it's worth examining. Efficiency is not the bottom line. Cost is the bottom line.

Turning to possibilities for solar power satellites, we have to look first at the question of what's the most cost effective way to convert solar power to electricity for the user. (It may be that the simplest approach will be to build amorphous solar cells for direct use on the ground, and forget about space altogether!) However, there is an alternative, shown in Figure 10 that I looked at in quite a bit of detail back in 1974. I named it STAG, for the Solar Tracking Adaptive Geometry. (Some of you might enjoy the fact that it started out being called STAG because it was first conceived as grown-up BAMBI, but that is an in-joke with a different motive!)

The STAG idea basically is to eliminate waste heat by using a big, very low-weight (possibly inflatable) light collector and designing it as a reflective filter so that you use only the part of the solar spectrum that you need to pump the laser and let the unwanted black body radiation simply pass through. We did a detailed examination of a strawman concept using iodine as the lasant. The light collector focuses the sun to a large plenum in which most of the waste heat is accountable only to the photon efficiency of the lasing process, which is quite high. The emerging 1.3 micron wavelength photons are then focused on the adaptive optics array, which transmits the beam to the ground or to users elsewhere in space.

We compared this method with another strawman, an indirectly pumped Brayton cycle carbon-monoxide electric discharge laser, and we found that the direct pumping iodine laser compared favorably. Even though the iodine STAG device is very big, its weight would be quite reasonable for a 100 MW unit. This suggests the possibility of building piecemeal power plants of about a hundred megawatts apiece and beaming the power to local users on the ground, in the air, or in space. It's about the same amount of power produced by a typical power plant on the ground. So the idea would be to bring the power down to a low cost collector just adjacent to the user facility on the ground or to other large users in space. One laser could access many users in the course of a day.

Objections to laser power beaming to the earth have often been based upon weather factors. If you're bringing the power down to collectors that are local to existing power plants for the purpose of feeding the national grid, the statistical coverage of the clouds is not too bad. A lot of the country is accessible all the time, as you can easily see from pictures taken from space. This is substantiated by the data in Figure 11 taken, I think, from an old Lockheed study.

One other point I want to make is that lasers for NASA applications would have to operate more or less continuously at very high power levels. Lasers for DoD applications have traditionally been conceived for short run times at very high power. The free electron laser emerges as a prime candidate for both of these classes. This will be a comfort to the electrical engineers in the audience who may be worried because I'm not harping on microwaves. It's really just a question of wavelength! The FEL works just as well for microwaves as it does for lasers, and, in fact, it's demonstrated the highest and most efficient power generation at millimeter wavelengths ever achieved. Figure 12 shows the basic principles of an FEL.

Finally, a plug for my company, Kaman Corporation. I decided long ago that one of the most taxing problems standing in the way of beamed power is the fact that we don't know how to build very large optics cheaply enough to achieve the things that we dream of. Kaman has invested a substantial amount of IR&D money to solve this problem, and we now have a glorious new technology that we're going to reveal at the SPIE meeting in Orlando at the end of March. This will be a totally new approach to building very large optical apertures. Basically, we know how to produce phased arrays for optical wavelengths. The approach makes full use of the economies of the silicon microprocessor industry, and I think it can greatly reduce scaling difficulties and costs. We have named her PAMELA, which means "Phased Array Mirror, Extendable Large Aperture". She is represented crudely by Figure 13, which shows that she is composed of thousands of small "smart" segments, each a precision machine carrying two microprocessors, edge sensors capable of measuring position to $\lambda/40$ at visible wavelengths, and long-throw actuators that can conjugate disturbances in the atmosphere or in the optical system.

Table 1

HIGH POWER SPACE APPLICATIONS

- K-BAND WIDE-COVERAGE RADAR
  - AIR TRAFFIC MONITORING AND IDENTIFICATION
  - SHIP TRAFFIC MONITORING AND IDENTIFICATION
  - CLEAR AIR TURBULENCE MAPPING
  - DEFENSE
- ELECTRIC PROPULSION FOR ECONOMICAL ORIBIT RAISING (LEO TO GEO, ETC.)
- DIRECT-BROADCAST TV TRANSMISSION
- ADVANCED REMOTE SENSING
- INDUSTRIAL PROCESSES
- LIFE SUPPORT FOR LARGE MANNED SPACE STATIONS

Table 2

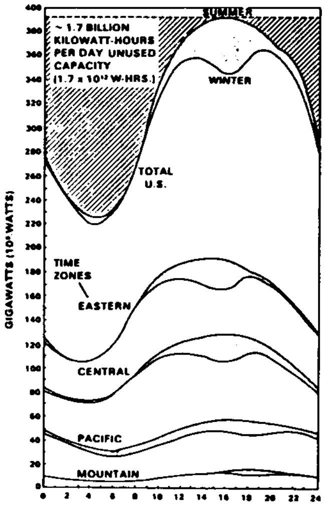
SHUTTLE RENDEZVOUS WITH TUGBOAT IN LEO. RESIDUAL SHUTTLE MAIN TANK FUEL IS TRANSFERRED TO TUG. TUG THEN BOOSTS MAIN TANK OR FULL SHUTTLE PAYLOAD TO GEO.

- I_{SP} = 1,500 SECONDS
- ΔV = 5,630 METERS/SEC (EACH WAY)
- TUG SPACECRAFT DRY MASS = 4,400 Kg.
- AVAILABLE FUEL MASS ≥ 3,640 Kg.*
- MAIN TANK DRY MASS (OR ALT. PAYLOAD) = 32,300 Kg.

- TOTAL REQUIRED ENERGY = 4,500 GJ.
- MINIMUM ONE WAY MISSION DURATION = 5.2 DAYS
- MINIMUM REQUIRED LASER POWER = 10.2 MW

* 520 Kg. H_2 + 3,120 Kg. Lox

ESTIMATED TYPICAL DAILY ELECTRIC LOAD VARIATIONS FOR THE U.S. IN 1985



ESTIMATED TYPICAL DAILY ELECTRIC LOAD VARIATIONS FOR THE UNITED STATES IN 1985. STIPPLED AREAS INDICATE SEASONAL RANGE. LINED AREA REPRESENTS UNUSED OFF-LOAD CAPACITY.*

*DEVELOPED FROM DATA SUPPLIED BY EDISON ELECTRIC INSTITUTE, NY, NY

Figure 1

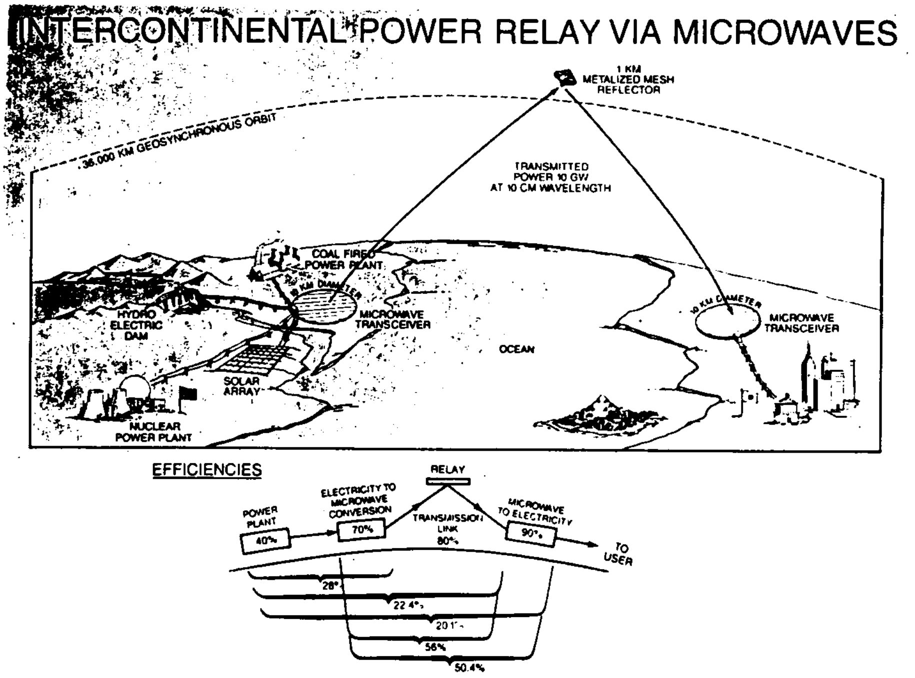


Figure 2

ORIGINAL PAGE IS OF POOR QUALITY

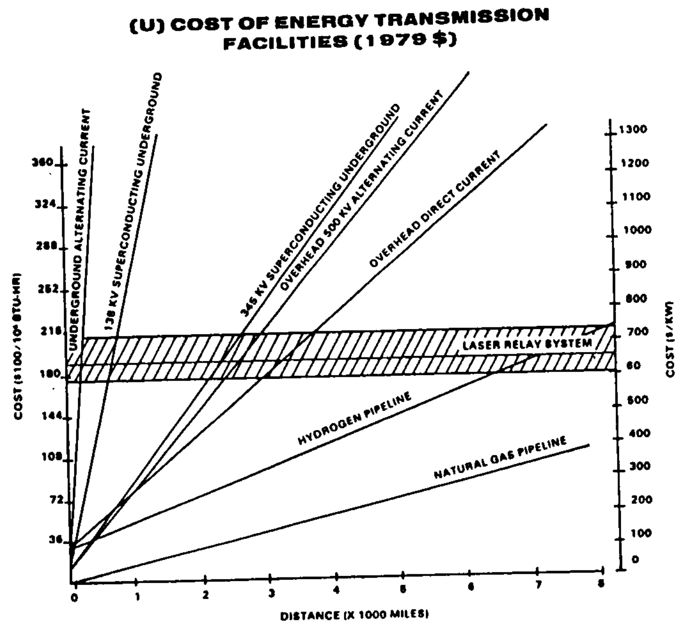
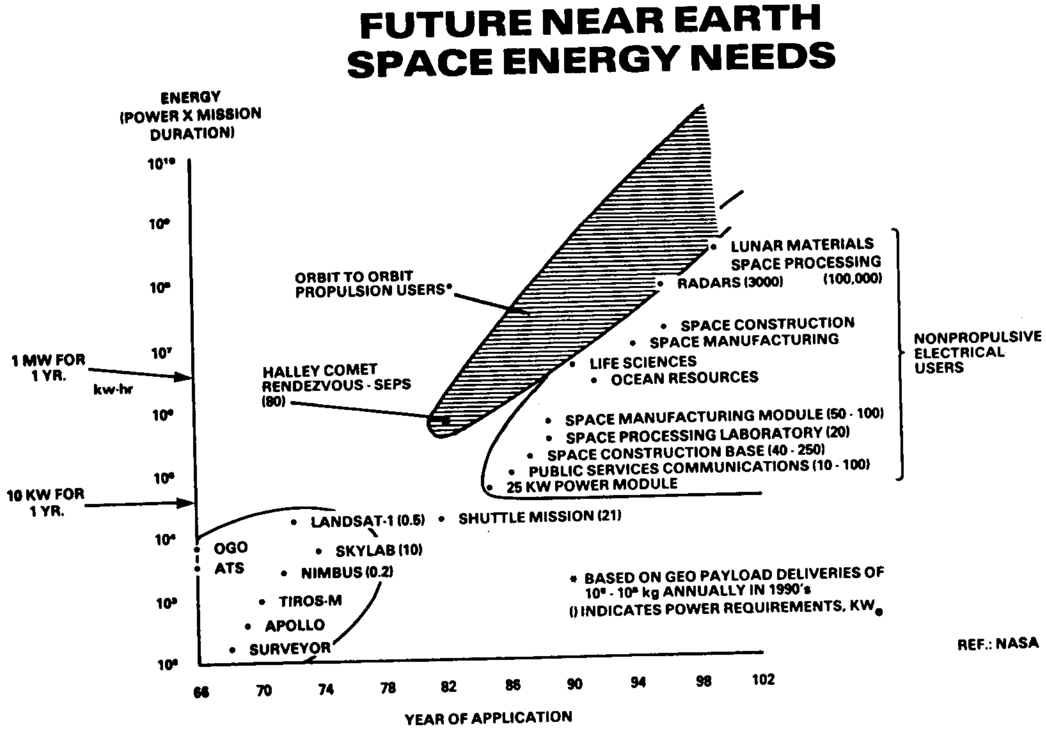


Figure 3



* BASED ON GEO PAYLOAD DELIVERIES OF 10^6 - 10^8 kg ANNUALLY IN 1990's
() INDICATES POWER REQUIREMENTS, KW_e

REF.: NASA

Figure 4

LASER PROPULSION APPLICATIONS *
PARAMETERS FOR ORBIT RAISING FROM 185 KILOMETERS

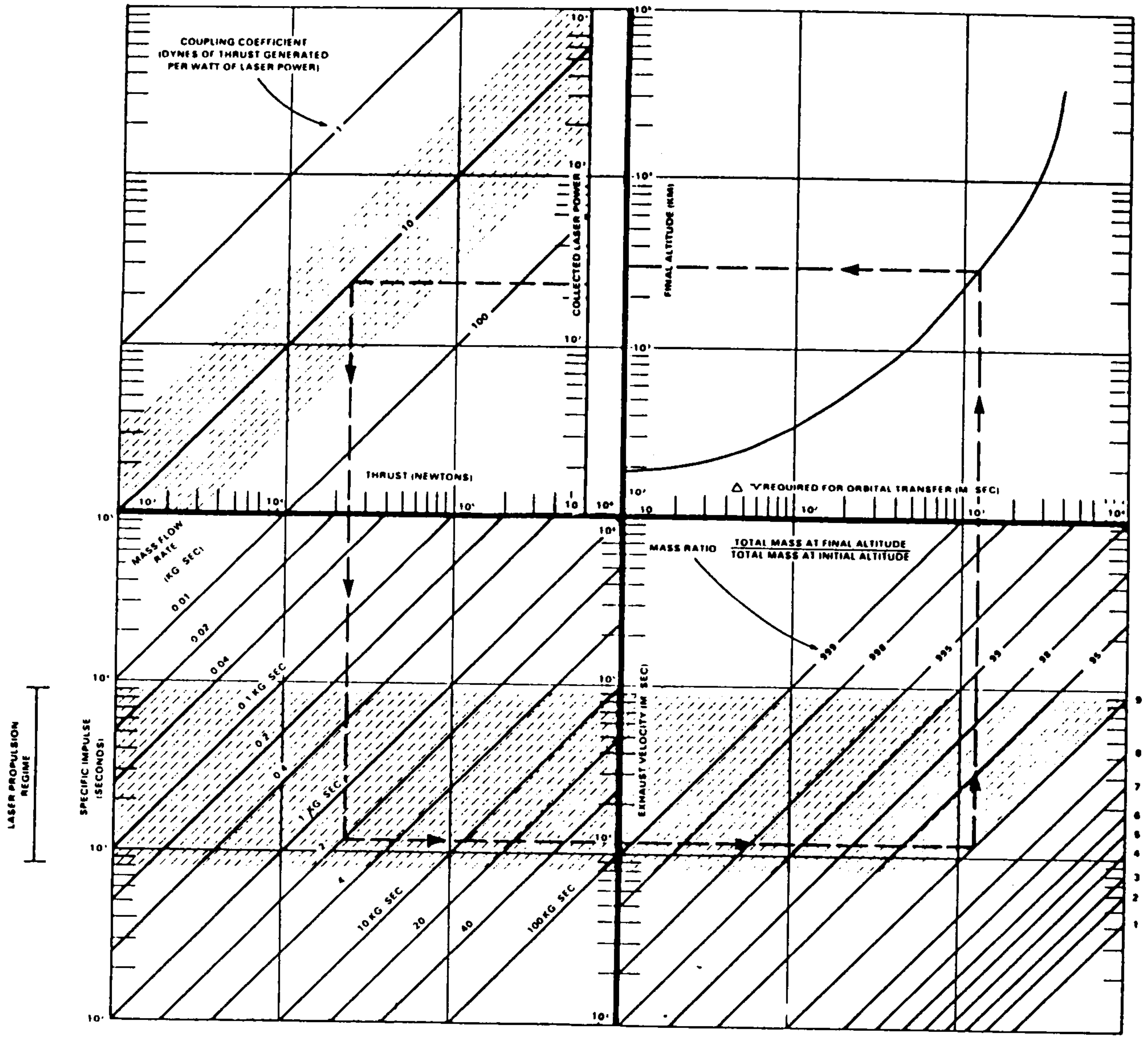


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*Figure legend on next page.

Figure 5

Long running high energy lasers provide an exciting option for propulsion systems to perform orbital transfer. Significant payloads can be raised to long-term parking orbits using moderate size laser systems with run times of less than a day.

As previously mentioned, there are many ways to group and plot intersecting system parameters to serve as mission analysis tools. The "first estimate" charts shown on the next two pages show the logical relationships among all of the principal parameters of laser propulsion for orbit changing. The first chart relates laser power to achievable orbital height for specified performance of the laser propulsion engine. The second chart uses a plausible tug model to find the duration of operation to raise a given payload to a given orbital height using the laser power found from the first chart.

In the upper right hand quadrant, the facing graphic plots the key mission parameter of a given increase in orbital velocity (total Δv) required to deliver any payload from a 185 kilometer orbit to any selected orbital altitude. The remaining curves represent parametric assumptions to describe particular propulsion system options that lead to required laser power (upper left hand quadrant). The significant engine performance parameters are specific impulse, I_{sp}, and the energy coupling coefficient, C, which relates rocket thrust to collected laser power. The chosen combination of C and I_{sp} defines the required fuel flow rate. Knowing what altitude is desired then defines the mass fraction (final-total-mass/initial-total-mass) required to get there. Alternatively, for a specified mass fraction, the chart shows what altitude can be reached.

An example of how to use this plot is shown for the mission of raising a 32 metric ton payload (approximate weight of the expended shuttle main tank) from 185 kilometers to 3000 kilometer orbit using 3.6 metric tons of residual hydrogen and a range of tug-like propulsion systems weighing between 1 and 5 metric tons (i.e., mass fraction approximately 0.9). Exhaust velocity for this example is selected as 10,000 meters per second, corresponding to a thrust of 23,000 Newtons, and the coupling coefficient is chosen to be C =12 dynes per watt. If these assumptions comprise a valid propulsion system, then the total power required is approximately 200 megawatts.

Stippled areas have been added to the chart to designate areas of validity or plausibility. The chart may not be accurate to within 10 percent for mass ratios lower than 0.9 because the fuel mass is sufficiently large that it will affect optimum mission paramters (see next chart). The other boundaries of the stippled areas indicate a plausible regime vis-à-vis achievable physics.

To go further, we must adopt a model of the laser tugboat. The mass of the tug is primarily related to the thrust, both because of the size of the engine and pumps and because of the required stress bearing components of the system as a whole. (Interestingly, the laser light collectors will have the same diameter regardless of the thrust for a specified laser wavelength.)

(Figure 5)

PERFORMANCE PARAMETERS OF LASER ORBITAL TRANSFER VEHICLE

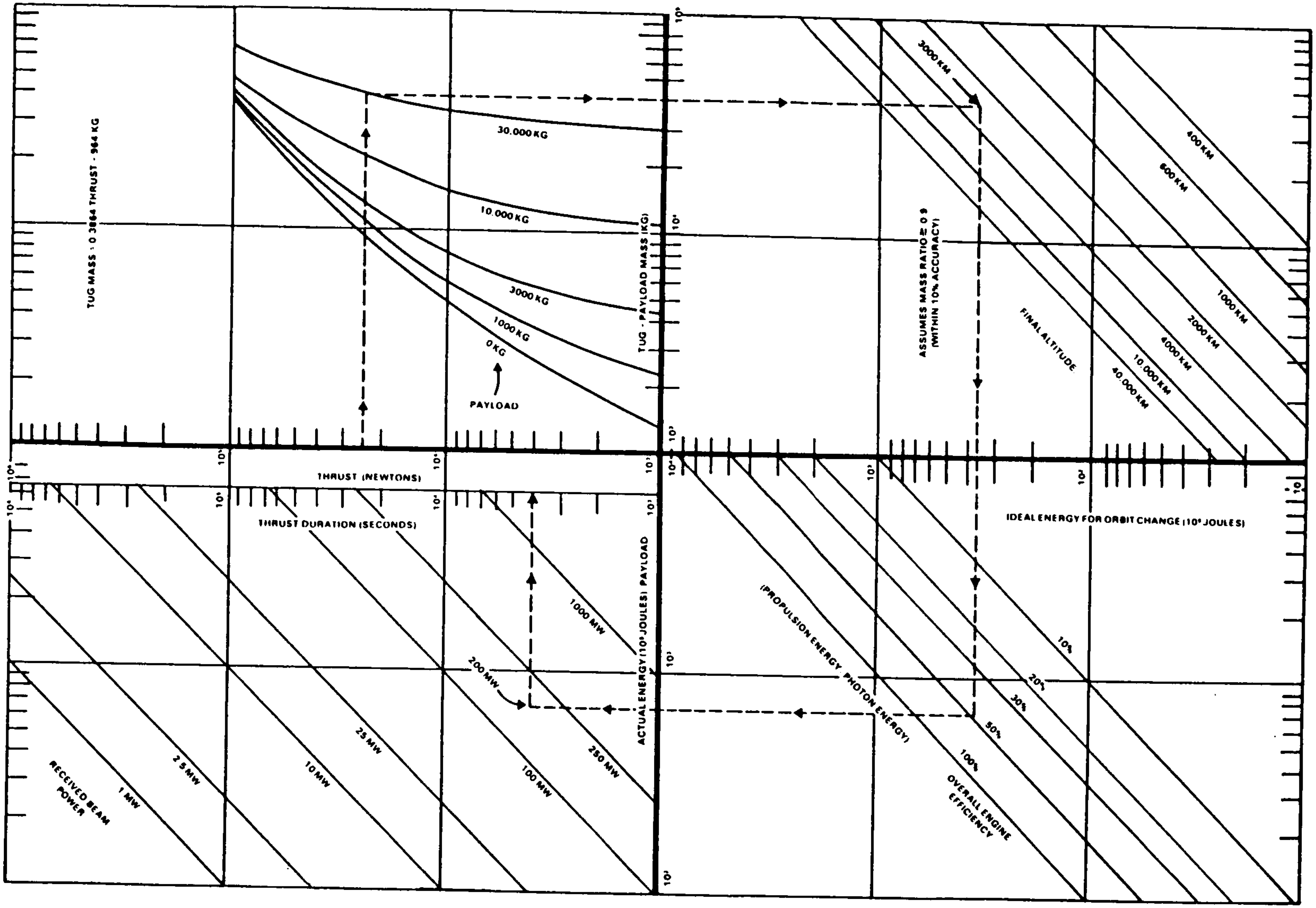

Figure 6 (Figure legend on next page.)

NASA LASER PROPULSION APPLICATIONS (CONTINUED)

TRW* has modelled a laser propelled tug which seems to have plausible and justifiable characteristics. For our purposes here, we have adopted the TRW tug model as expressed by the equation on the facing chart. We also assume that the fuel mass will, in general, be a small fraction of the tug plus payload mass (<10%).

It is important to understand that this chart is "slaved" to the chart on the previous page. The same thrust, altitude, and laser power must be used here that were chosen on the previous chart. In addition, the laser engine conversion efficiency is closely related to the coupling coefficient on the previous chart for a given engine design. Fifty percent efficiency is regarded as a reasonable value. With these constraints we can then find the total thrust time to perform the mission.

The dashed line applies to the mission of raising the Space Shuttle main tank to a 3000 kilometer orbit from 185 kilometers. It can be seen that this mission can be accomplished in ~3500 seconds of thrust time with 200 megawatts of delivered laser power. Or, retracing all of the steps, we find that the same mission can be performed in ~26,000 seconds (7.2 hours) with 20 megawatts of laser power.

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* Reference: M. Huberman et.al., "Investigation of Beamed Energy Concepts for Propulsion", Volume 1, by TRW Defense and Space Systems Group, prepared for AFWL, Edwards AFB, CA, October 1976.

(Figure 6)

NATURAL RADIATION DOSE

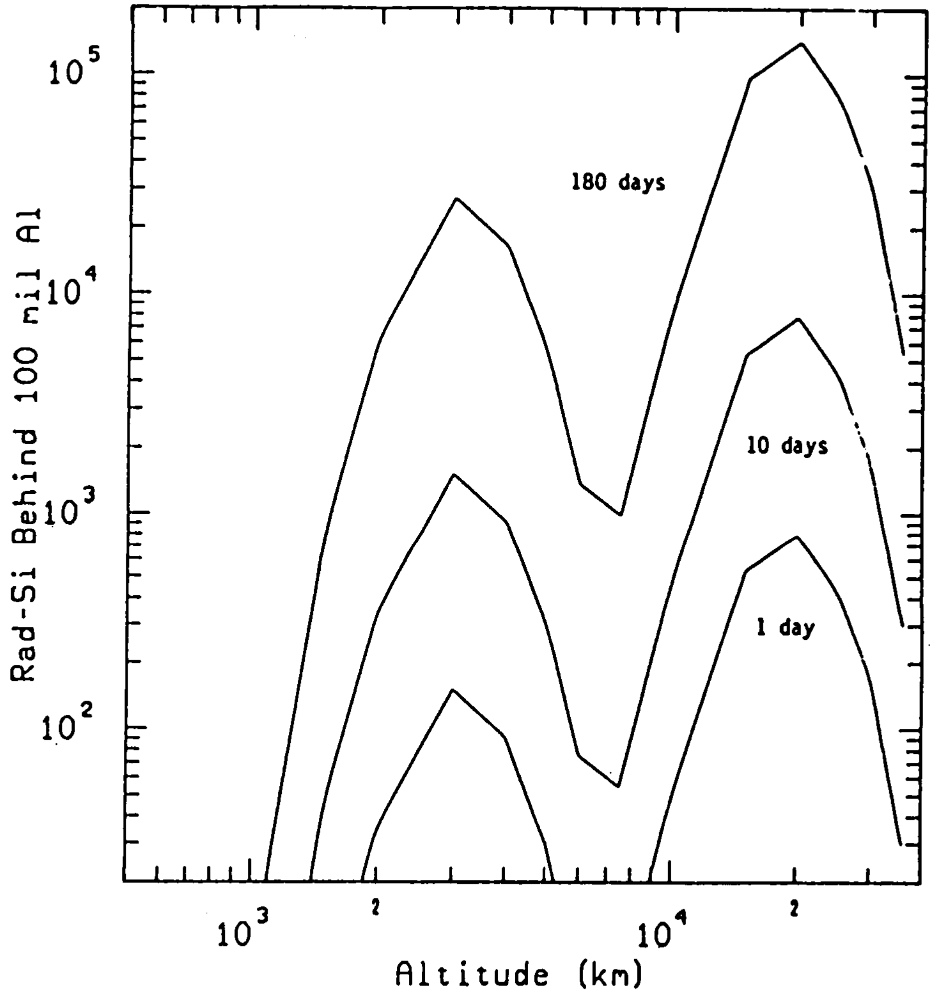


Figure 7

FRACTION OF U.S. TOTAL ELECTRICAL ENERGY NEEDED TO BUILD A SPACE COLONY

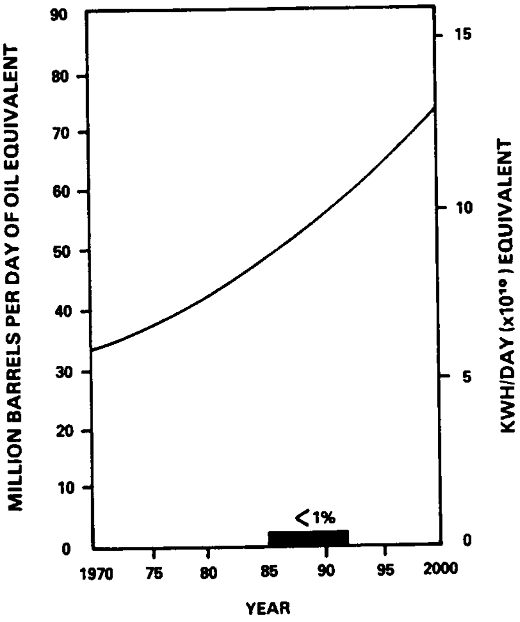
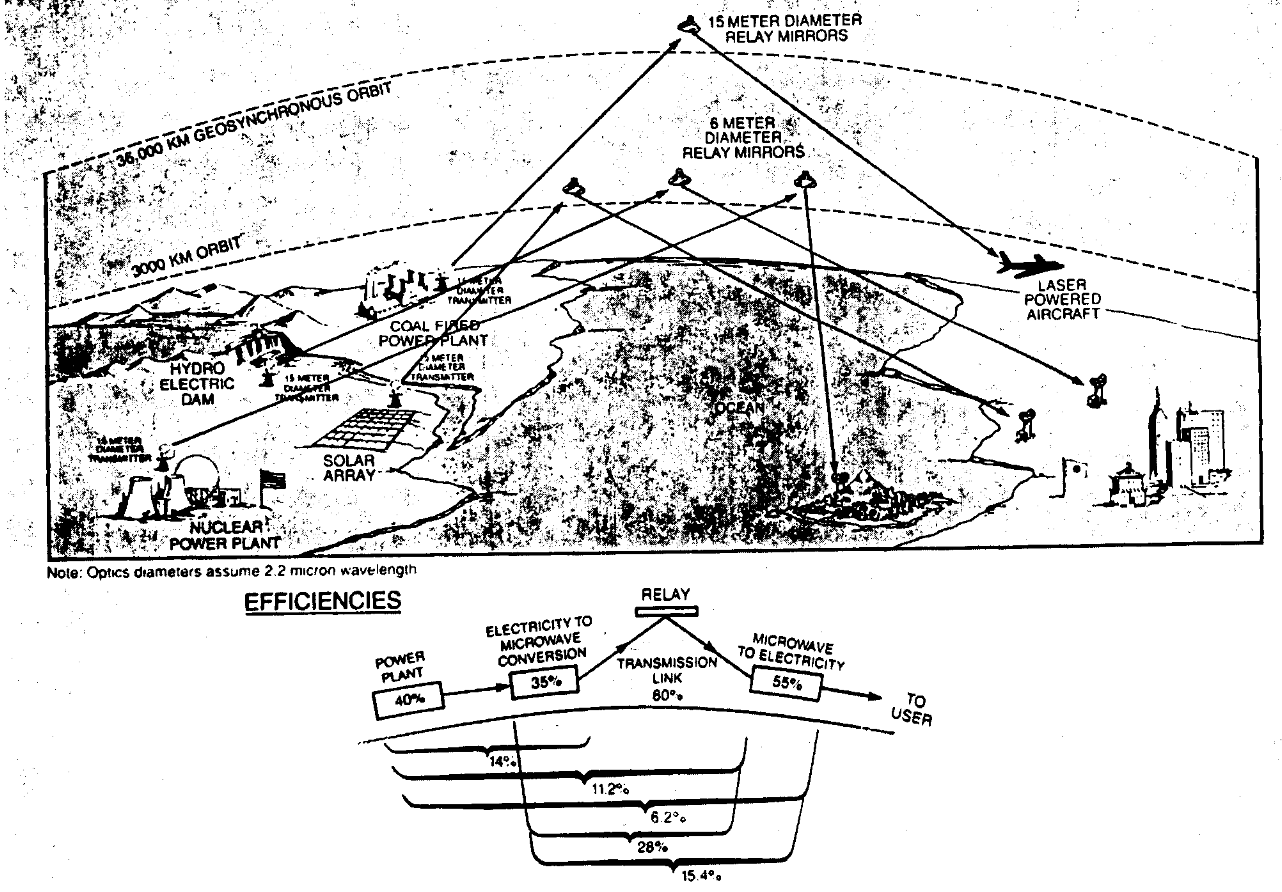


Figure 8

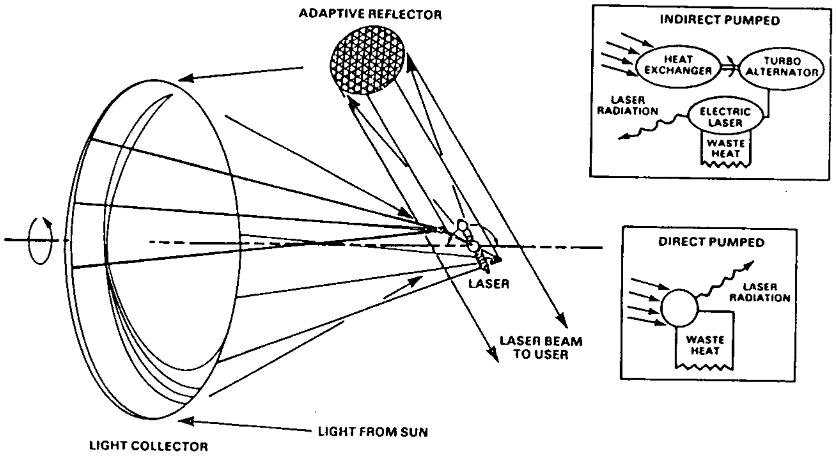
INTERCONTINENTAL POWER RELAY VIA LASER BEAMS



Note: Optics diameters assume 2.2 micron wavelength

Figure 9

SOLAR POWERED LASERS IN SPACE



There are several plausible concepts for solar powered lasers in space. Direct solar-pumped lasers may be particularly interesting because of their simplicity, provided that they can be made sufficiently efficient and cost effective.

The "hammer-and-tongs" approach to building a continuously operating high laser system in space would involve the use of some sort of solar powered electrical generator to run a conventional electric discharge laser (EDL) or a free electron laser (FEL). Indeed, this may prove to be a straightforward method if high overall efficiencies can be achieved by such lasers as the FEL (/50%), the CO EDL (/50%), or the Excimer (/15% at short wavelengths). A baseline case CO EDL concept developed by W. J. Schafer Associates has an estimated system mass, of 131,000 Kg for a 100 MW laser*. The four major contributors to the mass of this system are the sunlight collector, the adaptive projector optics, the laser (with its power generator), and the waste heat radiator. In electrical laser systems, the latter two components dominate because the solar concentrator can be of very light construction and the projector optics are relatively minor components of the entire system.

Directly pumped solar lasers are very different in conception. The sun is a large angular source (/0.5 degree) so that the image at the focus of a large concentrator is still large even for very short focal lengths. (A 1 Km diameter concentrator intercepts 1 GW of solar power. A focal ratio of 0.4 yields an image approximately 4 meters in diameter.) Hence, the lasing volume must be large also. This necessitates development of a new class of laser especially suitable for use in space. Interestingly, the power scales with volume of the laser and thus increases as the cube of the linear diameter, while the mass scales with the wall areas which increases only as the square. (The lasing medium is a gas of negligible weight.) Hence, larger devices have better specific weight per megawatt transmitted.

The biggest problem with direct-pumped lasers is that the solar spectrum is very broad, while the absorption lines of most lasing gases are very narrow. Hence, only a small fraction of the available sunlight can be utilized. This equates to low overall efficiency, which seems fatal to the concept at first glance. It is possible, however, to use clever filtering at the primary collector and/or a "black-body Chamber" pumping cavity to improve the effectiveness markedly.

New and important progress is being made in the area of waste heat rejection by A. Hertzberg at the University of Washington. Laboratory experiments have proven the feasibility to reducing the heat radiator mass by a factor of at least ten by allowing the heat to melt a meterial which can be broken into thousands of tiny droplets to achieve very large surface radiation area. This breakthrough should profoundly affect the feasibility of high energy systems in space.

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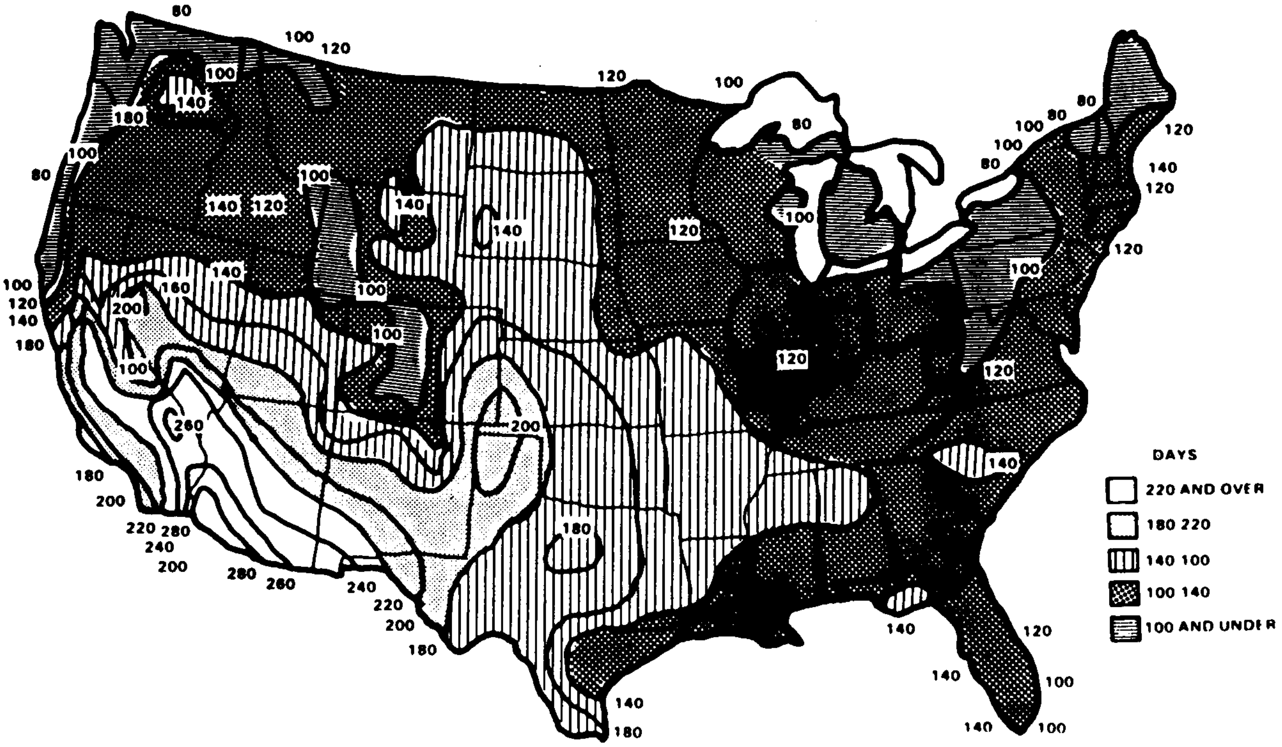
*For an extensive discussion of the physics and engineering of solar powered lasers in space see for example the paper "New Candidate Lasers for Power Beaming and Discussion of their Applications" by John D. G. Rather in Radiation Energy Conversion in Space, V. 61 of AIAA Progress in Astronautics and Aeronautics (1978).

Figure 10

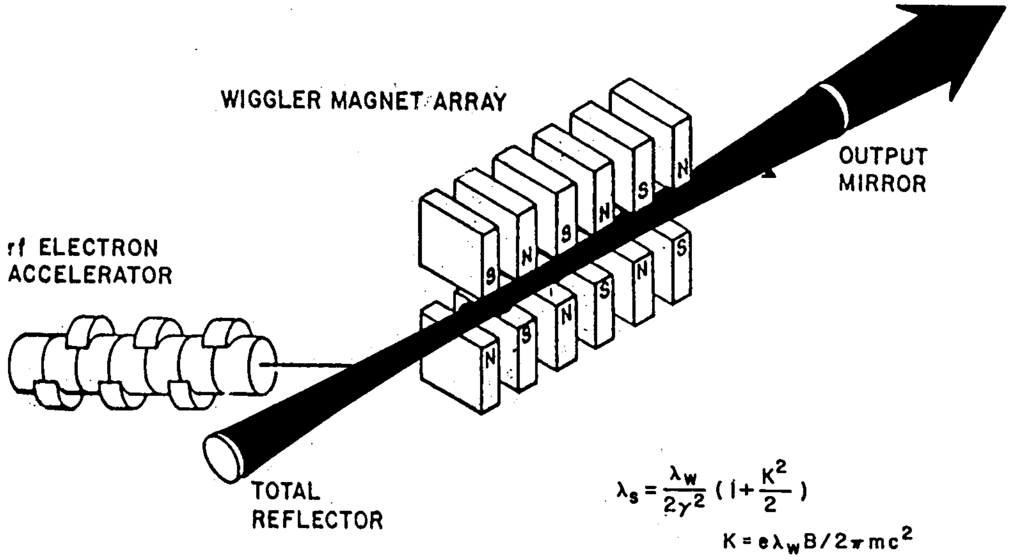
(U) LOCATION OF GROUND SITES DEPENDS PRIMARILY UPON AVERAGE ANNUAL NUMBER OF CLEAR DAYS



(UNCLASSIFIED)

Figure 11

BASIC ELEMENTS OF A COMPTON-REGIME FREE ELECTRON LASER



$$\lambda_s = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$K = e\lambda_w B/2\pi mc^2$$

Figure 12

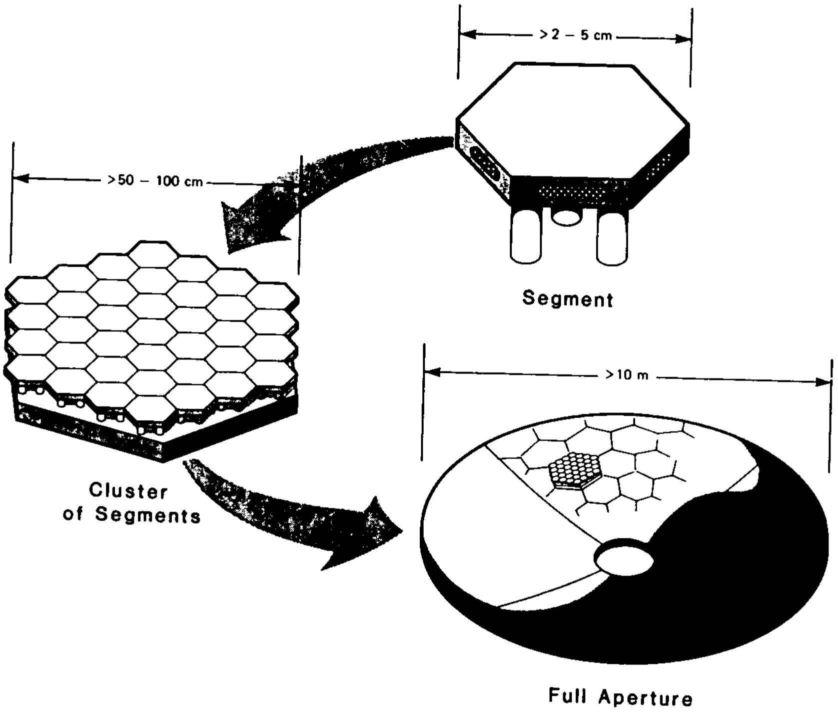


Figure 13