NASA Conference Publication 2214

Space Laser Power Transmission System Studies

Proceedings of a symposium held at NASA Langley Research Center Hampton, Virginia October 14-15, 1981

NASA

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Edited by
M. D. Williams and E. J. Conway
Langley Research Center
Hampton, Virginia

Proceedings of a symposium held at
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NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1982

PREFACE

In 1972, NASA began research on laser power transmission in space. Several research centers were involved in aspects of the program such as electric discharge laser systems, nuclear-pumped lasers, space optics, quantum electronics, laser propulsion, and conversion of laser light to electricity. Organizational changes in the late 1970's led to a restructured program with less emphasis on electric-discharge lasers and nuclear-pumped lasers - a program which focussed rather on solar-pumped lasers and conversion of laser power to thrust and electrical power. Recent congressional and advisory committee interest in NASA high-power laser applications and technology necessitated reconsideration of the program scope and structure. Reevaluation of prior mission and system studies was a part of that reconsideration which was needed to assess the urgency of attention, if any, required by new or important applications of laser technology. This symposium provided that reevaluation. In addition, it informed new members of the program about accomplishments of the past decade and allowed them to discuss perceived needs. Although many concepts for further investigations were disclosed, a consensus developed that near-term studies should be evolutionary and that there were no applications requiring urgent attention.

This publication is a synopsis of the talks presented at the symposium. It is composed primarily of prints of the summary viewgraphs used. Some viewgraph prints are accompanied by additional comments as provided by the speaker (with editing in some cases); other prints do not require additional comments, or comments were not provided.

M. D. Williams
E. J. Conway

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PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

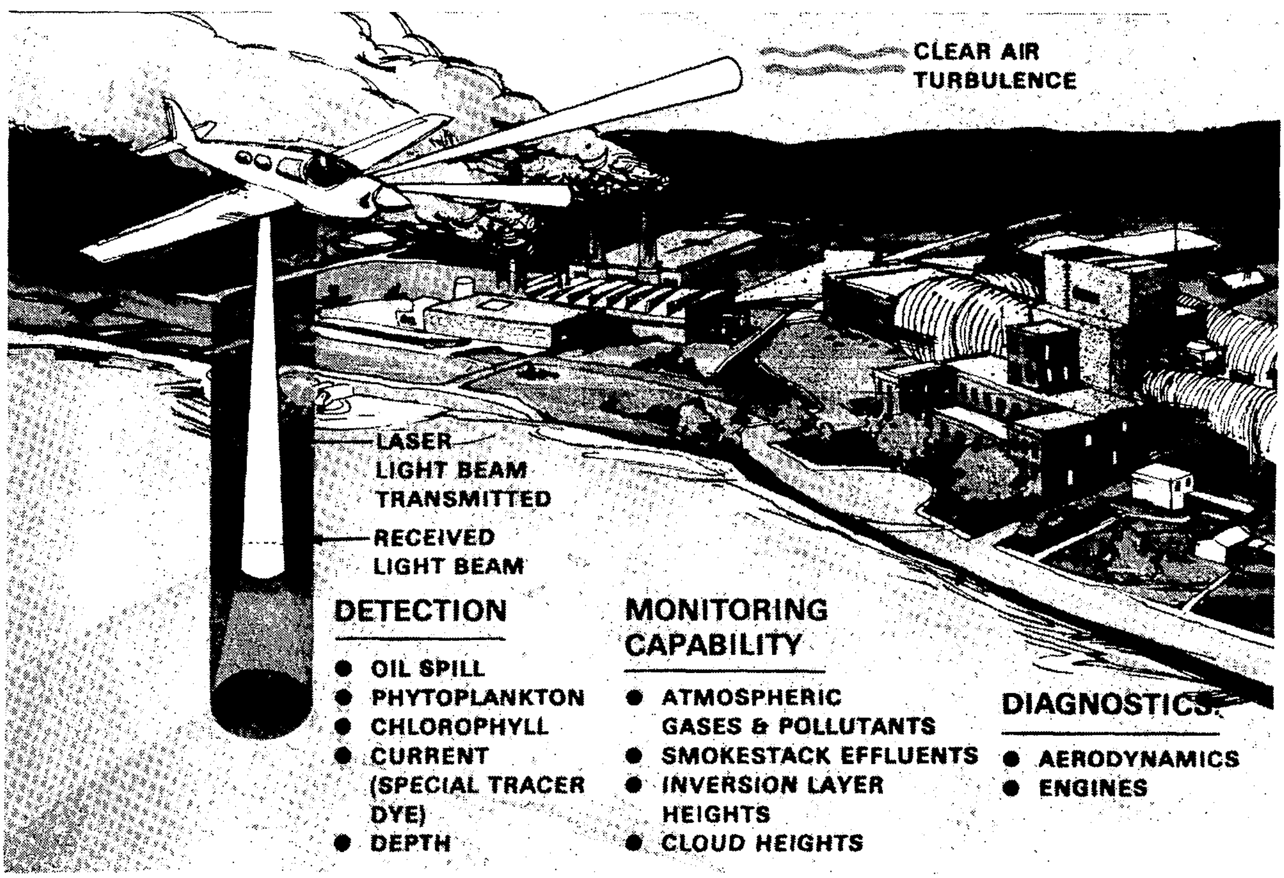
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

Lynwood P. Randolph
October 1981

CURRENT NASA APPLICATIONS OF LASERS

NASA has already made considerable use of lasers for both ground-based and aircraft-based remote sensing applications. From the ground, use of laser ranging techniques has produced several important results including determination of orbits of spacecraft with greater precision, measurement of inversion layer heights, and crustal motions of the Earth. As illustrated, lasers flown in aircraft have been used to understand the problems generated by pollution of the environment as well as to provide a method of monitoring the properties of the oceans. NASA has developed airborne systems to measure atmospheric pollutants such as carbon monoxide and nitrous oxide and soon will be able to include about 12 additional pollutants of interest to environmentalists. Flight tests have been conducted on instruments that measure the properties of bodies of water such as the shallow water depths of lakes, rivers, and estuaries, the presence of oil-spills, the concentrations of phytoplankton and chlorophyll, the extent of turbidity, and thermal profiles. In addition, laser systems have been adapted to improve aircraft performance by measuring the velocity of gas flow in wind tunnels and aircraft turbines, by measuring the velocity of atmospheric winds, and by detecting the presence of clear air turbulence.



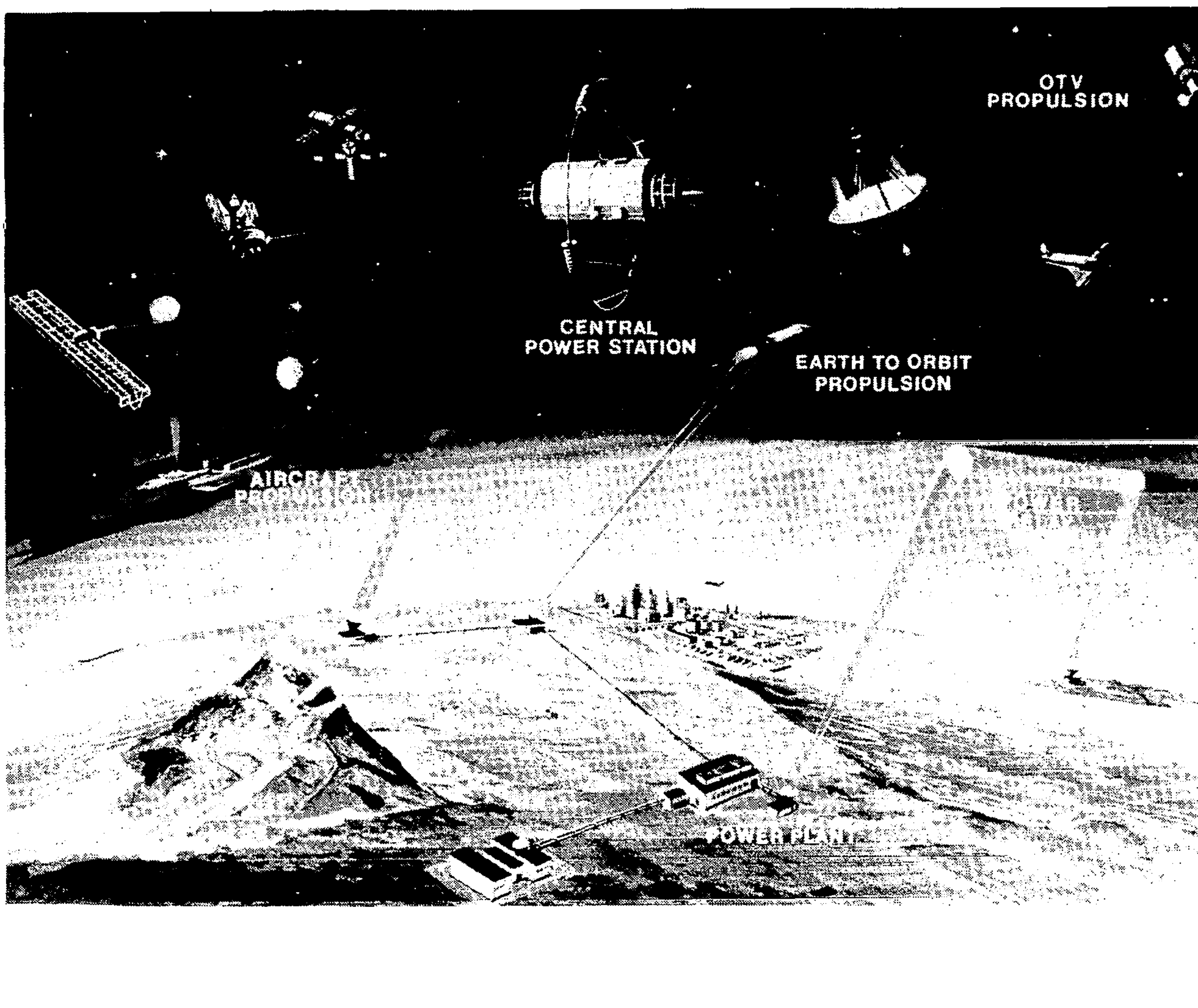
WHY CONSIDER HIGH-POWER LASERS IN SPACE?

Large increases in space power are anticipated for both civilian and military use in the next two decades. In order to facilitate the development of near-earth space, lower-cost power will be needed. A central power station may offer economy of size for supplying power to multiple users. Lasers may provide advantages which could make the central power station concept a reality. Laser power transmission may also provide increased access to and capabilities in deep space.

- **LARGE INCREASES IN SPACE POWER AND ENERGY REQUIREMENTS PROJECTED.**
- **LOWER COST POWER AND PROPULSION KEY TO DEVELOPMENT OF NEAR-EARTH SPACE.**
- **LASER ENERGY TRANSMISSIONS WILL PROVIDE INCREASED ACCESS TO AND CAPABILITIES IN SPACE.**
- **POTENTIAL ECONOMICS OF SIZE WITH MULTI-PURPOSE CENTRAL POWER SYSTEMS.**

POTENTIAL APPLICATIONS OF HIGH POWER LASERS

While no single application appears to offer tremendous payoffs, a rich variety of possibilities exist: a central power station operated on solar or nuclear energy, laser power orbit-transfer-vehicles, a laser powered aircraft, launch propulsion from earth to orbit, and a power relay system.



RECENT ACTIVITIES IN SPACE LASERS

Some recent activities in FY 1981 related to space lasers were:

1. A Space Based Laser Report was requested and submitted to Congress.
2. Initial Airborne Laser Laboratory experiments have taken place.
3. Two High Energy Laser Review Group (HELRG) meetings were held.
4. An AIAA sponsored Laser Systems and Technology Conference was held with participation from Congress, DOE, DOD, NASA, and industry.

FY 1981

APRIL - MAY	SPACE-BASED LASER REPORT (CONGRESS)
MAY - JUNE	AIRBORNE LASER LABORATORY
JUNE	HELRG (HUNTSVILLE, ALA)
JULY	LASER SYSTEMS AND TECHNOLOGY CONFERENCE (WASHINGTON, DC AND BOSTON, MA)
SEPTEMBER	HELRG (LIVERMORE, CA)

OUTLOOK FOR SPACE R&T

The outlook for the Space-to-Space Laser Power Transmission Program is one of cautious optimism. As a part of the Space R&T activities, which support national needs, serve as the backbone of the Agency, fund university research, and provide a future talent pool, the laser program can provide the technology necessary for making a rational decision on future development of laser power transmission. Caution must be exercised in maintaining a balance between significant technical accomplishments and program justification based on potential applications.

- BACKBONE OF THE AGENCY
- SUPPORTS NATIONAL NEEDS (i.e., EARTH RESOURCE MONITORING, MILITARY, ETC.)
- FUNDS UNIVERSITY RESEARCH
- PROVIDES TALENT FOR THE FUTURE

SOME GENERAL THOUGHTS FOR A SYMPOSIUM ON SPACE LASER POWER TRANSMISSION SYSTEM STUDIES

INTRODUCTION

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

Edmund J. Conway
October 1981

HISTORICAL PERSPECTIVE

NASA has used lasers in its research ever since they became available in the 1960's. Early applications generally involved low-power lasers for optical alignment or basic laboratory research. More recently, the Agency has begun to employ lasers, over a wide power range, in active environmental monitors, for example. In 1972, OAST initiated research on high-power lasers for power transmission. Several Centers were involved, and the Headquarters focus of this program was the Research Division. The research program was quite broad, involving laser development, laser effects on materials, and quantum electronics.

In the late 1970's, the program changed significantly with OAST's Research Division functions being absorbed into the Research and Technology Division. Within the past year, renewed and focused interest has developed in high-power space-based lasers, and an augmentation plan is being developed. As part of this plan, an early system study is contemplated.

- HIGH-POWER LASER PROGRAM:
    - INITIATED IN 1972--LERC, ARC, LARC, JPL.
    - FUNDED BY RESEARCH DIVISION OF OAST.
    - BROAD CONTENT.
- PROGRAM UPHEAVAL:
    - LERC -- 1977 -- DISCONTINUED PROGRAM.
    - ARC -- 1978 -- DISCONTINUED PROGRAM.
    - LARC -- 1980 -- REORIENTED PROGRAM.
- HIGH-POWER SPACE-BASED LASER (AUGMENTATION) PLAN -- 1981:

    EARLY SYSTEM STUDY PLANNED.

GENESIS OF THIS MEETING

The concept behind this meeting developed while discussing the contemplated system study during a meeting on the augmentation plan. The concept is that we must educate ourselves to be smart buyers of a future study of laser power transmission, because a range of studies has been performed since 1972. In addition, the mechanics of structuring a new study requires discussion.

- NEED TO BUILD ON, BUT NOT REPEAT, PREVIOUS SYSTEM STUDIES (BY EDUCATING OURSELVES NOW).

- NEED TO DEFINE LASER POWER TRANSMISSION SYSTEM PARAMETERS OFFERING PAYOFF FOR NASA SPACE POWER AND PROPULSION REQUIREMENTS.

HOW WILL LASER POWER TRANSMISSION IN SPACE PAY OFF FOR NASA?

The two most frequently proposed concepts for demonstrating NASA payoff by laser power transmission are: (1) economy of scale; and (2) a new source of energy. Concepts based on a new source of energy depend upon technically revolutionary ideas. Chief among these are laser thermal propulsion, and laser chemistry and plasma formation.

Economy-of-scale suggests that big can be efficient. This idea is particularly applicable to laser-to-electric power conversion for electric propulsion or for spacecraft utility power. It is an attractive concept, similar to terrestrial electric utilities, because in situ power generation is replaced with central generation and distribution. However, the economy-of-scale argument is not straightforward, and deserves much care in development.

- **ECONOMY OF SCALE -- DEFINE PAYOFF PARAMETERS:**
  - LASER-TO-ELECTRIC POWER CONVERSION
    - ELECTRIC PROPULSION
    - SPACECRAFT ELECTRIC POWER
  - THERMAL POWER FOR SPACE PROCESSING
- **NEW SOURCE OF ENERGY -- DEFINE PAYOFF PARAMETERS:**
  - LASER THERMAL PROPULSION
  - LASER CHEMISTRY, PLASMA FORMATION, . . . FOR UNIQUE APPLICATIONS.

AN ECONOMY OF SCALE: SYSTEMS MENSURATION OF LARGE SPACECRAFT

A paper[1] was presented at the Large Space Systems Technology Conference in 1980 using an economy-of-scale argument. The stated purpose of the study was to find out if, by putting experiments from several small spacecraft onto one large spacecraft, money could be saved since only one control system, one power generation and distribution system, etc., would be required.

From this study, we should learn something about developing a case based on economy of scale.

1 DeRyder, L. J.: An Economy of Scale: System's Mensuration of Large Spacecraft. Large Space Systems Technology - 1980, Volume I - Systems Technology, NASA CP- 2168, 1981, pp. 87-103.

PURPOSE: TO GAIN INSIGHT INTO THE SYSTEM/SUBSYSTEM TECHNOLOGY AND COST PARTICULARS OF USING MULTIPURPOSE SPACE PLATFORMS VERSUS SEVERAL SIZES OF BUS-TYPE FREE-FLYER SPACECRAFT TO ACCOMPLISH THE SAME SPACE EXPERIMENT MISSIONS.

APPROACH: A SET OF OSS/OSTA EXPERIMENT MISSIONS COMPATIBLE WITH A ROCKWELL-DESIGNED SCIENCE AND APPLICATIONS PLATFORM WERE SELECTED TO SIZE SEVERAL SPACECRAFT BUS DESIGNS. COMPUTER MODELS OF THE SPACECRAFT BUS DESIGNS AND THE ROCKWELL P-2 PLATFORM WERE CREATED TO OBTAIN DATA RELATIVE TO SIZE, WEIGHT, POWER, PERFORMANCE, AND COST.

ECONOMY OF SCALE SUMMARY

The figure here is the summary slide from the presentation.[2] It contains five points, but only the first three are germane: (1) large scale did produce economy; (2) DDT&E cost was the dominant factor; and (3) the large spacecraft requires less total mass in orbit.

Although the study showed that economy of scale did pay off for the case developed, the cost advantage came primarily from reduced DDT&E for the single large spacecraft when compared to the set of small spacecraft. (This was not the concept originally thought likely to produce the saving and was found only because a complete analysis was performed.) A second payoff was in transportation cost because of the lower total weight of the platform.

Based on this single example, it appears that intuition and incomplete analysis can be poor guides when considering economy of scale.

[2] See footnote on previous page.

- LARGE SCALE DOES PRODUCE ECONOMY.
- DDT & E COST IS THE DOMINANT FACTOR.
- PLATFORM OFFERS A TRANSPORTATION COST ADVANTAGE DUE TO LESS TOTAL MASS TO ORBIT.
- NO DATA EXIST ON THE COST OF TEST AND CHECK-OUT IN ORBIT.
- PROGRAMMATIC EFFECT ON INDIVIDUAL EXPERIMENT COST SIGNIFICANT.

A FUTURE LASER POWER TRANSMISSION STUDY

Any future laser power transmission study must show applications having NASA payoffs and define technology objectives to guide research. Also, it seems clear that the general philosophy of the study must be carefully coordinated with the approach in order to lead to believable conclusions.

MUST:

- SHOW APPLICATIONS WITH PAYOFFS TO NASA.
- DEFINE MINIMUM PERFORMANCE LEVELS FOR COMPONENTS, AS TECHNOLOGY OBJECTIVES.

PRELIMINARY STUDY ON THE USE OF LASERS FOR THE TRANSMISSION OF POWER

BALL AEROSPACE
SYSTEMS DIVISION
DECEMBER 1976

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Donald H. Humes
October 1981

Expanded Abstract

The Ball Aerospace Systems Division report entitled "Preliminary Study on the Use of Lasers for the Transmission of Power," by J. Frank Coneybear and Charles H. Chandler, dated December 1976, is a broad study of the use of lasers in space, describing possibilities and presenting ideas rather than specifying a system in detail.

The authors feel that the economic payoff of lasers in space will be in supplying energy for the Earth. Using lasers for space-to-space energy transmission may have operational advantages and economies for the user, but probably will not be an economical means of generating power. However, the authors feel that a system to provide space-to-space energy transmission should be built as the first step in the development of large space power stations to beam energy to the Earth.

Much of the report was devoted to Earth-side use and to comparisons with microwave systems. However, there is quite a bit of information pertinent to the subject of our meeting (i.e., space-to-space energy transmission using a laser).

Some Basic Considerations

Laser transmission of power is attractive because laser beams are narrow, "tight" beams with little divergence, so that spacecraft would require only small collectors to receive the energy.

Such a narrow beam must be aimed precisely or it will completely miss a spacecraft receiver. Fortunately, the aiming precision required is within the goals NASA has set for itself in the Large Space Telescope Program.

If solar energy is used to pump the laser, either directly or indirectly, some outages will occur when the system is in the shade. If nuclear-pumped lasers are used, there need not be any outages.

- **BEAM DIVERGENCE**
- **AIMING**
- **OUTAGES**

Beam Divergence

The divergence of a laser beam can be estimated for long-distance transmission by the equation

$$d = 0.9\ \lambda\ R/D$$

where d is the diameter of a laser beam at some distance R from the laser, D is the aperture diameter of the laser, and λ is the wavelength of the transmitted radiation. This intrinsic divergence is caused by the diffraction that all electromagnetic radiation exhibits upon emerging from an exit aperture, so that beam rays cannot be parallel. An important aspect of this relationship is that the size of the "spot" is inversely proportional to the size of the transmitting aperture. The "spot" size is directly proportional to the wavelength of the laser.

Spacecraft operating in cislunar space could use receivers measured in 10's of meters, if the laser beam was in the visible range, and 100's of meters for infrared lasers. But even laser beams diverge too much to make transmission of power through interplanetary space practical.

If several lasers are used at the power station, the divergence can be reduced by phase-locking the lasers. Then the effective size of the laser beam varies with the square root of the actual aperture areas.

		D=3m	
R,km		d,m (λ=.5 μm)	d,m (λ= 5 μm)
35,800	(GEO-LEO)	5.4	54
384,000	(Moon-LEO)	57.6	576
78,000,000	(GEO-Mars)	11,700	117,000
628,000,000	(GEO-Jupiter)	94,200	942,000

Aiming

State-of-the-art aiming capabilities are already approaching the precision required for point-to-point transmission for ranges comparable to the Earth-Moon distance. For example, assume a laser spot of 60 meters and that jitter losses are equal to diffraction losses. In this case, a receiving aperture 100 meters in diameter will intercept 90 percent of the beam energy if the pointing accuracy is 0.1 microradians.

• MOON–LEO ($\lambda = .5\ \mu m$, D=3m, d=57.6m)	0.1 μrad
• SKYLAB TELESCOPES	4.9 μrad
• LARGE SPACE TELESCOPE	0.05 μrad
• NASA 1985 GOAL	0.01 μrad

Laser Power Requirements

The authors feel that the goal of a space laser power station program should be providing power to the Earth. For this to be practical, it must be done on a large scale. They suggest a 1-gigawatt system would be needed. This is the size of a typical nuclear plant in this country.

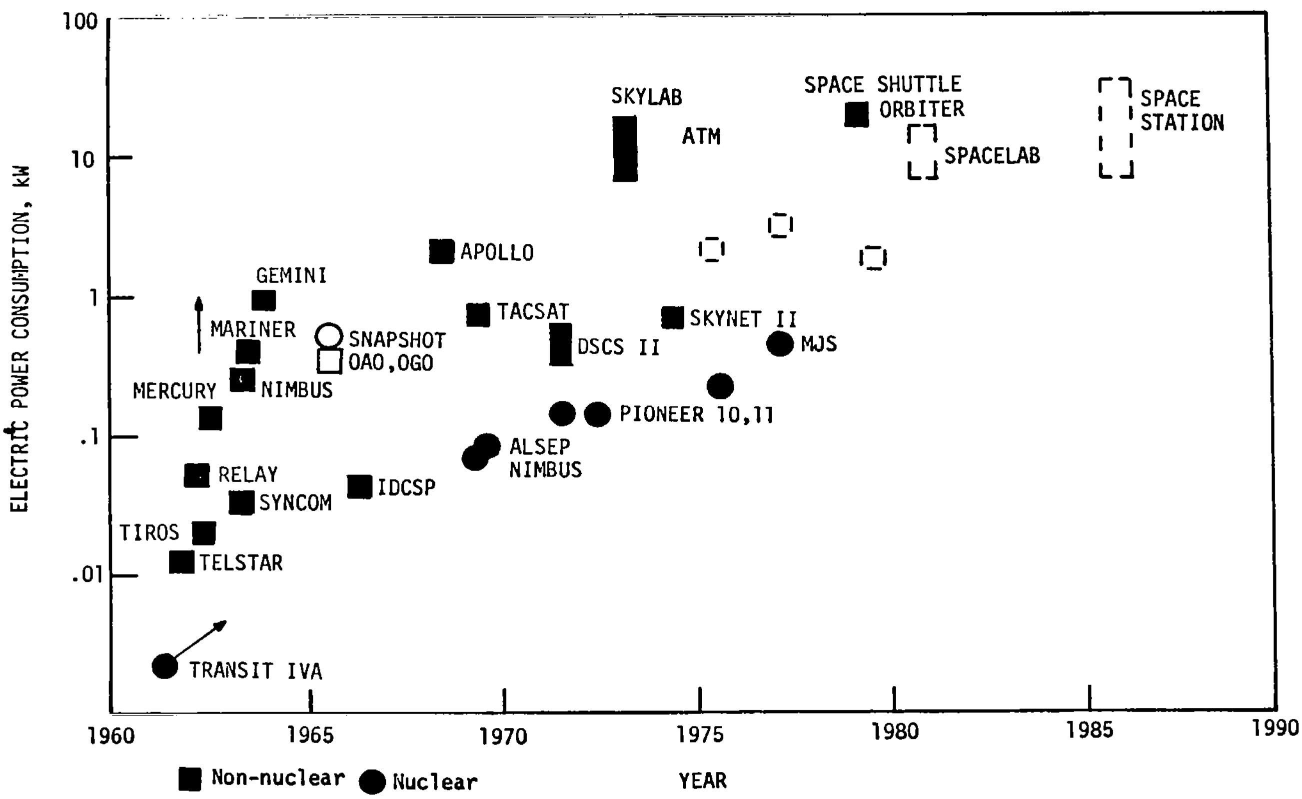
Providing power for rocket propulsion, which looks like a good candidate for laser power transmission, would also require about a 1-gigawatt system.

A system to supply energy to spacecraft need only have about a 10-megawatt capacity. The authors feel such a system could provide many of the advantages of prototype operations, prior to the installation of systems for Earth-size power or rocket propulsion.

USE	POWER
Earth–side power	1 GW
Rocket propulsion	1 GW
Spacecraft power	10 MW

Spacecraft Power Requirements

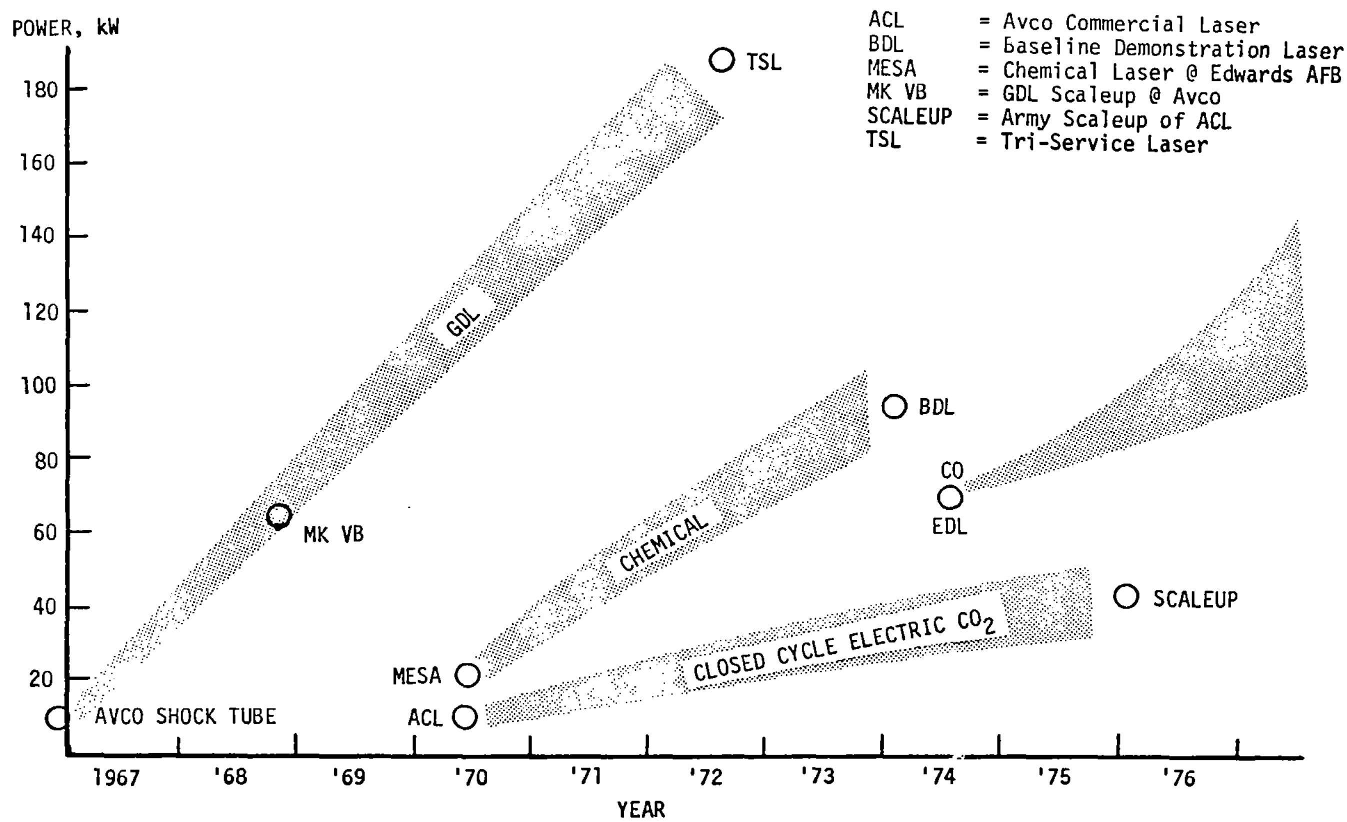
Spacecraft to date have required less than 100 kW. Assuming multiple users, it would seem that multiple beams with a total power on the order of megawatts to tens of megawatts might be needed around 1990.



Power History of High-Power Lasers

Although 1976 lasers were of low power compared to those needed in space, the authors expressed faith that the explosive trends in the laser field would continue and would make gigawatt lasers available by 1990.

The authors made a selection of the most promising laser candidate--choosing the CO supersonic gas flow electric discharge laser. There is only one point for such a laser on the power history graph, but they felt it was a point of departure for almost unlimited development. This laser lases at a wavelength of 5 μm.



Redirection of Beam

If a laser power station is to service many spacecraft, it will need devices, like mirrors, to redirect the beam.

The authors came to the conclusion that mirrors could not be made 100 meters in diameter with the $\lambda/20$ surface finish needed and that, therefore, they were not adequate for redirecting the beam.

The authors expressed faith that the newly devleoping technology of adaptive optics could provide excellent redirective devices. In addition, such devices could improve beam quality by correcting the divergence and even correcting small aiming errors.

The possibility was mentioned that the primary laser could be used to pump another laser at a redirection site.

- **MIRRORS**
- **ADAPTIVE OPTICS**
- **SECONDARY LASERS**

Other System Parameters

The authors could not make a clear choice when they considered the other system parameters; the pumping source, the location of the power station, and the type of converter at the receiver. They stated that the choices depend somewhat on the use (i.e., Earth-side power, rocket propulsion, spacecraft power). Because they were most interested in Earth-side power, they concentrated most of their discussions on such systems.

Solar energy is free and clean, but requires large collectors, and there are outages to contend with. Since the electric discharge laser was favored by the authors, they considered conversion from solar energy to electricity. Thermodynamic conversion is cheaper and more efficient at the present, but gyroscopic effects are produced. Solar cells may be cheaper than thermodynamic converters in the future and would not produce gyroscopic effects. Nuclear energy sources can be small and compact and provide continuous power, but they are "dirty."

A power station at GEO would be close to Earth, which would hold down transportation costs, and it would be close to the users, which would reduce the size of the receivers needed. But a station at GEO would not have the stability that one on the moon would have, and assembly costs would be less on the moon because of its gravity. A power station on the moon would spend long periods in the shade, suggesting that a nuclear pumping source should be used. With only small quakes, no wind, and no neighbors, safe operation of a nuclear plant on the moon may be easy to insure at a low cost.

- PUMPING SOURCE
  - Nuclear
  - Solar
    - Photovoltaic
    - Thermodynamic
- LASER LOCATION
  - GEO
  - Moon
  - Lagrange points
- CONVERSION AT RECEIVER

  (not considered for spacecraft)

Suggested Space-to-Space Power Transmission System

The authors suggest that space-to-space transmission of power would best be accomplished by placing a 10-megawatt nuclear-pumped laser on the Moon. They suggest a thermodynamic plant be used to convert nuclear energy to electricity. Gyroscopic effects are not a concern on the lunar surface. A CO supersonic gas flow electric discharge laser is suggested.

These suggestions were made, however, without regard to the costs involved, and the cost of transporting a system to the Moon could be great. The authors explored some of the costs, weights, and efficiencies that could be expected, but left some areas unexplored and therefore could not estimate the total cost of a system or show whether a space power system would be cost effective. The authors felt an attempt to do so was not appropriate at the time.

Efficiency

The efficiencies of the components (and hence, the overall efficiency) were estimated for the most interesting system, i.e., an indirect solar-pumped CO electric discharge laser for supplying energy to the Earth. For conversion from laser energy to electricity on the Earth, the authors would suggest a thermodynamic converter.

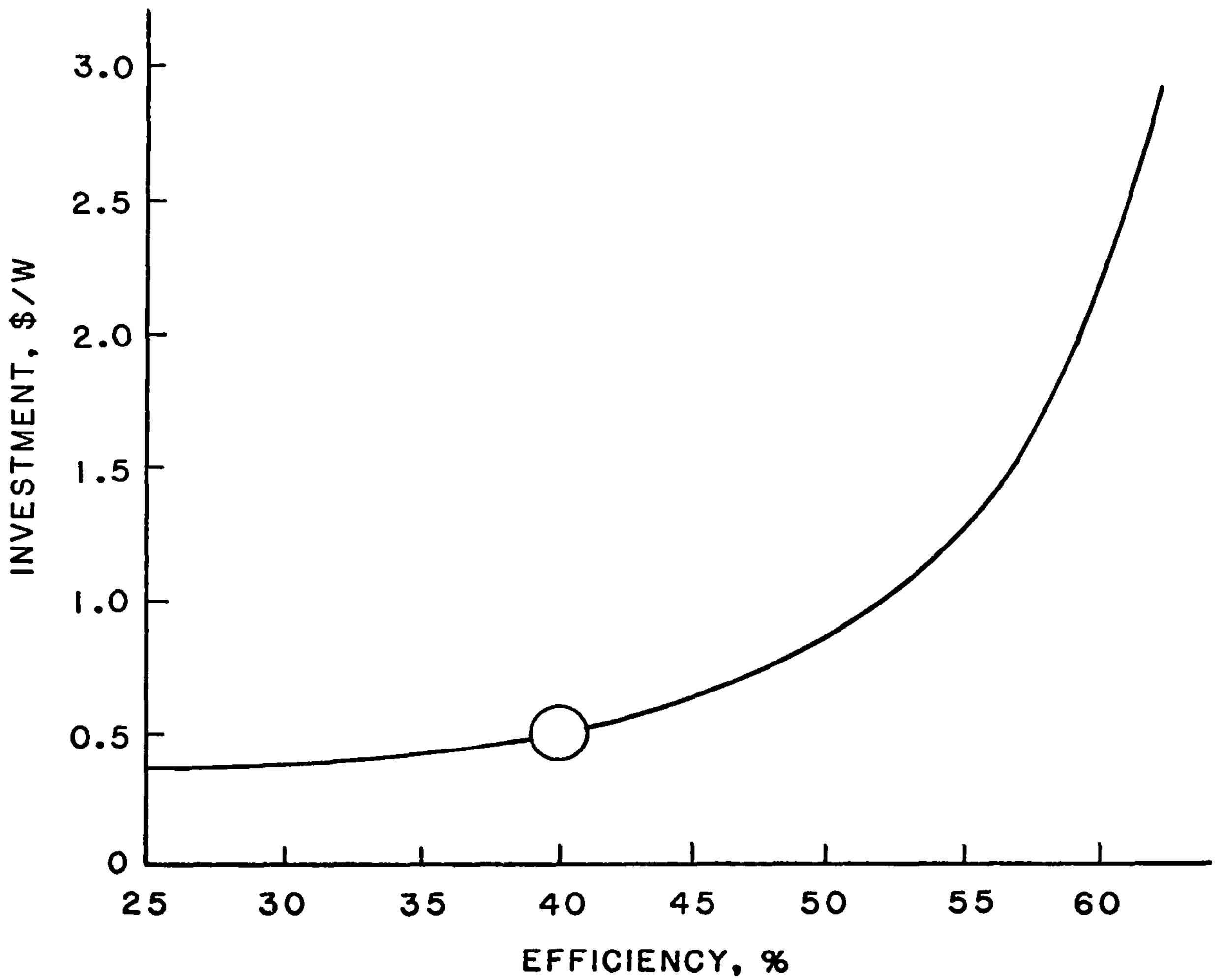
The authors neglected to study the spacecraft converter, a component important to our interest in space-to-space power transmission. In addition, they neglected the efficiency of a nuclear-pumped laser.

	NOW	FUTURE
● CONVERSION OF SOLAR ENERGY TO ELECTRICITY		
● Photovoltaic	14%	26%
● Thermodynamic	50%*	50%*
● LASER		
● CO/EDL, supersonic flow		50%
● REDIRECTIVE DEVICE		
● Adaptive optics		90%

* varies with cost

Efficiency of a Thermodynamic Converter

The efficiency with which heat can be converted to electricity in a thermodynamic converter depends on the capital invested in the device. Efficiencies greater than 60 percent can be obtained, but overall costs for energy from thermodynamic systems on Earth are found to be minimized when a 40-percent efficient converter is used.



Weight

Weight is important because transportation costs depend directly on weight. The authors estimated the weight of the devices to convert solar energy to electricity for pumping the laser.

- CONVERSION DEVICE – SOLAR ENERGY TO ELECTRICITY

	NOW	FUTURE
• Photovoltaic	14 kg/kW	1 kg/kW
• Thermodynamic	6 kg/kW	6kg/kW

Transportation Costs

Transportation costs using the Space Shuttle, a freighter suggested by Boeing, and a ram rocket of the future were estimated. Transportation to GEO would require the use of a tug or a high-energy upper stage unless the power station used its own power to move itself from LEO to GEO. Transportation to the Moon requires a high-energy upper stage.

	NOW (space shuttle)	FUTURE (Boeing freighter)	FAR FUTURE (ram rocket)
LEO	$550/kg	$44/kg	$33/kg
GEO*	$2200/kg (tug)	$220/kg (super tug)	$180/kg (HEUS)
Moon	$18000/kg (HEUS)	$2200/kg (HEUS)	$1100/kg (HEUS)

* Perhaps moved from LEO to GEO under own power

HEUS means some high energy upper stage required

Fabrication Costs

Some of the fabrication costs of a laser power system for Earth-side power have been estimated. The assembly costs in space were not estimated, although the relative expense of assembling a power station at GEO, on the Moon, and on Earth has been estimated.

Again, some of the costs of a space-to-space transmission system, such as the receiver and converter on the spacecraft, have been neglected.

- EARTH–SIDE PRODUCTION
  - Converter (solar to electricity)

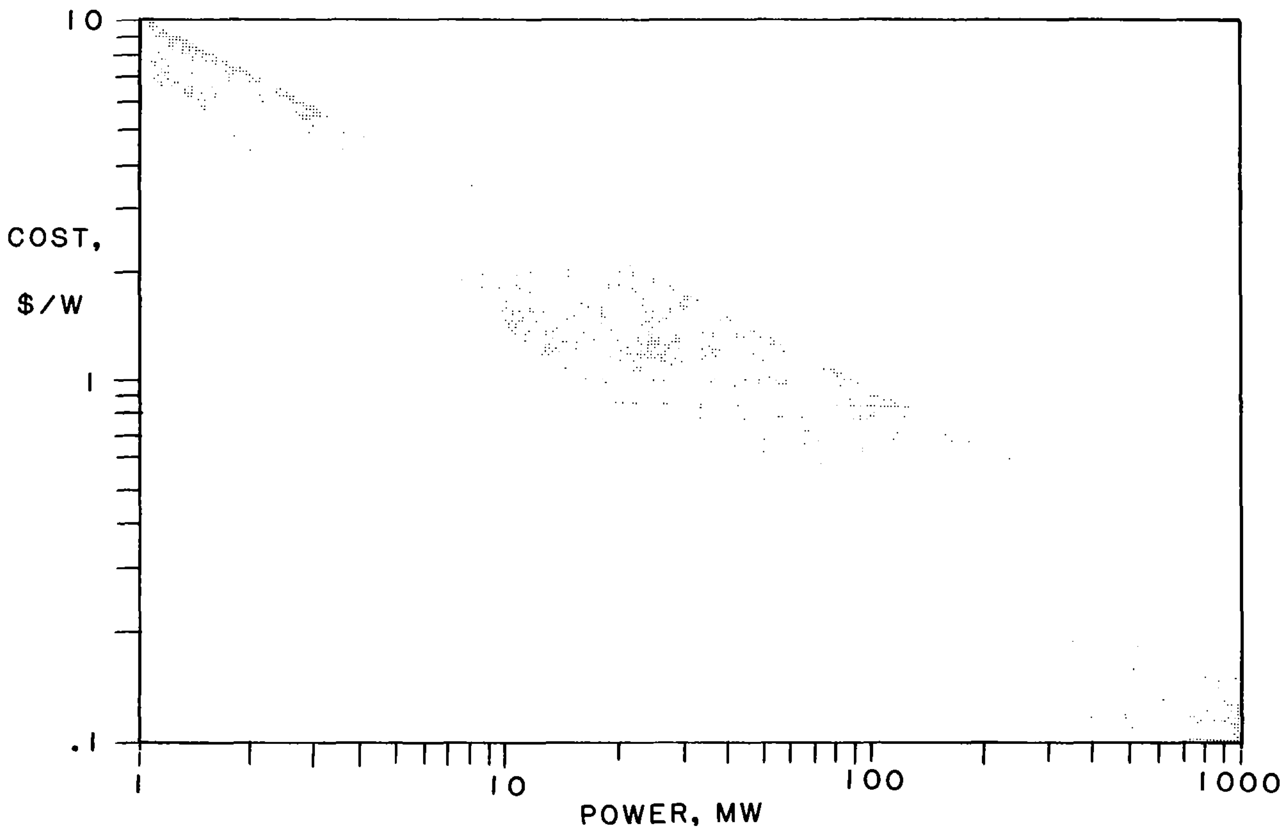
	NOW	FUTURE
• Photovoltaic	$175/W	$1/W
• Thermodynamic	$1/W*	$1/W*
● Laser		$1–$10/W‡
● Adaptive optics		small

- SPACE ERECTION COSTS
  - LEO or GEO — 8X
  - Moon — 4X

* varies with efficiency ‡ varies with power X is cost to erect on Earth

Cost of Laser

The cost of a laser depends on its power. The authors expressed faith that when 10-megawatt lasers are built, they will cost 12 to 30 million dollars, and that the gigawatt lasers needed for Earth-side power and rocket propulsion will cost less than 300 million dollars (and perhaps as little as 50 million dollars).



A STUDY TO SURVEY NASA LASER APPLICATIONS
AND
IDENTIFY SUITABLE LASERS FOR SPECIFIC NASA NEEDS

W. J. SCHAFER ASSOCIATES, INC.
FEBRUARY 1978

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Russell J. De Young
October 1981

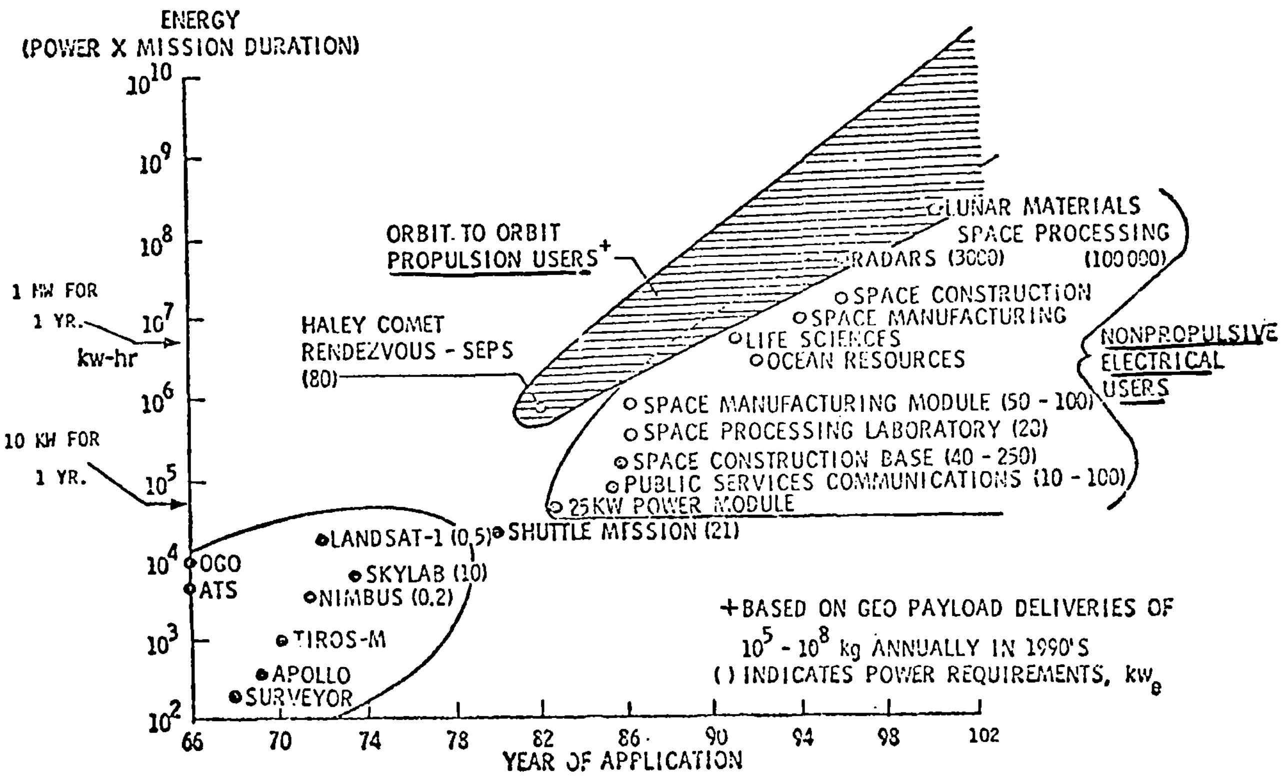
Abstract

This study, by W. J. Schafer Associates, Inc., was contracted by the Jet Propulsion Laboratory (NAS7-100). The primary goal of the study was to identify all potential applications of high-power lasers which might, in particular, use the JPL copper-halide laser under development. A wide range of applications were identified with strong emphasis on remote sensing applications. Power beaming and laser propulsion were also identified as major areas of interest to NASA.

Purpose of Study:

- Identify relations between clearly defined NASA applications and appropriate lasers in the basic research inventory.
- Justification for basic laser research.
- Assess need for medium power ($\leq$ 20 kW) lasers in visible spectrum.

Future near-Earth applications are outlined on the graph. Both electrical and propulsion users are shown. Hundreds of megawatts of power will be needed in the late 1990's to power all the missions indicated.



FUTURE NEAR EARTH SPACE ENERGY NEEDS*

IDENTIFIED POTENTIAL APPLICATIONS OF HIGH-POWER LASERS

-- LASER PROPULSION --

- Laser heats gas to high temperatures (higher than chemical reactions); expelled from nozzle with high specific impulse ($\approx$ 1300 sec).

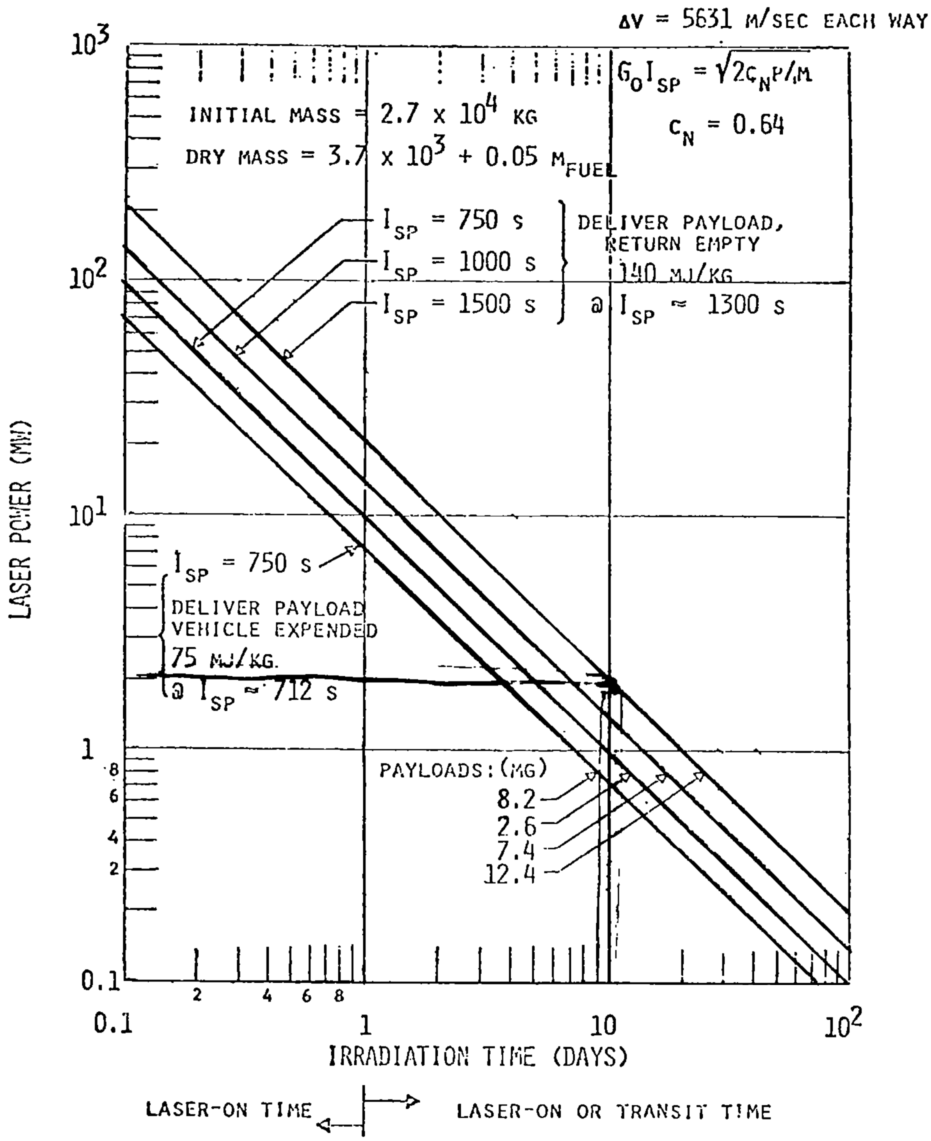
- "No informed opinion questions that this method of propulsion is possible."

- A 1-gigawatt Earth-based laser could propel 1 ton of payload into LEO every 5 minutes.

- Near-term uses for laser: propulsion, attitude control, station-keeping, orbit changing, etc.

- "Our assessment is that laser propulsion will play such an important role in future space development and exploitation that it must be pushed ahead."

Laser power requirements for payload delivery from LEO to GEO by laser propulsion are shown on the graph. The shuttle payload is 30 megagrams; thus 12.4 megagrams is approximately half a Shuttle payload. For a 10-day round trip OTV transit time, a 12.4-megagram payload can be delivered to GEO using a laser power of 2 megawatts.



POWER REQUIREMENT FOR PAYLOAD DELIVERY FROM LEO TO GEO BY LASER PROPULSION. THREE MISSIONS ARE ILLUSTRATED.

IDENTIFIED POTENTIAL APPLICATIONS OF HIGH-POWER LASERS

-- POWER BEAMING --

- Laser beam essentially like superconductor connecting transmitter and receiver.

- 70 to 80 percent of the weight of present satellites is for power generation; laser power beaming reduces to 20 percent.

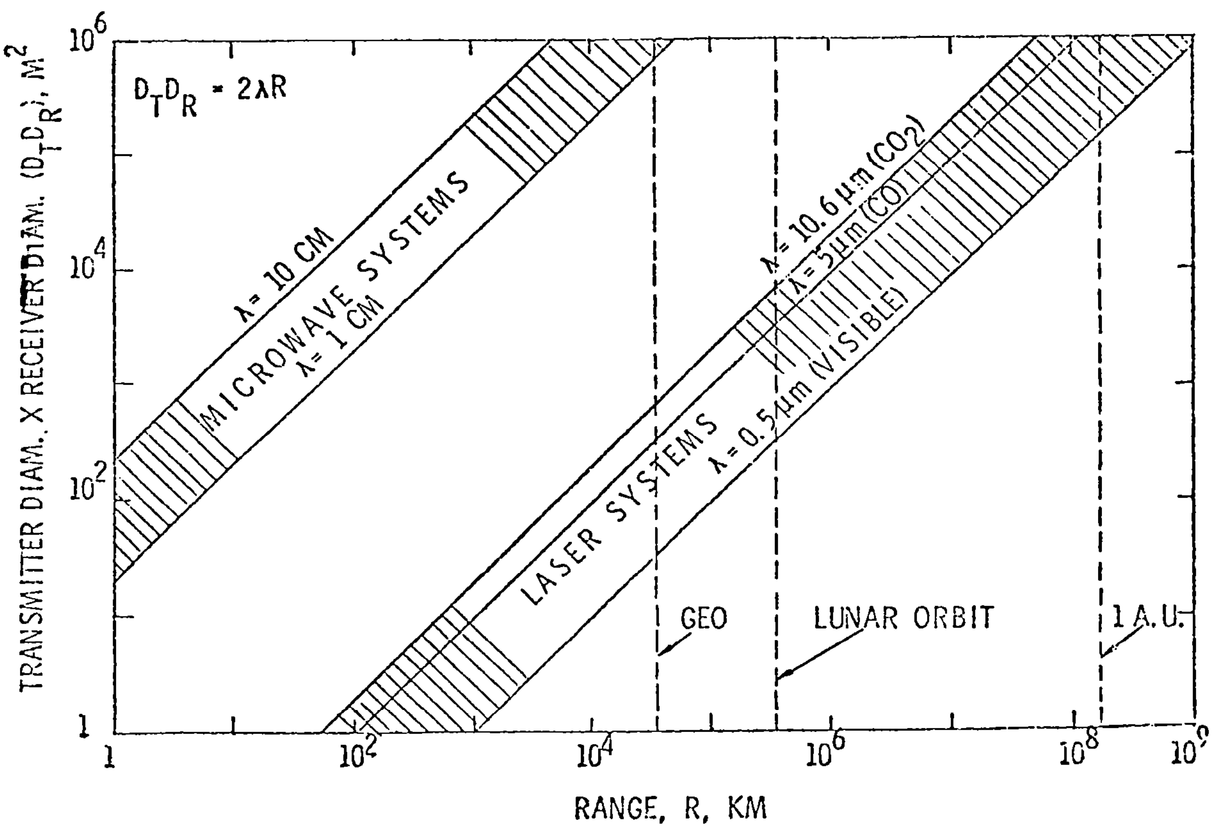
- Laser SPS possibly more versatile than microwaves.

- Laser power beaming could produce storable fuels at receiver.

- Laser propulsion possible.

- Near-term experiment on Shuttle; 4.5 M diameter optics using copper halide laser (0.51 μm) at 10- to 100-kW power levels for power beaming.

This slide shows the reduced antenna area needed for laser transmitter/receiver systems when compared to microwave systems. The difference is simply the result of the laser's shorter wavelength.



TRANSMITTER/RECEIVER SIZES VS RANGE*

IDENTIFIED POTENTIAL APPLICATIONS OF HIGH-POWER LASERS

-- REMOTE SENSING --

- Primarily interested in JPL's copper-halide lasers.
- "... Overwhelming need for a better way to obtain timely world-wide weather information to use for inputs to detailed computer models of the Earth's climate."

Other Remote Sensing Applications:

- LIDAR, high-resolution images of planetary surfaces and ranging.
- Stimulated planetary surface fluorescence, information on minerals, soil conditions, type of vegetation, etc.
- Water depth soundings, identify surface pollutants, ship and submarine detection.
- Range gating of laser beam in atmosphere, composition, pressure, temperature, wind velocity as a function of altitude.
- Atmospheric chemistry, monitoring ambient molecular species, changes in atmosphere by solar wind, volcanoes, artificial pollutants.

IDENTIFIED POTENTIAL APPLICATIONS OF HIGH-POWER LASERS

-- PHOTOCHEMISTRY AND ISOTOPE SEPARATION --

- Possible economical production of H_2 and O_2 from water.
- Total laser efficiency quite important.
- Copper-halide laser suitable except for wavelengths.
- Green light laser, destructively stimulated algae for water purification or constructively for methane production.

IDENTIFIED POTENTIAL APPLICATIONS OF HIGH-POWER LASERS

-- MATERIALS PROCESSING AND MANUFACTURING --

- Localized heating of surface by laser permits pattern etching, hole boring, fusion of dissimilar metals, deep-clean welds at high speed.
- Refuse ceramic castings that crack during curing.
- Laser advantageous for large-scale manufacturing, but poor efficiency.

IDENTIFIED POTENTIAL APPLICATIONS OF HIGH-POWER LASERS

-- OCEANIC APPLICATIONS --

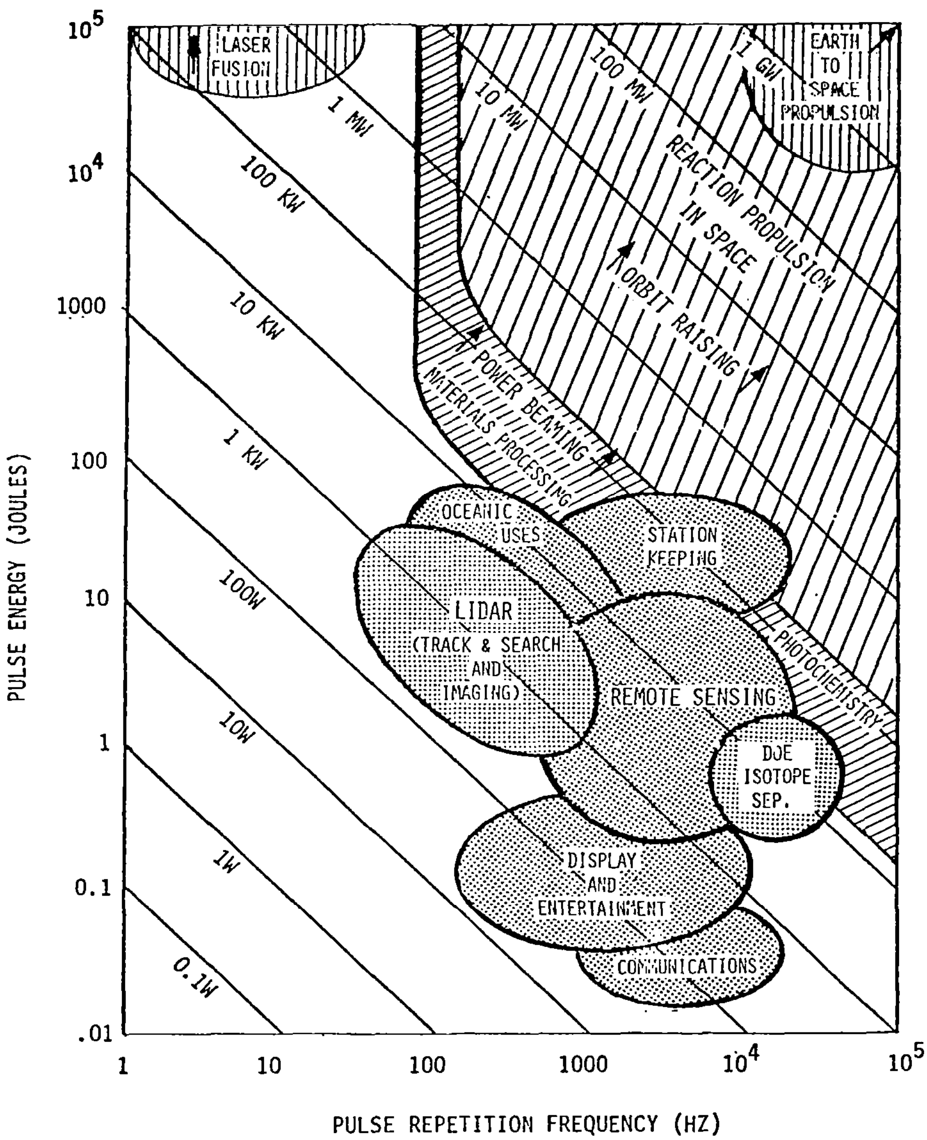
- LIDAR application; detect ocean bottom contours, texture, or presence of ships.
- Spectrographic applications; transmisivity is used to diagnose ambient material or internal wave motions caused by natural perturbations.
- Surface probing; reflection examined to determine character of wave patterns or natural currents.
- Unidirectional underwater communication.
- Copper-halide laser mesh with these applications.

IDENTIFIED POTENTIAL APPLICATIONS OF HIGH-POWER LASERS

-- DISPLAY, ENTERTAINMENT, AND COMMUNICATIONS --

- "Very detailed, dramatic displays created by computer-controlled beams are very important."
- Three-dimensional computer holographic presentation of air traffic radar information.
- Gigabit-per-second data rates over interplanetary distances by laser.

The graph shown is a map of identifiable potential high-power laser applications. The coordinates are labeled for pulsed (CW) lasers. The graph maps out power level regions for the applications discussed in the study. Power beaming requires less than 100 kilowatts where propulsion requires greater than 1 megawatt of power.



LASER APPLICATION DOMAIN AS FUNCTION OF LASER ENERGY, PULSE RATE, AND TOTAL POWER. OVERLAY SHOWS EMERGING DOMAINS COVERED BY TWO PRIME LASER CANDIDATES FOR HIGH POWER AT SHORT WAVELENGTHS.

Conclusions

We can state with confidence that the JPL work is very inportant and that it is presently the best option for the several applications that we have emphasized in this report.

Basic research program at JPL on copper halide lasers terminated in 1980:

--15 watts average at 10 kHz

--1-percent "wall plug" efficiency

INVESTIGATION OF POSSIBILITIES FOR SOLAR-POWERED HIGH-ENERGY LASERS IN SPACE

W. J. SCHAFER ASSOCIATES, INC.
MAY 1977

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Russell J. De Young
October 1981

Abstract

This study contract (NASW-3048) was one of the first system studies to investigate solar-pumped lasers in detail. A baseline CO electric discharge laser system was shown to be technically feasible. The most promising direct solar-pumped laser was identified to be CF_3I. Using the "STAG" solar laser concept and CF_3I, it was found that such a system could be weight-competitive with the baseline CO laser system.

Purpose of the study:

- "Brainstorming" effort to find all promising solar laser candidates.
- Review the literature for possible solar laser candidates from optical pumping experiments.
- Concentrate on a small number of identified possible candidate systems.

SOLAR LASER SYSTEM CHARACTERISTICS

- Limitations

  -- low specific intensity (1400 W/m^2)
  -- low ultraviolet radiation intensities of 6000°K blackbody.
  -- few simple materials of interest for lasers.
  -- waste heat disposed of direct solar laser
  -- narrow band absorbers

- Concept to Overcome Limitations

  -- design solar collector as enormous filter; focus useful radiator only.
  -- conceptual solar laser "Solar Tracking Adaptive Geometry " (STAG) system

- Pump Power at Focal Spot

$$Q_f = \frac{1.56 \times 10^4}{f_\#^2} \ kW/m^2 \qquad f_\# = \frac{f}{D}$$

  -- for f/0.4 (smallest desirable), then Q_f = 9.75 kW/cm^2 at the focal spot
  -- only limit to total energy is practical limits of concentrator diameter.

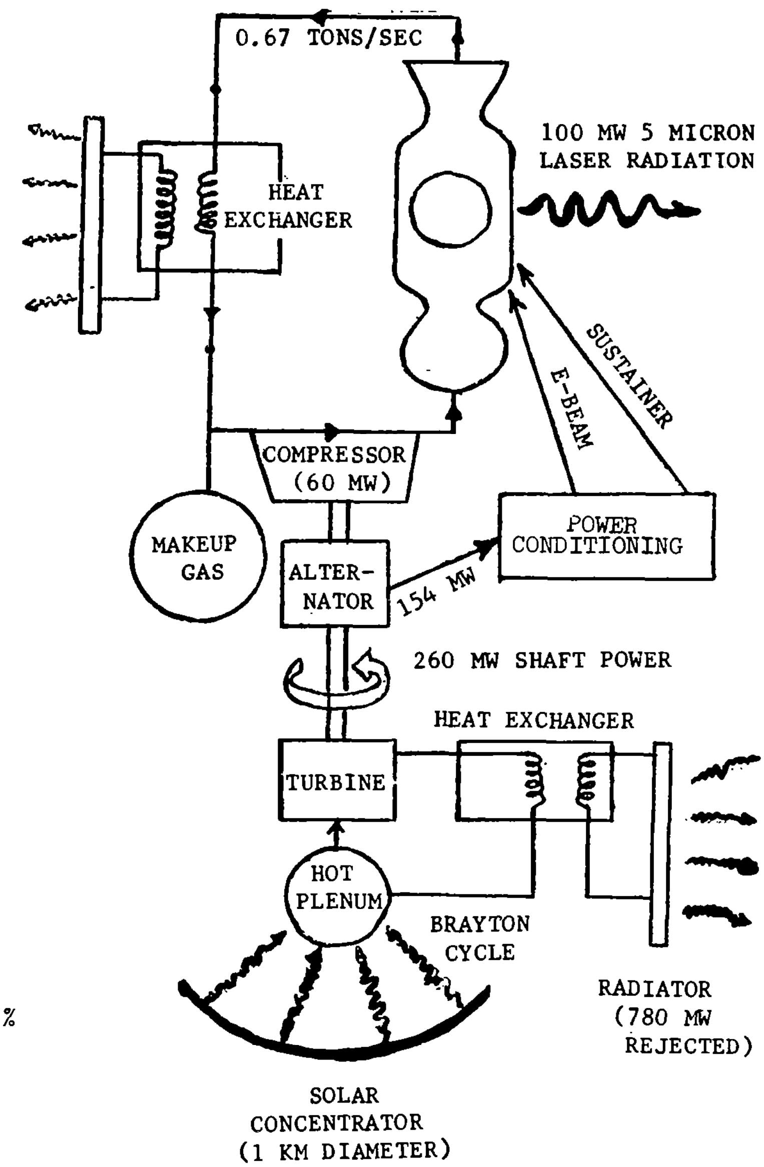
100-MEGAWATT CO ELECTRIC DISCHARGE LASER BASELINE SOLAR LASER SYSTEM

- Overall conversion efficiency of ≈ 11 percent.

- Complex: four separate closed-loop fluid cycles, pumps, ducting, fluid storage, generator, power conditioning equipment.

- Total weight of 131,000 kg (collector, radiator, etc.).

Shown below is a baseline, technically achievable solar-energized CO laser system. The solar collector collects 1 gigawatt of solar radiation and focuses it into a liquid metal chamber. The hot liquid metal gas goes through a conventional thermodynamic cycle, producing 154 megawatts of electricity. An E-beam with sustainer field is used to excite the CO which lases and produces 100 megawatts of optical power at 5 micrometers. A gas-dynamic cycle is needed to cool the CO gas for high efficiency lasing.



ASSUMPTIONS

T = 65°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%

100 Megawatt Supersonic Carbon Monoxide
Electric Discharge Laser Powered by Solar Energy

IODINE LASER

"A lengthy search of the literature in the Library of Congress for data on optically pumped lasers produces surprisingly little useful material."

1. Data on wide band visible absorption in solids.

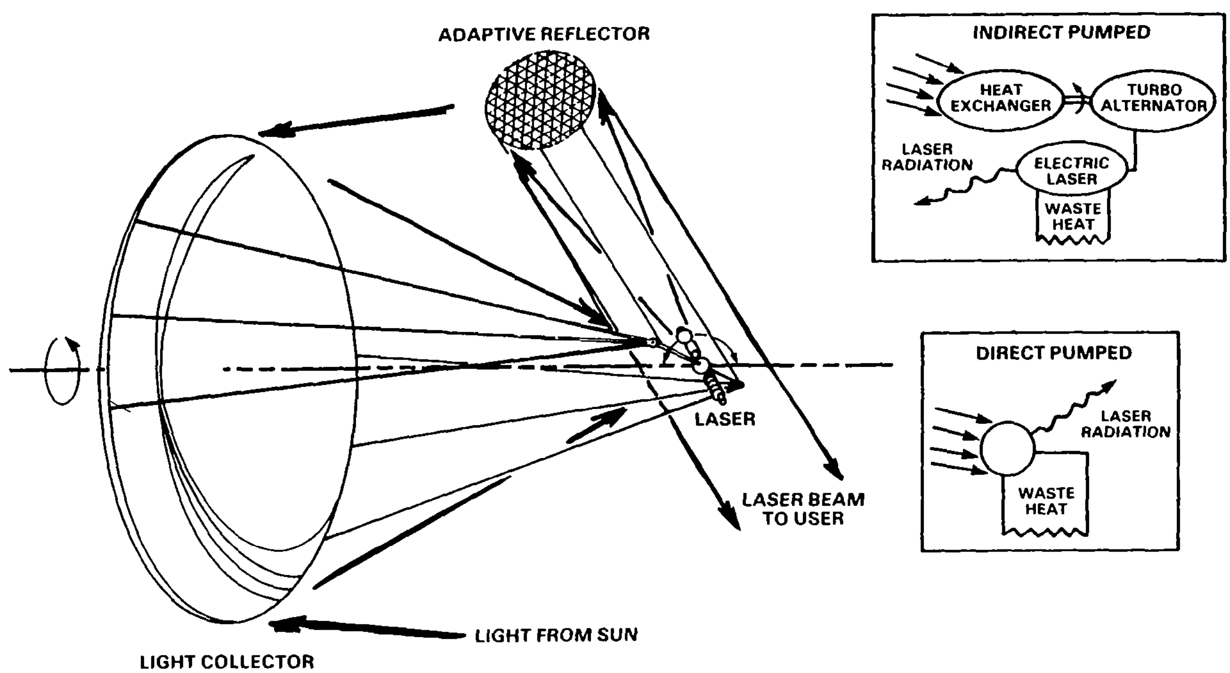
2. Data on coincidences between emission lines of excited gases and upper state of laser gas.

Best documented candidate: CF_3I

- $\lambda_L = 1.315\ \mu m$
- $D_{CF_3-I} = 2.5$ eV
- $\Delta\lambda_R = .05\ \mu m$
- Magnetic dipole transition: $5^2P_{1/2} \rightarrow 5^2P_{3/2}$
- $\eta_T = \eta_f\ \eta_L = 0.5$ percent

"Solar Tracking Adaptive Geometry" (STAG) direct solar-pumped laser system is shown below. Unfiltered sunlight is collected and focused onto a (CF_3I) gas laser. An adaptive reflector is used to focus the laser beam (diffraction limited transmission) to a distant user.

STAG CONCEPT



Assuming a total system efficiency of 1 percent (10 percent laser and 10 percent filter efficiency), then the total estimated weight of a STAG laser would be 1.4×10^5 kilograms. This corresponds to 4.6 space shuttle trips. It is interesting to note that the system component with the highest weight is the laser.

STAG SYSTEM WEIGHT

Key parameter in any space-based system is total weight W_S

$$W_s = \underbrace{\left(\frac{W_L}{P_L}\right) P_L}_{\text{laser}} + \underbrace{\left(\frac{W_P}{d_p^n}\right) D_p^m}_{\text{adaptive projector}} + \underbrace{\left(\frac{W_c}{a_c}\right) A_c}_{\text{concentrator}} + \underbrace{\left(\frac{W_R}{a_R}\right) A_R}_{\text{heat radiator}}$$

where

$W_p = 10^4 \text{kg}; \ D_p = 10 \text{ M}$ $\qquad P_L = \underline{100 \text{ megawatts}}$

$\frac{W_c}{a_c} = 6 \times 10^{-3} \text{ kg/m}^2$ $\qquad A_c = 7.2 \times 10^6 \text{ m}^2$

$\frac{W_R}{a_R} = 1 \text{ kg/m}^2$

laser efficiency = 10 percent
filter efficiency = 10 percent
total efficiency = 1 percent

Total weight of

$$W_s = \approx 7 \times 10^4 \text{ kg} + 1.1 \times 10^3 \text{ kg} + 4.3 \times 10^4 \text{ kg} + 2.3 \times 10^4 \text{ kg}$$

$$= \underline{1.4 \times 10^5 \text{ kg}} \approx \frac{4.6 \text{ space shuttle trips}}{(30{,}000 \text{ kg to } 150 \text{ miles})}$$

If we assume a CF_3I STAG solar laser, then GL_A = .81 for the small signal gain. A 100-megawatt CF_3I system would have a total weight of 180,000 kilograms.

SOLAR LASER GAIN EXPRESSION

$$I_L = I_o \, e^{GL_A}$$

$$GL_A = \frac{0.24}{\left(e^{2.4/\lambda_p} - 1\right)} \cdot \frac{1}{f_\#^2} \cdot \frac{\lambda_L^4}{\lambda_p^4} \cdot \frac{\Delta\lambda_p}{\Delta\lambda_L} \quad \frac{\tau_{loss}}{\tau_{21}}$$

For the CF_3I system:

λ_L = 1.315 μm

λ_p = 0.275 μm

τ_{loss} = 1.3 x 10^{-3} sec

$\Delta\lambda_p$ = 0.05 μm

$\Delta\lambda_L$ = ????

τ_{21} = 0.1 sec

Gives:

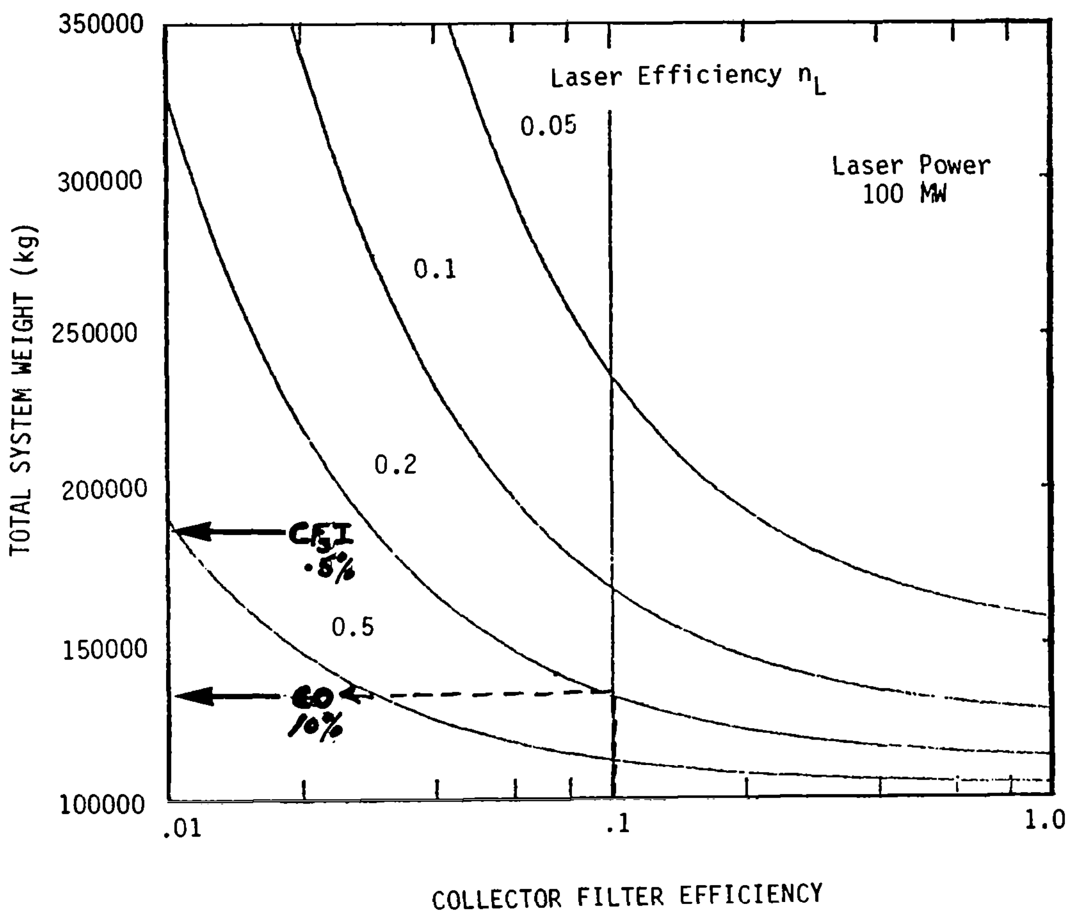
$$GL_A = \frac{0.13}{f_\#^2}$$

$= \underline{0.81}$ for $f_\#$ = 0.4

Total system weight = <u>180,000 kg (100 MW)</u> for CF_3I solar-pumped laser system.

This figure shows the relation between total system weight and collector filter efficiency η_F as well as laser cycle efficiency η_L for a 100-megawatt direct solar laser system. The total system efficiency is $\eta_T = \eta_L \eta_F$. The lower arrow corresponds to the 10-percent efficient CO electric discharge laser system, and the upper arrow the 0.5-percent efficient CF_3I direct solar-pumped laser system. It should be noted from the figure that a direct solar laser, with a filter efficiency of 10 percent and a laser cycle efficiency of 20 percent (η_T = 2 percent), can compete with the electric discharge CO laser system.

DIRECT SOLAR LASER WEIGHT versus EFFICIENCY



OTHER DIRECTLY PUMPED LASERS

- Dye Laser
  - low efficiency
  - need better data
- Liquid Inorganic Chlorides
  - $POC\ell_3:ZrC\ell_4:Nd^{+3}$
  - $POC\ell_3:SnC\ell_4:Nd^{+3}$
  - higher heat capacity than solids
  - broad absorption in visible

HYBRID SCHEMES

- Solar-driven MHD electric discharge laser.
- Xe partially ionized and heated by Sunlight expanded supersonically; "tickled" by high voltage produces flash of UV-rich light CF_3I.

CONCLUSIONS AND RECOMMENDATIONS

- 100-megawatt laser can be energized by the Sun.
- Weights of systems will lower with improved efficiency.
- More research on laser candidates, adaptive projector, etc.
- System studies should include the user; strong impact on system characteristics.
- Payoffs will have enormous consequences for future of the United States.

NASA HIGH-POWER LASER TECHNOLOGY WORKSHOP

OAST WORKSHOP at GENERAL RESEARCH CORPORATION
MARCH 1979

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Richard B. Lancashire
October 1981

NASA HIGH POWER LASER TECHNOLOGY WORKSHOP

- SPONSORED BY OAST; HELD AT GENERAL RESEARCH CORPORATION, FEBRUARY 28 - MARCH 1, 1979
- PURPOSE: TO PROVIDE NASA WITH RECOMMENDATIONS FOR R&T PROGRAMS LEADING TO THE APPLICATION OF H.P. LASERS IN FUTURE MISSIONS
- STEERING COMMITTEE APPOINTED TO FORMULATE RECOMMENDED PROGRAM TO NASA
  - ED GERRY, CH., SCHAFER ASSOCIATES
  - ABE HERTZBERG, UNIVERSITY OF WASHINGTON
  - PETER GLASER, A. D. LITTLE, INC.
  - MAX HUNTER, LOCKHEED
  - CARL SCHWENK, NASA

NASA HIGH POWER LASER TECHNOLOGY WORKSHOP

- AGENDA INCLUDED DOD CONTRACTORS DESCRIBING DOD PROGRAMS IN LASER DEVICE AND TRANSMISSION TECHNOLOGY AS WELL AS BRIEFINGS BY LeRC, LaRC, MSFC, ARC, GSFC, JPL, AND WALLOPS ON VARIOUS NASA LASER PROGRAMS
- DIFFERENCES IN DOD AND NASA PROGRAM OBJECTIVES WERE STRESSED: LENGTH OF OPERATING TIMES; BEAM PROPAGATION DISTANCES; COOPERATIVE "TARGETS"
- GENERAL CONSENSUS WAS NASA COULD NOT DEPEND ON DOD EFFORT TO COMPLETELY SUPPLY POSSIBLE NEEDS OF H.P.L. TECHNOLOGY

NASA HIGH POWER LASER TECHNOLOGY WORKSHOP

SPECIFIC RECOMMENDATIONS AND GOALS FOR NASA R&T

- LASER R&D

  1. kWs TO 50 MW
  *2. LONG DURATION, CLOSED-CYCLE OPERATION - NEEDS DEMONSTRATION
  3. LONG DURATION, OPEN-CYCLE OPERATION POSSIBLE FOR SOME GROUND BASED "MISSIONS"
  4. WAVELENGTHS NEEDED - UV TO IR
  5. SINGLE LINE OUTPUT NEEDED FOR MANY APPLICATIONS
  6. HIGH PUMP TO LASER MEDIUM CONVERSION EFFICIENCY
  7. MATERIALS - WINDOWS, HARDWARE, ETC., FOR LONG DURATION OPERATION
  *8. SOLAR PUMPING - DIRECT AND INDIRECT
  9. NUCLEAR PUMPING - DIRECT AND INDIRECT

- BEAM CONTROL (TRANSMISSION)

  DOD R&D BETTER MATCHED TO NASA REQUIREMENTS. NASA SHOULD FOLLOW CLOSELY AND PURSUE INDEPENDENTLY:

  1. PHASE-LOCKING OF LASER SYSTEMS
  2. LONG OPERATION OF LARGE, ADAPTIVE OPTICS

*EARLY EMPHASIS REQUIRED

NASA HIGH POWER LASER TECHNOLOGY WORKSHOP

- APPLICATIONS STUDIES

  *1. SPS - SYSTEM IN GEO ONLY
  - SYSTEM IN SUN-SYNC. ONLY
  - SYSTEM IN COMBINATION SUN-SYNC./GEO

  2. PROPULSION - ORBIT-TO-ORBIT TRANSFER
  - GROUND BASED LASER
  - LASER POWERED AIRCRAFT
  - LASER-ELECTRIC O.T.V.

  3. POWER BEAMING (OTHER THAN SPS) - GROUND TO SPACE
  - SPACE TO SPACE
  - GROUND TO GROUND

  4. CONVERSION - LASER TO ELECTRIC (ALL FORMS)
  * - LASER TO ENTHALPY (HEAT ENGINES)
  - LASER TO CHEMICAL PROCESSING (PHOTOCHEMISTRY)
  - LASER TO MATERIALS PROCESSING

- TECHNOLOGY DEMONSTRATIONS

  1. SOLAR PUMPING OF LASERS
  2. LASER TO ELECTRIC CONVERSION
  3. HIGH POWER LASER HEATED THRUSTER (100 kW)

*EARLY EMPHASIS REQUIRED

LASER SYSTEM STUDIES

Closed Cycle Gas Dynamic Laser Design Investigation
United Technologies Corporation (January 1977)

Closed Cycle Electric Discharge Laser Design Investigation
Hughes Aircraft Company (March 1978)

CW Excimer Laser
Hughes Research Laboratories (August 1976)

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

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REVIEWED BY:
Richard B. Lancashire
October 1981

LASER SYSTEM STUDIES

- PERFORM ANALYTICAL INVESTIGATION TO ASSESS SCALEUP AND DESIGN FEATURES FOR A MW CLOSED CYCLE CW SYSTEM OPERATING IN SPACE OR AIRBORNE IN 1990.

- PERFORM CONCEPTUAL DESIGN FOR COMPONENTS & SYSTEM

- ESTABLISH DESIGN OPTIMUM
  - WEIGHT, VOLUME, POWER

- IDENTIFY CRITICAL TECHNOLOGIES

- COMPARE WITH PREVIOUS DOD STUDIES

CLOSED-CYCLE GAS DYNAMIC LASER DESIGN INVESTIGATION

NASA CR135130 CONTRACT NO. NAS3-19705 JANUARY 1977

UNITED TECHNOLOGIES CORPORATION
PRATT & WHITNEY AIRCRAFT GROUP

W. E. YOUNG AND G. W. KELCH

FOR

NASA LeRC

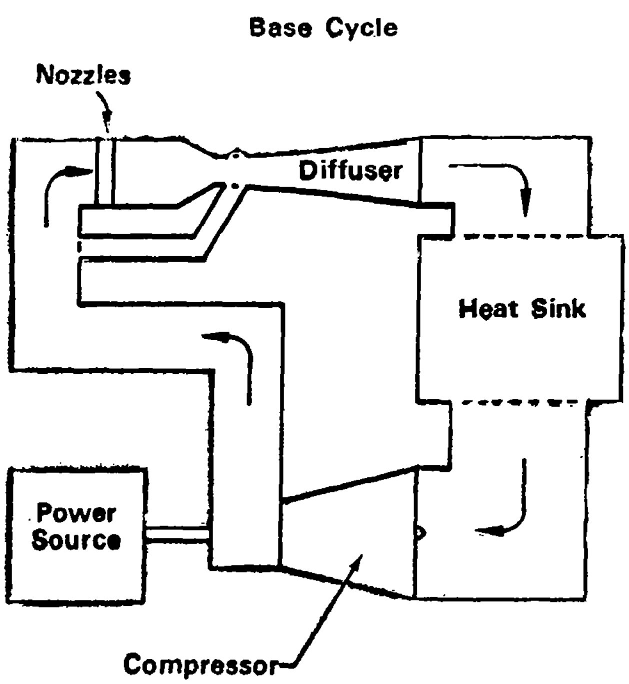
R. B. LANCASHIRE, PROJECT MANAGER

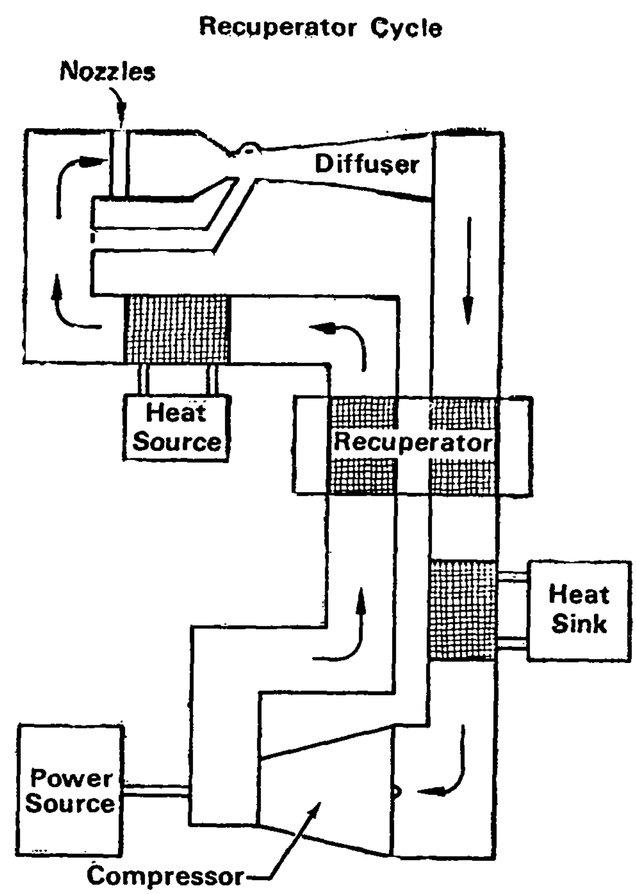
CLOSED-CYCLE GDL STUDY

GROUND RULES

- OPTIMIZE CLOSED CYCLES, CO_2, GDL SYSTEM BASED ON MINIMUM SHAFT POWER
- IGNORE PRIME POWER SOURCE AND RADIATOR (BOTH WERE EVENTUALLY CONSIDERED)
- OPTIMIZATION APPROACH ESTABLISHED FOR 1 MW SPACE-BASED SYSTEM. EXTEND TO 1 MW AIRBORNE SYSTEM AND 5 AND 10 MW SPACE AND AIRBORNE SYSTEMS

CLOSED CYCLE SCHEMATICS

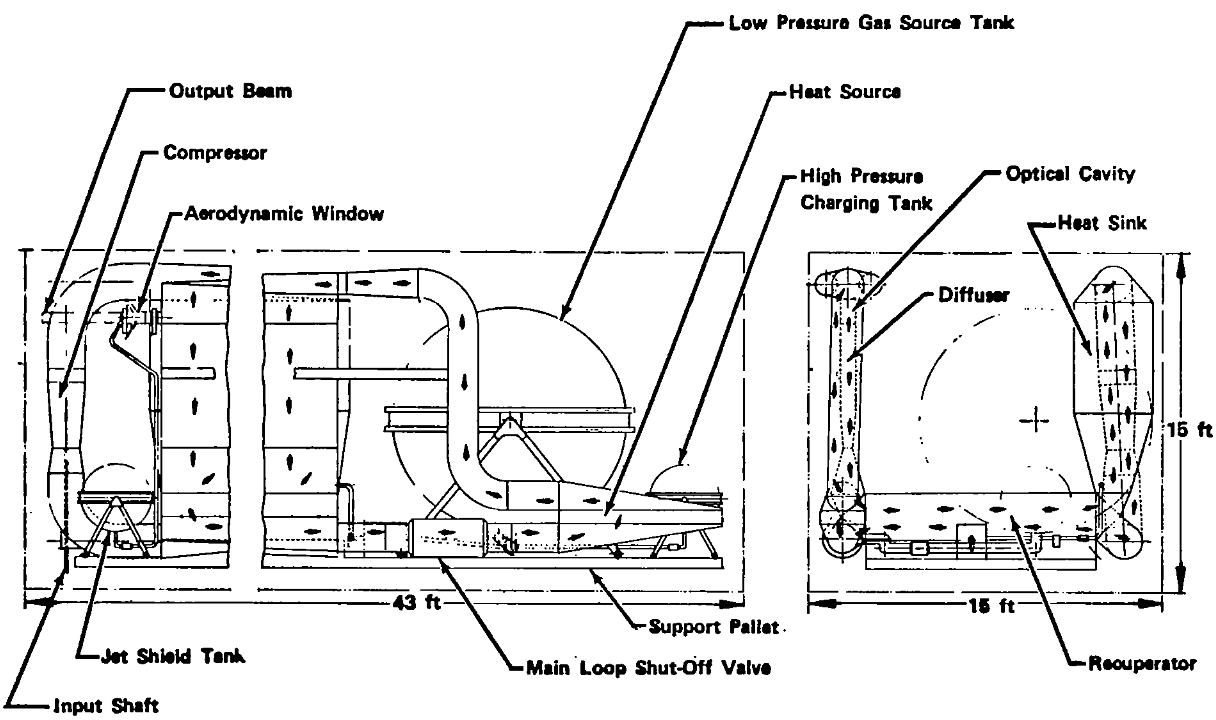




DESIGN TABLE SUMMARY

	BASE CYCLE	RECUPERATOR CYCLE
CAVITY SPECIFIC POWER, K_J/LB	10.4	10.4
COMPRESSOR POWER, HP	31,800	11,801
HEAT REJECTION REQUIREMENTS, BTU/SEC	22,500	13,657
HEAT SOURCE REQUIREMENT, BTU/SEC	0	6,262
CYCLE THERMAL EFFICIENCY, %	1.1	2.4
LASER/COMPRESSOR POWER EFFICIENCY, %	4.2	11.4
LASER LOOP WEIGHT, LB	49,600	107,000
TOTAL SYSTEM WEIGHT, LB	1.56×10^6	0.72×10^6

CLOSED CYCLE GDL
SPACE APPLICATION



GDL SYSTEMS STUDY CONCLUSIONS

- COMPRESSOR POWER SOURCE AND SPACE RADIATOR DOMINATE LOOP WEIGHT AND VOLUME - LOOP~10% TOTAL WEIGHT
- RECUPERATOR CYCLE IS MOST ATTRACTIVE FOR BOTH SPACE AND AIRBORNE APPLICATIONS,~10% EFFICIENCY, SMALLER COMPRESSOR.
- SPACE SYSTEM REQUIRES MULTIPLE SPACE SHUTTLE FLIGHTS AND ASSEMBLY IN SPACE - 1 MW LOOP REQUIRES 2 FLIGHTS
- AIRBORNE SYSTEM POWER LEVEL LIMITED TO 1-2 MW FOR C5A CARRIER.

CLOSED-CYCLE ELECTRIC DISCHARGE LASER DESIGN INVESTIGATION

NASA CR135408 CONTRACT NO. NAS3-20100 MARCH 1978

HUGHES AIRCRAFT COMPANY

P. K. BAILEY AND R. C. SMITH

FOR

NASA LeRC

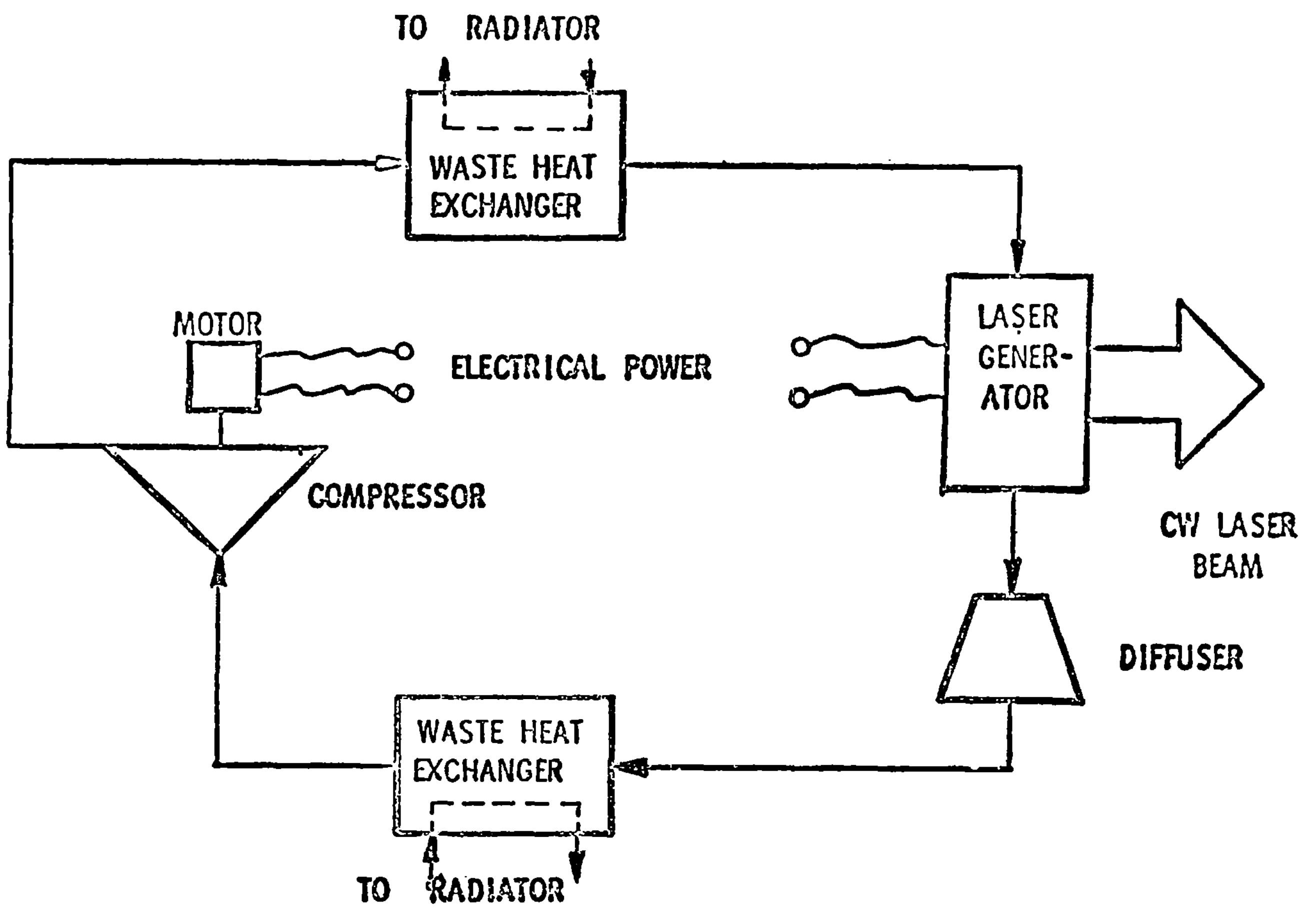
J. G. SLABY, PROJECT MANAGER

CLOSED-CYCLE EDL STUDY

GROUND RULES

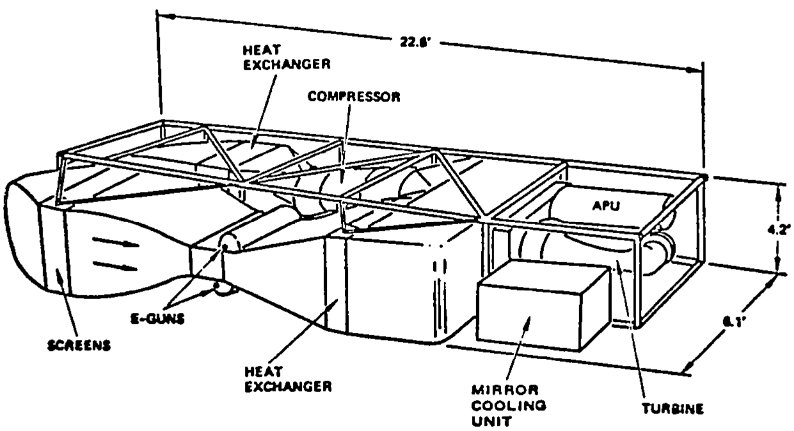
- SAME AS FOR GDL STUDY EXCEPT OPTIMIZED FOR MINIMUM WEIGHT
- ADDED SCOPE OF 1 MW SPACED-BASED CO SYSTEM

CLOSED CYCLE GASEOUS EDL SYSTEM (CO_2 OR CO)

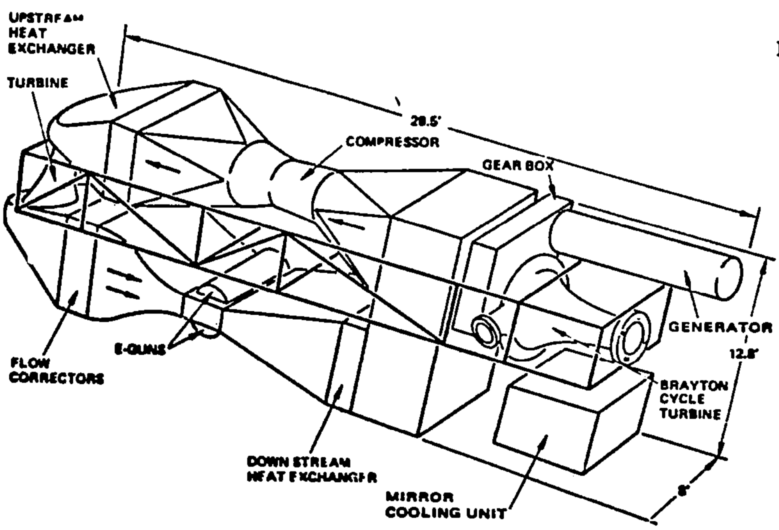


1 M WATT SPACE SYSTEMS

	Supersonic CO_2 GDL	Subsonic CO_2 EDL	Supersonic CO EDL
System weight (Kg)	316,154	20,440	16,963
Laser loop (Kg)	38,669	2,840	2,780
Laser loop power conversion (%)	–	15.1	22.7
Solar-laser conversion (%)	–	2.5	3.8
Collector area (M^2)	–	29,500	19,500
Radiator area (M^2)	–	2,800	2,600



1 Mwatt CO_2 laser - space.



5 Mwatt CO_2 laser - space.

LASER SYSTEMS STUDIES

CONCLUSIONS

- MUST INCLUDE PRIME POWER SOURCE AND RADIATOR IN FUTURE STUDIES
- 5 MW EDL REQUIRES ONE SHUTTLE FLIGHT; 1 MW GDL REQUIRES MULTIPLE SHUTTLE FLIGHTS
- ELECTRICAL EXCITATION MORE VOLUME/WEIGHT EFFICIENT THAN THERMAL EXCITATION
- FUTURE MULTI-MEGAWATT LASERS (10s OF MW) MOST LIKELY WILL BE MADE UP OF SMALLER (~5 MW) LASERS. PHASE LOCKING NECESSARY

NEW LASING MEDIA

OBJECTIVES

WAVELENGTH IN VISIBLE OR NEAR INFRARED FOR

- EFFICIENT ATMOSPHERIC PROPAGATION
- SMALLER, MORE CONVENTIONAL OPTICS
- SPECIFIC END USE REQUIREMENTS

  EFFICIENT ENERGY CONVERSION

  EXCITE SPECIFIC CHEMICAL REACTIONS

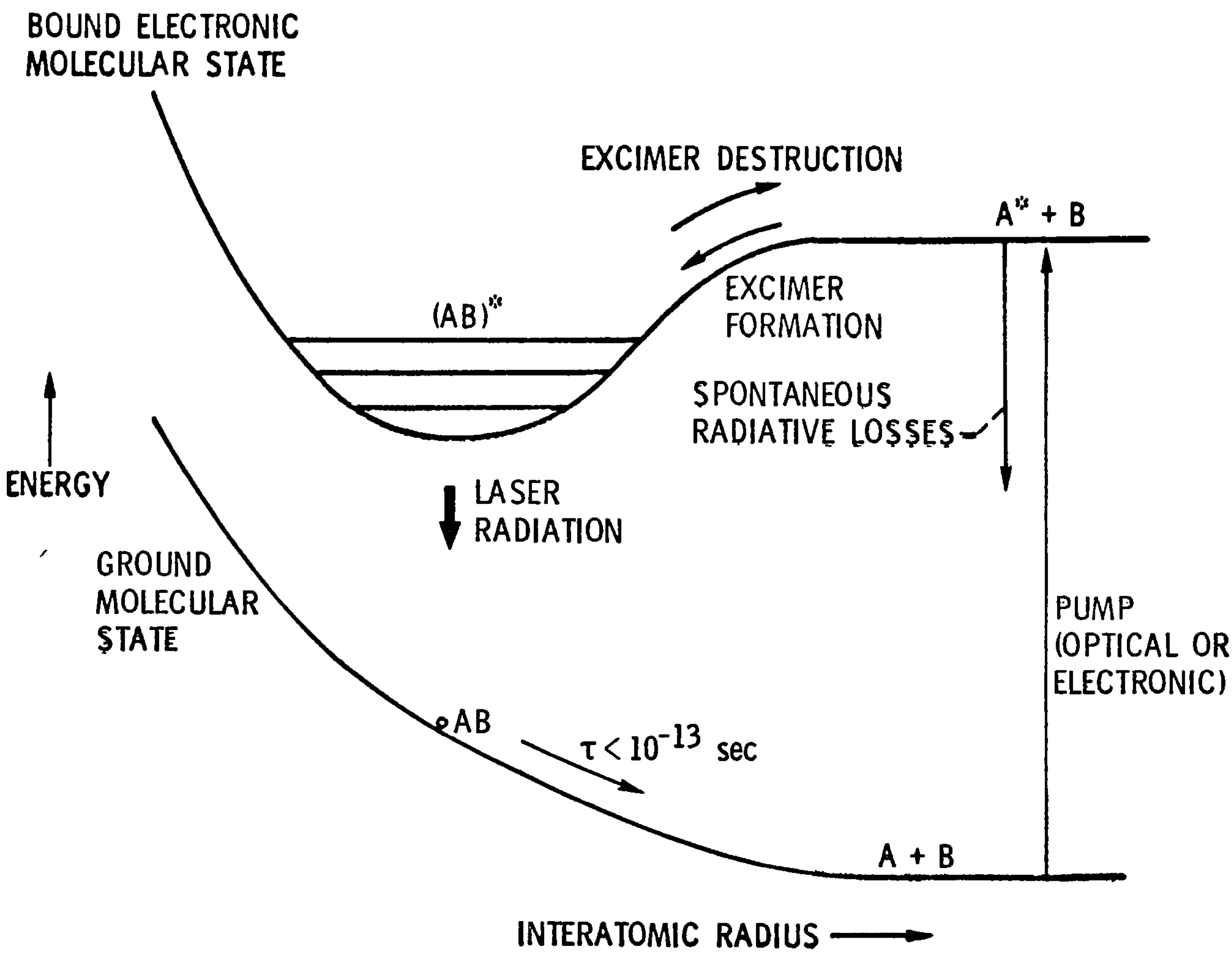
EXCIMER LASER

HIGH POWER

HIGH EFFICIENCY

DESIRABLE WAVELENGTHS

ENERGY LEVEL DIAGRAM FOR MOLECULE AB SHOWING PROCESSES IMPORTANT IN CREATING PROSPECTIVE DISSOCIATION LASER



CW EXCIMER LASER

CONTRACT NO. NAS3-19707 AUGUST 1976

HUGHES RESEARCH LABORATORIES

A. J. PALMER, ET. AL.

FOR

NASA LeRC

DR. J. DUNNING, PROJECT MANAGER

CW EXCIMER LASER

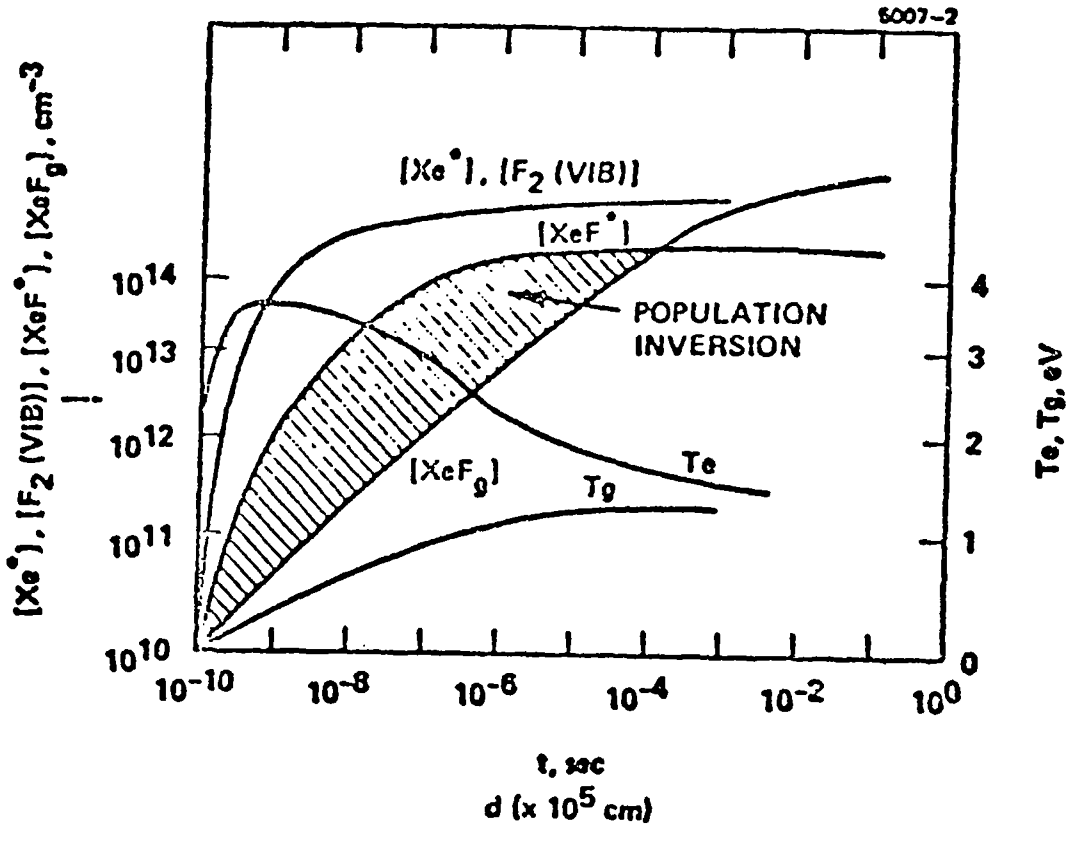
OBJECTIVE: OBTAIN DESIGN CHARACTERISTICS AND SCALING DATA ON CW EXCIMER LASERS

- DEMONSTRATE A SCALEABLE CW EXCIMER LASER USING Xe-F, Xe-K OR Hg^2
- COMPLETE COMPUTER MODEL FOR EACH SYSTEM

RESULTS

- WRITTEN DETAILED COMPUTER CODE TO PREDICT PERFORMANCE
- BUILT LABORATORY DEVICES FOR XeF AND K-Xe/K_2
- SEEN FLUORESCENCE IN XeF

ANALYTIC BASIS FOR HIGH POWER FLOWING EXCIMER LASER



*CW OUTPUT POWER ≃ 10 MW/liter

CW EXCIMER LASER

CONCLUSIONS

- Xe/K_2 SYSTEM HAD LOWEST THRESHOLD OF THOSE SYSTEMS STUDIED
- NEED TO DEMONSTRATE LASING TO TOTALLY CONFIRM MODEL
- TECHNOLOGY ISSUES OUTSTANDING
  - DISCHARGE STABILITY
  - POWER DENSITY
  - COOLING
- CONSTRUCTION OF A TEST BED DEVICE WILL BE COSTLY

DESIGN INVESTIGATION OF SOLAR-POWERED LASERS FOR SPACE APPLICATIONS

MATHEMATICAL SCIENCES NORTHWEST, INC.
MAY 1979

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Richard B. Lancashire
October 1981

OBJECTIVE

- TO INVESTIGATE FEASIBILITY OF USING SOLAR POWERED CW LASERS FOR SPACE POWER TRANSMISSION

- TO SELECT BEST OF SEVERAL COMPETING CONCEPTS FOR A CONCEPTUAL DESIGN

GROUND RULES

- CW LASER POWER OF 1 MW

- SYSTEM COMPONENTS OPTIMIZED FOR MINIMUM WEIGHT AND VOLUME FOR SHUTTLE TRANSPORT

- DEVELOPMENT TECHNOLOGY BE AVAILABLE IN 1990 TIME FRAME

OPTICAL PUMPED LASER REVIEW

- BROADBAND OPTICAL PUMPING OF SOLID STATE, PULSED LASERS IS WELL ESTABLISHED, RUBY; ND:YAG

- OPTICALLY PUMPED GAS LASERS HAVE BEEN DEMONSTRATED BUT NOT EXTENSIVELY STUDIED

- DIRECT SOLAR PUMPING OF BOUND-BOUND TRANSITIONS IS INEFFICIENT EVEN IF QUANTUM EFFICIENCY IS HIGH; ABSORPTION BAND SMALL RELATIVE TO EFFECTIVE SOLAR BANDWIDTH

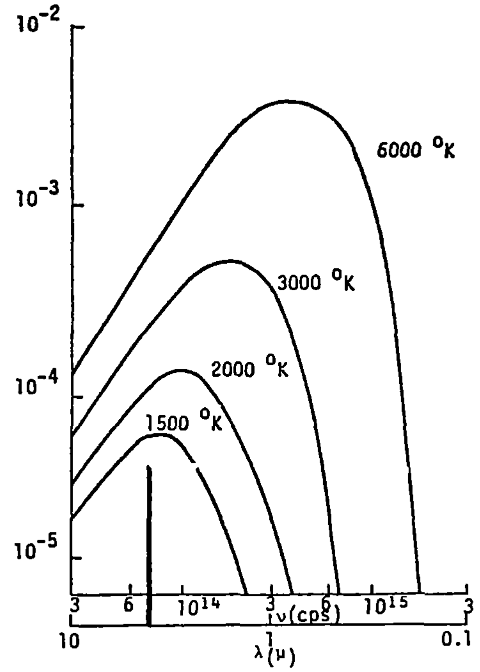
SOLAR PUMPED LASANT TYPES

- DIRECT OR VISIBLE PUMPED: VISIBLE LASING
- DIRECT OR VISIBLE PUMPED: INFRARED LASING
- INFRARED PUMPED: INFRARED LASING

INDIRECT SOLAR-PUMPED LASERS

- SOLAR RADIATION ABSORBED AND RE-RADIATED VIA INTERMEDIATE BLACK BODY
- FOCUSSED SUNLIGHT WOULD HEAT B.B. TO 2000° K TO 3000° K
- INTERMEDIATE B. B. WOULD SURROUND LASING MEDIUM
- KEY TO PROCESS IS THAT RADIATION IS CONTINUOUSLY RE-EMITTED AT THE WAVELENGTH WHICH HAS BEEN DEPLETED BY SELECTIVE ABSORPTION OF LASANT GAS

BLACKBODY SPECTRAL DISTRIBUTION AT SELECTED TEMPERATURES



- GREATER FRACTION OF IR AVAILABLE AT LOWER B.B. TEMPERATURES
- FOUR TIMES GREATER ABSORPTION EXPOSURE AREA POSSIBLE WITH INTERMEDIATE B.B.

EFFICIENCY CONSIDERATIONS

$$\eta = \frac{\text{LASER POWER } (P_L)}{\text{COLLECTOR AREA (A)} \cdot \text{SOLAR FLUX (S)}} \quad \text{OR} \quad A = \frac{P_L}{\eta S}$$

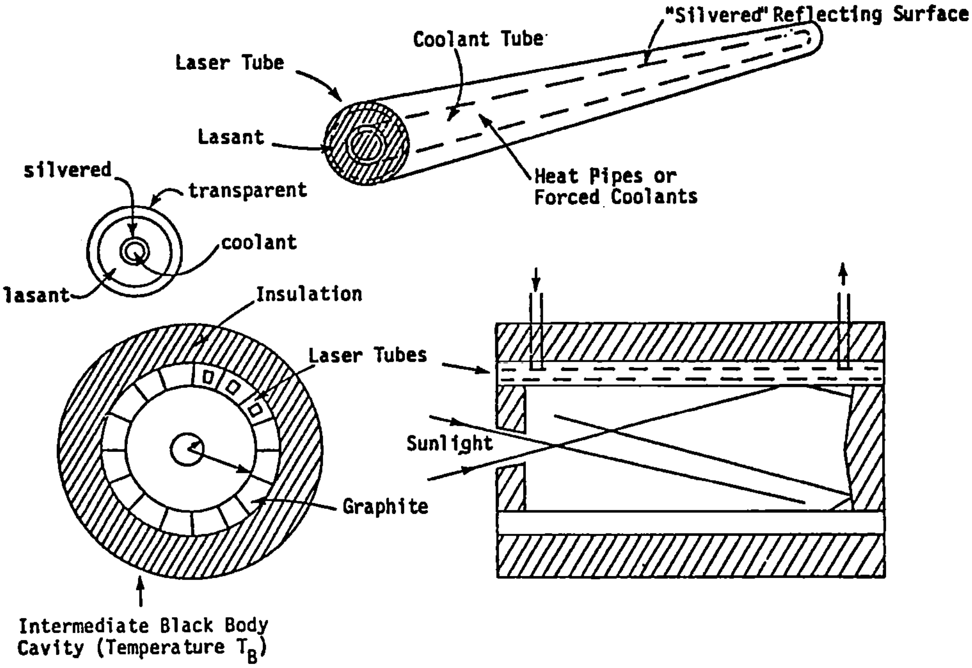
MUST MAXIMIZE η TO MINIMIZE COST

$$\eta = \eta_C \cdot \eta_B \cdot \eta_L \cdot \eta_S$$

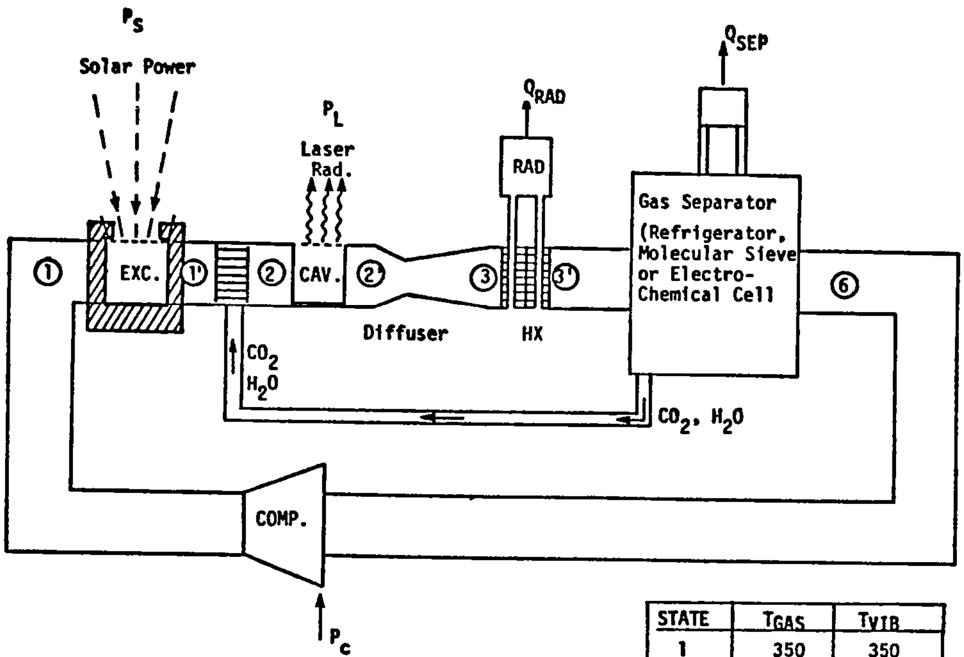
C - COLLECTOR
B - SPECTRUM UTILIZATION
L - LASER
S - SYSTEM COMPONENTS

CO OR CO_2 LASING IS DICTATED

STATIC INDIRECT OPTICALLY PUMPED GAS LASER

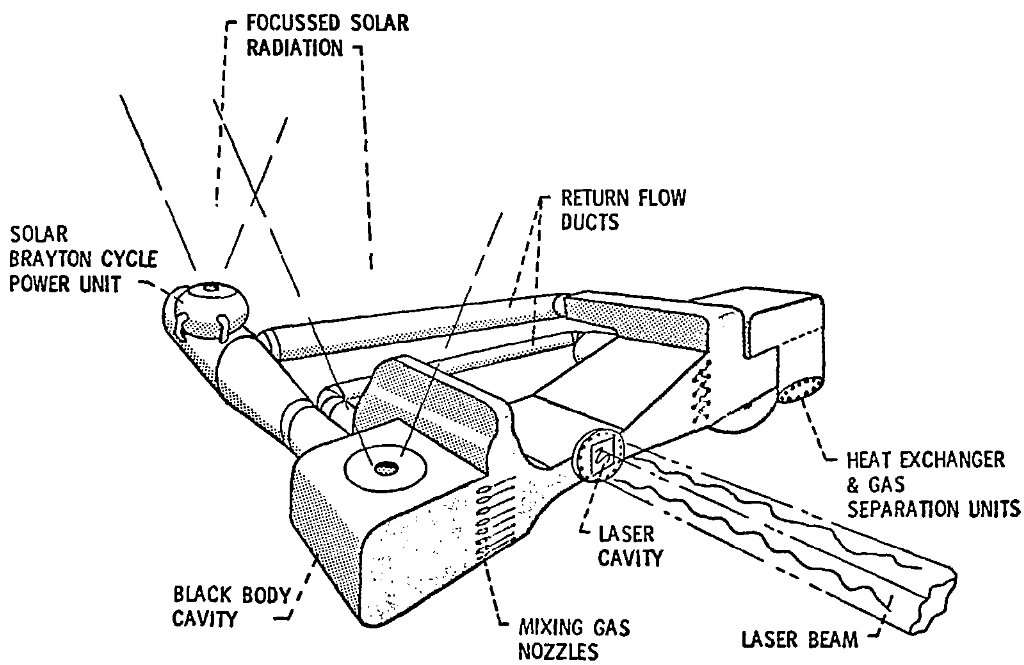


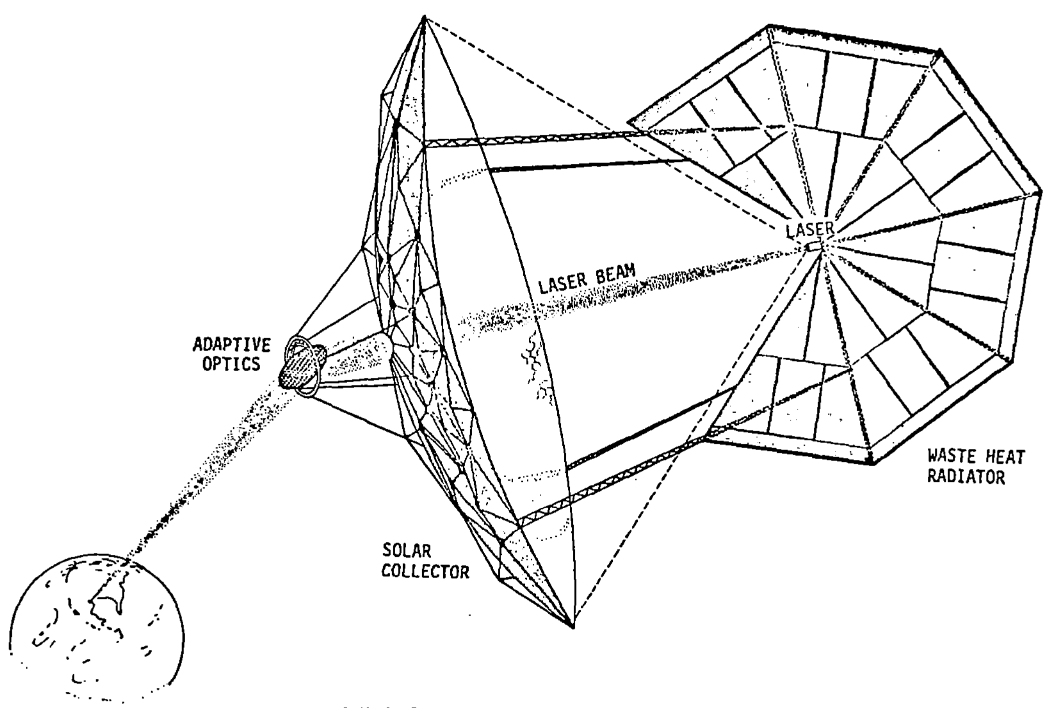
SOLAR PUMPED MIXING LASER



STATE	T_{GAS}	T_{VIB}
1	350	350
1'	350	1900
2	350	1900
2'	500	950
3	535	535
3'	375	375
6	340	340

ARTIST'S SKETCH OF CO/CO_2 FLOW-MIXED SOLAR-PUMPED LASER FOR SPACE APPLICATIONS





Artist's Concept of 1 MW Solar-Pumped Laser,

Solar Laser Weight Comparison
(1 MW Laser Output)

	Laser Type				
	EDL*		GDL*	OPL*	
Components	Supersonic CO	Subsonic CO_2	Supersonic CO_2	Direct CF_3I	Indirect Static CO_2
Laser Loop					
Ducts, Nozzle, Diffuser, Cavity, Mirrors, Window Cooling Subsystem	1,574	1,662	6,292	600	600
Radiator and Heat Exch.	445	240	5,023	874	2,070
Flow Loop Compressor	250	275	1,216	250	(N/A)
Gas Make-up Purification	250	258	(N/A)		
Recuperator	(N/A)	(N/A)	18,330	(N/A)	(N/A)
Collector and Heat Exch.			2,112		
Power Source:					
Turbine/Recuperator/ Compressor	4,350	4,700	7,199	(N/A)	(N/A)
Radiator and Heat Exch.	4,163	4,500	8,565		
Collector/Concentrator/ Cavity Absorber	5,670	8,600	15,889	58,560	3,200
Power Conditioner	260	205	(N/A)	(N/A)	(N/A)
Black Body Cavity	(N/A)	(N/A)	(N/A)	(N/A)	2,400
Total Weight (kg)	16,962	20,440	64,626	60,284	8,270

*EDL = Electric Discharge Laser
GDL = Gas Dynamic Laser
OPL = Optically Pumped Laser

CRITICAL TECHNOLOGY AREAS

- VERIFY INDIRECT PUMPING CONCEPT IN LAB
- INTERMEDIATE BLACKBODY DESIGN FOR LOW HEAT LOSS AND HIGH TEMPERATURE OPERATION
- INFRARED TRANSPARENT MATERIALS FOR LASING CAVITY
- NEED REFINED METHODS OF GAS SEPARATION FOR MIXING GAS LASER; CRYOGENIC SYSTEM FOR CO LASER
- ADVANCED HEAT EXCHANGERS AND SOLAR COLLECTOR/CONCENTRATOR

UTILITY OF AND TECHNOLOGY FOR A SPACE CENTRAL POWER STATION

Paul F. Holloway and L. Bernard Garrett
NASA Langley Research Center

Presented at the Second AIAA Conference on Large Space Platforms
February 1981

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
L. Bernard Garrett
October 1981

UTILITY OF AND TECHNOLOGY FOR A SPACE CENTRAL POWER STATION

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EXPANDED ABSTRACT

The technological and economical impacts of a large central power station in Earth orbit on the performance and cost of future spacecraft and their orbital-transfer systems are examined. It is shown that beaming power to remote users cannot be cost-effective if the central power station uses the same power generation system that would be readily available for provision of on-board power. Similarly, microwave transmission and reception of power through space for use in space cannot be cost-competitive with on-board power or propulsion systems; the size of the receiver is simply prohibitive. Laser transmitters/receivers will be required to make central power stations feasible.

Analysis of the cost-effectiveness of meeting Earth-orbiting spacecraft electrical demands from a central power station indicates that this application cannot justify the investment required for the central station. However, remote-power transmission for propulsion of orbital-transfer vehicles promises major cost benefits (within the bounds of the assumptions made herein) of a sufficient magnitude to fully justify the research and development activities necessary to enable the central power station. Direct nuclear-pumped or solar-pumped laser power station concepts are particularly attractive with the laser thermal propulsion system and/or the laser electric propulsion system. These systems are also competitive on a mass and cost basis with a photovoltaic power station. Based on these results, key technology needs which must be met to enable a viable central power station in the future are identified.

INTRODUCTION

It is anticipated that power demands in orbit will increase exponently over the next few decades as applications and industrialization activities expand. In fact, it is generally accepted that the rate of space industrial development will depend primarily on the cost of transportation to, through, and from space, and the cost of electrical power in space.

The concept of a central power utility in space may provide an economical means of meeting the increased power demands. The purpose of this paper is to conduct a first-cut evaluation of the utility of a central power station in Earth orbit. Two classes of users are considered: (1) Earth-orbiting satellites requiring electrical power for routine operations to meet mission goals, and (2) orbital-transfer vehicles (OTV) requiring power for propulsion.

Three concepts for central, space-based power stations are considered. The first is a photovoltaic array system representing normal state of the art for proven technology with the same assumptions for costs, weight, and efficiency used for the on-board baseline system. The second is a direct nuclear-pumped laser system based on a rapidly evolving technology. Finally, a direct solar-pumped laser system based on an exciting new technology that is just now emerging in the laboratory is evaluated. Both microwave and laser transmission of energy from the central power station to the users are considered.

For comparison purposes, the baseline electrical power system is assumed to be photovoltaic power provided with conventional on-board systems at costs, weight, and efficiency projected to be attainable by the end of the century. The OTV remote energy application for laser thermal and laser electric propulsion systems is compared against projected technological advances in conventional chemical and solar electric propulsion stages.

The technologies required to enable the systems discussed are delineated. The authors hope that this paper will provide the stimulus for further analysis and discussion that will ultimately provide the necessary direction to effectively focus the near-term technology efforts and maximize the utilization of these technologies in the future.

COMPARISON BASELINE SYSTEMS

On-Board Photovoltaic Power

Silicone solar cells have been used extensively for on-board power levels ranging from a few watts to a few kilowatts. Continued development of these systems can be expected, aimed primarily at increasing the ratio of power to weight and reducing costs. As power demands increase, other cell materials, such as gallium arsenide, offering higher efficiency will become increasingly attractive. Efficiencies (ref. 1) of 18.6 percent have already been achieved with gallium arsenide (GaAs) solar cells in the laboratory as compared to the customary 12-15 percent for production silicon cells. (ref. 2) In addition, the higher operating temperature capability (ref. 3) of GaAs and its radiation resistance (ref. 4) and self-annealing characteristics (ref. 5) promise reduced size for a given power output and longer life with reduced maintenance. A weight penalty for the use of GaAs rather than silicon might be expected. However, if GaAs annealing is as effective as it currently appears, double-cover glass radiation shields will not be required. This factor, coupled with the potential for development of thin (approximately 10 μm) high-efficiency cells, would give GaAs a power-to-weight ratio advantage over silicon. Regardless of the final outcome, analyses conducted during this study have shown that total costs are insensitive to the weight differences associated with a very pessimistic GaAs weight projection. Hence, the on-board power systems of the future are assumed to be GaAs photovoltaic arrays with an efficiency of 20 percent (ref. 6).

On-Board Propulsion

Chemical Orbital-Transfer Vehicles. The baseline chemical OTV (fig. 1) uses spherical propellant tanks and a lightweight composite truss structure in a configuration developed for an earlier study (ref. 7). A hydrogen-oxygen rocket engine with a specific impulse of 476 seconds is assumed. The payload, propellant, and vehicle dry weights are 100,000 kg, 280,000 kg, and 20,000 kg, respectively. Seven-day round-trip times from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO), and return with a 50-flight lifetime are assumed for space-based operations.

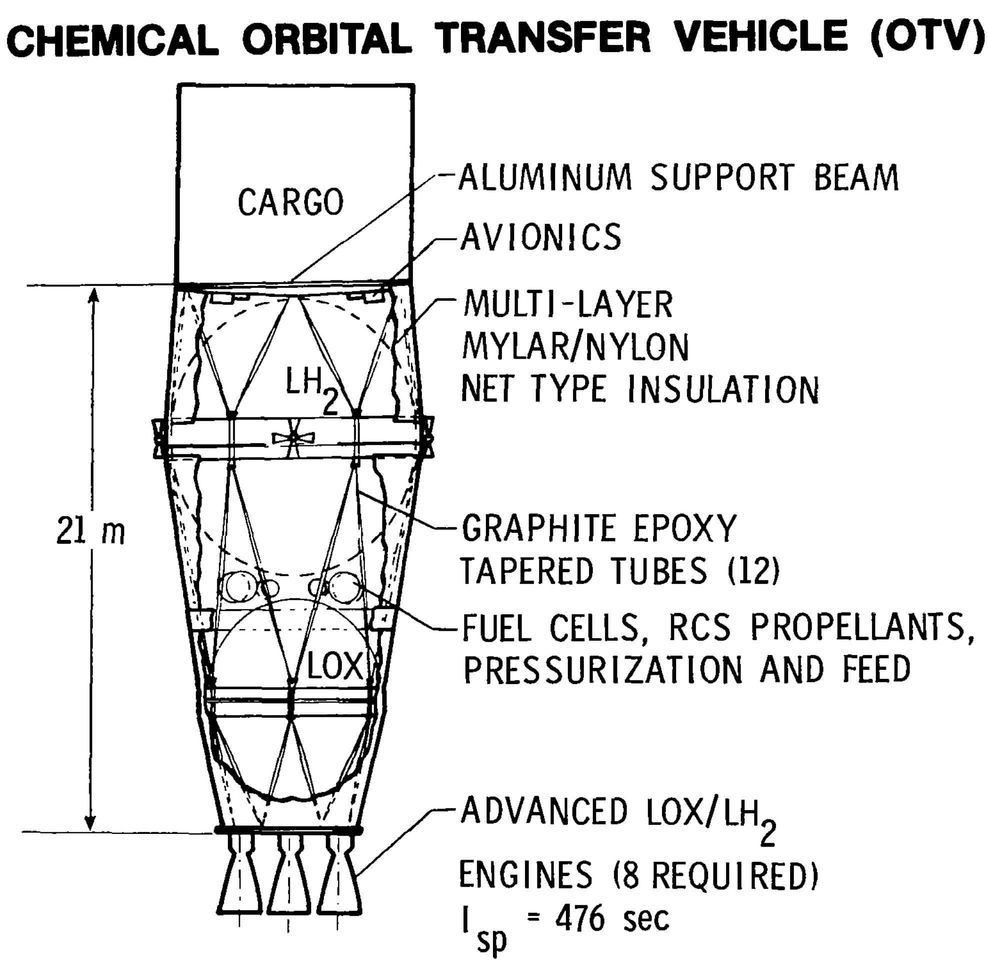

Figure 1 (from ref. 7).

Solar electric propulsion system orbital-transfer vehicles.- Solar electric propulsion system (SEPS) cargo OTV's have been studied extensively. (See, for example, refs. 8 and 9.) A representative configuration (ref. 8) is shown in figure 2. Argon ion thrusters are assumed to provide an I_{sp} of 6,000 seconds. The payload, propellant, and vehicle dry weights are 100,000 kg, 17,000 kg, and 24,000 kg, respectively. With an initial thrust-to-weight (T/W) ratio of 5×10^{-5} and 3.3 MW_e power delivered to the thrusters, a round-trip time from LEO to GEO and return of 173 days results. While the test results to date on the self-annealing characteristics of GaAs solar cells (ref. 5) are very promising, the total radiation environment has not yet been simulated. This, coupled with the lifetime required of the continuous-burn thrusters for the long trip durations, led the authors to assume a three-flight lifetime for this space-based OTV.

The chemical and SEPS orbital-transfer performance characteristics are summarized in table A1 of the Appendix.

SOLAR ELECTRIC PROPULSION SYSTEM CONCEPT

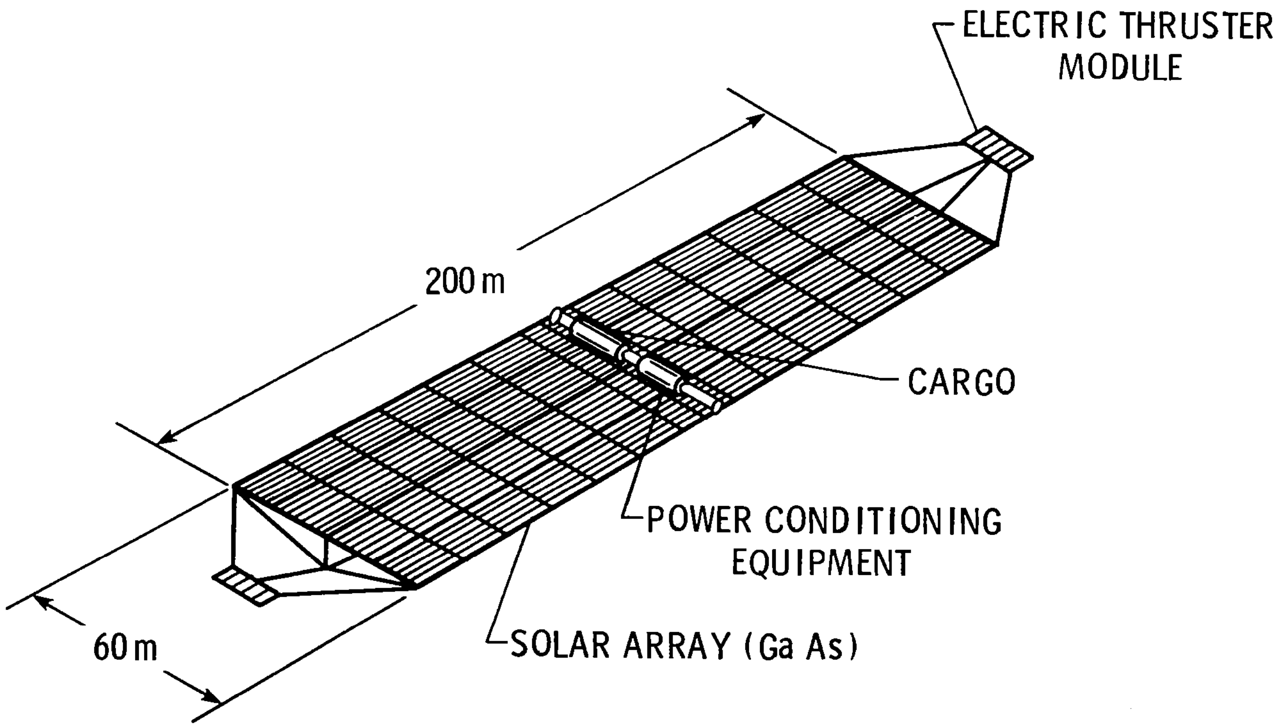

Figure 2

Space-Based Central Power Stations

Three central power staton concepts located in GEO are considered: a solar-powered photovoltaic array, a direct nuclear-pumped laser and a direct solar-pumped laser power station. In all of these systems it is assumed that power is beamed to remote users via laser or microwave. For all three concepts, the major systems and subsystems are sized for a total of 100 MW of laser power radiated at the transmitter.

Transmitter and receiver systems.- A selection of transmitters and receivers is required for the development of central power stations addressed in this study. Both microwave and laser energy transmission/reception are possible over the long distances in space that would be associated with a central power station. The sizes of the transmitter and receiver for such systems are functions of their operating wavelength and transmission distance or range, not necessarily power level. Transmitter and receiver size versus range is shown in figure 3 for diffraction-limited microwave and laser systems operating at the various wavelengths λ applicable to each system.

TRANSMITTER/RECEIVER SIZES VERSUS RANGE

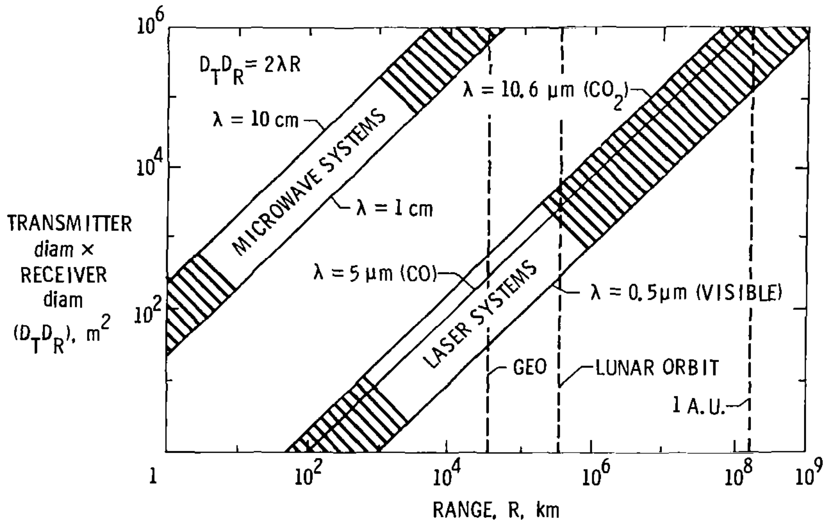

Figure 3

To transfer power over geosynchronous distances on the order of 40,000 km microwave transmitter and receiver diameters of 1 to 10 km will be required, whereas laser systems because of their shorter wavelengths can operate with much smaller transmitter and receiver diameters, ranging from 5 to 30 m.

Consider now the prospects of remote versus on-board power for these two types of transmission/receiver systems. For a microwave receiver (rectenna) of 2 km diameter, the equivalent area of on-board photovoltaic cells would produce almost 1 GW_e of power.

For a 20-m-diameter laser receiver, the equivalent area of on-board solar cells would produce approximately 100 KW_e of power. Several users in the tens to hundreds of kW_e power range are expected in future missions (ref. 10); however, no missions have been defined which would require the 1 GW_e power commensurate with the microwave receiver size. Nonetheless, if power levels of that magnitude were required they could be provided by an on-board system at a lower cost than that required for the microwave transmitter and receiver systems. Thus, the remainder of this paper considers only laser transmitter and receiver systems.

Two types of receivers are compatible with laser energy transmission--photovoltaic arrays for direct conversion to electricity, and optical collectors that focus the concentrated laser energy on thermal conversion engines. A specially tuned laser transmitting near the visible wavelength (5000 to 9000 Å) would increase photovoltaic conversion efficiencies to 40 to 50 percent (ref. 11). Laser thermal conversion system efficiencies could range between 50 to 75 percent. (See, for example, ref. 12.)

Photovoltaic array.- GaAs solar cell arrays with 20 percent conversion efficiency and electric discharge laser systems with a 30-percent efficiency are assumed. A solar-powered photovoltaic central power station with laser energy transmission systems is shown in figure 4. Array dimensions of 1800 m by 600 m achieve 100 MW_L total power output at the transmitters. Two independent, high-energy electric discharge laser (EDL) systems, each about 15 m square and 40 m long (ref. 13), radiate power to 30-m-diameter laser transmitters.

PHOTOVOLTAIC ARRAY CENTRAL POWER STATION CONCEPT

$100\ MW_L$

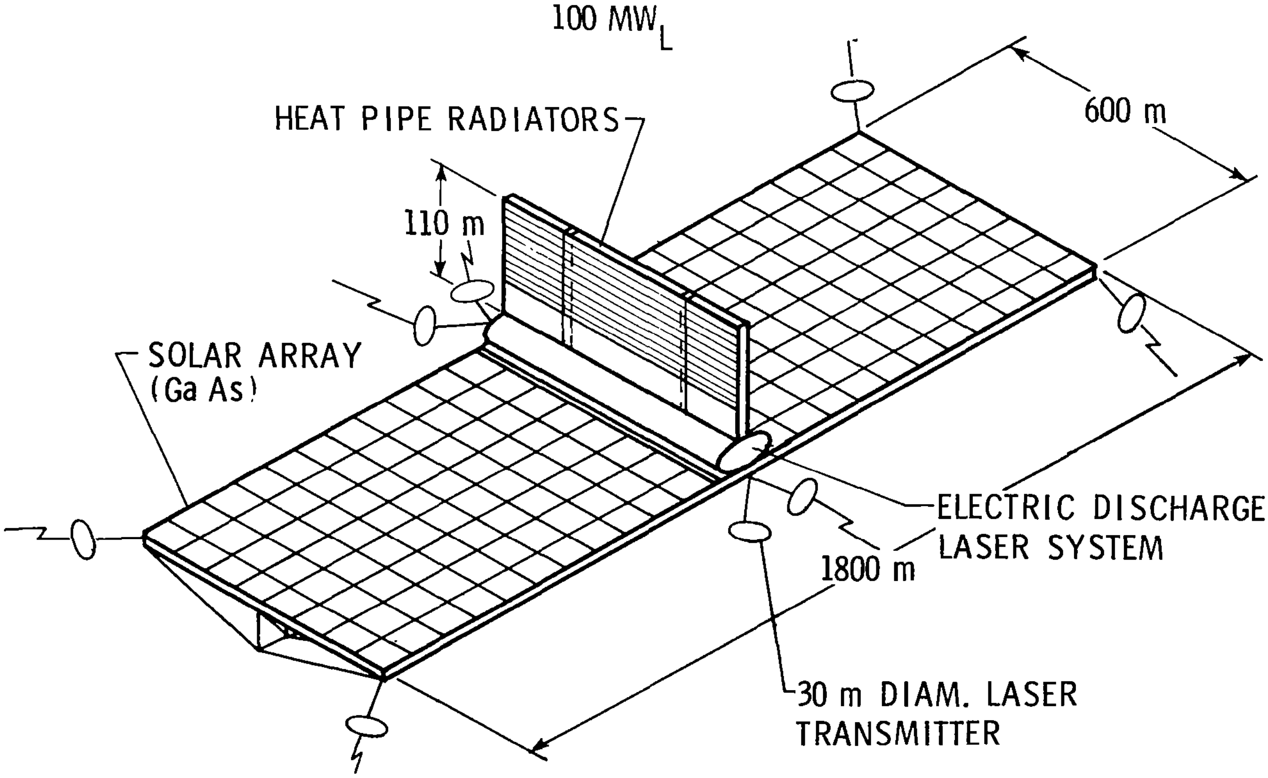

Figure 4

A cycle schematic of this approach is shown in figure 5. Passive heat rejection systems incorporated in the photovoltaic array radiate the unusable solar energy. Heat-pipe radiators arranged in a planar array with a total area of 70,000 m^2 (based on an estimated specific area of 0.25 m^2/kW_T for 500 to 700 K rejection temperature) are extended radially from the laser system to reject the unusable thermal energy in the laser.

Since 30 percent electrical-to-laser energy conversion efficiency is assumed the GaAs solar array is required to produce 330 MW_e of electrical power to yield 100 MW_L laser power output. The low-voltage array output must be processed to provide the relatively high voltage (kV range) required to drive the EDL. The laser system consists of subsonic or supersonic diffusers, the laser cavity and beam optics, compressor, heat exchanger, and the lasant gas make-up system. CO and CO_2 gases are the leading lasant candidates. Monson (ref. 14) estimated open-cycle efficiencies of 60 percent and 25 percent for CO and CO_2, respectively, resulting in closed-cycle efficiency estimates of 29 and 18 percent. One technique of achieving the higher 30-percent efficiency would utilize turbogenerator bottoming cycles (not shown in the cycle schematic) to recover waste heat from the laser.

With a closed-cycle operation the lasant gas may be recycled. For the CO_2 system, a temperature of 700 K is anticipated at the laser gas output side. A heat exchanger and radiator system is required to dispose of waste heat. The CO system must operate at low temperature to achieve high efficiency, and a refrigeration cycle is required. While this cycle would also generate waste heat, it would lower the temperature of the gas output so that no further cooling would be required.

The laser and gas loop of the system involves extending the application of existing technologies to the long-life closed-cycle operations required. Open-cycle EDL's have demonstrated efficiencies in the 30- to 40-percent range and output power at the multihundred kW levels for short periods of time (refs. 15 and 16). Thus, this is the most technologically mature of the the three control power station concepts considered in this analysis.

CYCLE SCHEMATIC FOR SOLAR-ARRAY-POWERED ELECTRIC DISCHARGE LASER

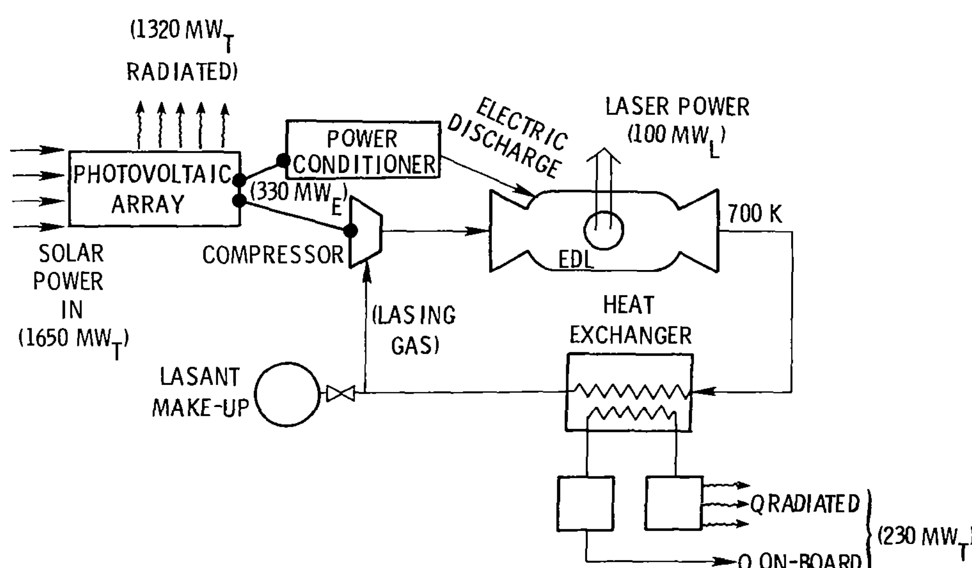

Figure 5

Direct nuclear-pumped laser.- The direct nuclear-pumped laser (DNPL) power station concept shown in figure 6 is built around a gas core reactor fueled with UF_6 as proposed by Rodgers (ref. 17). The lasant is mixed with UF_6 so that the laser generation system is integral with the reactor. Fission fragments from the nuclear reactions collide with the lasant gas constituents, exciting the gas levels sufficiently to produce lasing. One possible design of a nuclear-pumped laser taken from Rodgers (ref. 17) is shown in figure 7. The physical dimensions are for a total reactor power of 100 MW. If the nuclear-to-laser power conversion efficiency reaches the projected 10 percent (ref. 17), then this system would output 10 MW_L of laser power. This is a power-intensive nuclear reactor system capable of operating between 2 MW and 2000 MW. Thus, the overall 5-m diameter and 6-m length should be representative of a 100-MW_L laser output system. Multiple or ganged laser cavities are used to mitigate thermal effects associated with the high-power system. Heat-pipe thermal radiators of 400,000 m^2 are required if all excess heat from the nuclear-to-laser energy conversion process is rejected to space. However, Rodgers suggests that a bottoming turbogenerator cycle can be used to recover 9 percent of the waste heat as electrical power for on-board use.

DIRECT NUCLEAR-PUMPED LASER POWER STATION
100 MW_L

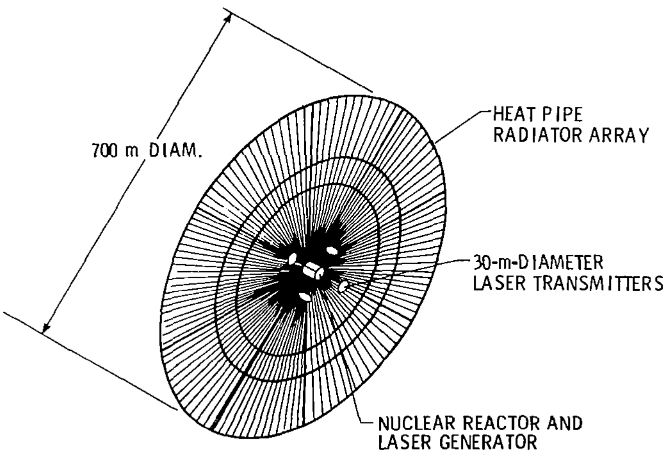

Figure 6

CONCEPTUAL UF_6 GASEOUS NUCLEAR-PUMPED LASER REACTOR

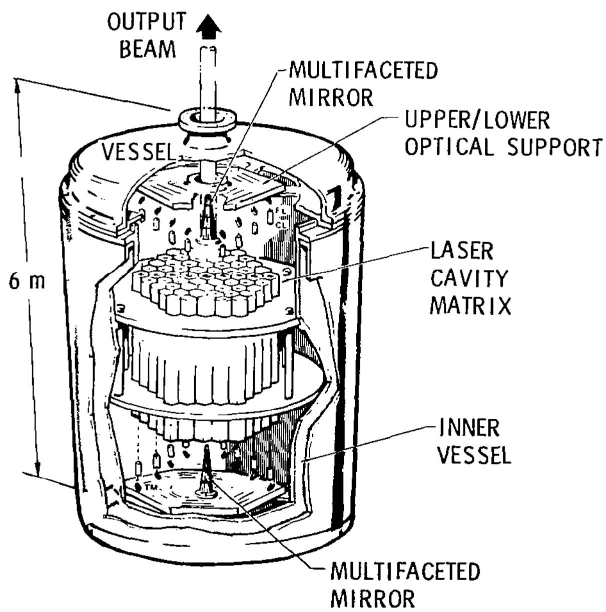

Figure 7

A schematic for long-term, closed-cycle operation of the direct nuclear-pumped laser power station (again based on the work of Rodgers (ref. 17)) is presented in figure 8. Subsystem power requirements based on projected efficiencies and representative operating temperatures are noted on the figure. A nuclear-to-laser power conversion efficiency of 10 percent is assumed resulting in a 100-MW_L power output. Fuel and laser gas reprocessors and make-up systems are added for long-term, closed-cycle space operations.

Since UF_6 would be depleted by the fission process in the reactor, the residual fission fragments must be removed and the depleted UF_6 replaced. Some lasing gas may also have to be replaced. A fuel-lasant reprocessor would remove undesirable elements produced in the fission process. The transuranium elements could be injected back into the reactor core and transmuted into either stable forms or usable fuel.

Boody et al. (ref. 18) note that experimental nuclear pumping of a CO lasant has yielded 1 percent conversion efficiency and projects that a 10-percent efficiency is achievable in future systems. Rodgers (ref. 17) points out that theoretical maximum efficiencies of 7 and 13 percent have been estimated for XeF and I_2 nuclear-pumped lasers. DeYoung (ref. 19) in a recent paper reports on a ^{3}He-Ar nuclear-pumped laser that has yielded 1 kilowatt of power. This output power represents quantum leaps (ref. 20) (six orders of magnitude) that have been achieved in output power in the last 5 years.

CYCLE SCHEMATIC FOR DIRECT NUCLEAR-PUMPED LASER

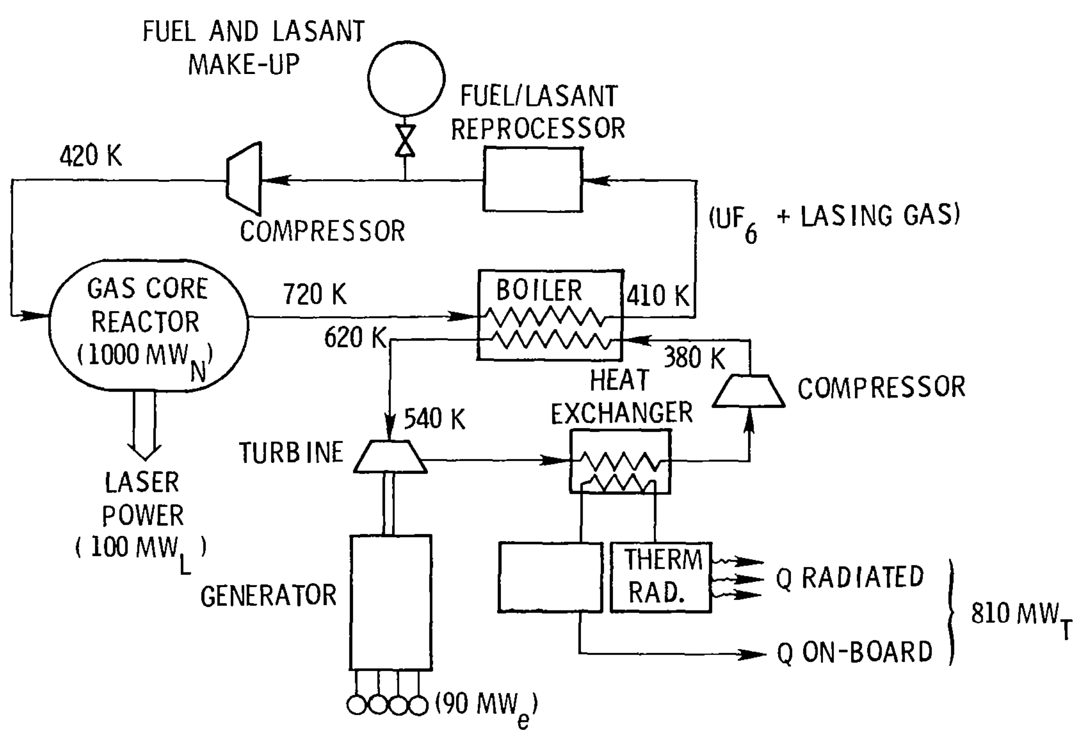

Figure 8

Direct solar-pumped laser.- Direct solar-pumped laser (DSPL) power station concepts and future performance estimates have been projected by Monson (ref. 14), Rather (ref. 21), and Taussig et al. (ref. 22). The technology for solar-pumped lasers is still in the earliest laboratory stages, and insufficient data are available to accurately quantify overall system performance. However, based on a survey of the literature and on-going experimental efforts, an overall solar-to-laser energy conversion efficiency in the range of 1 to 20 percent is assumed.

A conceptual design of a 100-MW_L solar-pumped laser power station is shown in figure 9. For this study, efficiencies of 10 percent and 1 percent are assumed requiring collector diameters of 1000 and 3000 m, respectively, to concentrate the low-level solar radiation (1.4 kW/m^2) on the transparent laser tubes.

DIRECT SOLAR-PUMPED LASER POWER STATION CONCEPT

100 MW_L

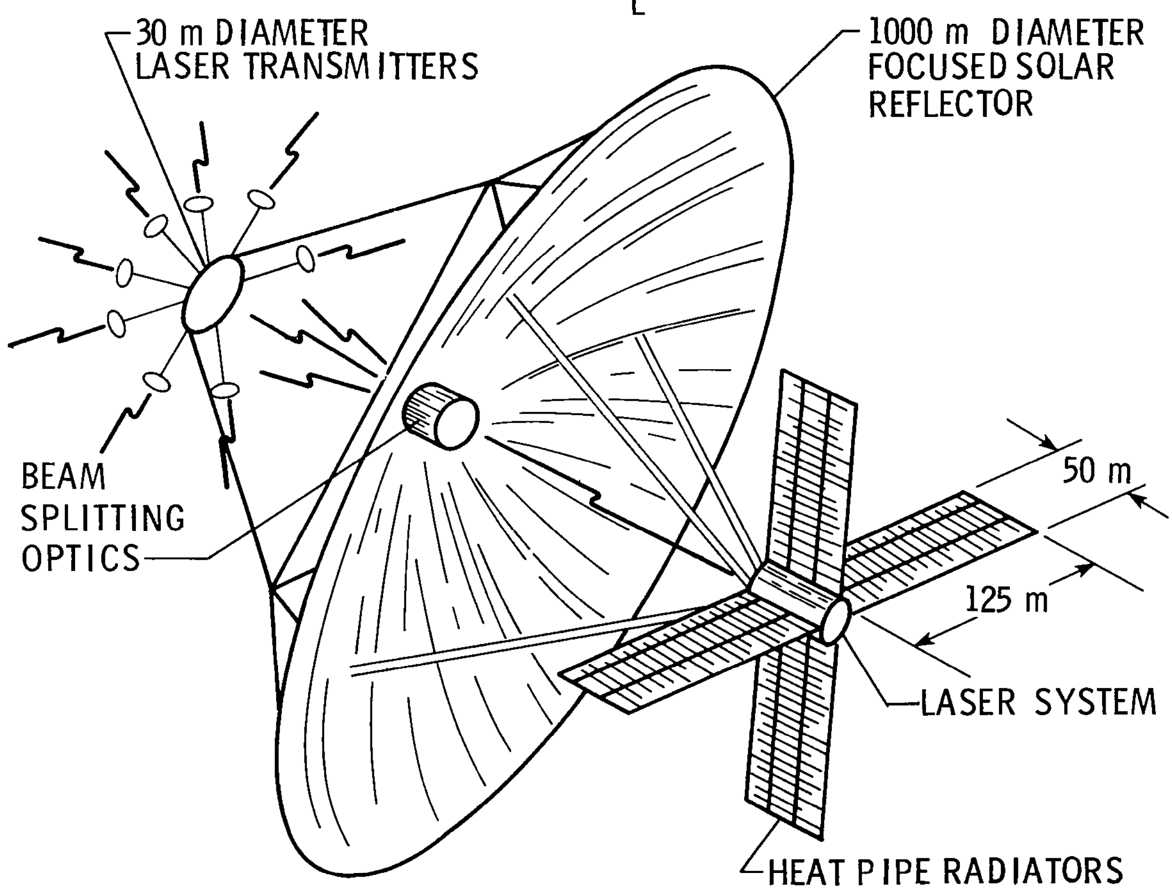

Figure 9

The construction of a 100-MW_L laser will be limited by the optical elements such as mirrors and windows. Therefore, this analysis uses an array of 50 laser tubes (each 1 m in diameter and 50 m long) in a cylindrical pattern of 20 m diameter as shown in figure 10. Improvements during the next 20 years in areas such as transmission through optical elements should be significant, but may still be insufficient to permit construction of a 100-MW_L laser in a single unit.

Assuming that a solar-filtering reflector material can be developed to reflect only the portion of the solar spectrum usable for lasing (20 percent), and that 50 percent of this reflected solar energy goes into lasing energy (for a 10-percent overall solar-to-laser energy conversion), then approximately 25,000 m^2 of heat-pipe thermal radiators are needed for the laser. The use of high-emissivity materials on the back side of the solar concentrator could be used to passively radiate the unusable solar energy absorbed by the concentrator.

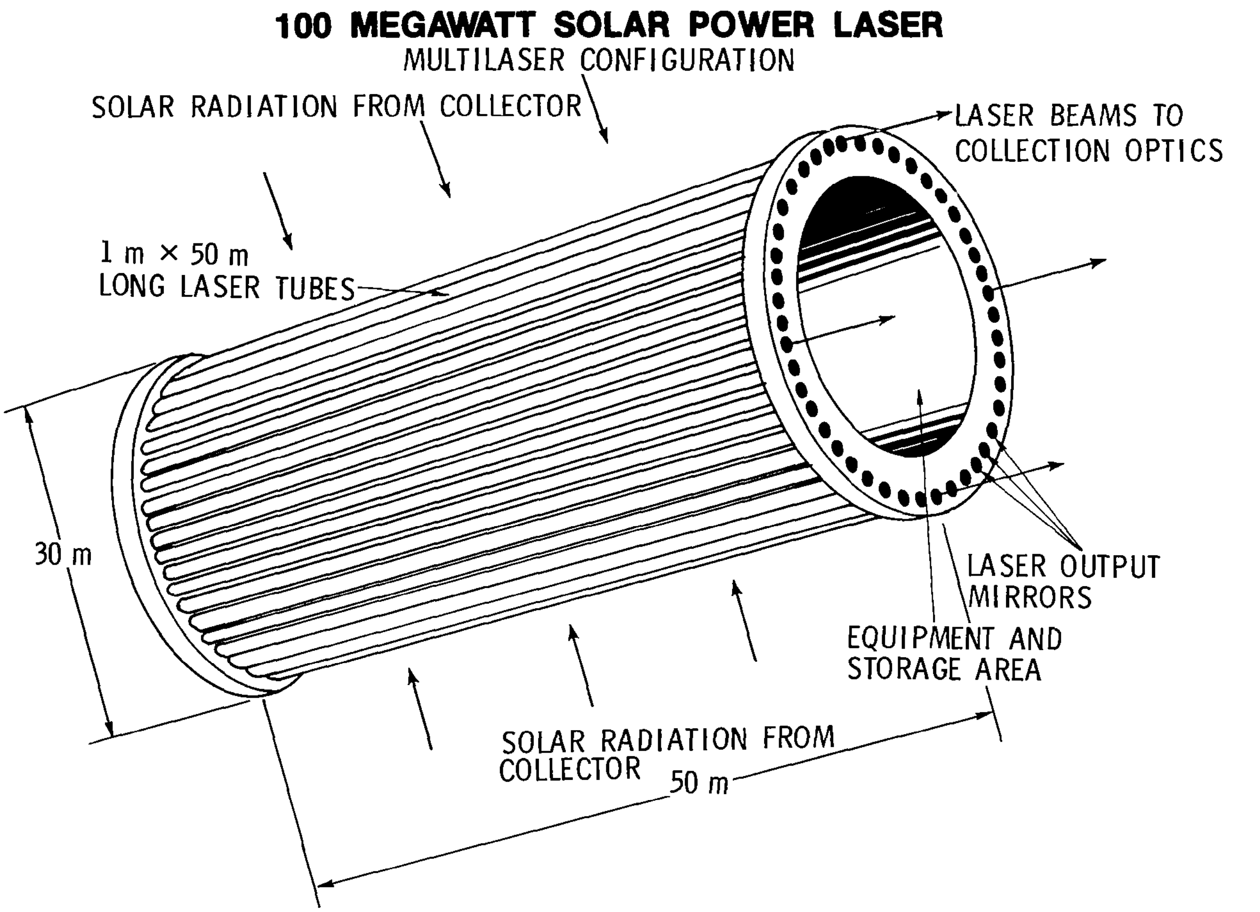

Figure 10

Solar energy, if sufficiently concentrated, can induce lasing in selected gases. Although this technology is in its infancy, the potential exists for relatively low overall cost due to simplicity of operation. Conversion efficiency of 0.1 percent solar-to-laser energy was recently achieved at Langley Research Center (ref. 23). The cycle schematic for a direct solar-pumped laser (DSPL) is shown in figure 11. Subsystem power requirements and representative operating temperatures are noted on the schematic for the 10-percent solar-to-laser energy conversion efficiency. As mentioned previously, the 10-percent overall conversion efficiency assumes a 50-percent filtered solar-to-laser radiation conversion efficiency, an efficiency approached by a NOCl lasant absorbing in the far ultraviolet to 6500 Å. Other lasants such as IBr or C_3F_7I will not achieve a 50-percent solar-to-laser conversion efficiency and a system having 5 percent efficiency (worst case) representing a 1-percent overall conversion efficiency is included in the subsequent mass and cost analyses. A gas temperature of no more than 700 K is anticipated because higher temperatures are detrimental to known lasing gas inversion processes. Several laser systems under consideration employ molecules which dissociate prior to lasing and do not regenerate themselves. Consequently, an on-board gas reprocessor may be required to reproduce the lasant gas by other means (chemical, etc.).

Of the three systems studied, the DSPL potentially presents the least challenge to achieving the long-life space power station operations required which makes it an attractive candidate even at 1 percent overall efficiency. Laboratory efforts are under way to characterize candidate lasant gases and expand the bandwidth of usable solar energy. The large, lightweight solar concentrator presents technological challenges in the design, on-orbit assembly, and operational control of the spacecraft.

CYCLE SCHEMATIC FOR DIRECT SOLAR-PUMPED LASER

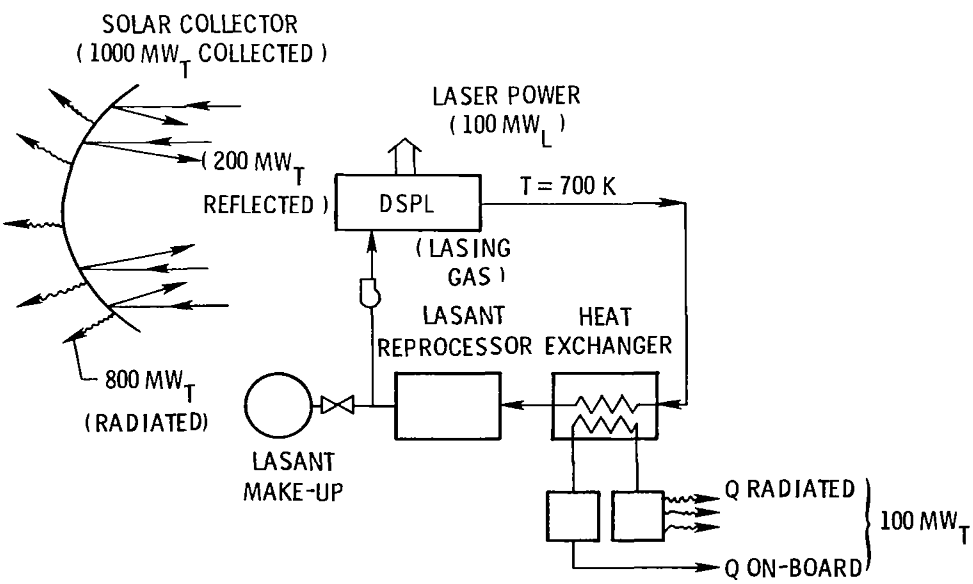

Figure 11

Remotely Powered Propulsion Systems

If a space-based central power station is available, new options are possible for orbital-transfer vehicles. For this study, two OTV concepts tailored to capitalize on the central power station are compared with the more conventional chemical and SEP OTV's.

Laser thermal propulsion.- The laser thermal propulsion system (LTPS) shown in figure 12 is similar to that previously presented in reference 24. The hydrogen propellant is heated by the laser beam from the central power station. The laser thermal engine has a thrust of 10,000 N and an I_{sp} of 1,500 seconds resulting in an exhaust power of 70 MW and a startburn thrust-to-weight ratio of 0.03. To reduce gravity losses resulting from the low T/W and the duration of the individual engine burns, the LEO-to-GEO transfer trajectory uses 10 perigee burns of about 15 minutes each and a 1.5-hour circularization burn. The payload, propellant, and vehicle dry masses are 20,000 kg, 9,900 kg, and 2,200 kg, respectively. Fourteen-day round-trip times are assumed to allow for cargo unloading and OTV maintenance. A 50-flight lifetime is assumed for a total thruster operation time of about 400 hours.

LASER THERMAL PROPULSION SYSTEM

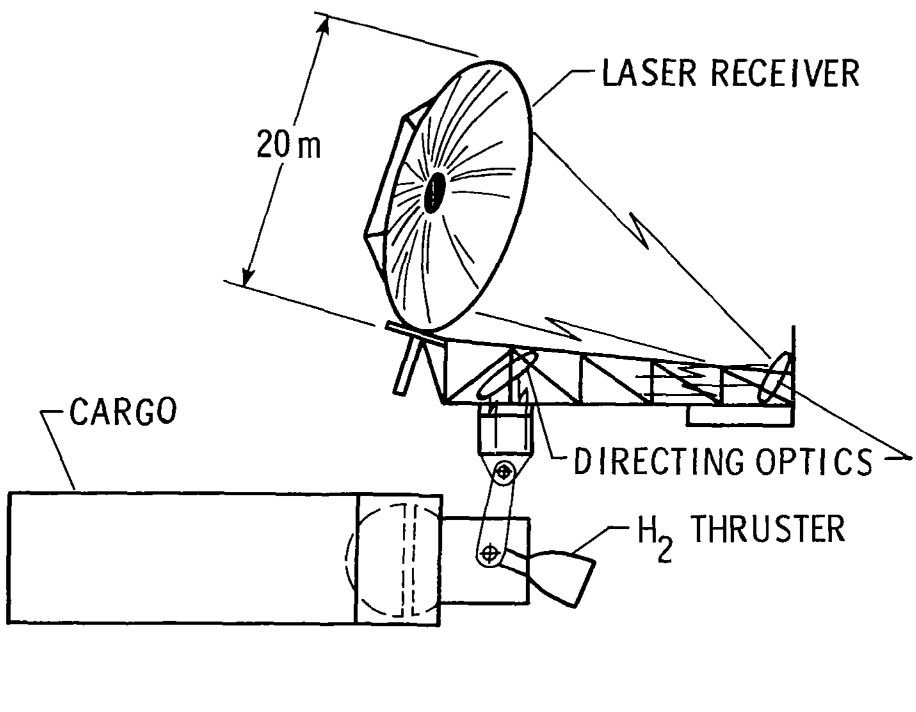

Figure 12

Laser electric propulsion.- The laser electric propulsion system (LEPS) shown in figure 13 is similar in most respects to the baseline SEPS OTV. The principal differences are the size and makeup of the solar cell array. The array is much smaller (20 m diameter) and is assembled to be more efficient (50 percent laser-to-electrical power conversion) because the laser beam is more concentrated than sunlight and has a narrow band which, with enabling technology developments and infrared-to-visible wavelength frequency conversion, can be made to match the absorption characteristics of the solar cells. For this OTV, the payload, propellant, and vehicle dry mass are 100,000 kg, 14,000 kg, and 11,000 kg, respectively. Round-trip time from LEO to GEO of 158 days is required. The three-flight lifetime assumed for the SEPS OTV is also used for the LEPS for a total thruster operation time of about 11,000 hours.

The LTPS and LEPS orbital-transfer performance characteristics are also summarized in table A1 of the Appendix.

LASER ELECTRIC PROPULSION SYSTEM CONCEPT

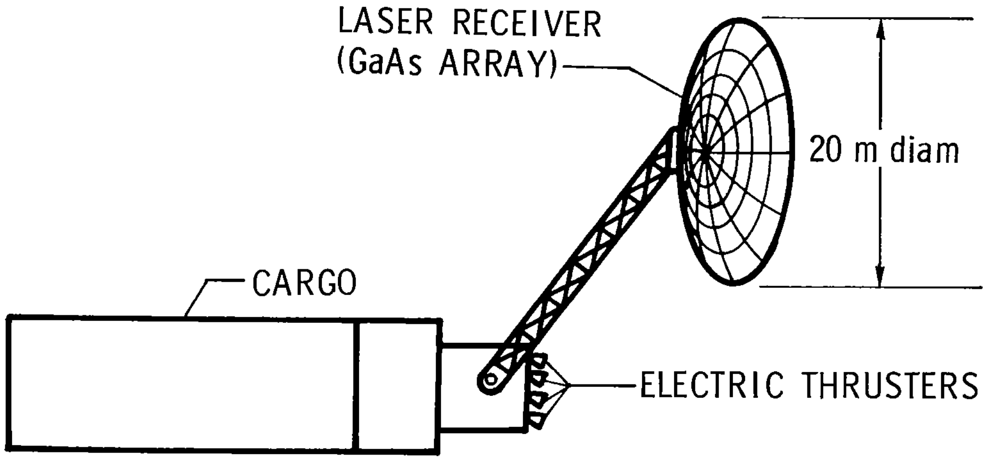

Figure 13

Central Power Station Mass and Cost Estimates

Comparative mass and cost estimates for the major components of the candidate advanced systems are based on a 100-MW_L power output at the transmitter. The assumptions made here are the basis for the performance characteristics and the development of the cost-estimating relationships presented in reference 25. Summaries of these mass and cost estimates for each of the central power station concepts are presented in figures 14 and 15, respectively. Details of these estimates are discussed on subsequent pages.

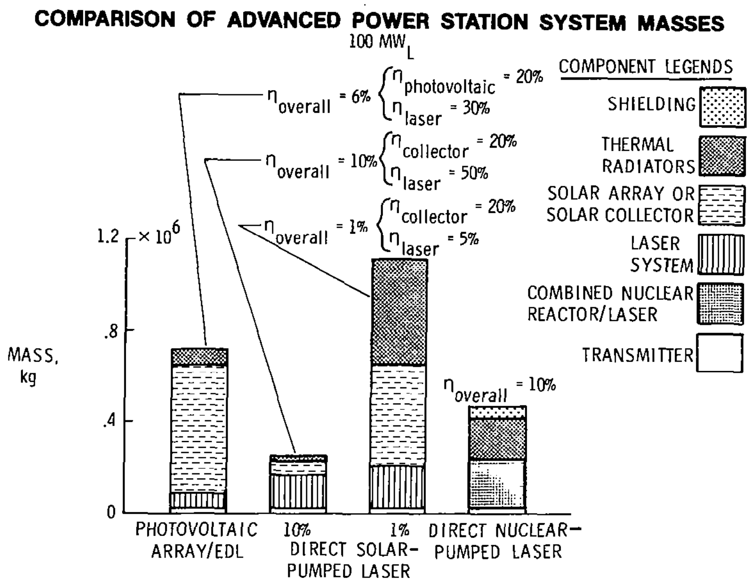

Figure 14

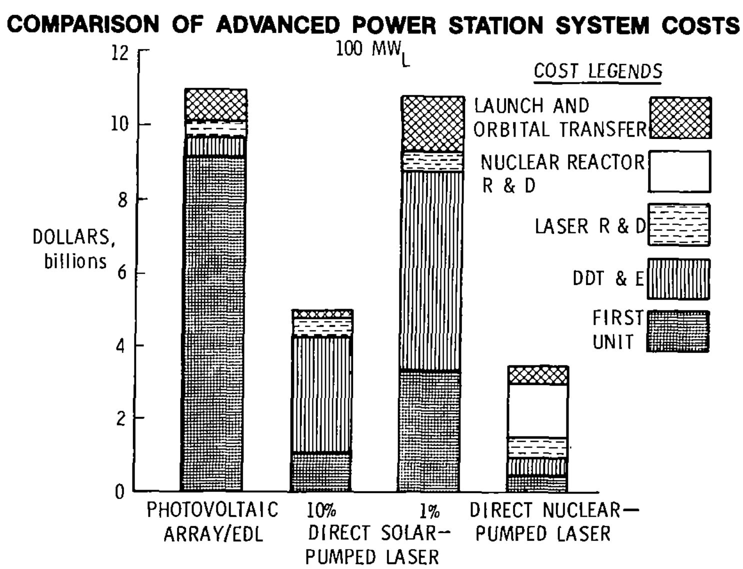

Figure 15

Photovoltaic Power Station

Mass estimate.- The mass of the GaAs array is calculated assuming 1.5 kg/kW_e at the array busbar based on reference 26. The mass of the spacecraft systems (array supporting structure, stability, and control) is assumed to be in the range of 10 to 12 percent of that for the array. Previous work has estimated the specific mass of the electric discharge laser to range from 0.5 kg/kW_L (ref. 19) to 1.4 kg/kW_L (ref. 10). For this analysis, a 30-percent efficiency and a specific mass of 0.6 kg/kW_L is assumed. The heat-pipe thermal radiator systems for laser waste heat rejection at 700 to 800 K are estimated to have a mass of 0.23 kg/kW_T of heat radiated. (See, for example, ref. 22.) The 30-m-diameter laser transmitter systems are projected to weigh 3×10^4 kg each (ref. 21). Hence, the approximate masses for the resulting systems of the power staion are:

System	Mass, kg
GaAs Array (330 MW_e)	495,000
S/C Systems (structure, controls)	60,000
EDL (100-MW laser)	60,000
Thermal Radiator (for 230 MW_T)	55,000
One Laser Transmitter (30-m diam.)	30,000
Total Spacecraft Mass, kg	∿700,000

Cost estimate.- Projected cost estimates for photovoltaic arrays and electric discharge lasers vary by several orders of magnitude. Conway (ref. 6) projects costs of 1 to 3 × 10^5 \$/kW_e output at the array busbar for advanced GaAs systems. Conversely, a Solar Power Satellite (SPS) analysis (ref. 26) projects costs in the range of 300 to 5000 \$/kW_e for mass-produced arrays. Coneybear (ref. 16) has observed that a similar disparity exists in the cost estimates for the high-power EDL. He projects decreasing costs per kW_L output with increasing power levels. At 100 kW_L, his estimates range from 300 to 800 \$/kW_L output. Similarly, Jones (ref. 13) estimates \$48,000 per kW_L output for a single 910-kW_L laser and \$300 per kW_L for multiple buys of a 910-MW_L output laser system.

A cost of \$25,000 per KW_e is assumed herein for the 20-percent-efficient GaAs array. EDL systems are estimated at \$$10^4$ per kW_L output. Power station launch and orbital-transfer (from LEO to GEO) costs are estimated at \$1,000/kg and \$50/kg, respectively. The orbital transfer costs are derived from tables A1 and A2 and assume the use of reusable ion thruster systems. Power for the thrusters is assumed to be produced by the first unit power station itself. Seven ion thruster systems, each producing orbital transfer for 10^5 kg at a cost of \$30M each, are utilized for the 700,000-kg power station transfer. Upon completion of the transfer, these thruster systems are returned to LEO for integration with cargo-carrying OTV's. Prorated costs for the one-way power station orbital-transfer trip are thus \$35M. Research and development (R&D) and design, development, test, and evaluation (DDT&E) are assumed to total \$1B (i.e., \$500 M each).

Hence, the approximate costs for the 100-MW_L photovoltaic array/EDL power station are:

Cost Element	Cost, \$M
First Unit	
Array (330 MW_e @ \$25,000/kW_e)	8,200
EDL (100 MW_L @ \$10,000/kW_e)	1,000
Transmitter (30 m diam.)	100 ea
Launch (700,000 kg @ \$1,000/kg)	700
Orbital Transfer (700,000 kg @ \$50/kg)	35
R&D	500
DDT&E	500
Total	~\$11,000 M

Direct Nuclear-Pumped Laser Power Station

Mass estimates.- Rodgers' (ref. 17) estimate of 140,000 kg has been assumed for the gas-core reactor laser system, The fuel reprocessing and waste-heat disposal system specific masses of 0.04 and 0.02 kg/kW nuclear power, respectively, were taken from Williams and Clements (ref. 27). The mass of the turbogenerator/compressor is based on 0.27 kg/kW_e generator power (ref. 21), and the radiator mass assumes 0.23 kg/kW_T of waste heat (ref. 22). Williams and Clements have also estimated that 2250 kg/m^2 of nuclear shielding (shadow shield) are required for a 23,000-MW nuclear power system. Scaling this to 100 MW nuclear power yields 100 kg/m^2 of shielding to enclose the 5-m-diameter 6-m-long nuclear reactor and the fuel reprocessing and waste disposal systems. The volume of the latter two systems is assumed to be three times that of the reactor itself. The resulting system masses of the utility are:

System	Mass, kg
Reactor/Laser (1000 MW, nuclear, 100-MW_L laser)	140,000
Fuel Reprocessing	40,000
Waste Disposal	20,000
Turbogenerator/Compressor (90 MW_e)	25,000
Thermal Radiator (810 MW_T)	185,000
Nuclear Shielding	60,000
One Laser Transmitter (30 m diam.)	30,000
Total Spacecraft Mass, kg	∿500,000

Cost estimate.- Terrestrial-based solid-fueled nuclear plants operating at 20 to 30 percent efficiency cost about $\$300/kW_e$ in 1973 (ref. 28) and less than $\$1000/kW_e$ in 1976 (ref. 26). A space-based, power-intensive gas-core reactor with its much smaller size and higher temperature capability operating at a 30-percent efficiency should not exceed the $\$1000/kW_e$ cost of the terrestrial system. Thus, for the space-based system operating at a 10-percent overall efficiency for nuclear-to-laser energy conversion, a cost of $\$3000/kW_L$ output power is assumed. The fuel reprocessor, waste heat disposal and turbogenerator systems are estimated to add another $\$1000/kW_L$ to the costs, resulting in a total of $\$4000/kW_L$ output power for the direct nuclear-pumped power station. The nuclear reactor or the Brayton cycle turbogenerators can provide adequate on-board power for the orbital-transfer ion thrusters.

Extensive R&D costs would be required to develop this system. The analysis assumes costs of $1500M and $500M for the gas-core reactor and laser R&D costs, respectively. DDT&E costs for a small-scale version of the 100-MW_L flight unit are estimated to be the same as the first space-based operational unit costs.

Hence, the approximate costs for the DNPL power station are:

Cost Element	Cost, $M
First Unit	
DNPL (100 MW_L @ $\$4000/kW_e$)	400
Transmitter (30 m diam.)	100 ea
Launch (500,000 kg @ $1,000/kg)	500
Orbital Transfer (500,000 kg @ $50/kg)	25
R&D	
Nuclear Reactor	1,500
Laser	500
DDT&E	400
Total	~$3,500 M

Direct Solar-Pumped Laser Power Station

Mass estimate.- System masses were computed with the Large Advanced Space Systems (LASS) computer-aided design and analysis program developed by Leondis (ref. 29). Calculations were made for both a 10-percent efficiency with a solar collector of 1000 m diameter and a 1-percent efficiency with a 3000-m-diameter collector. The solar collector is a parabolic reflector which consists of a 0.5-mil aluminized Kapton reflective surface and a high-emissivity chromium-back surface to passively radiate the unusable solar energy to space. The supporting collector structure is a graphite composite truss system designed as shown in figure 16. Graphite composite elements also support the 50 quartz laser tubes shown in figure 10. Each tube is 1 m in diameter, 50 m long and 0.3 cm thick. The resulting system masses are:

System	Mass, kg	
Solar Collector	η = 10%	η = 1%
Reflective Membrane	25,000	260,000
Supporting Structure	35,000	230,000
Laser (100 MW_L output)		
Laser Tubes	90,000	90,000
Supporting Structure	60,000	60,000
Thermal Radiator	25,000 (for 100 MW_T)	440,000 (for 1900 MW_T)
Attitude Control System	5,000	30,000
Laser Transmitter (30 m diam.)	30,000	30,000
Total Spacecraft Mass, kg	270,000	1,150,000

STRUCTURE CONCEPT FOR DIRECT SOLAR-PUMPED POWER STATION

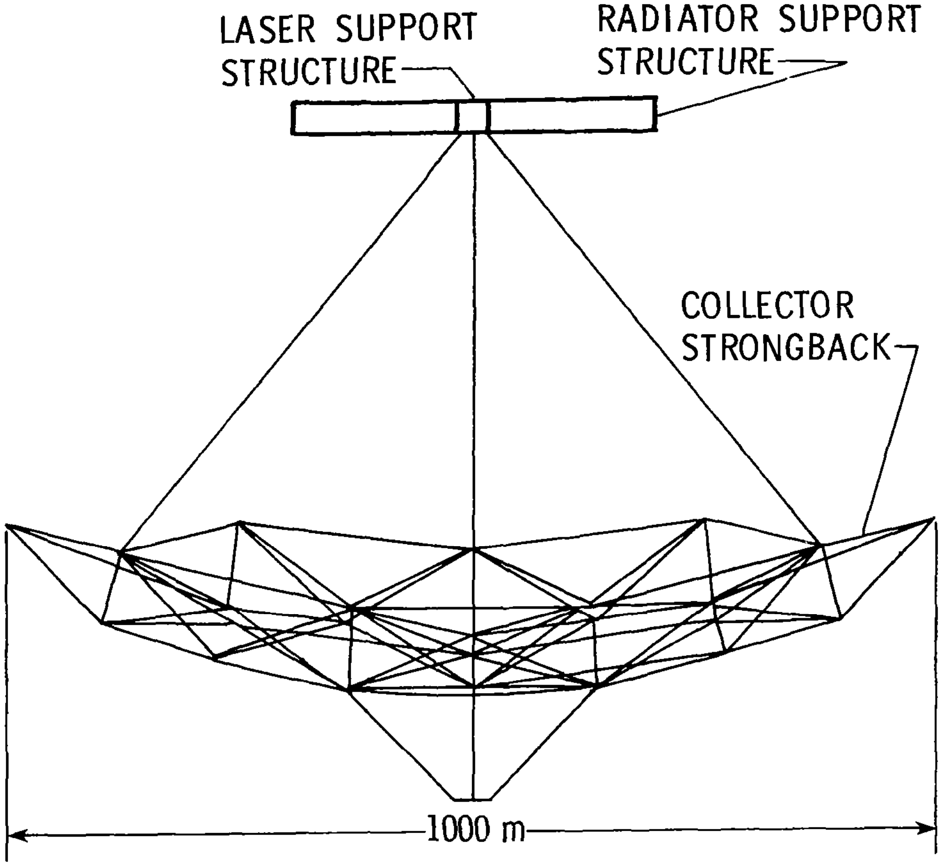

Figure 16

Cost estimate.- First unit and DDT&E costs for the major structural components and control systems costs were calculated with the LASS program (ref. 29) from the cost-estimating relationships developed specifically for large advanced spacecraft. The computed costs are 12,000 and 34,000 $\$/kW_L$ output power for the 10- and 1-percent solar-to-laser power systems, respectively. The solar-pumped-laser DDT&E costs were calculated at 2.5 and 1.6 times the first unit costs for the 10- and 1-percent systems, respectively. The bulk of the cost is associated not with the laser system but with the large spacecraft (structure and control system) DDT&E effort required to develop flight-qualified units of a size that is unprecendented in space or on Earth. Laser system R&D costs of $500M are assumed for both DSPL power stations.

The DSPL may not be capable of providing power to reusable thruster systems for orbital transfer of the first unit from LEO to GEO. Use of chemical OTV's would cost approximately $90M and $360M for the 10-percent and 1-percent efficient DSPL's, respectively, including propellant launch costs. Hence, the approximate costs for the DSPL power station are:

Cost Element	Cost, $M
10% Solar-to-Laser DSPL	
DSPL (100 MW_L @ $\$12,000/kW_L$)	1,200
Transmitter (30 m diam.)	100
Launch (270,000 kg @ $1,000/kg)	270
Orbital Transfer (chemical OTV)	90
R&D	500
DDT&E	3,000
Total cost for 10%-Efficient DSPL	∿$5,000 M

Cost Element	Cost, M
1% Solar-to-Laser DSPL	
DSPL (100 MW_L @ $\$34,000/kW_e$)	3,400
Transmitter (30 m diam.)	100 ea
Launch (1,150,000 kg @ $1,000/kg)	1,150
Orbital Transfer (chemical OTV)	360
R&D	500
DDT&E	5,400
Total cost for 1%-Efficient DSPL	∿$10,900 M

Comparative Analysis

Mass estimates for the candidate central power stations are shown in figure 14. On a comparative mass basis, the 10-percent-efficient, direct solar-pumped laser power station is most attractive. However, the authors estimate that the uncertainties in system and subsystem masses could result in an error band for the overall power station masses on the order of 0.5 to 2. With this level of uncertainty, if the DSPL efficiency is much less than 10 percent then all of the central power station concepts would be competitive on a mass basis.

On a relative mass basis, certain systems will consistently show mass advantages over other systems for the various power stations. For example, the DSPL reflector/concentrator will consistently have a lower mass per unit area than the photovoltaic array (0.03 vs 0.4 kg/m^2, respectively, assumed in this analysis). To a first-order approximation, supporting structural and control system masses per unit area for the solar concentrator or solar array should be about the same. Rigid body control system masses would be somewhat higher for the photovoltaic array. However, there are offsetting surface figure control actuator masses required by the DSPL concentrator for focusing the solar radiation on the laser tubes. Active surface controls should not be required for the photovoltaic array, since local excursions from solar normal (within ± 5 percent) would have negligible influence on performance.

Relative changes in the efficiencies of the DSPL power station system (even for the same overall efficiency) would significantly modify the systems masses. For example, in the case of the 1-percent DSPL, if only 10 percent of the solar spectrum is usable for lasing (rather than the assumed 20 percent) and the laser is 10 percent efficient (rather than the assumed 5 percent), the solar collector mass would be double that shown in figure 14, and the thermal radiator mass would decrease by a factor of two. The net effect on the total power station mass would be negligible in this instance.

A relatively heavy waste-heat rejection system is required for the DNPL power station because of the low operating temperatures. Future research efforts may produce lasant gases which lase at higher temperatures. If so, the overall nuclear-pumped laser cycle could be operated at higher temperatures than those shown in figure 8. This would improve the efficiency of the bottoming Brayton cycle, reduce the amount of waste heat to be rejected, and raise the heat rejection temperature. This combination of changes would lead to a reduced radiator mass requirement and result in a DNPL power station that is equally competitive on a mass basis with the 10-percent DSPL power station.

Summary cost comparisons for each of the major systems, including launch costs of $1,000/kg of power station mass, are shown in figure 15. Cost of the DNPL power station is projected to be about a factor of three less than the probable costs of the lower efficiency DSPL and the photovoltaic array/EDL power stations. The photovoltaic array power station costs are dominated by the cost of the photovoltaic array itself, whereas the DSPL and DNPL costs are associated principally with the smaller scale laboratory research and development and the spacecraft prototype DDT&E costs--not the first operational unit. Even with the low photovoltaic array cost estimates used in this analysis ($25,000 per kW$_e$), the direct-pumped laser power stations are clearly candidates for future space-to-space power systems. Failure to reduce the array costs to this level would give an even more overwhelming advantage to the direct-pumped laser systems over the current state-of-the-art photovoltaic array/EDL approach.

USER BENEFITS

Potential benefits of space-based central power stations are examined for two classes of future users: (1) Earth-orbiting satellites requiring electrical power, and (2) orbital-transfer vehicles requiring power for propulsion.

Earth-Orbiting Satellites

Cost-estimating relationships are developed in ref. 25 for both on-board and remotely powered satellites. It is shown in that paper that the beaming of continuous power to electrical users is never cost-effective when the same fundamental power generation system that is used on the central power station is readily available as an on-board system. Thus, the photovoltaic array central power station can never compete with on-board photovoltaic arrays. This is due simply to the additional inefficiencies introduced in the energy conversion, transmission, and reconversion systems which are not required for on-board, self-powered systems. At projected system efficiencies, the cost and size of the photovoltaic array on the central power station would be at least seven times greater than the corresponding total cost and size of arrays for self-powered satellites.

On-board and remote electrical power cost ranges for user satellites are shown in figures 17 and 18 for the DNPL and the DSPL power stations, respectively. The estimated cost per KW_e to the user is plotted versus the average power required by each user. The figures indicate that remotely powered satellites would be marginally competitive at best, with \$100,000 to \$300,000 per KW_e solar arrays and then only in the 10 to 100 megawatt average power level ranges. Mass-produced solar array costs could possibly decline to the solar power satellite analysis estimates (ref. 26) of \$300 to \$5000 per KW_e.

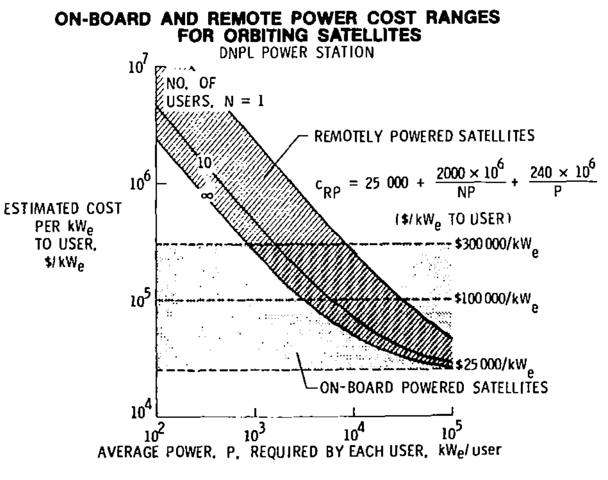

Figure 17

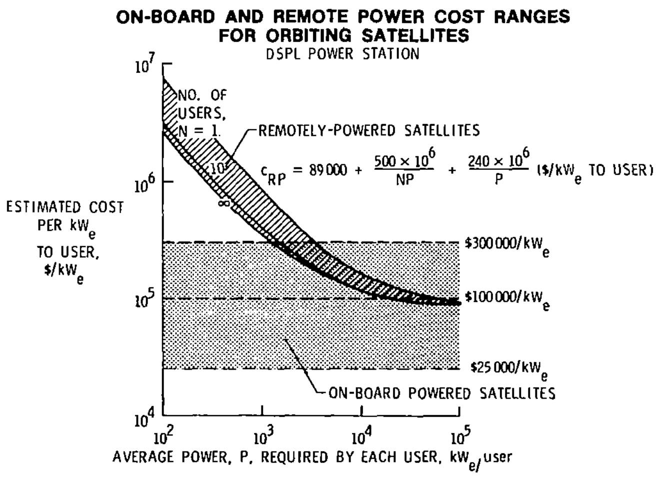

Figure 18

At these optimistically low costs remotely powered satellites would not be cost-competitive at any power level with on-board self-powered satellites.

Although no orbiting satellite users identified in the NASA mission model (ref. 10) require power above the hundreds of kilowatts levels, it may be speculated that in the distant future space industrialization activities will expand to large-scale manufacturing plants requiring megawatts of power. Thus, on the surface (should solar-array costs remain sufficiently high to provide a cost advantage to remotely powered systems in the 10 to 100 MW_e ranges) the question of development of a space-based power station to remotely power a number of 10+ MW_e satellites appears to be one of timing (perhaps by the middle of the next century). However, a more logical question would be to ask if there is a less costly alternative to the photovoltaic array on-board power system for very large power needs. For example, a power-intensive nuclear system at $1,000 to $10,000 per installed KW_e could be installed on-board at significantly lower cost to the user than that for purchase of power from a central power station.

Thus, it is concluded that the implementation of a central space-based power station for the sole purpose of remotely powering Earth-orbiting satellites cannot be justified economically. However, if other applications lead to the development of such a system, orbiting satellites could use available excess power in a cost-effective manner. The orbital-transfer application discussed in the following section may provide this economic justification.

Remotely Powered Propulsion Systems

The results presented here are an expansion of an earlier study reported by Garrett and Hook (ref. 30). The comparison of on-board propulsion with remotely powered propulsion is based on the delivery of cargo from LEO to GEO and return. All OTV's are assumed to be space based. An advanced chemical system is compared with a remotely powered laser thermal propulsion system (LTPS), and a solar electric propulsion system (SEPS) is compared with a remotely powered laser electric propulsion system (LEPS). The OTV performance characteristics have already been discussed and are summarized in table A1. Overall cost estimate data used in this analysis of competing transportation vehicles are given in table A2.

Rather than use a specific mission need projection for a specific time period, the scenario considered (fig. 19) assumes delivery of 10^6 kg mass from LEO to GEO in the first year of operation of the central power station. The mass delivery demand increases at a rate of 10 percent annually thereafter. Thus, in 20 years the payload to GEO demand has increased by a factor of six. The chemical, SEP, and LEP systems deliver the payload in increments of 10^5 kg per trip. Thermal constraints (caused by focusing multimegawatts of power on small area windows and cavities) are assumed to limit the LTPS to 2×10^4 kg of cargo per trip which is consistent with the delivery of 70 MW of thruster power. Initially, one advanced, single-stage, chemical OTV or three laser-powered LTPS OTV's are required. Alternatively, five SEPS or LEPS would be required because of the long trip times (approximately 180 days per round trip) associated with these systems. The number of operational vehicles required is shown for each propulsive system based on the 50-trip lifetime assumed for chemical and LTPS OTV's and the three-trip lifetime assumed for SEPS and LEPS. Also noted in parentheses is the cumulative number of vehicles retired from service.

The total power requirements for the SEPS/LEPS and for the LTPS OTV are noted on the ordinate of figure 19. Each LEPS OTV requires continuous power, whereas since the LTPS requires power only during brief perigee and orbital circularization phases, power from the central power station can be cycled between the multiple LTPS OTV's, and only one transmitter is required.

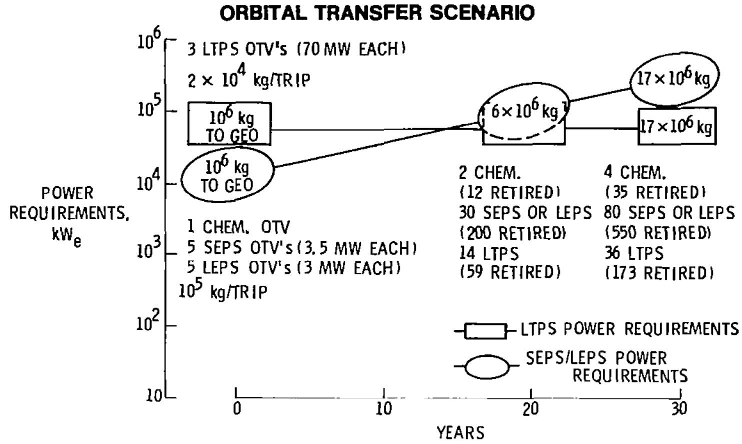

Figure 19

Cumulative cost components for the total OTV system and all launch costs required including those for the cargo are shown in figures 20 and 21 for the competitive OTV systems. The costs for chemical systems, because of the massive propellant requirements, are dominated by the launch costs. Costs for the SEPS are almost equally divided between the launch and photovoltaic array costs.

CUMULATIVE COST COMPARISONS OF CHEMICAL AND REMOTELY POWERED LTPS OTV's

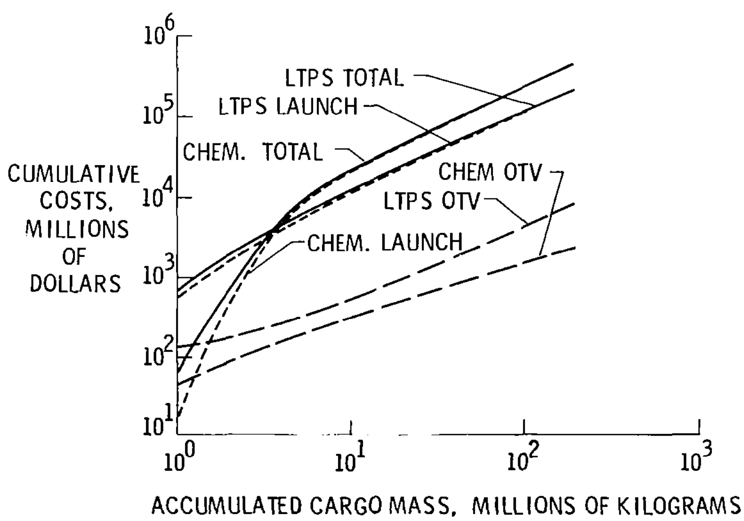

Figure 20

CUMULATIVE COST COMPARISONS FOR SEPS AND REMOTELY-POWERED LEPS OTV's

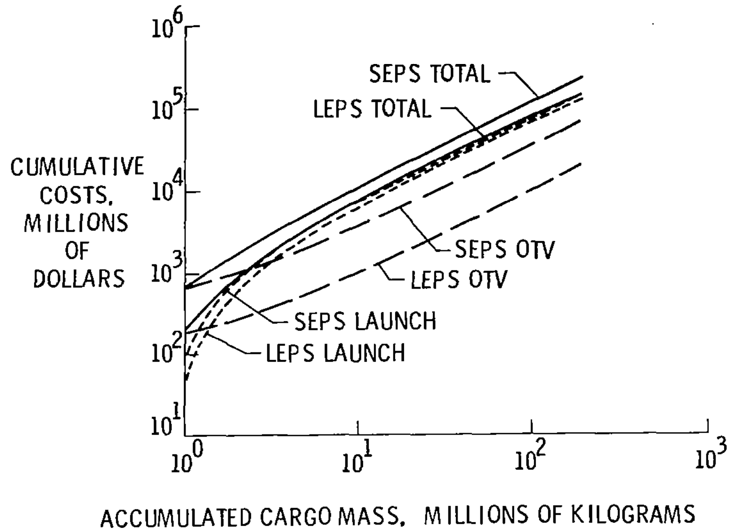

Figure 21

Estimated cumulative cost advantages of remotely powered LTPS over the chemical OTV and remotely powered LEPS over SEPS are shown in figure 22. The remotely powered systems costs include amortization of a space-based DSPL central power station (∿200 MW_L output) which has been sized to meet the cumulative power requirements of the OTV's on the 20th year. Cumulative costs savings in a 30-year period for remotely powered over conventional OTV's are projected to be $270B for LTPS over chemical and $60B for LEPS over SEPS. The use of the alternative DNPL power station would show similar cost advantages for the remotely powered systems. The photovoltaic array central power station when used for LEPS remote power would be only marginally competitive with SEPS because of the inefficiencies of the laser power energy conversion, transmission, and reconversion processes. However, a photovoltaic array central power station providing remote power to a LTPS would show a cost savings on the order of $200B, even if GaAs costs reach the upper estimate of $300,000 per kW_e. The conclusion that the remotely powered orbital-transfer systems (LTPS/LEPS) are more cost-effective than conventional systems (chemical/SEPS) would not change unless the central power station costs increase by at least an order of magnitude higher than assumed in this analysis or unless launch costs decrease by more than an order of magnitude. Studies of heavy-lift launch vehicles which might be developed for launching solar-power satellites (see, for example, ref. 31) have projected launch costs in the $50/kg range, as compared with the $1000/kg assumed in this analysis. If future payloads could be launched at $50/kg, then the remotely powered LTPS (including amortization of the central power station) and the chemical OTV's would result in about the same costs. The LEPS-over-SEPS costs advantage over a 30-year period would remain at about $50 to $60 billion because of the difference in solar array costs of the two systems if launch costs were reduced to $50/kg.

Consequently, even if the more optimistic cost projections for on-board solar arrays and launch come to fruition, central power station concepts for remotely powering orbital-transfer vehicles show sufficient relative economic advantages over advanced conventional OTV's to justify pursuit of laboratory experiments and technology developments along several fronts.

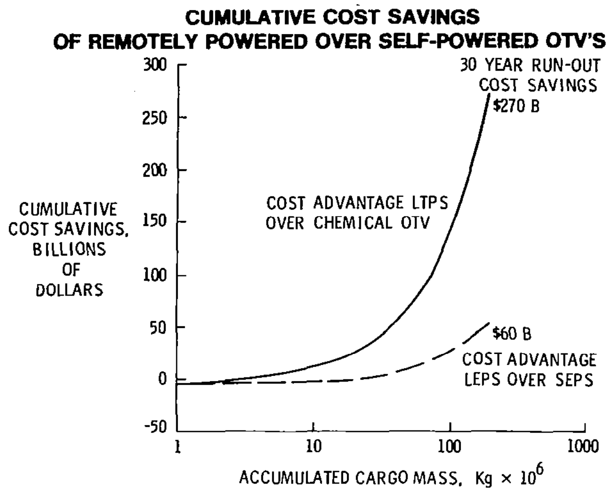

Figure 22

Other Applications

Given the apparent economic justification for a space-based central power station for remotely powered orbital transfer, the application of this capability to other users may be considered. Within the time frame of a central power station, for example, laser-powered aircraft may be feasible (ref. 32). Similarly, remotely powering spacecraft beyond Earth orbit could be easily accomplished from a central power station designed to support remotely powered propulsion OTV's.

Further downstream, a central power station could be a major step in enabling mining of the moon and asteroids to replace depleted Earth resources. This capability might even make feasible the recovery of asteroids.

The ultimate applications of a central power station in space are left to the imagination of the reader and of future generations. Nonetheless, it is fair to say that if a system such as the central power station can be justified for a single use, such as remotely powered propulsion, the spinoff applications will be numerous and diverse.

FUTURE WORK

As stated in the introduction, the authors hope this paper will stimulate further analysis that will serve to provide near-term direction to development of the technology required in the long term to fully reap the benefits available from exploitation of space. Although the three space-based central power stations considered in this paper are among the leading contenders for future space power generation, they are by no means an exhaustive set. An indirectly pumped solar laser, for example, would have basically the same characteristics of the DSPL system except that the laser cell would be surrounded by a blackbody cavity which would be heated by solar radiation. This concept allows the peak of the solar spectrum to be shifted to match the peak absorption wavelength of the lasing gas. Overall solar-to-laser energy converison may be improved over DSPL systems. However, the development of high-temperature long-life materials for the laser windows will be required.

Another promising approach would use a high-efficiency gas-core reactor operating at high temperatures to create electricity via turbogenerators and possibly magneto-hydrodynamic (MHD) systems to drive relatively high-efficiency CO EDL's. This might result in improved efficiencies over direct nuclear-pumped projections and reduce the thermal radiator sizes at least an order of magnitude because of less waste heat and higher rejection temperatures. However, this system requires the development of ultra-high-temperature materials and, in some cases, materials resistant to corrosive chemical processes prior to commitment to space operations. Williams and Clement (ref. 26) provide performance, mass, and costs estimates for the gas-core reactor/MHD system.

The general area of converters for laser light deserves special attention. While the conversion systems treated in the present paper have efficiencies in the range of 50 percent, the theoretical possibility of significantly higher conversion efficiencies should be recognized. Because of its nearly monochromatic, coherent nature, laser light is essentially a zero-entropy medium. Hence, most of the energy in laser light is potentially available for conversion rather than being in a disordered, unavailable form. Creative new approaches to converter design, capitalizing on this potential, would significantly enhance the central power station benefits discussed in this paper.

The analysis presented herein, while only a first-cut approximation at best, identifies potential cost savings and increased mission flexibility of sufficient magnitude to readily justify more refined and detailed studies. The space-based central power plant may well be a suitable focus for the next quantum step toward a true "space age."

TECHNOLOGY NEED IMPLICATIONS

A cost savings potential has been established for advanced, space-based central power stations for remotely powered propulsion applications. With this economic justification, a central power station may also be cost-effective in providing electrical power needs for Earth-orbiting satellites or in enabling a variety of other space missions which are beyond the realm of possibility today.

The technology feasibility is quite another situation. The body of the paper identifies many of the technologies that must be developed in order to make a central power station a reality. The most pressing need is for experimental and theoretical research to address on a small scale those fundamental technologies that are critical to future central power stations. The primary critical technology needs for the central power stations relate to the efficiency of the power conversion. Mass and cost sensitivities are appropriate figures of merit to consider in the assessment of technology needs at the systems level. A dramatic variation in total mass and cost is shown in figures 14 and 15 in the comparison of the 10-percent- and 1-percent-efficient DSPL power stations. The cost and mass increases of the 1-percent-efficient system (relative to the 10-percent efficiency) are driven primarily by the necessary increase in solar collector and thermal radiator sizes, not by changes in the laser system. Similar relationships exist for the other central power station concepts.

A listing of first-order research and technology needs which are critical to enabling the laser systems and their attendant large spacecraft is presented in table 1. For any of the laser systems possible, long-life, closed-cycle operation and low maintenance are mandatory.

TABLE 1.- KEY RESEARCH AND TECHNOLOGY NEEDS

SOLAR-PUMPED LASER

- More efficient lasing system (> 1%)
- Long-life, closed-cycle operation
- High-temperature lasing media
- Chemically stable lasing gas
- High-power optics

NUCLEAR-PUMPED LASER

- High-power gaseous core laser reactor (>1 MW)
- Long-life, closed-cycle operation
- Fission fragment/lasing gas interactions physics
- Higher temperature lasing gases (>700 K)
- High-power optics

SPACECRAFT AND OTV

- Large highly accurate adaptive optical collectors and transmitters
- Laser to electrical power converters
- Large high-temperature thermal radiators
- High-accuracy distributed control systems
- High-temperature materials
- Long-life high-reflective materials
- On-orbit assembly

Availability of power-intensive systems will be a controlling factor governing the rate of space utilization and industrialization over the next century. Unfortunately, the funding support for research and technology development work in this field is small even though the funding needed for advanced power systems is very modest relative to the potential benefits. For example, the nuclear power program for space applications has suffered fitful starts and terminations over the last two decades and is almost nonexistent today. Solar-pumped lasers are in the early laboratory stage and even after the technology is developed will require at least a decade to achieve spaceflight readiness.

A forecast for generic space power systems development is shown in figure 23. This scenario projects incremental increases in installed photovoltaic array power up to 1 MW for orbiting satellite needs. Above 1 MW_e the photovoltaic array sizes become so large that spacecraft control considerations will dictate the development of more compact power-intensive systems such as nuclear reactors. These power-intensive systems could be available after the turn of the century to support applications requiring on-board power above the 1-MW_e level. With time, incremental improvements in power-intensive systems and direct-pumped laser system should increase the output capabilities and the minimum power threshold could be lowered to make these systems economically competitive with advanced photovoltaic arrays. Perhaps by the end of the year 2020, space transportation traffic volume (propulsion) coupled with other power demands could lead to the implementation of a central power station with an output level of 10 to 100 MW.

Even in that distant time, 40 years in the future, the scope of feasible space activity will be heavily reliant on the success achieved in our research laboratories during the next two decades. Further analysis is critical to solidifying the need and providing direction for advanced energy generation research.

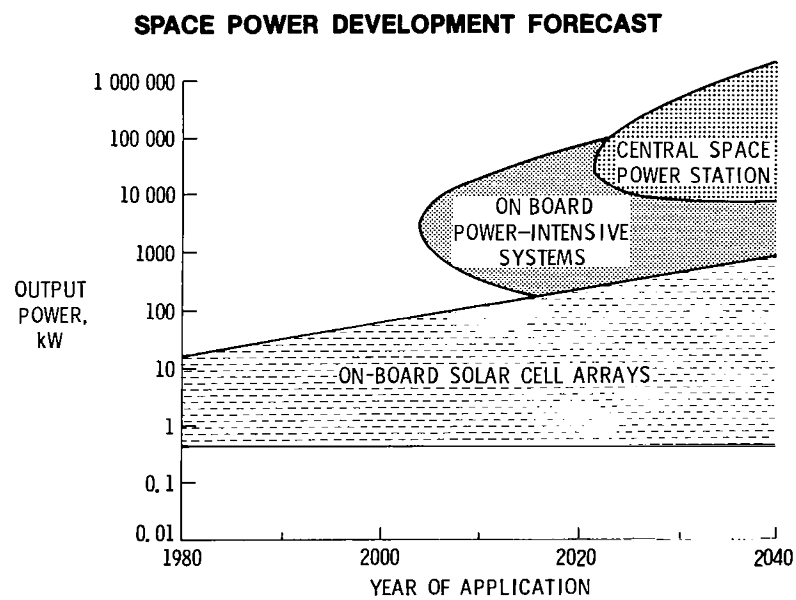

Figure 23

CONCLUSIONS

The need for a central power station in the future will depend on many factors. Beaming power to remote users cannot be cost-effective if the central power station uses the same power generation system that would be readily available for provision of on-board power. Similarly, microwave transmission and reception of power through space for use in space cannot be cost-competitive with on-board power or propulsion systems; the size of the receiver is simply prohibitive. Laser transmitters/receivers will be required to make central power stations feasible.

Analysis of the cost-effectiveness of meeting Earth-orbiting spacecraft electrical demands from a central power station indicates that this application cannot justify the investment required for a central power station. Conversely, remote-power transmission for propulsion of orbital-transfer vehicles promises major cost benefits (within the bounds of the assumptions made herein) of a sufficient magnitude to fully justify the research and development activities necessary to enable the central power station. Either of the direct-pumped laser power station concepts is particularly attractive with the laser thermal propulsion system and/or the laser electric propulsion system. These systems are also competitive on a mass and cost basis with a photovoltaic power station.

The most critical assumption that leads to the above conclusions is that the launch costs from Earth to LEO will remain in the range of 1,000 $/kg currently quoted for the Space Transportation System. However, if Earth-to-orbit launch costs were to be reduced significantly (at least an order of magnitude), the remotely powered laser thermal propulsion system would be comparable in cost to the chemical OTV. In this event, a single use (propulsion of OTV's) would not be sufficient to justify a central power station; however, multipurpose uses might still provide a convincing justification. Enabling technology and engineering development needs for implementation of the future space-to-space power systems are summarized in figure 24.

ACKNOWLEDGMENT

The authors gratefully acknowledge the many contributions to this paper made by John J. Rehder, who conducted the orbital-transfer analyses, and Dr. Nelson W. Jalufka, who provided the majority of inputs on the direct-pumped laser systems.

CONCLUDING REMARKS: TECHNOLOGY AND ENGINEERING DEVELOPMENT NEEDS

SYSTEMS ANALYSIS

- ACCELERATING SYSTEMS: ONLY CASE FOR SPACE-TO-SPACE POWER
- COULD BE USED TO AUGMENT ELECTRICAL-USING ORBITING SATELLITES POWER NEEDS
- NEED INTEGRATED TRANSPORTATION SYSTEM STUDY FOR FUTURE SYSTEMS
- COSTS/PERFORMANCE ESTIMATE UNCERTAINTIES
- DESIGN AND ANALYSIS CAPABILITIES REQUIRED FOR UNTESTABLE (ON THE EARTH) LARGE STRUCTURES.

POWER

- ELECTRIC DISCHARGE LASER: CLOSED CYCLE - LONG LIFE - HIGH POWER - CONTINUOUS OPERATION
- NUCLEAR POWER: GAS-CORE REACTOR/DIRECT-PUMPED LASER EMBRYONIC
- SOLAR-PUMPED LASER EMBRYONIC
- SOLAR ARRAYS: HIGH EFFICIENCY - LOWER COST - RADIATION RESISTANCE - CONTROLLABLE ON ORBIT
- HIGH POWER OUTPUT REQUIRED FOR ALL UTILITY CONCEPTS (100 MW^+)
- EFFICIENT LASER FREQUENCY CONVERTERS
- EFFICIENT LASER-TO-ELECTRICAL POWER CONVERTERS

STRUCTURES

- LARGE STRUCTURES - SOME WITH LARGE MASS CONCENTRATION
- FIGURE CONTROL MIRROR ARRAYS
- THERMAL RADIATOR DESIGNS

MATERIALS

- RADIATION RESISTANT STRUCTURAL MATERIALS
- HIGH TEMPERATURE MATERIALS FOR LASERS AND LASER RECEIVING SYSTEMS

CONTROLS

- POINTING AND FIGURE CONTROL: LASER TRANSMITTER/RECEIVER
- POWER AND ENERGY REGULATION/MANAGEMENT
- RIGID/FLEXIBLE BODY CONTROL SYSTEMS

ASSEMBLY/OPERATIONS

- ON-ORBIT ASSEMBLY REQUIRED FOR MANY SYSTEMS/SOME ARE DEPLOYABLE
- ON-ORBIT MAINTENANCE/RESUPPLY
- AUTOMATED OPERATION OF UTILITY/OTV's
- POTENTIALLY OPERATIONALLY COMPLEX FOR MANY USERS/LARGE SYSTEMS

Figure 24

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APPENDIX

COST DATA FOR CONVENTIONAL AND REMOTELY PWERED ORBITAL-TRANSFER VEHICLES

Four orbital-transfer vehicles (OTV's) are considered in the comparison of conventional and remotely powered transportation of cargo from low Earth to geosynchronous Earth orbits. An advanced chemical system is compared with a remotely powered laser thermal propulsion system (LTPS) and a solar electric propulsion system (SEPS) is compared with a remotely powered laser electric propulsion system (LEPS). Data on the assumed characteristics and performance of the competing transportation vehicles are given in table A1. Overall cost data estimates are given in table A2. OTV performance and cost data were obtained from references 7 to 9 and 24 and from in-house vehicle analysis programs and data bases.

CHARACTERISTICS	OTV SYSTEM			
	CHEM	SEPS	LEPS	LTPS
Propellant	LOX/LH_2	Argon	Argon	LH_2
Specific Impulse, sec	476	6,000	6,000	1,500
Round Trip Time, days	7	173	158	14
Lifetime, number of round trips	50	3	3	50
Cargo Delivered/Trip, kg	10^5	10^5	10^5	2×10^4
Power Requirements, KW_e	--	3,300	3,000	70,000
Collector/Receiver System	N/A	GaAs Array	GaAs Array	Laser Concentrator
- Efficiency	--	20%	50%	60%
- Size, m^2	N/A	12,500	314 (20-meter diameter)	314
Mass Fractions, percent				
- Dry	5	18	9	7
- Propellant	70	12	11	29
- Cargo	25	70	80	64
Round Trip Fuel Requirements, kg	275,000	18,000	14,300	9,900 (for 2×10^4 kg cargo/trip)

Table A1. Transportation Vehicle Performance Characteristics

TRANSPORTATION VEHICLE	COSTS	
	UNIT/SUBSYSTEM	SYSTEM
Shuttle Transportation System Launch	\$1,000/kg	
Chemical OTV (LOX/LH_2)		\$ 40 x 10^6 each
SEPS OTV (3.5 MWe)		\$ 146 x 10^6 each
- Solar Array and OTV Subsystems	\$116 x 10^6 per OTV	
- Ion Thrusters	\$ 30 x 10^6 per OTV	
LEPS OTV (3.0 MWe)		\$ 33 x 10^6 each
- Laser Receiver and OTV Subsystems	\$3.3 x 10^6 per OTV	
- Ion Thrusters	\$30 x 10^6 per OTV	
LTPS OTV (70 MWe)		\$ 40 x 10^6 each
Propellant:		
- Argon	\$0.40 per kg	
- LOX/LH_2	\$0.47 per kg	
- LH_2	\$2.20 per kg	

Table A2. Transportation Vehicle Cost Estimates

LASER ROCKET SYSTEM ANALYSIS

LOCKHEED MISSILES AND SPACE COMPANY INC.
SEPTEMBER 1978

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Richard B. Lancashire
October 1981

LASER ROCKET SYSTEMS ANALYSIS

OBJECTIVE - TO IDENTIFY MISSIONS, DESIGN REQUIREMENTS, AND CRITICAL TECHNOLOGY AREAS; AND TO COMPARE TO CONVENTIONAL SYSTEMS.

VARIABLES -

LASER POWER	5-1000 MW
WAVE LENGTH	0.55-10.6 μM
NUMBER OF LASERS	1 OR MULTIPLE (PHASE LOCKED)
NUMBER OF TRANSMITTING STATIONS	1 OR MULTIPLE
TRANSMITTER DEPLOYMENT	GROUND, AIR, SPACE (LEO, MEO, GEO)
TRANSMITTER/RECEIVER OPTICS	3-30 METERS
THRUST	100-30,000 POUNDS
I_{sp}	1000-2000 SECONDS

LASER PROPULSION

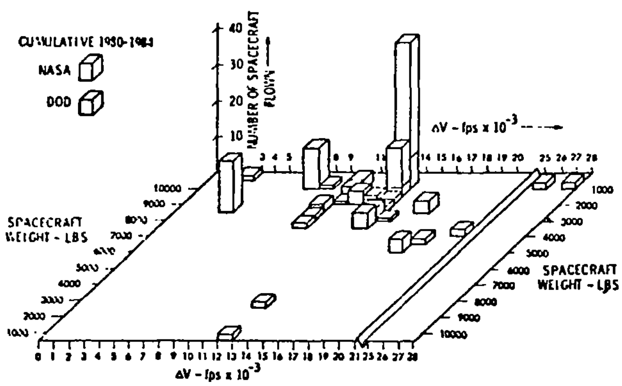
CONCEPT:
- TRANSMISSION OF POWER FROM REMOTE LASER STATION TO ROCKET VEHICLE; USE OF LASER RADIATION TO HEAT PROPELLANT

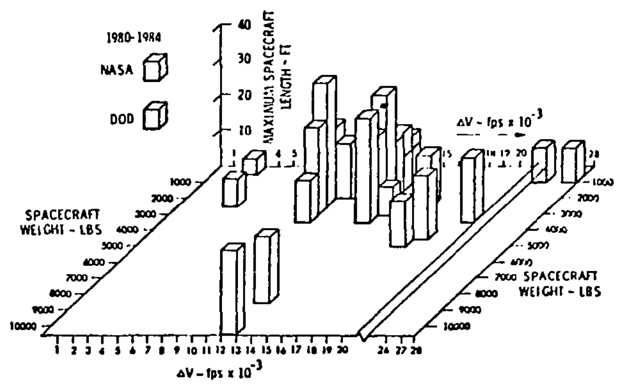
APPLICATIONS:
- ORBITAL TRANSFER
- INTERPLANETARY INJECTION
- ORBIT DRAG MAKE-UP
- VEHICLE LAUNCH

TRANSMITTER:
- GROUND
- AIRCRAFT
- SPACE STATION

ADVANTAGES:
- INDEPENDENT CONTROL OF THRUST, I_{SP}, AND PROPELLANT
- ENERGY REMOTE TO VEHICLE
- HIGHER I_{SP} THAN CHEMICAL SYSTEMS

REPRESENTATIVE INTERIM UPPER STAGE (IUS) MISSION MODEL





MISSION MODEL – 1995–2005

	ΔVELOCITY (m/s)	(ft/s)	PAYLOAD WEIGHT (kg/lb)	NOMINAL NUMBER PER YEAR	STEADY ACTIVITY PER 10 YR	ACTIVITY LEVEL MULTIPLIERS CASE 3	CASE 6	CASE 8	CASE 11
GEOCENTRIC MISSIONS									
CURRENT PROJECTED									
HI. ELLIP., HI. INC.	2,743	9,000	1,361/3,000	5	50	2	0	1	3
GEOSYNCHRONOUS	4,298	14,100	2,268/5,000 RT	15	150	1	0	1	0.5
ADVANCED			11,340/25,000 R						
GEOSYNCHRONOUS SPACE STATION	4,298	14,100	24,949/55,000 D	10	100	0	5	0	0
GEOSYNCHRONOUS SPS	4,298	14,100	148,000/326,000	400	4,000	0	1	1	2
EXTREME LAT. COVERAGE	6,095	20,000/YR	2,268/5,000	10	100	1	0	0	1
ORBIT MAINT. OF LG. STRUCTURES (LEO)	91	300	45,000/99,000 TO 340,000/750,000	10	100	1	0	2	1
INTERPLANETARY MISSIONS									
CURRENT PROJECTED									
MERCURY ORBITER	5,182	17,000	4,173/9,200	–	4	1	0	1	2
PIONEER SATURN/URANUS/TITAN PROBE	12,192	40,000	499/1,100	–	2	1	0	0	2
ADVANCED									
NEPTUNE JUPITER FLYBY	12,192	40,000	3,175/7,000	–	2	1	0	2	0
URANUS ORBITER – 3.5-YR TRIP TIME	20,117	60,000	907/2,000	–	2	1	0	1	1
NUCLEAR WASTE DISPOSAL	9,144	30,000	4,536/10,000 TO 13,609/30,000	30	300	0	0.05	0.25	0

NOTE: RT – ROUND TRIP PAYLOAD WEIGHT
D – DELIVERED PAYLOAD WEIGHT
R – RETURNED PAYLOAD WEIGHT

SYSTEM SPECIFICATIONS

LASER TRANSMITTER UNIT	SMALL (2,268 KG) PAYLOAD	LARGE (148,000 KG) PAYLOAD
LASER DEVICE TYPE	CLOSED CYCLE EXCIMER	CLOSED CYCLE EXCIMER
LASER POWER (MW)	16	490
TRANSMITTING APERTURE DIAMETER (M/FT)	30/98.4	30/98.4
OBSCURATION (ID/OD)	0.2	0.2
NUMBER OF GIMBALS	2	2
ELECTRICAL POWER SUPPLY (MW)	131	4,00
ORBIT	CIRCULAR	CIRCULAR
ALTITUDE (KM/NMI)	500/270	500/270
INCLINATION (DEG)	28.5	28.5
UNIT WEIGHT KG/LBM	$685\text{X}10^3/1511\text{X}10^3$	$12\text{X}10^6/26\text{X}10^6$

SYSTEM SPECIFICATIONS

PROPULSION UNIT	SMALL PAYLOAD	LARGE PAYLOAD
PAYLOAD (KG/LBM)	2,268/5,000	148,000/326,000
REQUIRED INPUT POWER (MW)	13.4	418
RECEIVING APERTURE DIAMETER (M/FT)	4.25/13.94	4.5/14.76
OBSCURATION (ID/OD)	0	0
NUMBER OF GIMBALS	1	1
VELOCITY INCREMENT (M/S/FT/S)	10,500/34,450	10,000/32,810
THRUST (N/LBF)	1,000/225	31,100/7,000
UNIT WEIGHT (KG/LBM)	5291/11,665	$115\text{X}10^3/253\text{X}10^3$

SYSTEM SPECIFICATIONS

ENERGY RELAY UNIT	SMALL PAYLOAD	LARGE PAYLOAD
RECEIVER APERTURE DIAMETER (M/FT)	8/26.25	8/26.25
OBSCURATION (ID/OD)	0	0
NUMBER OF GIMBALS	2	2
TRANSMITTER APERTURE DIAMETER (M/FT)	3/9.84	3/9.84
OBSCURATION (ID/OD)	0.2	0.2
NUMBER OF GIMBALS	2	2
INTEGRAL PROPULSION	YES	YES
V CAPABILITY (M/S/FT/S)	5,250/17,225	5,250/17,225
UNIT WEIGHT (KG/LBM)	8,465/18,662	$68X10^3/151X10^3$

LCC COST COMPARISON CASE 3 (SPACE)

Mission Composition:	450	5,000 lb P/Ls
	10	5,000 lb Expendable P/Ls
Number of OTV's =	Laser	Cryo
	16	22

LCC Costs (In Millions of Dollars)

Cryogenic System	Category	Space-Based Laser Rocket System
473.00	DDT&E	1,377.80
694.43	Investment and Spares	442.99
0.0	Laser System Deployment	482.00
759.16	OTV Deployment and OPS	295.77
254.21	Refurbs.	302.54
12,611.36	Fuel Resupply	1,627.02
14,792.16	Total Consant Year LCC Costs (FY '77 $M)	4,528.12
5,821.70	Total LCC Costs Discounted to (1984)	2,456.40
	Discounted Cost Ratio (Chem/Laser)	2.37
	Discounted Cost Ratio w/o DDT&E	4.08

LCC COST COMPARISON CASE 6 (SPACE)

Mission Composition:	4,500	326,000 lb P/Ls
	14	326,000 lb Expendable P/Ls
Number of OTV's =	Laser	Cryo
	87	160

LCC Costs (In Millions of Dollars)

Cryogenic System	Category	Space-Based Laser Rocket System
992.0	DDT&E	4,204.90
7,787.86	Investment and Spares	3,736.53
0.0	Laser System Deployment	981.50
6,544.79	OTV Deployment and OPS	1,304.22
3,491.46	Refurbs.	2,015.38
203,685.22	Fuel Resupply	18,678.93
222,501.33	Total Constant Year LCC (FY '77 $M)	30,921.46
70,568.306	Total LCC Discounted to (1987)	11,954.83
	Discounted Cost Ratio	5.90
	Discounted Cost Ratio w/o DDT&E	8.02

SETV COMPARISON GROUND RULES

	SSETV	LSETV
• ROUND-TRIP TIME (DAYS)	220	161
• MAXIMUM NUMBER OF MISSIONS/VEHICLE IN TEN (10) YEARS OF OPERATIONS	16	22
• ION THRUSTER MODULE REPLACEMENT FREQUENCY (NUMBER OF MISSIONS)	4	5
• VEHICLE REFURBISHMENT FREQUENCY (NUMBER OF MISSIONS)	8	10
• AVERAGE NUMBER OF MISSIONS PERFORMED PER VEHICLE PRIOR TO EXPENDABLE MISSION	2	2
• VEHICLE DEPLOYMENT FLIGHTS	2 SHUTTLES	1.2 HLLVs
• ON-ORBIT ASSEMBLY REQUIRED	YES	YES
• LAUNCH VEHICLE COST/FLIGHT	\$13.5 M	\$6.5 M
• FUEL RESUPPLY AND REFURBISHMENT FLIGHTS ON FLIGHT SHARING BASIS	YES	YES

LCC COST COMPARISON 3 – SETV VERSUS LASER SYSTEM

MISSION COMPOSITION: 450 5,000 LB P/L's
10 5,000 LB EXPENDABLE P/L's

NUMBER OF OTV'S =

LASER		SETV
16	SMALL	37

LCC COSTS (IN MILLIONS OF 1977 DOLLARS)

S.SETV	CATEGORY	SPACE-BASED LASER ROCKET SYSTEM
375.87	DDT&E	1377.80
1104.81	INVESTMENT & SPARES	442.99
0.0	LASER SYSTEM DEPLOYMENT	482.00
1350.15	OTV DEPLOYMENT & OPS.	295.77
423.79	REFURBS	302.54
718.03	FUEL RESUPPLY	1627.02
3972.65	TOTAL REAL YEAR LCC	4528.12
2048.49	TOTAL PRESENT VALUE COST (1984)	2456.40

LCC COST COMPARISON 6 – SETV VERSUS LASER SYSTEM

MISSION COMPOSITION: 4,500 326,000 LB P/L's
14 326,000 LB EXPENDABLE P/L's

NUMBER OF OTV'S =

LASER		SETV
87	LARGE	217

LCC COSTS (IN MILLIONS OF 1977 DOLLARS)

L. SETV	CATEGORY	SPACE-BASED LASER ROCKET SYSTEM
660.31	DDT&E	4204.90
11407.21	INVESTMENT & SPARES	3736.53
0.0	LASER SYSTEM DEPLOYMENT	981.50
4225.23	OTV DEPLOYMENT & OPS.	1304.22
8298.64	REFURBS	2015.38
8689.45	FUEL RESUPPLY	18678.93
33280.84	TOTAL REAL YEAR LCC	30921.46
14590.93	TOTAL PRESENT VALUE COST (1984)	11954.83

PROPULSION SYSTEM COST COMPARISON

NUMBER OF MISSIONS IN 10 YEAR PERIOD - PAYLOAD, LB	CHEMICAL/LASER COST RATIO W/DDT&E (W/O DDT&E)	ELECTRIC/LASER COST RATIO W/DDT&E
115	1	
460 - 5000	2.4 (4.1)	.83
4514 - 326000	5.9 (8.0)	1.22

STUDY RESULTS

- LASER ROCKET SYSTEMS POTENTIALLY OFFER A SIGNIFICANT SAVINGS IN NATIONAL BUDGET ALLOCATED TO SPACE TRANSPORTATION
- ORBITAL TRANSPORTATION OF CURRENT TYPE PAYLOADS REQUIRES 16-MW LASER POWER SPACED BASED OR 37.5-MW GROUND BASED
  - TRANSPORTATION COSTS ARE REDUCED BY FACTOR OF 2.4
- SPS ORBITAL TRANSPORTATION REQUIRES 490-MW LASER POWER SPACE BASED OR 1000-MW GROUND BASED
  - TRANSPORTATION COSTS ARE REDUCED BY FACTORS UP TO 7
- TECHNOLOGY ADVANCEMENT REQUIRED FOR
  - LASER
  - THRUSTER
  - LARGE, LIGHTWEIGHT, ADAPTIVE MIRROR
  - POINTING AND TRACKING

ABSTRACTS OF STUDIES ON LASER-THERMAL PROPULSION

Radiant Energy Absorption Studies for Laser Propulsion
Physical Sciences, Inc.

Laser-Heated Rocket Studies
Physical Sciences, Inc.

Analytical Study of Laser-Supported Waves in Hydrogen
Physical Sciences, Inc.

Laser-Heated Rocket Thruster
Rocketdyne Division of Rockwell International

Laser Propulsion Support Program
The BDM Corporation

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Lee W. Jones
October 1981

RADIANT ENERGY ABSORPTION STUDIES FOR LASER PROPULSION

G. E. CALEDONIA, P. K. S. Wu, AND A. N. PIRRI
PHYSICAL SCIENCES, INC. (CONTRACT NAS3-18528)

EXPANDED ABSTRACT

A study of the energy absorption mechanisms and fluid dynamic considerations for efficient conversion of high power laser radiation into a high velocity flow is presented. Although the contents of this study are applicable to the laser propulsion concept, they are not unique to this application and are useful for analysis of any system which requires the efficient conversion of laser energy to kinetic energy. The objectives are to (1) determine the most efficient absorption mechanisms for converting laser radiation into translational energy, and (2) examine the requirements for transfer of the absorbed energy into a steady flow which is stable to disturbances in the absorption zone. The first part of the study consists of a review of inverse Bremsstrahlung, molecular and particulate absorption mechanisms. The second part of the study consists of steady flow and stability considerations for conversion of the laser power to a high velocity flow in a nozzle configuration. The quasi-one-dimensional flow through a nozzle is formulated under the assumptions of perfect gas, instantaneous conversion of absorbed laser energy to temperature (equilibrium flow), and an absorption coefficient proportional to density and temperature raised to arbitrary powers. For a specified nozzle configuration, predictions of Mach number, temperature, density, and exhaust velocity are presented as a function of optical depth and the ratio of the laser power to inlet flow power. A "local" stability analysis is performed and a typical stability map of disturbance wavenumber versus nozzle position is presented. Neutral stability contours provide an indicator for proper design of nozzles with stable absorption zones.

LASER-HEATED ROCKET STUDIES

N. H. Kemp, R. G. Root, P. K. S. Wu, G. E. Caledonia, and A. N. Pirri

Physical Sciences, Inc. (Contract NAS3-19695)

EXPANDED ABSTRACT

This report describes studies of CW laser-heated rocket propulsion, in both the flowing-core and stationary-core configurations, with most attention focused on the former. (It is the second such study performed by PSI.) In the present work, the laser radiation considered was 10.6 μm, and the working gas was unseeded hydrogen. The areas investigated included initiation of a hydrogen plasma capable of absorbing laser radiation, the radiation emission properties of hot, ionized hydrogen, the flow of hot hydrogen while absorbing and radiating, the heat losses from the gas, and the rocket performance. The stationary-core configuration was investigated qualitatively and semi-quantitatively.

It was found that the flowing-core rockets can have specific impulses (I_{sp}) between 1500 and 3300 sec. They are small devices, whose heating zone is only millimeters to a few centimeters long, and millimeters to centimeters in radius, for laser power levels varying from 10 to 5000 kW, and pressure levels of 3 to 10 atm. Heat protection of the walls is a vital necessity, though the fraction of laser power lost to the walls can be as low as 10 percent for larger powers, making the rockets thermally efficient.

A number of major areas of uncertainty have been identified for further exploration. Chief among these are the properties of laser-supported combustion (LSC) waves in hydrogen. Others are an efficient method of heat protection, the effect of radial temperature profiles on radiation loss, and the effect of wider variation of operating parameters. For the stationary-core concept, absorption lengths of hot hydrogen radiation in cold hydrogen are needed, and a study of entrainment of the core gas by the flowing propellant gas should be made.

ANALYTICAL STUDY OF LASER-SUPPORTED WAVES IN HYDROGEN

N. H. Kemp and R. G. Root

Physical Sciences, Inc. (Contract NAS3-20381)

EXPANDED ABSTRACT

An earlier report by PSI describes a study of a CW laser-heated hydrogen rocket using 10.6 μm radiation. It was found that the properties of laser-supported combustion (LSC) waves in hydrogen were an important ingredient in modeling this rocket. They determine the temperature level reached by the gas, and the mass flux through the rocket. No theoretical or experimental studies of LSC waves in hydrogen are available. Therefore, a theoretical study of such waves has been made. A one-dimensional energy equation, with constant pressure and area, was used to model the LSC wave. This equation balances convection, conduction, laser energy absorption, radiation energy loss, and radiation energy transport. The latter is shown to be approximated well by a radiation conduction model. Solutions of this energy equation were obtained to give profiles of temperature and other properties, as well as the relation between laser intensity and mass flux through the wave. The calculations cover the range of pressures of 1, 3, 10, and 30 atm; 10.6 μm laser intensities from 10^4 W/cm^2 to 10^6 W/cm^2; and power levels of 10 kW and 5 MW. The physics of these waves leads to high peak temperatures (of order 20,000 K) because the absorption mechanism is inverse Bremsstrahlung, which requires a significant degree of ionization, and this occurs in hydrogen only above about 10,000 K. The high temperatures also lead to considerable radiation losses.

The flow through the LSC wave was then conducted through a variable-pressure, variable-area streamtube to accelerate it to high speed, with the propulsion application in mind. A numerical method for coupling the LSC wave model to the streamtube flow was developed, and a sample calculation was performed. The result shows that 42 percent of the laser power has been lost by the time the gas reaches the throat. This is in contrast with results for a similar case, where the LSC wave properties were only estimated, not calculated. There, only 5 percent of the power was found to be lost. The present, more realistic, calculations show the large losses incurred by the necessity of operating at high temperatures in hydrogen.

Several two-dimensional effects were estimated. Radial losses due to heat conduction and black radiation from the edge of the hot gas were found important at the 10 kW power level. They cause the intensity threshold for existence of the LSC wave to rise to values considerably higher than that which prevails if these losses are ignored. Beam convergence effects were also estimated by including beam area change in the laser absorption term. A calculation showed the mass flux required in a converging beam to be larger than in a parallel beam of the same initial intensity. Converging beams provide static stability for the wave position. Transverse velocity was also considered. It was concluded that in the radially confined flows of interest for propulsion applications, transverse velocities would be less important than in the unconfined flows where air experiments have been conducted.

It would be advantageous to produce LSC waves at lower temperatures to reduce the large radiation losses. This can be accomplished by introducing easily ionized seed into the hydrogen to allow laser absorption at lower temperatures. The amount of seed must be small enough so that the specific impulse is not adversely affected by its weight. It is recommended that studies of LSC waves in seeded hydrogen be conducted.

LASER-HEATED ROCKET THRUSTER

James M. Shoji
Rocketdyne Division of Rockwell International
(NASA Contract NAS3-17928)

EXPANDED ABSTRACT

In this study, Rocketdyne and Physical Sciences, Inc. (PSI) teamed for the purpose of performing an analysis and design of a 10 kW and a 5MW laser rocket thruster, followed by the fabrication of water-cooled and uncooled experimental thrusters, to be tested at 10 kW laser power level.

The specific objectives of the study were to:

(1) perform analysis and design of a 5 MW laser rocket thruster;

(2) design a 10 kW configuration through scaling and design analysis; and

(3) fabricate and deliver 10 kW experimental hardware, including the thrust stand and plasma initiation system.

The propellant to be used was hydrogen. Chamber pressure for the 10 kW thruster was 3.45×10^5 V/M^2 (50 psia). A detailed design of a 10 kW optical train was performed.

The attractive features of the laser-heated rocket thruster are:

1. Energy transfers from a ground or space-based laser energy generating system where weight constraints are not limiting to a weight-critical space vehicle.

2. Potential of 1000 to 2500-sec specific impulse with increase in vehicle payloads.

The calculated I_{sp} values for the point designs were 1232.5 sec at 10 kW laser input power, and 1363.3 sec at 5 MW power (with carbon seeding to cool the walls). It can be seen in figure 1 that 2000 sec (theoretical) is attained at a gas temperature of ≈ 5000°K; gas temperatures of twice that magnitude are required for a significant increase in I_{sp}. The absorption mechanism was assumed to be inverse Bremsstrahlung.

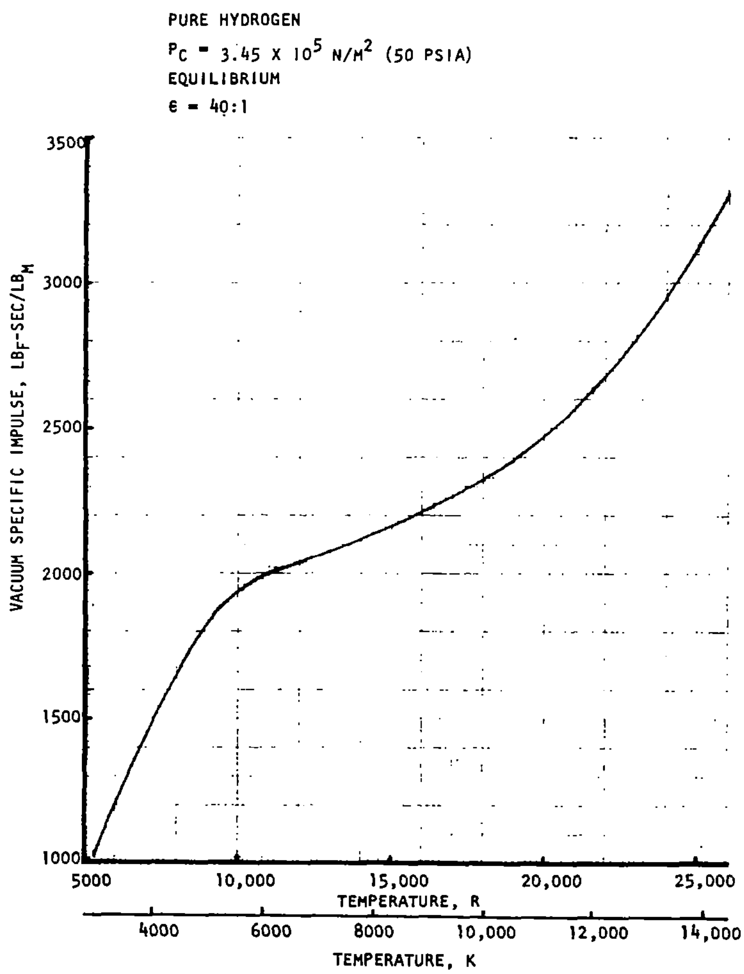


Figure 1. Theoretical Equilibrium Vacuum Specific Impulse Variation with Chamber Temperature for Pure H_2 (ε = 40:1)

LASER PROPULSION SUPPORT PROGRAM

John D. G. Rather and Peter Borgo
The BDM Corporation (NASA Contract NAS8-33973)

EXPANDED ABSTRACT

The overall objective of the study was to provide a substantial rationale for NASA's participation in an expanded effort to develop and exploit high energy laser technology, especially in laser propulsion. It is important to realize that the technical bases are complex, requiring attention to several different but interlocking factors, and it is not, therefore, sufficient to try to evaluate the worth of laser propulsion and power beaming by looking at individual pieces of the puzzle. Joint considerations of efficiency, cost, synergistic potential, time of achievement, and overall national objectives must be made. The best approach to be pursued depends upon the goal which is set.

The study was governed by this philosophy. It is an effort to (1) assess current and projected high energy laser technology programs of the DOD and (2) determine potential transfer of these technologies to NASA applications in laser propulsion and power beaming.

The state of current laser technology suggests that NASA should initially focus on ground-based, continuous wave laser systems, and should rely on development of large orbiting optical systems to deliver the laser energy via the "relay" concept. Pointing and tracking requirements are reduced in that cooperative, large-diameter optics are placed in precisely known orbits which minimize demands on the ground-based laser transmitting optics. Short wavelength lasers (2 μm) will minimize aperture sizes and take advantage of atmospheric propagation "windows".

The recent successful demonstration of a direct solar-pumped gas laser by NASA-Langley opens the possibility of developing simple and cost effective lasers for space deployment. Either these or long-running electric lasers (EDL's, Excimers, Free Electron Lasers) should exploit the full benefits of the space environment. The rotating-bed reactor should be assessed as a power source for electric lasers. Applicable system cost models must be developed for all these systems so that an accurate comparison of cost effectiveness of the potential candidate systems can be made.

SUMMARY OF HIGH ENERGY LASER TECHNOLOGY ASSESSMENT (NASA THRUSTS)

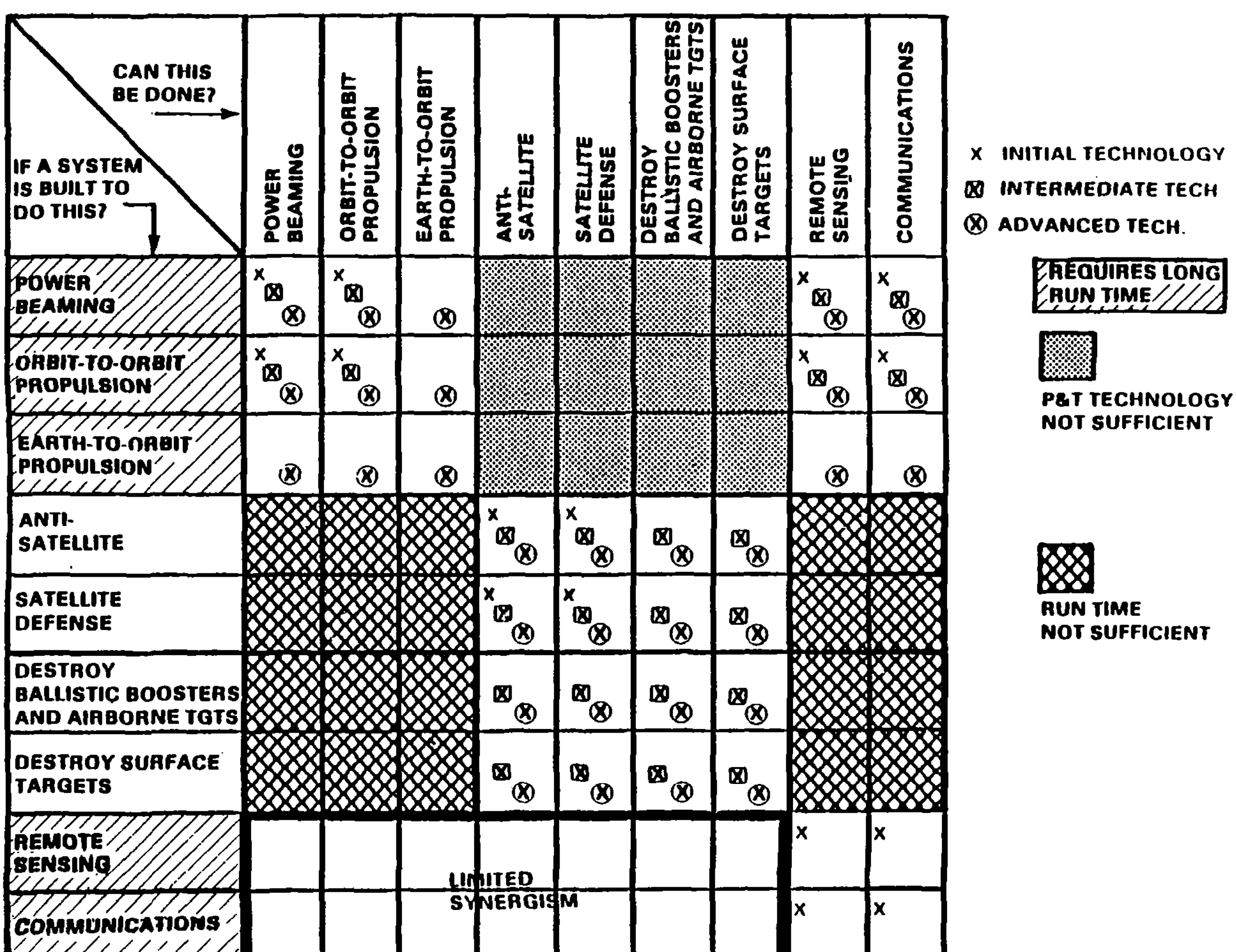
NASA PROGRAMS SHOULD:

- EXPLOIT THE POSSIBILITIES OF HIGH POWER, GROUND-BASED CW SYSTEMS USING RELAY OPTICS IN SPACE TO:
  - ELIMINATE WEIGHT AND VOLUME CONSTRAINTS ON LONG RUN-TIME LASERS;
  - DEVELOP LARGE (5-60 METER DIAMETER) ADAPTIVE OPTICS DEPLOYABLE WITH SPACE SHUTTLE AND HAVING LESS STRINGENT POINTING AND TRACKING REQUIREMENTS THAN DOD.
- EMPHASIZE SHORT WAVELENGTH LASERS (FEL, $\lambda \leqslant 2.2$ MICRONS) TO ACHIEVE:
  - VERY LONG RUN-TIME FOR EXTENDED MISSIONS:
  - COMPLEMENTARY R&D PROGRAM WITH DOD TO REDUCE DEVELOPMENT TIME AND MINIMIZE COST.
- AGGRESSIVELY DEVELOP DIRECT-PUMPED SOLAR LASERS FOR SPACE DEPLOYMENT
- EXPLOIT EMERGING ROTATING BED REACTOR TECHNOLOGY FOR SPACE-BASED HEL AND OTHER APPLICATIONS.
- DEVELOP APPLICABLE COST PROJECTION MODELS FOR ALL OF THE ABOVE SYSTEMS.

LASER PROPULSION SUPPORT PROGRAM

Study of the DoD programs and NASA programs and potential missions leads one to conclude that a high degree of synergism can exist with careful planning. The figure below is the result of detailed analysis of the relevant technologies. The basic question addressed is, "If a system can be built to do just one thing, what else might it also be capable of doing?" The primarily civilian applications are shaded in the left-hand column. They all require a capability for long laser running times. From observation of the matrix, it is obvious that either longer-running military laser systems or more precise C^3I (command, control, communications, and intelligence) for civilian laser systems increase the potential that a single generic system could perform all the space laser applications considered in this study.

SYNERGISMS AMONG SPACE LASER APPLICATIONS



LASER POWER CONVERSION SYSTEM ANALYSIS

LOCKHEED MISSILES AND SPACE COMPANY
SEPTEMBER 1978

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Richard B. Lancashire
October 1981

OBJECTIVES

- ORBIT-TO-ORBIT LASER POWER CONVERSION SYSTEM
  - IDENTIFY POTENTIAL MISSIONS
  - IDENTIFY EFFICIENT SYSTEM CONCEPTS
  - GENERATE CONCEPT DESIGNS
  - COMPARE COST AND PERFORMANCE WITH CONVENTIONAL SYSTEMS
  - EVALUATE TECHNOLOGY REQUIREMENTS AND DEVELOPMENT RISKS

- ORBIT-TO-GROUND LASER POWER CONVERSION SYSTEM (LSPS)
  - DEVELOP SPACE LASER POWER SYSTEM TO CONVERT SOLAR TO LASER ENERGY
  - EVALUATE LASER TRANSMISSION TO GROUND SITES FOR CONVERSION TO ELECTRICAL ENERGY
  - COMPARE COST EFFECTIVENESS OF LSPS TO SPS

GROUND RULES

- ORBIT-TO-ORBIT POWER TRANSFER
  - TRANSFER 1 TO 300 kW_E FROM REMOTE LASER TO SPACECRAFT

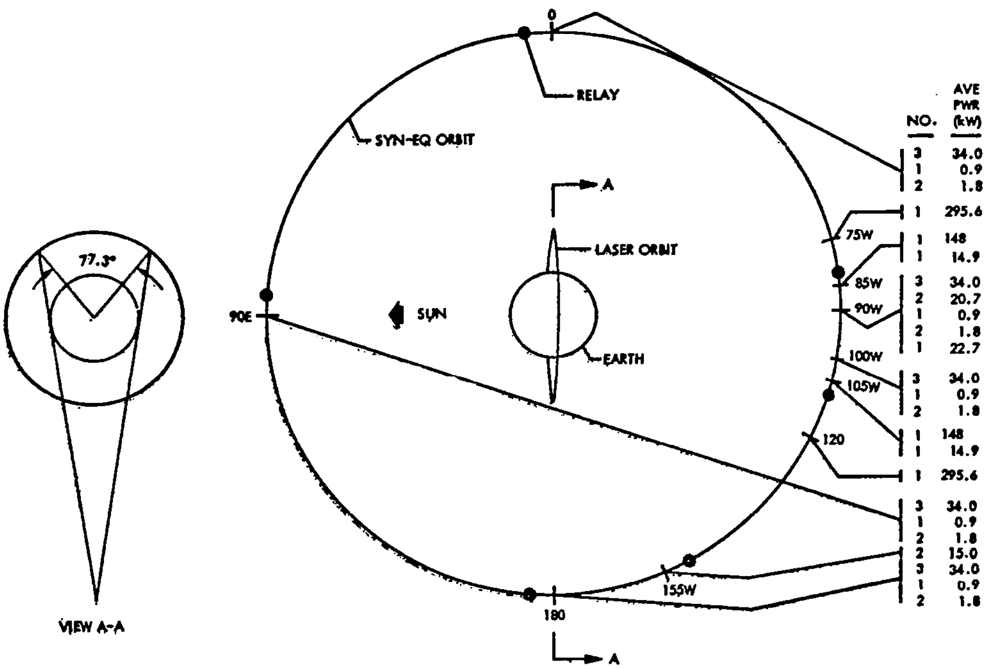
- ORBIT-TO-GROUND POWER TRANSFER
  - TRANSFER 100 TO 10000 MW_E FROM ORBITING LASER(S) TO GROUND SITES
  - CONSIDER PROOF-OF-CONCEPT EXPERIMENT

LASER POWER CONVERSION MISSION MODEL (1995–2005)

MISSIONS	SPACECRAFT WEIGHT* (kg)	ORBIT	NO. OPERATIONAL AT ANY TIME DURING 10-YR. PERIOD	kW POWER	EXPECTED VALUE	ACTIVITY LEVEL MULTIPLIERS		
						CASE 1 (NOM.)	2 (HIGH)	3 (LOW)
GEOSYNCHRONOUS (MILITARY INCLUDED)								
SYN. EQUATORIAL								
• ORBITAL ANTENNA FARMS (UP TO 8-COMMUNICATIONS SATELLITES PER FARM)	6,000	90°W, 0°, 90°E, 180°W, 100W	15	20-50	(35)	1	2	1
• PERSONNEL COMMUNICATIONS	7,300	90°W	2	21		1	1	1
• TV BROADCAST	6,500	85 & 105°W	2	150		1	3	2
• DIPLOMATIC HOT LINE	1,350	90°W, 0°, 90°E, 180°W, 100°W	5	1		1	1	1
• EARTH OBSERVATION/WEATHER	1,000-10,000	90°W, 0°, 90°E, 180°W, 100°W	10	.2		1	0	1
• ELECTRONIC MAIL	9,000	85°, 105°W	2	15		1	4	0
• COASTAL ANTICOLLISION PASSIVE RADAR	90,000	75°W, 120°W	2	300		1	2	0
• ASTRONOMY	4,500	155°	2	5-20	(15)	1	0	1
• ENERGY MONITOR		90°W	1	23		1	0	0
LOW EARTH ORBIT (MILITARY INCLUDED)								
100-600 NMI								
• SPACE PROCESSING		300 NMI, 28.5° INCL.	5	3-90	(35)	1	2	1
• ATMOSPHERIC TEMP. PROFILE SOUNDER	1,800	600 NMI POLAR	4	4		1	0	0
• SOLAR OBSERVATORY WEATHER MODIF. & EXPERIMENTATION		300 NMI, 55°	2	10-1000	(50)	1	2	0
• EARTH OBSERVATION SATELLITES	1,500-50,000	200 NMI-POLAR 500 NMI, 99.0°	4 4	5-100 5	(50)	1	2	1
• OCEAN CONDITION & WEATHER SATELLITE	1,500-50,000	500 NMI, 98.0°	4	5		1	2	1
600 NMI								
• TRANSPORTATION SERVICES/NAVIGATION		8,000 NMI POLAR	20-40	6		1	0	1
• WEATHER		700 NMI, 99.9°	5-10	2		1	2	0
PECULIAR MILITARY ORBITS CLASSIFIED	1,000-20,000	ELIPTICAL 287-24,500 NMI 63.5°	15	50-200 (?)		1	2	1

*LOWER WEIGHTS REPRESENT CURRENT OR NEAR TERM SATELLITE DESIGNS

GEO SATELLITE DEPLOYMENT



CANDIDATE SUBSYSTEMS

SUBSYSTEM/FUNCTION	CANDIDATES	TYPICAL EFFICIENCY (%)	REMARKS
ELECTRICAL POWER GENERATION IN SPACE	SILICON SOLAR CELLS	10.4 (7.3)	SIGNIFICANT DEGRADATION IN LOW EARTH ORBIT
	GALLIUM ARSENIDE CELLS	22 (12.5)	DEGRADATION IN LEO
	BRAYTON CYCLE	<40	LOW EFFICIENCY
	ENERGY EXCHANGER WITH TURBINE	58+	MAXIMUM EFFICIENCY POTENTIAL NOT ACHIEVED
	ENERGY EXCHANGER WITH BINARY CYCLE	73	MAXIMUM EFFICIENCY
LASER SUBSYSTEM FOR POWER TRANSMISSION	CO_2 EDL	20.2	EXCELLENT TECHNOLOGY BASE
	CO EDL	24.8	GOOD TECHNOLOGY BASE
	SOLAR PUMPED	(19.9)	LIMITED DATA
CONVERSION OF LASER POWER TO ELECTRICAL POWER	PHOTOVOLTAIC THERMAL ELECTRONIC (TELEC)	40 45	LOW EFFICIENCY LOW EFFICIENCY
	BRAYTON CYCLE	<40	LOW EFFICIENCY
	ENERGY EXCHANGER WITH BINARY CYCLE	73	HIGHEST EFFICIENCY

TYPICAL MISSIONS

	CIRCULAR ORBIT ALT (km)	CIRCULAR ORBIT INC (°)		AVE PWR (kW)	BASE-LINE EPS WT		4-HR LASER ORBIT (6,396 km) CHG (HR)	CYCLE (HR)	LASER PWR (kW)	BATT WT	REC WT	PWR ON REC (kW)	BATT CAP (kWH)
SPACE PROCESSING	555	28.5	5	34.2	5,900	5	0.0534	2.67	565	11,132	10,749	440	209
						10	0.267		1,216	12,523	11,623	946	235
						25	0.107		3,164	13,357	12,116	2,461	250
						50	0.053		6,476	13,638	12,283	5,038	256
						100	0.027		12,795	13,774	12,363	9,954	258
ATMOSPHERIC	1,110	90	4	4.0	2,400	5	0.648	3.24	66	1,580	1,547	51	30
						10	0.324		142	1,777	1,663	111	33
						25	0.130		370	1,896	1,733	288	36
						50	0.065		749	1,935	1,757	583	36
						100	0.032		1,532	1,955	1,769	1,192	37
SOLAR OBSERVATION	555	55	2	48.16	11,900	5	0.534	2.67	803	15,818	15,340	625	297
						10	0.267		1,728	17,796	16,510	1,345	334
						25	0.107		4,496	18,981	17,211	3,498	356
						50	0.053		9,203	19,381	17,448	7,159	364
						100	0.027		18,182	19,573	17,562	14,145	367
EARTH OBSERV (LG)	370	90	4	48.8	22,300	5	0.494	2.47	806	14,694	14,250	627	276
						10	0.247		1,736	16,531	15,337	1,350	310
						25	0.099		4,514	17,631	15,989	3,512	331
						50	0.049		9,246	18,003	16,209	7,193	338
						100	0.025		18,241	18,181	16,314	14,190	341
EARTH OBSERV (SM)	1,110	99	4	1.7	1,450	5	0.648	3.24	28	671	666	22	13
						10	0.324		60	755	716	47	14
						25	0.130		157	806	746	122	15
						50	0.065		318	822	756	249	15
						100	0.032		651	831	761	507	16

*ALL WEIGHTS IN POUNDS

POWER REQUIREMENTS: MISSIONS UNDER 50 kW_e

(Total Satellite Power = 1,383 kW_e)

Number of Lasers	Power Required (kW) Space: Laser	Space: Electrical	Ground: Laser	Ground: Electrical
1	14,686	73,430	42,477	212,383
2	7,282	72,820	21,062	210,620
4	3,579	71,580	10,352	207,040
10	1,363	68,150	3,942	197,100
20	620	62,000	1,795	179,500

CONCLUSIONS

- LASER ENERGY POWER CONVERSION SYSTEM FOR SATELLITES ONLY WILL PROBABLY NOT BE COMPETITIVE WITH CURRENT SATELLITE ELECTRICAL POWER SYSTEMS

- LASER ENERGY POWER CONVERSION SYSTEM FOR SATELLITES IN CONJUNCTION WITH A LASER ROCKET PROPULSION OR OTHER LARGE LASER SYSTEM MAY BE COMPETITIVE

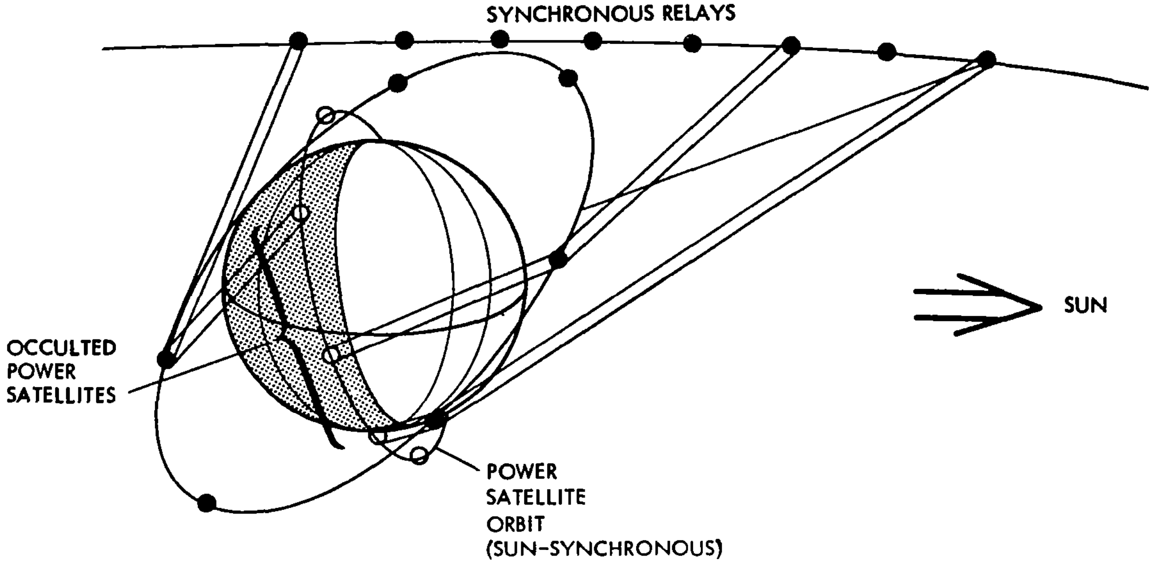
ADDITIONAL GROUND RULES FOR LSPS

- EMPHASIS ON SUBSYSTEM INTERACTIONS
  - PARTICULARLY POWER CONVERSION FOR BOTH SPACE VEHICLE AND GROUND SITE

- USE OPTICAL AND P&T SUBSYSTEMS DEVELOPED UNDER LASER ROCKET STUDY

- CONCEPTUAL DESIGN OF 500 kW SYSTEM

SYSTEM OVERVIEW



CANDIDATE SUBSYSTEMS

SUBSYSTEM/FUNCTION	CANDIDATES	TYPICAL EFFICIENCY (%)	REMARKS
ELECTRICAL POWER GENERATION IN SPACE	SILICON SOLAR CELLS	10.4 (7.3)	DEGRADATION IN LEO
	GALLIUM ARSENIDE CELLS	22 (12.5)	DEGRADATION IN LEO
	BRAYTON CYCLE	<40	-
	ENERGY EXCHANGER WITH TURBINE	58+	-
	ENERGY EXCHANGER WITH BINARY CYCLE	73	MAXIMUM EFFICIENCY
LASER SUBSYSTEM FOR POWER TRANSMISSION	CO_2 EDL	20.2	EXCELLENT DATA BASE
	CO EDL	24.8	GOOD DATA BASE
	SOLAR PUMPED	(19.9)	LIMITED DATA BASE
CONVERSION OF LASER POWER TO ELECTRICAL POWER ON THE GROUND	PHOTOVOLTAIC	< 40	-
	THERMAL ELECTRONIC (TELEC)	45	-
	BRAYTON CYCLE	40	-
	ENERGY EXCHANGER WITH BINARY CYCLE	73	HIGHEST EFFICIENCY

SYSTEMS CONCEPTS EVALUATED

SYSTEM	SOLAR ENERGY COLLECTOR	ELECTRICAL POWER CONVERSION	LASER SUBSYSTEM	GROUND POWER CONVERSION
I	REFLECTOR/CAVITY	ENERGY EXCHANGER AND BINARY CYCLE	CO_2 EDL	ENERGY EXCHANGER AND BINARY CYCLE
II	REFLECTOR/CAVITY	ENERGY EXCHANGER AND BINARY CYCLE	CO EDL	
III	REFLECTOR/CAVITY	ENERGY EXCHANGER AND BINARY CYCLE	SOLAR PUMPED LASER	
	REFLECTOR/SOLAR LASER CAVITY	→		
IV	REFLECTOR/SOLAR CELL ARRAY	SOLAR CELLS	CO_2 EDL	
V	REFLECTOR/SOLAR CELL ARRAY	SOLAR CELLS	CO EDL	

ORBITAL SYSTEM EFFICIENCIES

SYS. NO	TYPE	SOLAR REFLECTOR (OR ARRAY) (%)	SOLAR CAVITY (%)	SOLAR LASER CAVITY (%)	E.EXCH. & BINARY CYCLE (%)	POWER GEN. (%)	POWER COND. (%)	LASER S/S (%)	OPTICAL TRAIN (%)	SPACE APERTURE (%)	SPACE OVERALL
I	CO_2 EDL/ E.E. BINARY	85	83	–	73	98	95	20.2	99.7	99.7	9.62
II	CO EDL/ E.E. BINARY	85	83		73	98	95	24.8	99.7	99.7	11.82
III	SOLAR PUMPED CO_2	85	83	95	(73)	(98)	(95)	(19.9)	99.7	99.7	12.34
IV	CO_2 EDL/ SOLAR CELLS	10.6					95	20.2	99.7	99.7	2.02
V	CO EDL/ SOLAR CELLS	10.6					95	24.8	99.7	99.7	2.48

SPACE/GROUND SYSTEM EFFICIENCIES

SYS. NO.	TYPE	SPACE RELAY	ATM TRANS.	GROUND RECEIVER	GROUND CAVITY	E. EXCH & BINARY CYCLE	GROUND POWER GEN.	OVERALL SPACE/ GROUND	SYSTEM OVERALL
I	CO_2 EDL/ E.E. BINARY	90	85	96	98	73	98	51.5	4.96
II	CO EDL/ E.E. BINARY	90	78	96	98	73	98	47.2	5.58
III	SOLAR PUMPED CO_2	90	85	96	98	73	98	51.5	6.32
IV	CO_2 EDL/ SOLAR CELLS	90	85	96	98	73	98	51.5	1.04
V	CO_2 EDL/ SOLAR CELLS	90	78	96	98	73	98	47.2	1.17

PRELIMINARY SYSTEM ANALYSIS RESULTS

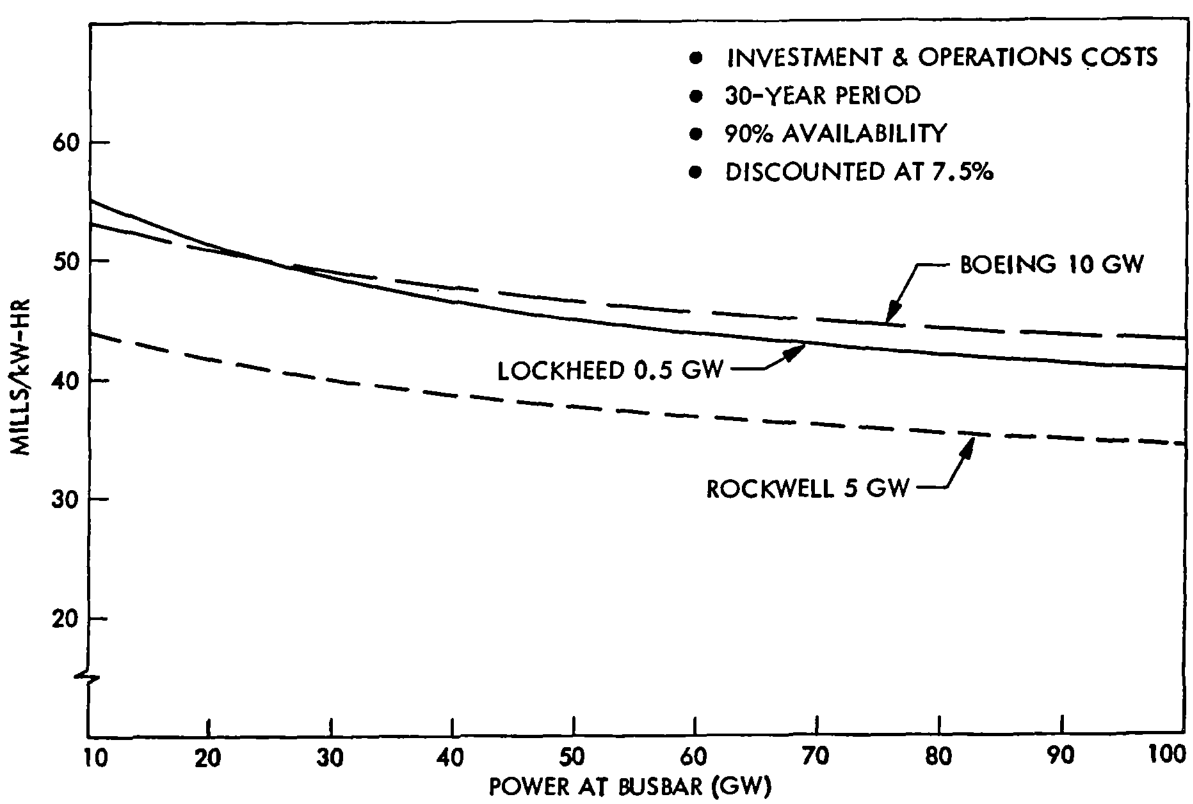
SYSTEM NO.	TYPE	POWER ON GROUND (MW)	SOLAR POWER RECEIVED (MW)	OVERALL EFFICIENCY (%)	ORBITAL SYSTEM WEIGHT (kg)
I	CO_2 EDL/ E.E. BINARY	100 500 1000	2,017.3 10,086.6 20,173.2	4.96	1,469,000 6,926,000 14,774,000
II	CO EDL/ E.E. BINARY	100 500 1000	1,890.2 9,450.9 18,901.9	5.29	1,468,100 7,126,500 14,241,600
III	SOLAR PUMPED CO_2	100 500 1000	1,573 7,865.9 15,732	6.32	1,926,000 7,107,000 14,353,000
IV	CO_2 EDL/ SOLAR CELLS	1000	95,524	1.04	22,840,000
V	CO EDL/ SOLAR CELLS	1000	89,500	1.17	21,840,000

TRANSPORTATION COSTS

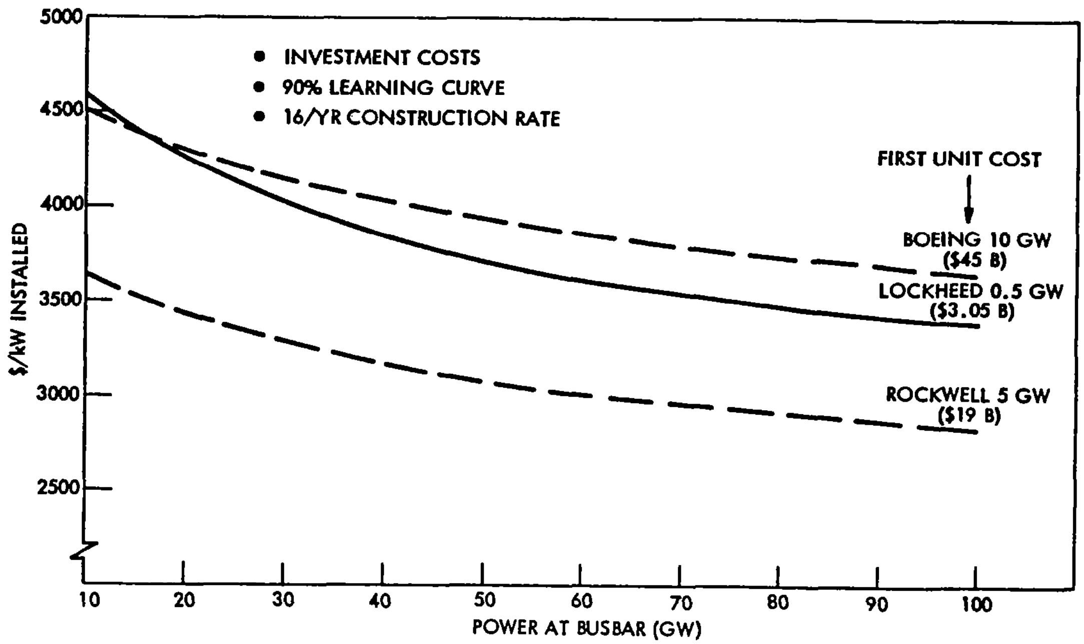
SPS WT = 200,000,000 LB   SLPS WT = 314,000,000 LB

	SPS	SLPS
MICROWAVE TO 28.5° LEO AT $14/LB	$2.8B	
LASER TO 97° LEO AT $21/LB		$6.57B
LEO TO GEO AT $59/LB	$11.8B	$0.01B
	$14.6B	$6.58B

MILLS/KW-HR COST COMPARISON (77 $)



\$/KW COST COMPARISON (77\$)



CONCLUSIONS

GENERAL:

- EFFICIENCIES GREATER THAN 5% ARE ASSURED
- ALL THREE LASER TYPES PRODUCE SIMILAR SYSTEM WEIGHTS

CO_2 EDL

- MORE AVAILABLE PERFORMANCE AND DESIGN DATA
- LOWEST ATMOSPHERIC TRANSMISSION LOSSES
- SPECTRA BEST SUITED FOR PHASED ARRAY

CO EDL

- LESS AVAILABLE PERFORMANCE AND DESIGN DATA
- HIGHER TRANSMISSION LOSSES THAN CO_2
- SMALLER APERTURES
- MULTIPLE LINES WILL PRODUCE PHASED ARRAY DIFFICULTIES

SOLAR PUMPED CO_2

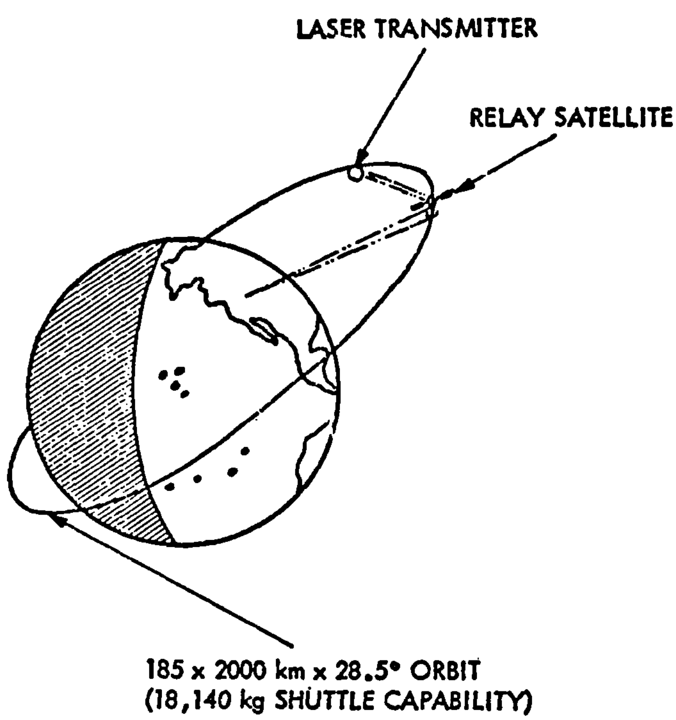
- MEAGER PERFORMANCE AND DESIGN DATA
- HIGHEST OVERALL EFFICIENCY BASED ON PERFORMANCE EXTRAPOLATIONS

RECOMMENDED FOR PRELIMINARY DESIGN: CO_2 EDL

SLPS PILOT PROGRAM ASSUMPTIONS

- SUBSCALE 500-kW PILOT DEMONSTRATION
- SUBSCALE POWER AND RELAY SATELLITES
- SUBSCALE GROUND STATION
- SHUTTLE LAUNCH VEHICLE – TWO LAUNCHES
- 185 x 2000 km 28.5° INCLINATION ORBIT
- ON-ORBIT CONSTRUCTION BASE NOT REQUIRED
- TECHNOLOGY DEVELOPMENT COSTS NOT INCLUDED
- COSTS IN 1977 $

LASER SPS PILOT PROGRAM OVERVIEW



PILOT PROGRAM SPECIFICATIONS

LASER TRANSMITTER SATELLITE	
ELECTRICAL POWER (kW)	3,958
LASER POWER (kW)	910
TRANSMITTER APERTURE DIAMETER (m)	4.7
RELAY UNIT	
TRANSMITTER APERTURE DIAMETER (m)	4.7
RECEIVER APERTURE DIAMETER (m)	4.7
GROUND STATION	
RECEIVER APERTURE DIAMETER (m)	18.75
ELECTRICAL POWER AT BUSBAR (kW)	500

SLPS PILOT PROGRAM COSTS ('77$M)

	POWER SAT	RELAY SAT	GRD. STATION	TOTAL
OPTICS AND SENSORS	$100	$ 94	$84	$278 M
POWER GENERATION	250	-	5	255
SPACECRAFT AND STRUCTURES	25	19	-	44
SUBTOTAL	$375 M	$113 M	$89 M	$577 M
FACILITIES AND GROUND EQUIPMENT				38
SYSTEM ENG., INTGR. AND TEST				110
SHUTTLE INTGR. AND FLIGHT TEST				73
PROGRAM MANAGEMENT AND DATA				59
PILOT PROGRAM TOTAL				$857 M

POTENTIAL OF LASERS FOR SPS POWER TRANSMISSION

PRC ENERGY ANALYSIS COMPANY
SEPTEMBER 1978

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

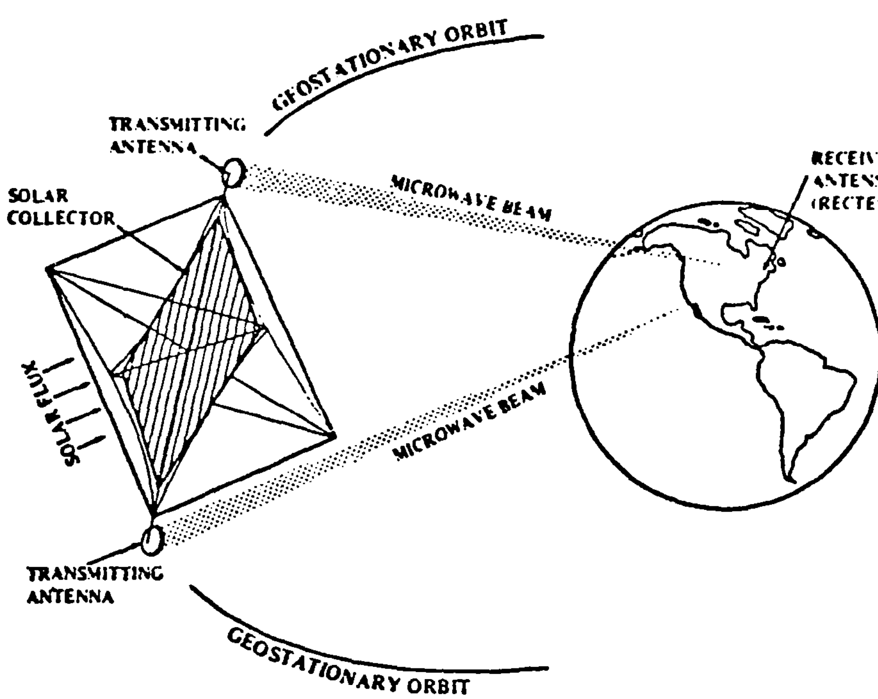
OCTOBER 14-15, 1981

REVIEWED BY:
Richard B. Lancashire
October 1981

OBJECTIVE

EVALUATE POTENTIAL OF LASER FOR TRANSMITTING POWER FROM SPACE POWER SATELLITE (SPS) TO EARTH

- DETERMINE LASER TECHNOLOGY STATE-OF-THE-ART
- COMPARE LASER POWER TRANSMISSION TO MICROWAVE TRANSMISSION FOR SPS



Major Elements of a Satellite Power System (SPS)

GROUND RULES

COMPARE LASER POWER TRANSMISSION TO MICROWAVE FOR SPACE POWER SATELLITE (SPS) APPLICATION

- USE NASA BASELINE SYSTEM SPS CONCEPT AS A REFERENCE
  - PHOTOVOLTAIC CONVERSION OF SOLAR POWER
  - MICROWAVE POWER TRANSMISSION SYSTEM (MPTS)
  - GEOSTATIONARY ORBIT
  - EARTH RECEIVER STATION BUSBAR POWER 10 GW

- SAFETY/RELIABILITY/MAINTAINABILITY OF LASER SYSTEM MUST BE EQUIVALENT TO BASELINE

- COMPARE POWER TRANSMISSION SYSTEM PERFORMANCE, CHARACTERISTICS

- SIX CASES ARE CONSIDERED

  CASES 1-3

  SPS MICROWAVE POWER TRANSMISSION SYSTEM (MPTS) REPLACED BY CO_2 EDL-BASED LASER POWER TRANSMISSION SYSTEM (LPTS)

  CASE 4

  SPS -- MPTS REPLACED BY IDEAL, COMPETITIVE LPTS

  CASES 5A-5B

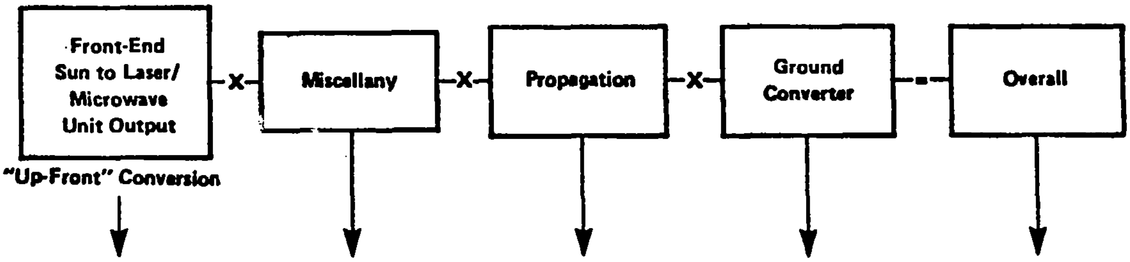
  SPS PHOTOVOLTAIC ARRAY AND MPTS REPLACED BY DIRECT SOLAR PUMPED LASER AND LPTS

		Sun to Solar Array Output	Miscellany	Microwave Unit or Laser Unit	Propagation	Ground Converter	Overall
MPTS	JSC	0.151	0.80	0.80	0.86	0.86	0.071
LPTS	#1	0.151	0.80	X 0.23	0.80	0.45	0.0100
	#2	0.151	0.80	0.235	0.88	0.45	0.012
	#3	0.151	0.80	X 0.25	0.88	0.75	0.020
	#4	0.151	0.80	0.83 R	0.95	0.75	0.071

X—X These CO_2 EDL efficiencies are from 10 to 35 percent higher than suggested by some in the field.

R This value is required for the overall efficiency of the LPTS #4, pumped with the photovoltaic array, to equal the JSC estimated efficiency for the MPTS. There has been no indication that this efficiency can be realized.

Comparison of Efficiencies of MPTS and LPTS Concepts



		"Up-Front" Conversion	Miscellany	Propagation	Ground Converter	Overall
LPTS	#5a	0.10*	0.80	0.90	0.75	0.054
	#5b	0.20*	0.80	0.80	0.65	0.083
MPTS	JSC	0.12**	0.80	0.86	0.86	0.071

*Solar pumped lasers.

**Photovoltaic array/klystron

Comparison of Efficiencies of Solar-Pumped Laser LPTS Concepts and the MPTS

CONCLUSIONS

- EARTH STATION RECEIVER FOR LPTS REQUIRES LESS LAND AREA 27M VS. 7700M
- LPTS HAS ADVANTAGE OF SMALL SCALE PROOF-OF-CONCEPT
- LPTS CANNOT COMPETE WITH MICROWAVE WHEN SOLAR ENERGY IS CONVERTED FIRST TO ELECTRICITY, BEFORE TRANSMISSION
- LPTS CAN COMPETE IF SOLAR PUMPING AT 10-20% EFFICIENCY CAN BE OBTAINED

RECOMMENDATIONS AND IMPACT ON FUTURE NASA HPL PROGRAM

- FORGET ABOUT LASER POWER TRANSMISSION FOR PHOTOVOLTAIC SPS
- PURSUE SOLAR PUMPED LASERS AS SPS ALTERNATIVE
    - IMPROVED EFFICIENCY
    - HIGH POWER OPERATION
    - RELIABILITY

SPACE LASER POWER TRANSMISSION

MATHEMATICAL SCIENCES NORTHWEST
LATE 1981

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Richard B. Lancashire
October 1981

OBJECTIVE

- ASSESS ADVANTAGES FOR SPACE MISSIONS USING LASER POWER TRANSMISSION CONCEPTS COMPARED TO ON-BOARD POWER GENERATION CONCEPTS

- FORMULATE RECOMMENDATIONS FOR FUTURE NASA LASER POWER TRANSMISSION PROGRAM. IDENTIFY CRITICAL TECHNOLOGIES, RESEARCH PRIORITIES

APPROACH

- REVIEW PROPOSED LASER POWER TRANSMISSION APPLICATIONS
  - COMPARE ADVANTAGES WITH ON-BOARD POWER GENERATION COST, TRANSPORTATION ENERGY, MISSION FLEXIBILITY, ETC.
  - IDENTIFY MISSIONS WHERE LASERS HAVE A DECIDED ADVANTAGE

- ASSESS TECHNOLOGIES ESSENTIAL FOR LASER POWER TRANSMISSION
  - EFFICIENCES, LEVELS OF DEVELOPMENT, COMPONENT MASSES, CONSTRAINTS, ETC.
  - IDENTIFY TECHNOLOGIES WHERE ONE COULD ENHANCE POTENTIAL OR ENABLE NEW MISSIONS
  - EVALUATE OVERALL SYSTEM PERFORMANCES

STUDY GROUND RULES

- CONSIDER BOTH GROUND-BASED AND ORBITING LASER POWER STATIONS
- POSSIBLE MISSION CATEGORIES INCLUDE:

Orbital (LEO,GEO)	Deep Space
Planetary (Orbiter, Surface)	Near Sun
Lunar	Orbital Transfer

- RELEVANT TECHNICAL ASPECTS INCLUDE:

Mass in Orbit	Environmental Interactions
Mission Flexibility	Laser Designs
Power Level	Optics and Receivers
Reliability	Efficiencies
Economics	Development Risk

- CONSIDER COMPETING LASER TYPES AND ENABLING TECHNOLOGIES

Feasible Laser - Mission Combinations

Mission Category	Laser System Requirements	Feasible Laser Systems	Outstanding Requirements
Earth Orbital			
LEO	Short Range	Excimer, Nuclear Pumped, Iodine	Low mass for GEO: ground-based laser option; solar with storage or nuclear.
GEO	Medium Range	FEL, CO and CO_2	
Planetary			
Orbital	Medium Range	All types of lightweight solar driven lasers	Orbital mass is critical; continuous solar exposure possible; nuclear laser feasible.
Surface	Medium Range		
Lunar Surface	Medium Range		
Deep Space			
Outer Planets	Distant	Excimer Iodine FEL	Short wavelength needed; very large aperture transmitters (VLAT); continuous solar exposure possible.
Outside Solar System	Distant		
Near Sun	Long Range	Optically pumped (iodine, CO, CO_2)	High solar intensity available for solar pumping.
Propulsion			
LEO-GEO Orbital Transfer	Short to Medium Range Atm-Gd (option)	Excimer, Iodine, FEL, CO, and CO_2	Scaling to very high powers; low orbital mass desired; ground-based laser option.
Station Keeping	Short or Medium Range Atm-Gd (option)		

Short Range - 10^2-10^3 km
Medium Range - 10^4-10^5 km
Long Range - 10^8 km (~1 AU)
Distant - > 40 AU

SUMMARY OF COMPONENTS BY WAVELENGTH

Wavelength Range (μm)	Laser Type	Lasant (λ-μm)	Transmitter and Receiver Optics: Diam.[a] (m)	Transmitter and Receiver Optics: Reflectivity[b] (Materials)	Receivers and Efficiency Range
0.1 to 0.35	Excimers	KrF (0.248)	3.8		
		XeCl (0.308)	4.2		
		I_2 (0.342)	4.5	>93%	Photovoltaic Cells
	FEL	——(Tunable)	2.4-4.5	(Al)	η = 20 to 45%
0.35 to 0.5	Excimers	XeF (.351, .353)	4.5		
		HgBr (0.5)	5.4		
	FEL	---(Tunable)	4.5-5.4		
0.5 to 1.0	FEL	---(Tunable)	5.4-7.6	93 to 99.5% (Cu)	
1μ to 4μ	Glass	NdYAG (1.06)	7.9		
	Atomic Iodine	CF_3I (1.319)	8.8	99.5 to 99.8% (Cu)	Heat Engines
	FEL	---(Tunable)	5.4-15.3		and Microrectenna
4μ to 10μ	EDL, Solar or	CO (≈5)	17.1		η = 35 to 75%
	Nuclear Pumped	CO_2 (9.3)	24.3	99.8% (Cu)	
	FEL	---(Tunable)	15.3-24.1		

[a] For 38,000 km range.

[b] Reflectivity for polished metal with coatings.

SUMMARY OF FEASIBLE SPACE-TO-SPACE LASER POWER TRANSMISSION SYSTEMS

	η_S[a]	η_C	η_L	η_{to}	η_R[c]	η_{ro}	η_e	η[f]
Excimer Laser (0.1 to .35μ)								
e-beam	14-50%	70%	5-8%	93%	60%	93%		1.2%
discharge	14-50%	90%	2-3%	to	to	to		0.6%
FEL (.35μ to 1μ)	14-50%	75-90%	15-50%[d]	98.5%	90%	98.5%	45%	11%
Iodine Lasers (1.3μ)	5%[b]	14-50%[b]	1-23%	98.5%	90%	98.5%		0.5%
Nuclear Pumped (Helium-Noble Gas) (1.8-3.5μ)	-----[e]	-----[e]	0.1-1%					0.7%
FEL (1μ to 5μ)	14-50%	75-90%	15-50%[d]	99.5%	97%	99.5%		16.7%
CO EDL (5μ)	14-50%	90%	20-30%				35%	10.0%
CO Nuclear Pumped (5μ)	-----[e]	-----[e]	3-5%				to 75%	3.7%
FEL (5μ to 10μ)	14-50%	75-90%	15-50%[d]					16.8%
CO_2 EDL 9.3μ	14-50%	90%	17-20%	99.8%	98.6%	99.8%		6.7%
CO_2 IOPL 9.3μ	92%[b]	14-50%[b]	10-15%					10.3%

[a] Assumed to be solar with a range in efficiency from 14% (present photovoltaic cells) to 50% (advanced solar thermal systems).

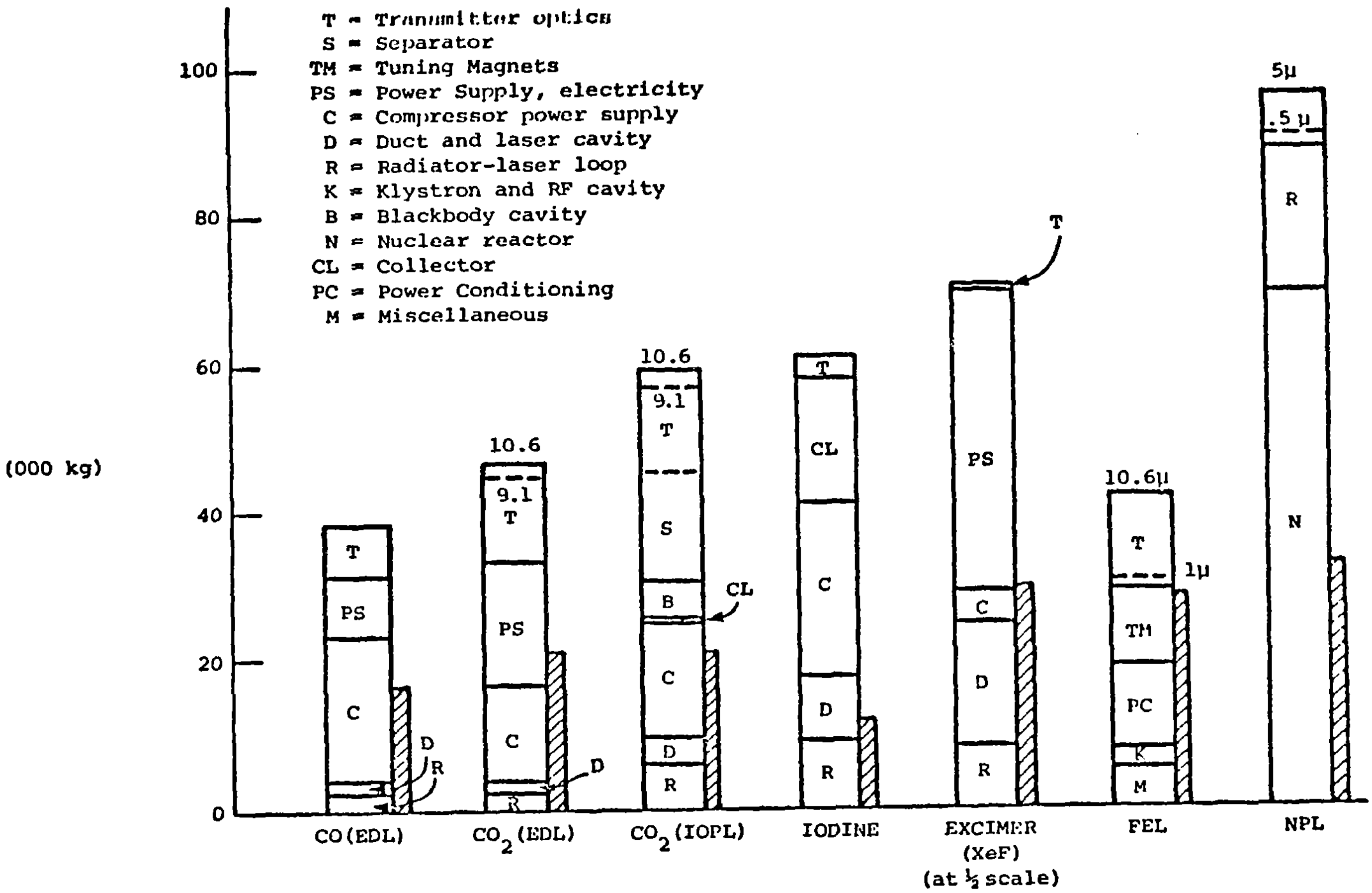
[b] In the case of direct and indirect pumped solar lasers, η_S and η_C are combined in column 1 for the input to the lasant; column 2 then refers only to the source and conversion efficiency for generating compressor power in the system.

[c] Assumed to have 7 reflecting surfaces: $\eta_R = (\eta_{to})^7$

[d] The FEL extraction efficiency and RF conversion efficiency (column 2) may combine in a complex way to form η_L.

[e] Nuclear pumped source and conversion efficiencies are contained in the overall laser efficiency, η_L.

[f] Neglects the relay transfer efficiency; equal to the product of the highest component efficiency in each category.



COMPARISON OF SPACE LASER TRANSMITTER MASSES FOR 1 MW AND 100 kW OUTPUT POWER

SYSTEM CONCLUSIONS

- Laser technology is developable for ground- or space-based power transmission.
- EDLs best developed; FELs show greatest promise; solar pumped lasers are serious contenders.
- Good atmospheric transmission from elevated sites for

  CO and CO_2 at select infrared lines

  Excimers and FELs in the visible
- Space power transmission up to 100 AU may be possible.
- Overall power transmission efficiency in space of 11 to 17% appears feasible for the wavelength range 0.25 to 10 μm.
- Relay satellite power transfer efficiencies are critical.
- Receiver converter technology under-developed; further analysis, design, and proof experiments required.

MISSION ANALYSIS SCENARIO

- ORBIT RAISING
- POWER SUPPLY
- BOTH ANALYZED WITH:
  - CHEMICAL
  - SOLAR
  - NUCLEAR
  - SPACE-BASED LASER
  - GROUND-BASED LASER
- RESULTS PLOTTED TRANSPORTATION ENERGY COSTS VS. NUMBER OF SATELLITES

MISSION CONCLUSIONS

- Laser Power to a large number of users in space can
  - Eliminate on-board energy storage
  - Load-share amongst users
  - Eliminate on-board peaking power capacity
- A Limited Mission Analysis Shows:
  - On-board power requires less energy to orbit than the corresponding laser power systems
  - Laser Power systems appear less expensive than on-board power at high activity, payload levels
- Many mission possibilities remain to be evaluated

CRITICAL TECHNOLOGIES

Laser Transmitters

Gas Clean-up

High Voltage, Pulsed Power Systems

Lifetime and Reflectivity of Optical Surfaces

Waste Heat Radiators

New Laser Concepts (e.g., dielectric lasers)

Laser Receivers

High Efficiency Photovoltaic Cells ($\lambda \lesssim 1\mu$)

Solid State Receivers for Longer Wavelengths:

- IR Detector Technology
- Microrectenna

New Receiver Concepts (e.g., Reverse FEL)

SUMMARY OF R & D RECOMMENDATIONS

Technology

- Demonstrate high efficiency receiver concepts
- Develop gas purity/clean-up requirements for space lasers
- Determine technology goals for pulsed power systems for space lasers
- Carry out initial design/evaluation studies of new lasers and receivers
- Test new concepts

Systems Analysis

- Determine the most attractive laser transmission systems
- Develop system performance goals for major components
- Determine the optimum number and size of relay satellites

Mission Analysis

- Evaluate a wider range of possible mission parameters to determine trade-offs between system configuration and mission requirements
- Conduct cost sensitivity analysis

THERMOELECTRONIC LASER ENERGY CONVERTER (TELEC)

RASOR ASSOCIATES, INC.
SEPTEMBER 1979

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Richard B. Lancashire
October 1981

TELEC

OBJECTIVE

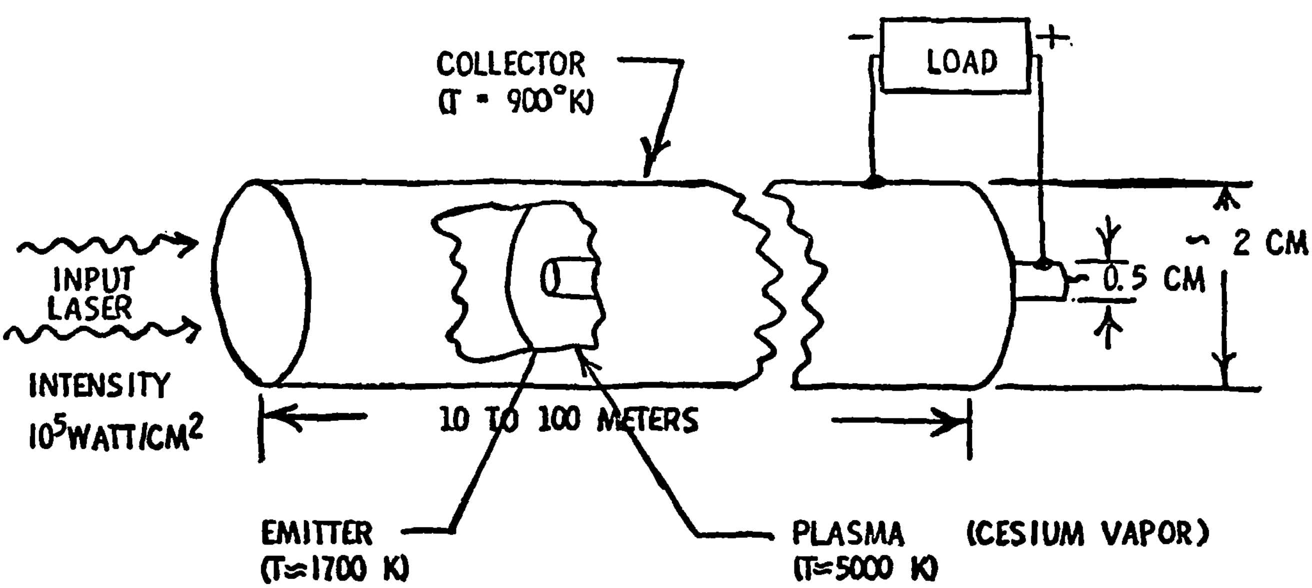
EVALUATE FEASIBILITY OF TELEC AS A POTENTIALLY EFFICIENCY AND LIGHTWEIGHT METHOD FOR LASER-TO-ELECTRIC POWER CONVERSION IN A SPACE LASER POWER TRANSMISSION SYSTEM

GROUND RULES

- PERFORM FEASIBILITY STUDY AND CONCEPTUAL DESIGN OF A 1 MW TELEC SYSTEM
- FABRICATE AND TEST SMALL SCALE TELEC CELL TO ABSORB 20% OF A 10 kW CO_2 BEAM

THERMOELECTRONIC LASER ENERGY CONVERTER (TELEC)

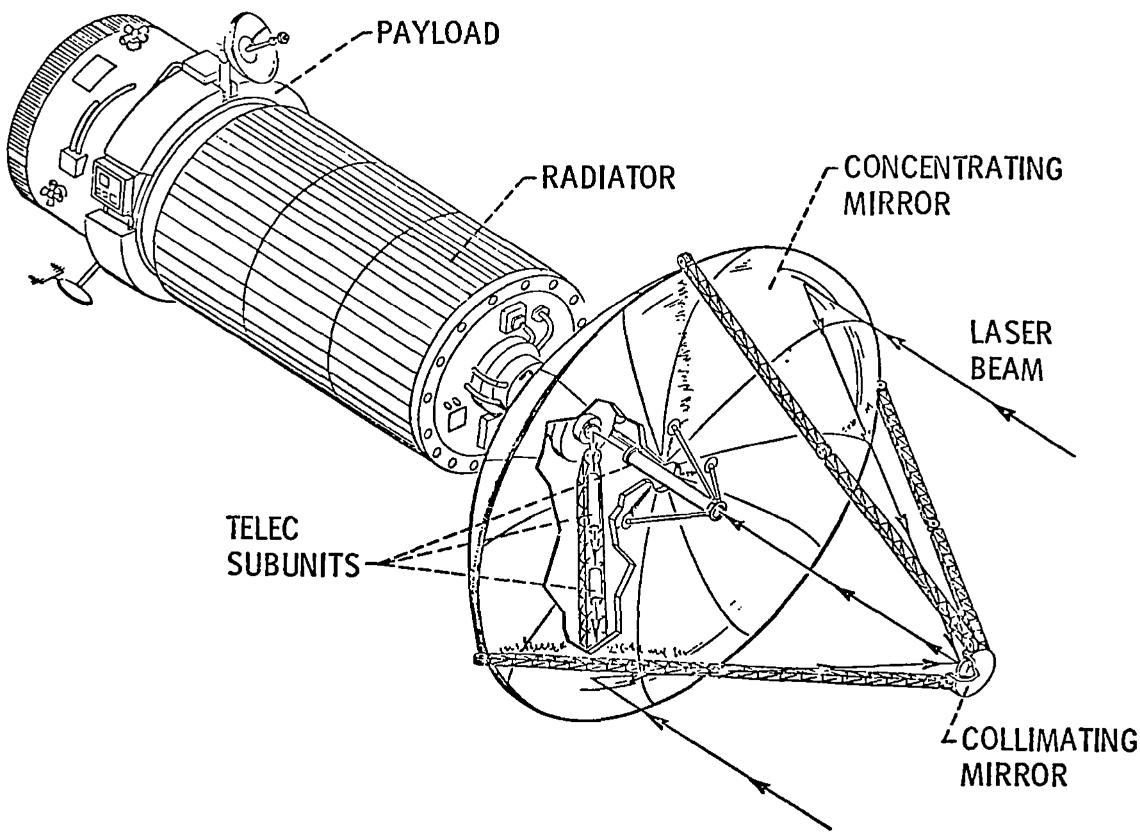
- A CONCEPT - SUGGESTED BY DR. NED RASOR
- POTENTIAL CONVERSION EFFICIENCY: 50%



FEASIBILITY OF 1 MEGAWATT TELEC

- THREE UNIT, SERIES CONNECTED TELEC DESIGNED TO ABSORB 95% OF THE INCIDENT CW, 1 MEGAWATT BEAM
- FOUR LONGITUDINAL EMITTER BLADES PLACED SYMMETRICALLY IN SLOTS OF THE CYLINDRICAL COLLECTOR
- CESIUM VAPOR WORKING FLUID AT 40-800 TON PRESSURE
- 25-100 METERS IN LENGTH (COULD BE FOLDED PATH)
- PREDICTED CONVERSION EFFICIENCY TO 48%

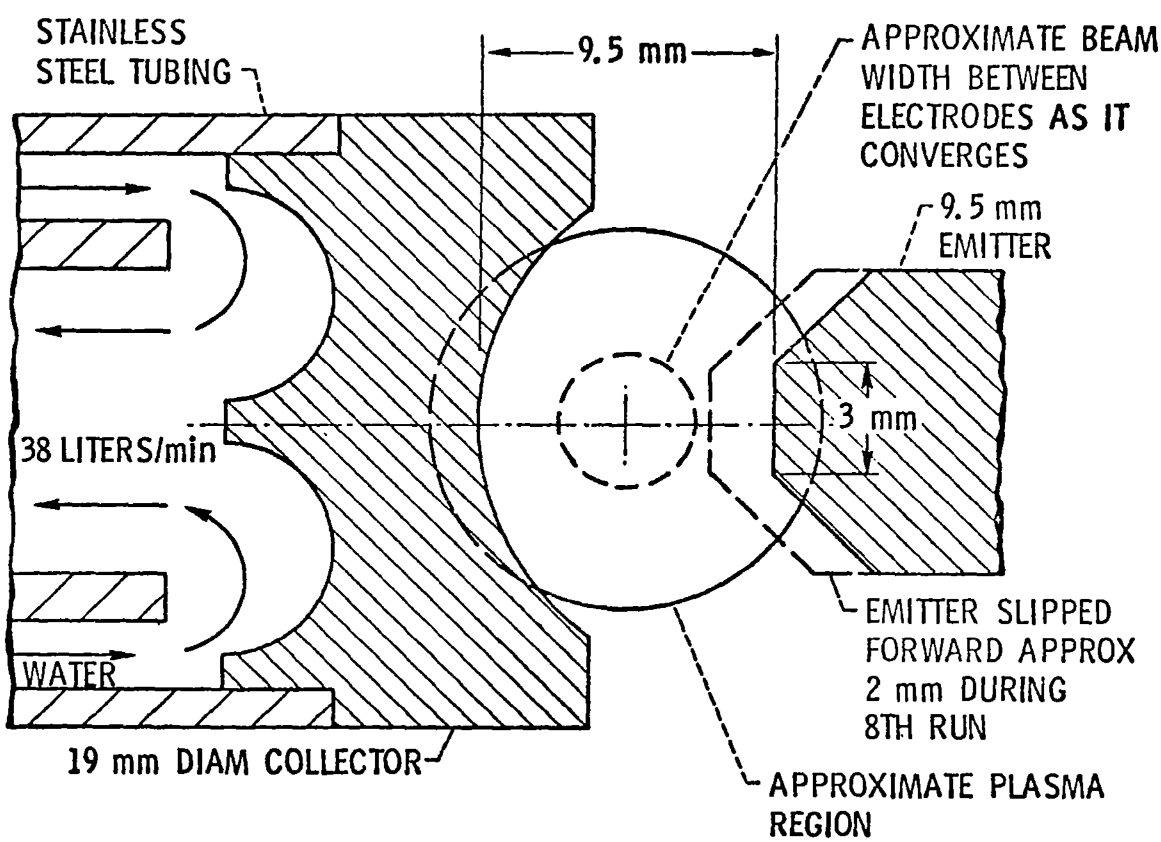
1 MW TELEC



TELEC PROOF-OF-CONCEPT EXPERIMENT

- CONTACT OF WATER COOLED COLLECTOR (SEGMENT OF HEMISPHERE) AND POINTED EMITTER WITH A LASER SUPPORTED PLASMA BALL IN ARGON AT ~840 TORR
- COLLECTOR/EMITTER AREA RATIO ABOUT 40
- INEFFICIENT CONVERSION SINCE COLLECTOR ENCLOSED ONLY SMALL FRACTION OF THE PLASMA
- MEASURED SHORT CIRCUIT CURRENT OF 0.7 AMPS AND OPEN CIRCUIT POTENTIAL OF 1.5 VOLTS

ARGON "TELEC" TEST



SMALL SCALE TELEC EXPERIMENT

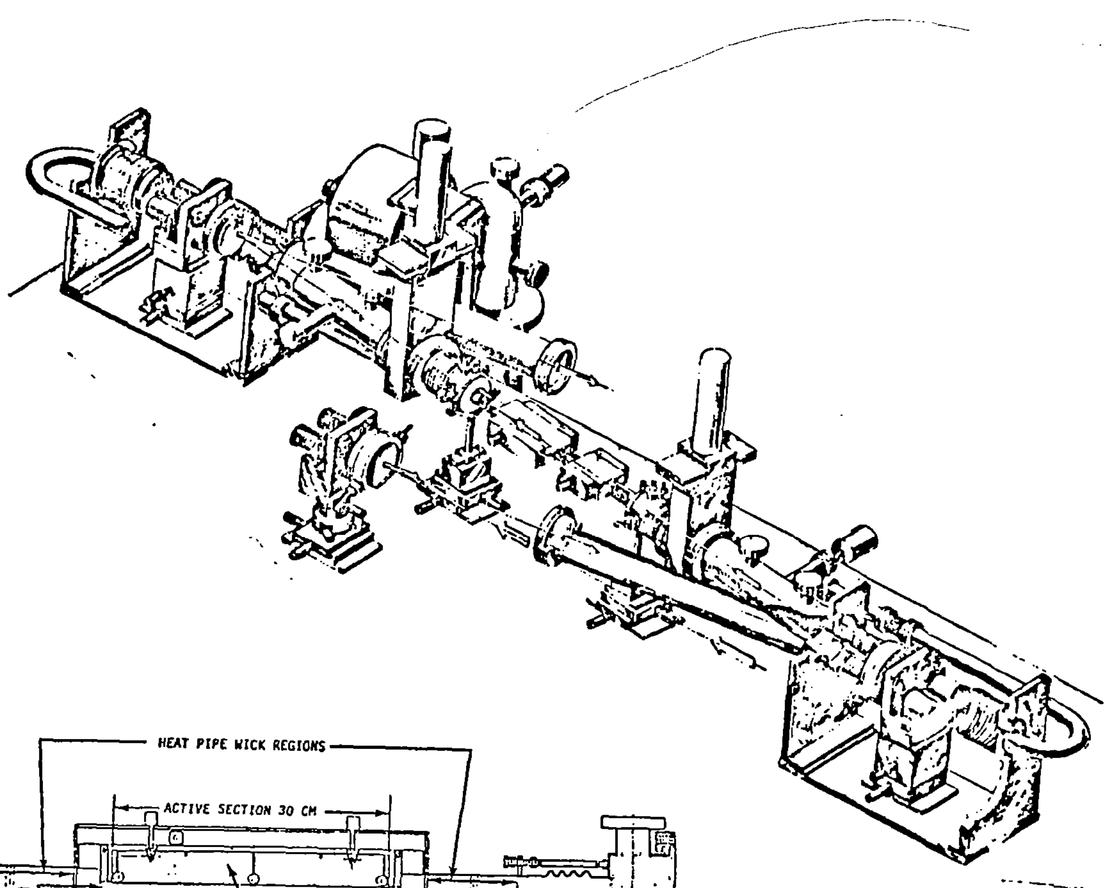
- DESIGNED, BUILT AND TESTED TELEC WITH 30 CM LONG ELECTRODES OF A GEOMETRY SIMILAR TO THE 1 MEGAWATT CONCEPT

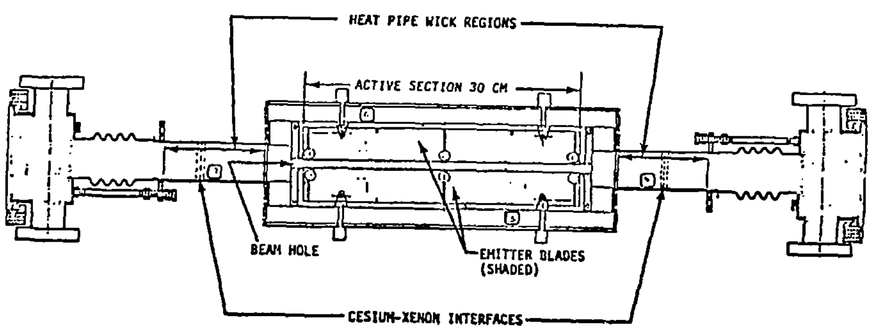
- TELEC OPERATION DEMONSTRATED WITH SEVERAL AMPERES OUTPUT AT 1 VOLT

- AVAILABLE LASER BEAM POWER ONLY SUFFICIENT FOR THRESHOLD OPERATION OF TELEC. INSUFFICIENT TO EVALUATE ANTICIPATED HIGH POWER CAPABILITY OF TELEC

- SUCCESSFUL DEMONSTRATION OF CESIUM VAPOR ISOLATION FROM THE OPTICAL PORTION OF TELEC BY A CESIUM-XENON INTERFACE (IMPORTANT FOR SCALE UP TO LARGE TELEC SYSTEM WITH FOLDED BEAM CAPABILITY AND OPTICS ISOLATION FROM CESIUM VAPOR)

TELEC
EXPERIMENT





TELEC

ACCOMPLISHMENTS

- FEASIBILITY STUDY AND CONCEPTUAL DESIGN OF A 1 MEGAWATT TELEC
- SUCCESSFUL TELEC PROOF-OF-CONCEPT EXPERIMENT (LASER FOCUS COVER, DECEMBER 1977)
- FABRICATED AND TESTED THE SMALL SCALE TELEC AND SUCCESSFULLY DEMONSTRATED CESIUM VAPOR ISOLATION, AS A WORKING MEDIUM OF THE TELEC, FROM THE OPTICAL SECTION BY A CESIUM VAPOR-XENON GAS INTERFACE

LASER TRANSMITTERS

Feasibility of a 30-Meter Space-Based Laser Transmitter
Itek Corporation (October 1975)

Analysis and Design of a High-Power Laser Adaptive-Phased Array Transmitter
Rockwell International (December 1977)

High-Power Phase-Locked Laser Oscillators
Rockwell International (May 1979)

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Richard B. Lancashire
October 1981

FEASIBILITY OF A 30-METER SPACE-BASED LASER TRANSMITTER

CR134903 CONTRACT NAS3-19400 OCTOBER 1975

ITEK CORPORATION

R. R. BERGGREN AND G. E. LENERTZ

FOR

NASA LeRC

DR. R. STUBBS, PROJECT MANAGER

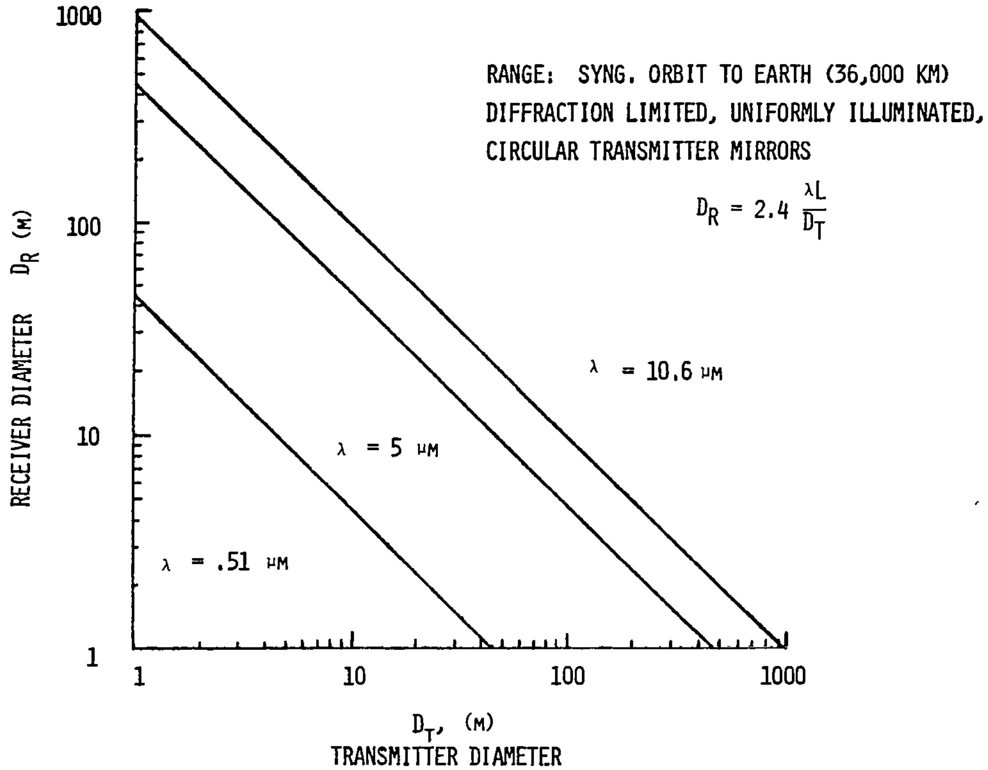
OBJECTIVE

STUDY THE FEASIBILITY OF DEPLOYING LARGE, DIFFRACTION LIMITED, HIGH POWER LASER TRANSMITTER MIRROR IN SPACE FOR SUCH APPLICATIONS AS PROPULSION AND POWER TRANSMISSION

GROUND RULES

BEAM WAVELENGTH	$10.6\text{X}10^{-16}$ M (CO_2)	
MIRROR HEAT FLUX	100 kW/M^2 (UNIFORM DISTRIBUTION ASSUMED)	
MIRROR ACCURACY	DIFFRACTION LIMITED PERFORMANCE, λ/20 SURFACE	
MIRROR REFLECTIVITY	.99	
POINTING STABILITY	$2\text{X}10^{-7}$ RADIANS	
MIRROR DIAMETER	30 METERS	
STOWED LENGTH (MAXIMUM)	18.3 METERS	
STOWED DIAMETER (MAXIMUM)	4.6 METERS	SPACE SHUTTLE LIMITATIONS
STOWED WEIGHT (MAXIMUM)	28,123 KG (62,000 LB.)	

LASER TRANSMITTER-RECEIVER SIZES



ELEMENTS OF SPACE LASER TRANSMITTER INVESTIGATION

STRUCTURAL CONCEPTS

MATERIALS SELECTION

THERMAL EFFECTS

VIBRATIONAL ANALYSIS

SPACE EFFECTS

ACTIVE CONTROL CONCEPTS

METHODS OF STOWING

METHODS OF DEPLOYMENT

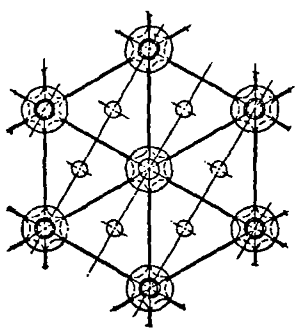
FAILURE MODE ANALYSIS

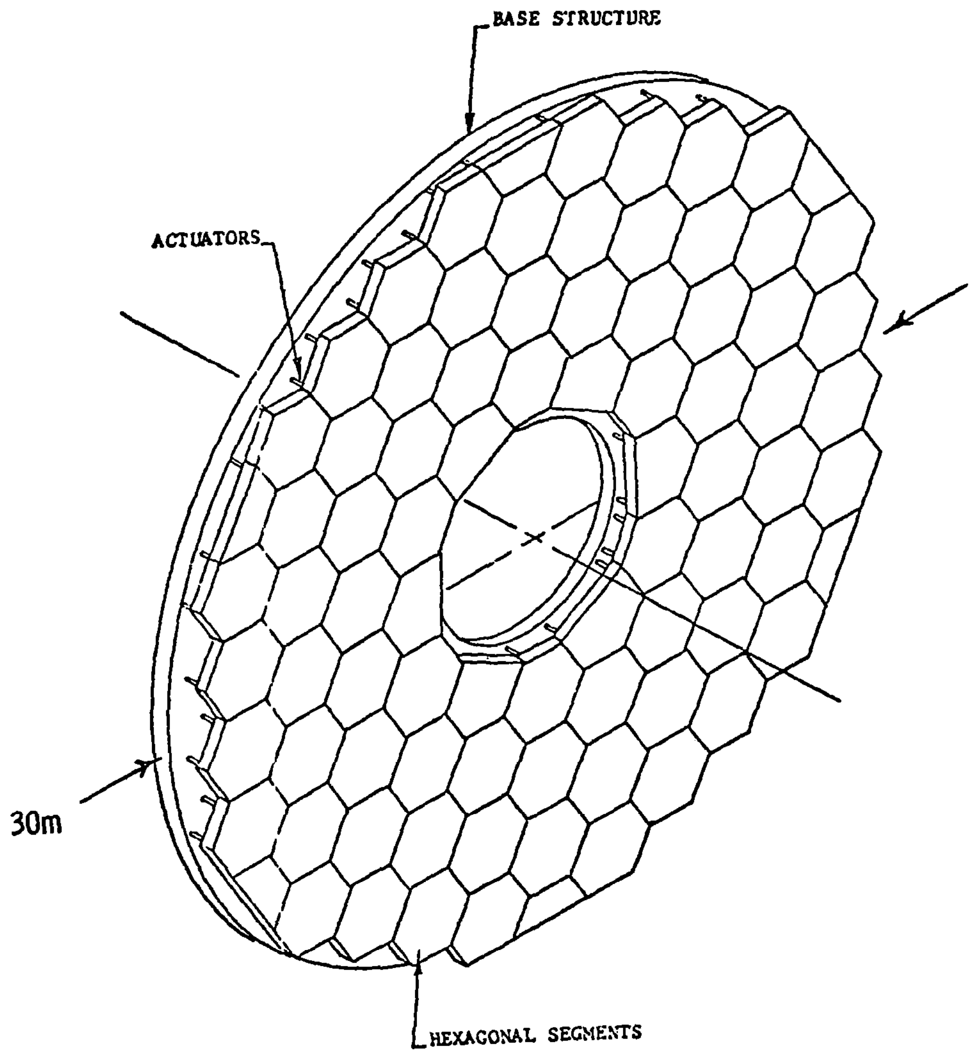
LARGE SPACE LASER TRANSMITTER

PRINCIPAL CONCLUSIONS:

- FEASIBILITY OF A 30 METER, DIFFRACTION LIMITED LASER TRANSMITTER DEPLOYED IN ORBIT HAS BEEN ESTABLISHED
- THREE CONCEPTS STUDIED - MOST PRACTICAL IS THE SEGMENTED MIRROR CONFIGURATION PARTIALLY ASSEMBLED IN SPACE
- ACTIVE MIRROR SURFACE CONTROL IS NECESSARY. ACTUATOR, SENSOR AND CONTROL LOGIC REQUIREMENTS CAN BE MET WITHOUT NEW TECHNOLOGY DEVELOPMENT
- MATERIALS OF LOW THERMAL COEFFICIENT SELECTED TO MINIMIZE COMPLEXITY OF ACTIVE FIGURE CONTROL SYSTEM ULE GLASS FACEPLATE, GRAPHITE - EPOXY SUPPORT STRUCTURE

CONCEPT FOR LARGE SPACE-BASED LASER TRANSMITTER MIRROR





RECOMMENDATIONS

- NASA MONITOR DOD EFFORTS
- DOD HAS PICKED UP CONCEPT; CONSIDERING OTHER TYPES

ANALYSIS AND DESIGN OF A HIGH-POWER LASER
ADAPTIVE-PHASED ARRAY TRANSMITTER

CR134952 CONTRACT NO. NAS3-18937 DECEMBER 1977

ROCKWELL INTERNATIONAL

ELECTRONIC DEVICE DIVISION

G. E. MEVERS, ET. AL.

FOR

NASA LeRC

DR. R. STUBBS, PROJECT MANAGER

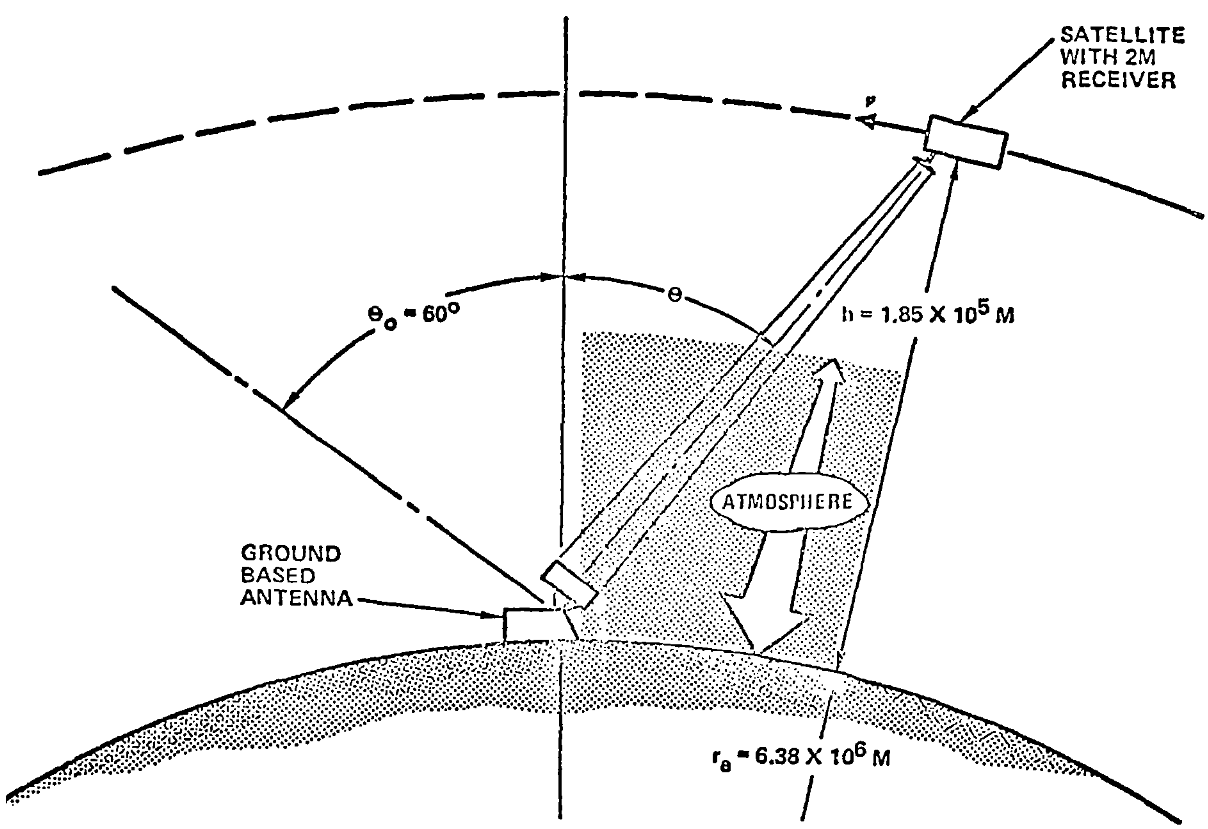
OBJECTIVE

- INVESTIGATE FEASIBILITY OF USING GROUND-BASED HIGH ENERGY LASER COUPLED TO AN ADAPTIVE ANTENNA TO DELIVER POWER TO A LOW EARTH ORBIT SATELLITE

GROUND RULES

- LASER TRANSMITTER LOCATED AT SEA LEVEL AND AT 3.5 KM (11,500 FT) ELEVATION
- *POWER LEVELS UP TO 5 MW*
- SATELLITE RECEIVER WITH 2 METER APERTURE IN 185 KM, CIRCULAR ORBIT (LEO)
- INVESTIGATE WAVELENGTHS OF 10.6 μM, 9.1 μM, 5 μM AND 3.8 μM

SATELLITE ORBITAL GEOMETRY



ELEMENTS OF STUDY

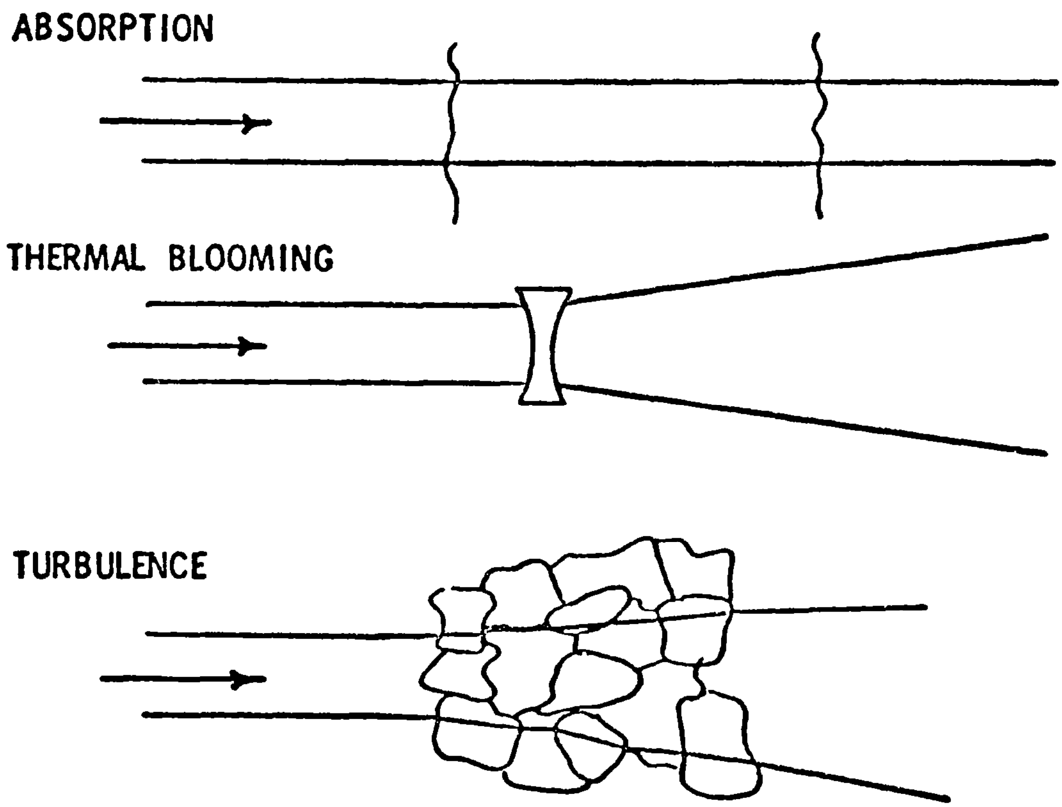
ATMOSPHERIC EFFECTS - ABSORPTION
- TURBULENCE
- THERMAL BLOOMING

ADAPTIVE COMPENSATION FOR TURBULENCE AND THERMAL BLOOMING

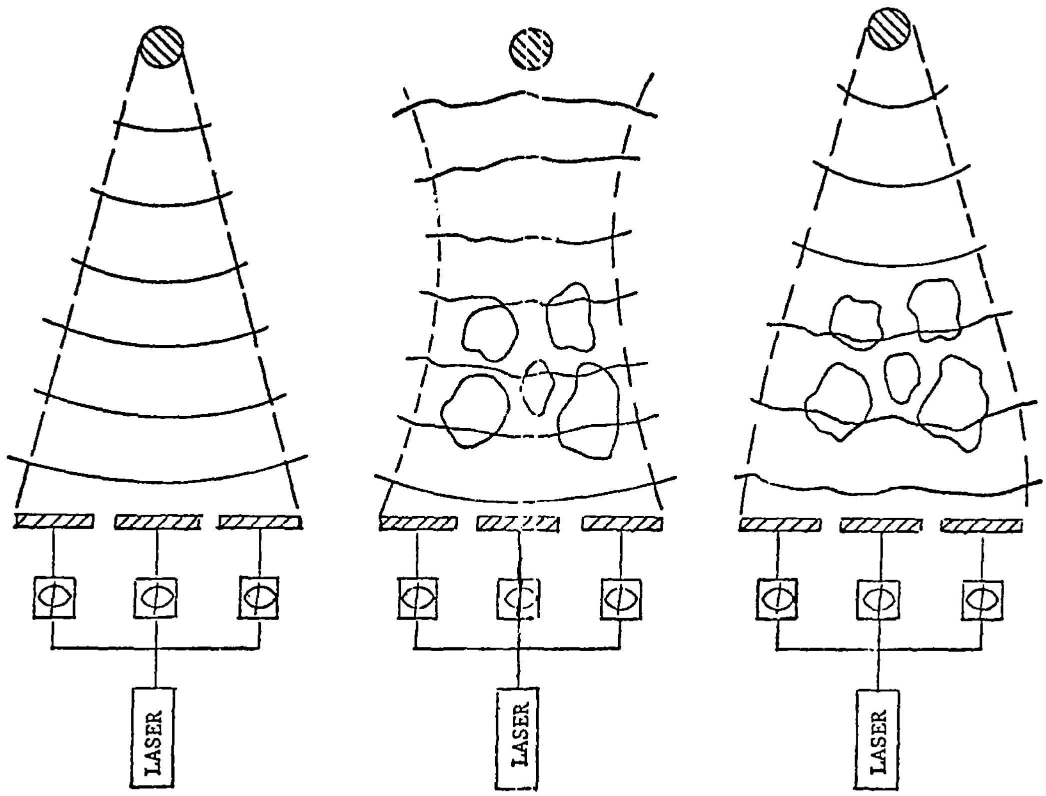
TRACKING REQUIREMENTS

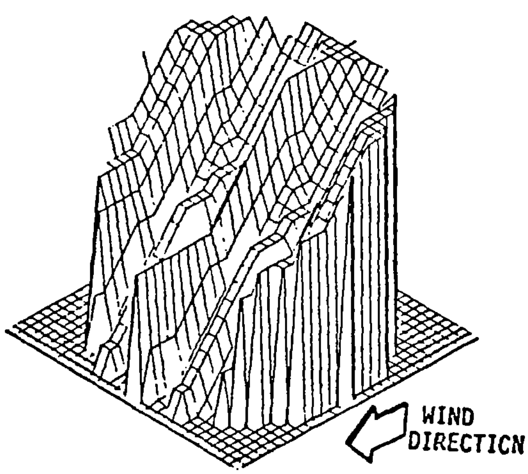
CONCEPTUAL DESIGN OF OPTIMUM SYSTEM

ATMOSPHERIC EFFECTS

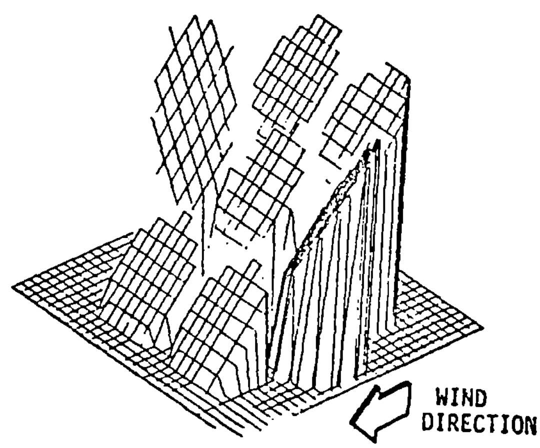


ADAPTIVE OPTICS FOR ATMOSPHERIC PROPAGATION





WAVEFRONT DISTORTION
WITHOUT ADAPTION

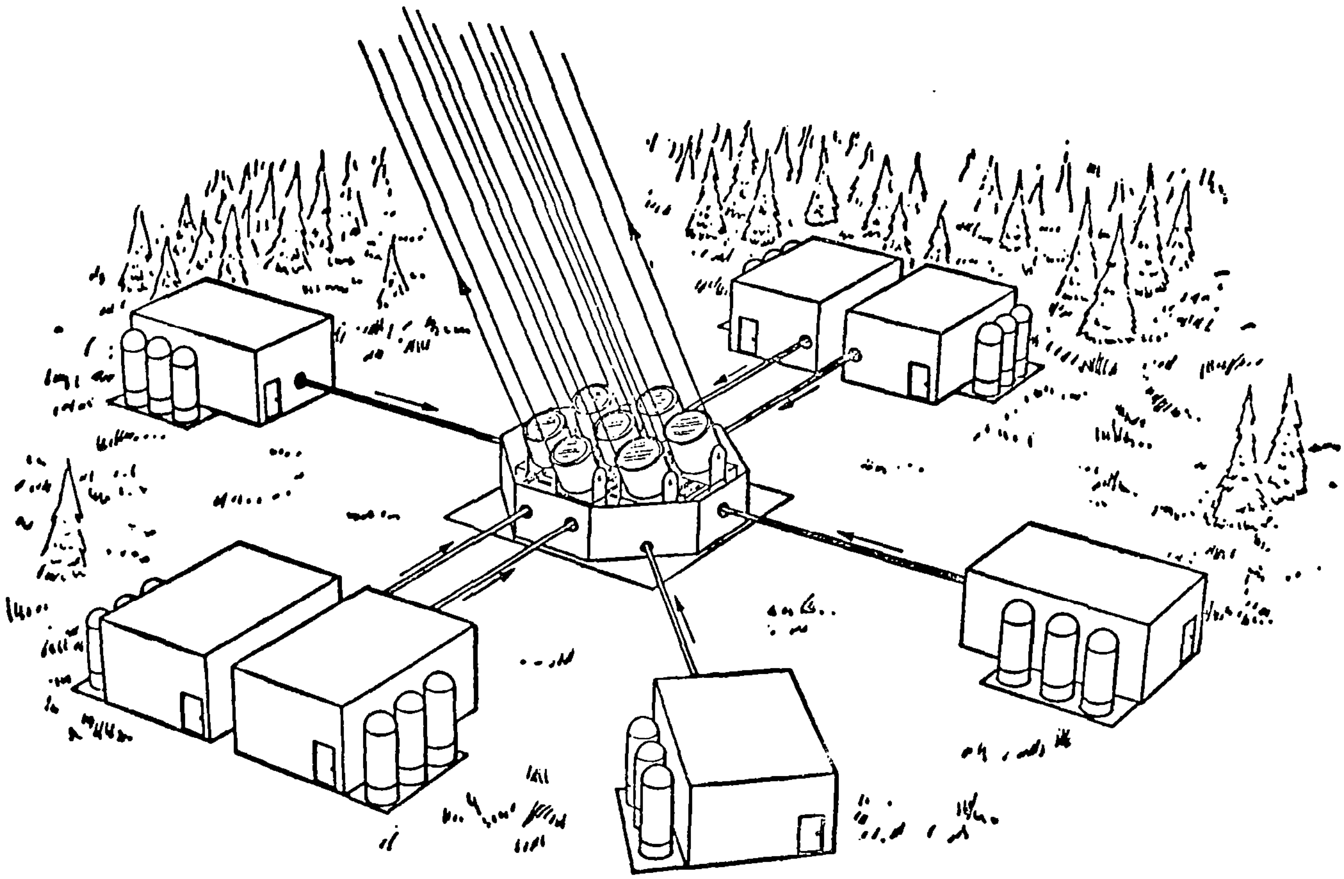


SEVEN-ELEMENT ARRAY ADAPTION
FOR PHASE CORRECTION

RESULTS AND CONCLUSIONS

- HPL TRANSMITTER SYSTEMS CAN BE DEVELOPED TO DELIVER MW POWERS TO SATELLITES WITH REASONABLE EFFICIENCY
- MOUNTAIN TOP LOCATION (3500 M) REDUCES ABSORPTION LOSSES ($< 5\%$) FOR MOST λ's
- TURBULENCE EFFECTS CAN BE SIGNIFICANTLY REDUCED BY ADAPTIVE SYSTEM. E.G. FOR CO_2, 87% TRANS. VS 40%
- THERMAL BLOOMING EFFECTS CAN BE ALMOST ELIMINATED BY ADAPTIVE SYSTEMS
- 9.1 μM FROM MOUNTAIN HAS OVERALL EFF. OF 53%; (72% DIFF.; 95% TURBO.; 100% THERM. BL.) SIMILAR OVERALL EFF. FOR 3.8 μM

CONCEPTUAL PHASE LOCKED LASER ARRAY INSTALLATION (5 MW)



CONCLUSION

- ADAPTIVE OPTICS, ALTHOUGH INITIATED TO CORRECT ATMOSPHERIC EFFECTS, ALLOW THE CORRECTION AND IMPROVED TRANSMISSION OF *ANY NON-IDEAL WAVEFRONT(S)*
- ANY NUMBER OF LASERS ARRAYED TO PRODUCE ANY DESIRED POWER LEVEL. NOT LIMITED BY SOURCE TECHNOLOGY
- EACH LASER CAN BE OPTIMALLY DESIGNED FOR MAXIMUM EFFICIENCY AND BEAM QUALITY
- REDUNDANT CHANNELS POSSIBLE

HIGH POWER PHASE-LOCKED LASER OSCILLATORS

CR134903 CONTRACT NO. NAS3-20376 MAY 1979

ROCKWELL INTERNATIONAL
ELECTRONICS DEVICE DIVISION

C. L. HAYES, ET. AL.

FOR

NASA LeRC

DR. R. STUBBS, PROJECT MANAGER

OBJECTIVE

EXPERIMENTALLY INVESTIGATE THE FEASIBILITY OF MECHANIZING AN ADAPTIVE ARRAY OF INDEPENDENT LASER OSCILLATORS FOR GENERATION OF A HIGH POWER COHERENT OUTPUT

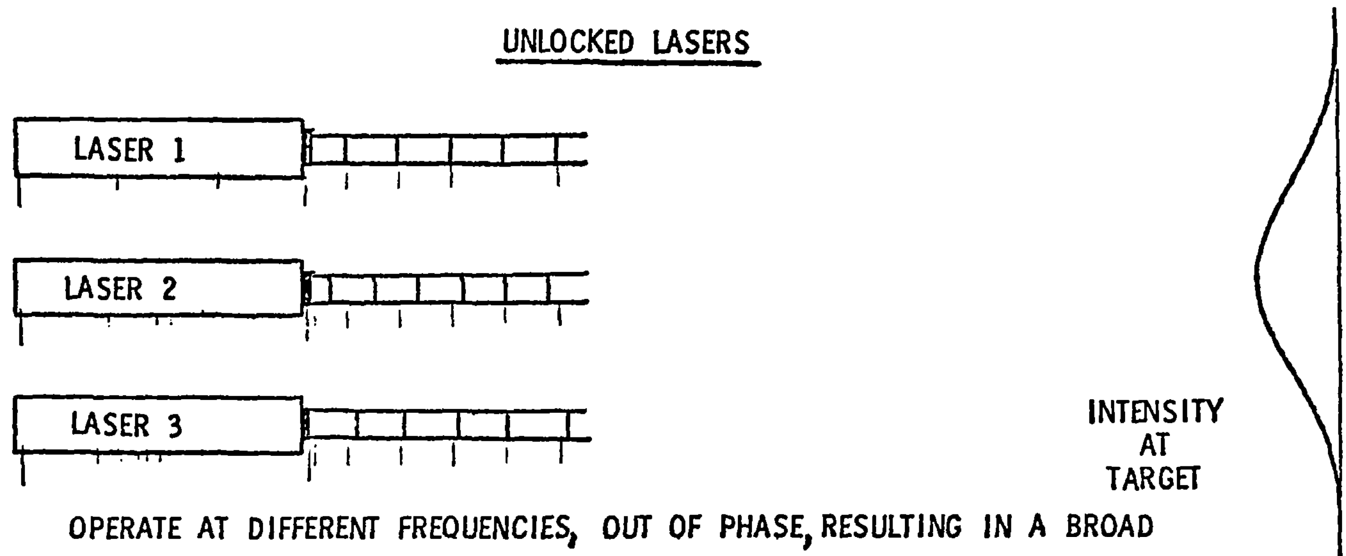
ELEMENTS OF INVESTIGATION

- ADDRESS CONTROL ISSUES OF PHASE LOCKING UNSTABLE RESONATORS AT LOW POWER LEVELS
- DEMONSTRATE PHASE LOCK (LOW POWER UNSTABLE RESONATORS)
- CHARACTERIZE OPERATIONAL LIMITS OF HIGH POWER CO_2 LASER

  ASSESS FREQUENCY STABILITY
  NOISE SOURCES
  OPTICAL PROPERTIES

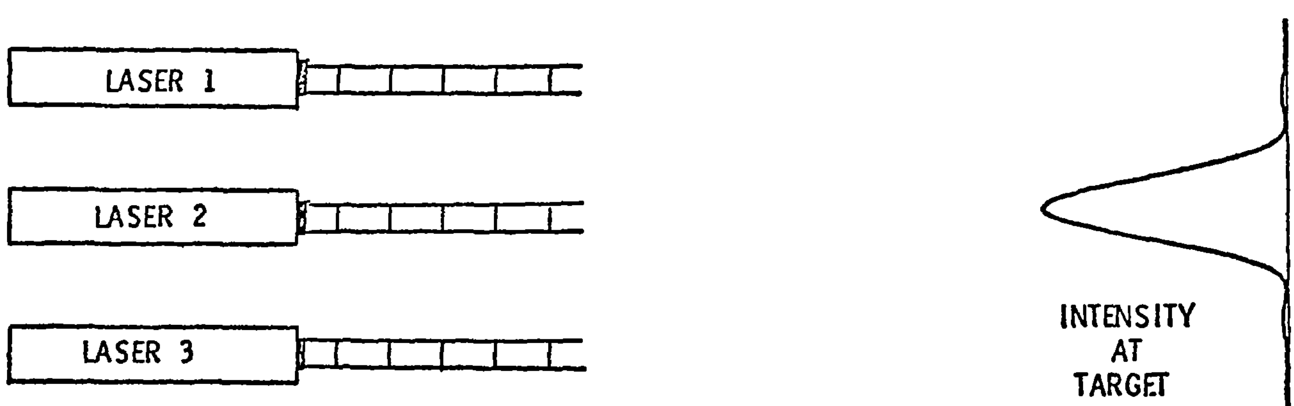
- DEMONSTRATE HIGH POWER PHASE LOCK

UNLOCKED LASERS



OPERATE AT DIFFERENT FREQUENCIES, OUT OF PHASE, RESULTING IN A BROAD PATTERN OF LOWER INTENSITY

PHASE LOCKED LASERS



PHASE LOCKING PRODUCES COHERENCE AMONG THE INDEPENDENT LASER OSCILLATORS RESULTING IN A TIGHT, HIGH INTENSITY BEAM AT RECEIVER

RESULTS AND CONCLUSIONS

- PHASE LOCK OPERATION BY CAVITY LENGTH CONTROL HAS BEEN DEMONSTRATED FOR FIRST TIME WITH KILOWATT LEVEL UNSTABLE RESONATORS

- ADDITIONAL DATA WERE COLLECTED TO CHARACTERIZE THE OPERATIONAL LIMITATIONS IMPOSED BY HIGH POWER CO_2 SYSTEMS

- CONTINUED EFFORTS SHOULD BE DIRECTED TOWARDS DESIGN OF PROOF-OF-CONCEPT DEMOSTRATION AT HIGH POWERS - UNIQUE NASA APPLICATION

LASER AIRCRAFT PROPULSION

UNIVERSITY OF WASHINGTON
AUGUST 1977

PRESENTED TO

SYMPOSIUM ON SPACE LASER POWER TRANSMISSION
SYSTEM STUDIES

LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

OCTOBER 14-15, 1981

REVIEWED BY:
Richard B. Lancashire
October 1981

OBJECTIVE

TO EXAMINE THE CONCEPT AND FEASIBILITY OF POWERING A COMMERCIAL AIRCRAFT DURING CRUISE OPERATION WITH A HIGH POWER CW LASER BEAM FROM A SOLAR POWERED SATELLITE IN GEOSYNCHRONOUS ORBIT

LASER AIRCRAFT PROPULSION SYSTEM

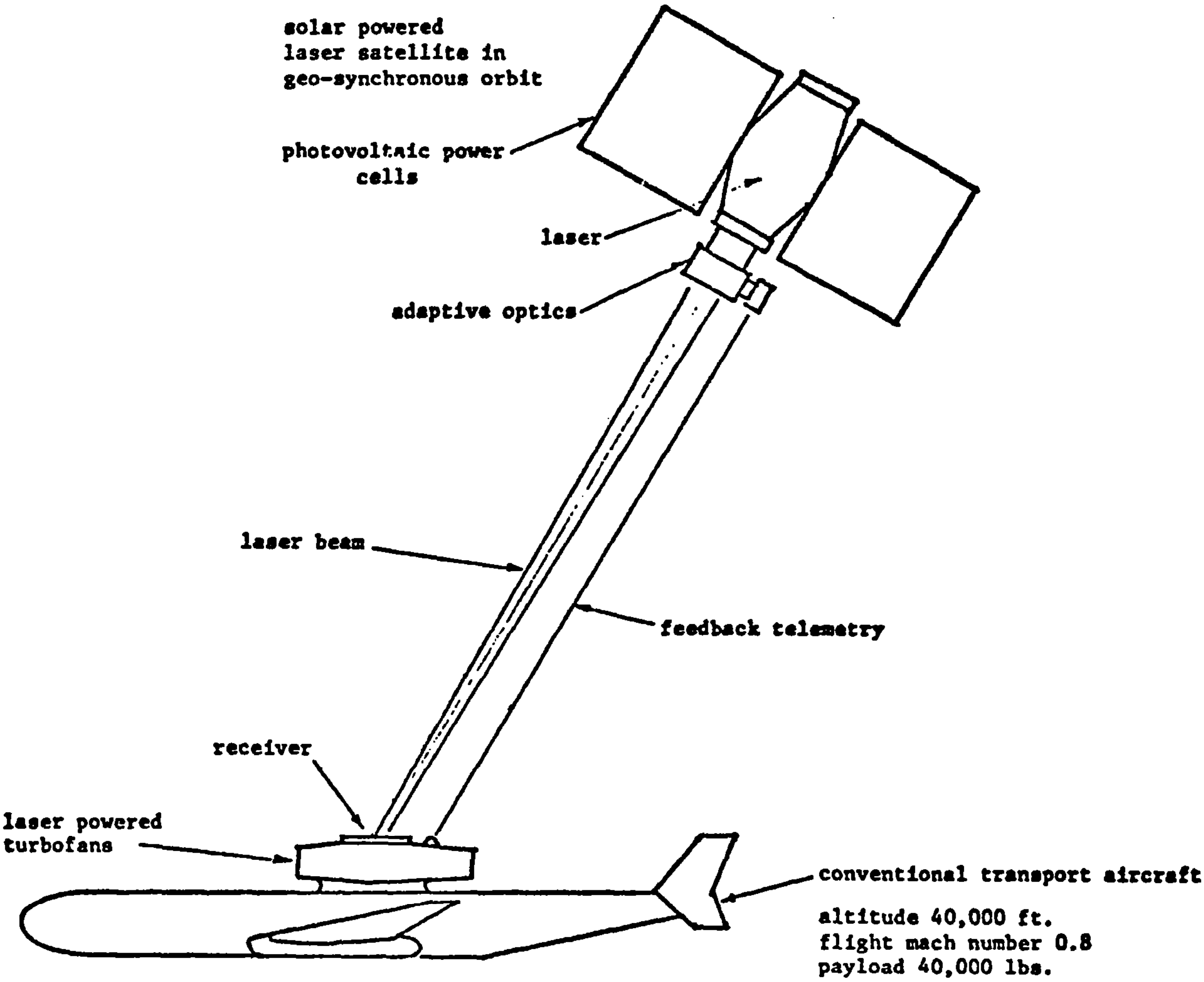
- MODIFIED LASER POWERED AIRCRAFT
- SATELLITE POWER STATION (SPS)

MODIFIED LASER POWERED AIRCRAFT

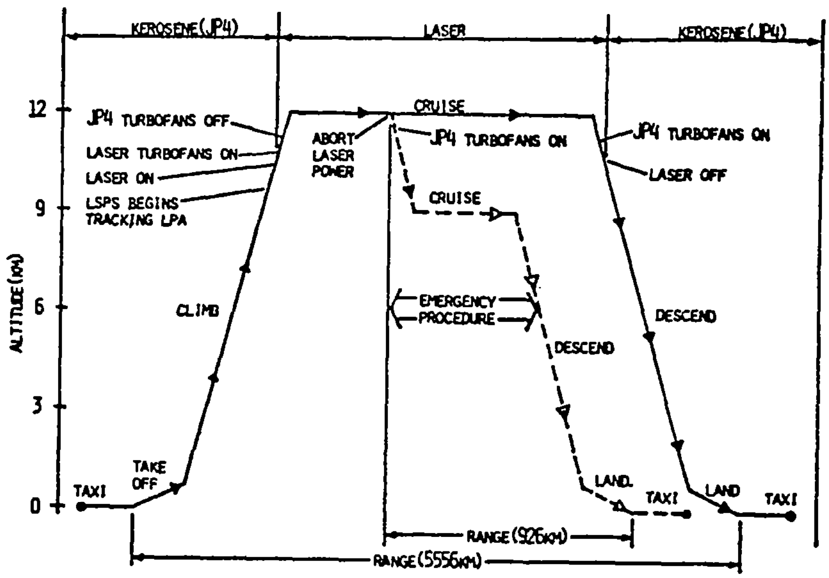
- MODIFIED BOEING FUEL CONSERVATIVE AIRCRAFT DESIGN
- LASER RECEIVER
- LASER TURBOFAN ENGINE WITH HEAT EXCHANGER FOR CRUISE FLIGHT
- JP-4 POWERED TURBOFAN ENGINES FOR TAKE-OFF, CLIMB, DESCENT AND LANDING

SATELLITE POWER STATION (SPS)

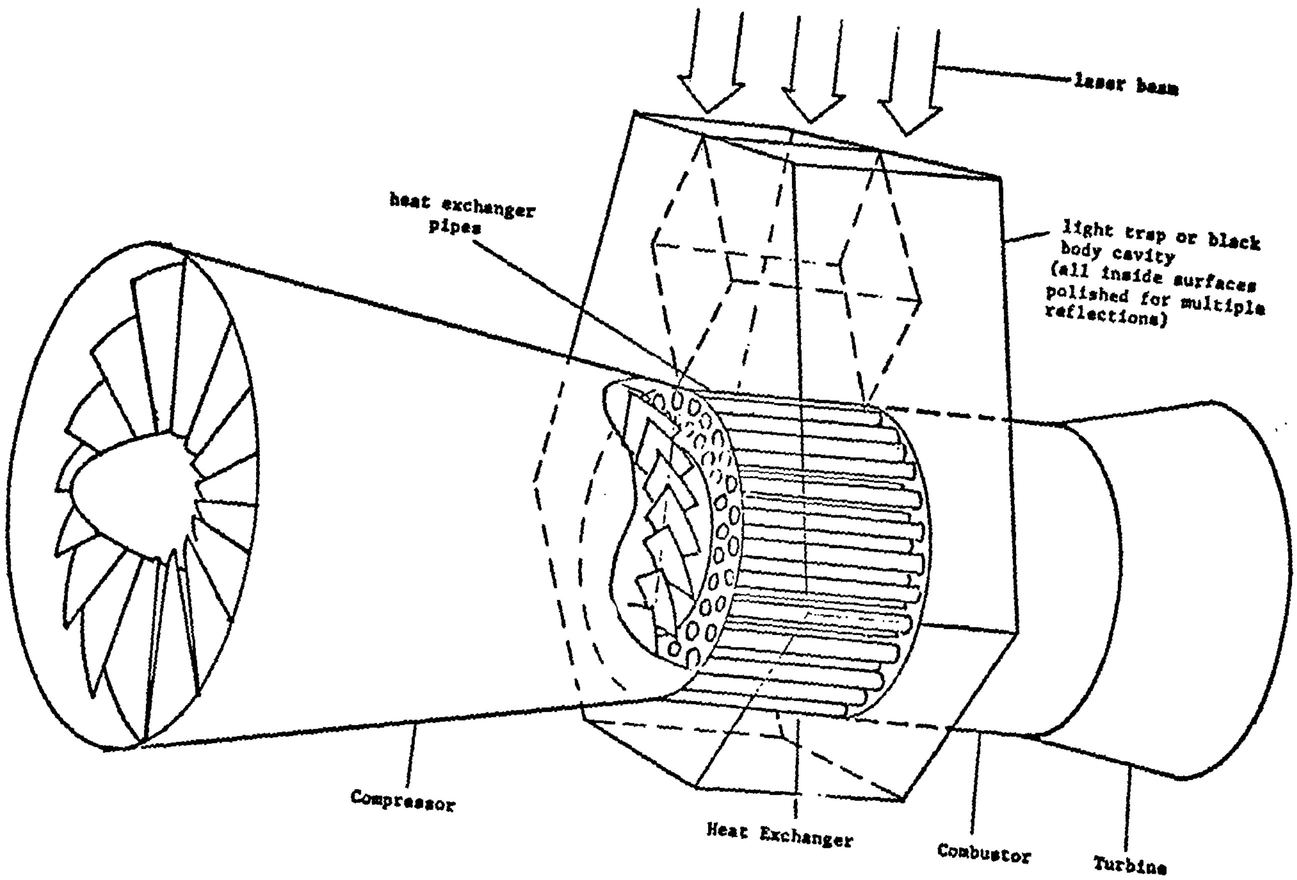
- SOLAR ENERGY COLLECTION SYSTEM WITH CONCAVE MIRRORS, PHOTOVOLTAIC CELLS, STRUCTURE AND ELECTRONICS - 15 GW_E
- LASER SYSTEMS (CO_2)
- RADIATOR SYSTEM
- ADAPTIVE OPTICAL SYSTEM
- LASER BEAM TRACKING



LASER POWERED AIRCRAFT TRANSPORTATION SYSTEM



Laser-powered airplane flight profile.



LASER POWERED TURBOJET-GENERAL ARRANGEMENT

AIRPLANE DATA

AIRPLANE TYPE	TAC/E	TAC/E JUMBO	LASER STAND.	LASER STRETCH	LASER JUMBO
NO. OF JP4 TURBOFANS	4	4	4	4	4
NO. OF LASER TURBOFANS	0	0	2	2	4
LASER POWER (MW)	0	0	35.9 (90)*	48.4 (100)*	71.2 (150)*
NO. OF PASSENGERS	196	350	196	238	350
MASS DISTRIBUTION (kg)					
WING GROUP	13749	25298	13749	13749	25298
VERTICAL TAIL	807	1484	1614	1614	2968
HORIZONTAL TAIL	1383	2544	1383	1383	2544
BODY GROUP	16670	30054	16670	20079	30054
LANDING GEAR	5779	9824	5779	5779	9824
FIXED EQUIPMENT	16670	28339	16670	20170	28339
STAND OPER ITEMS	4940	8398	4940	4940	8398
MISCELLANEOUS	975	1658	975	975	1658
KEROSENE TURBOFANS	6378	10332	6378	6378	10332
LASER TURBOFANS	0	0	8725	8725	17450
OVERALL EQUIPMENT WT.	67351	117931	74968	83792	132675
PAYLOAD WT.	18140	32400	18140	22200	32400
FUEL WT.	29809	51336	8022	9298	14145
TAKE OFF GROSS WT.	115300	201667	103045	115289	183410
WING AREA (m^2)	198.6	365.4	198.6	198.6	365.4
WING LOADING (kg/m^2)	580.4	551.9	518.9	501.9	580.5
CRUISE LIFT-DRAG RATIO	17.5	17.8	18.2	17.5	18.3
AIRFRAME COST ($M)	11.2	19.8	11.4	12.7	20.1
PROPULSION COST ($M)	2.3	3.8	5.6	5.6	10.2
TOTAL AIRCRAFT COST ($M)	13.5	23.6	17.0	18.3	30.3
FUEL SAVINGS/FLIGHT (kg)	0	0	21787	20511	37221

( )* - LSPS POWER REQUIREMENTS

MISSION MODEL

MISSION MODEL CONSTANTS

TIME PERIOD	30 YEARS
RANGE	5556 km
FLIGHTS/DAY/AIRPLANE	3
TOTAL PAYLOAD DELIVERED	178.8×10^9 kg

AIRPLANE TYPE	TAC/E	TAC/E JUMBO	LASER STANDARD	LASER STRETCH	LASER JUMBO
PAYLOAD MASS/AIRPLANE (kg)	18140	32400	18140	22200	32400
AIRPLANE FLEET SIZE	300	168	300	246	168
SATELLITE FLEET SIZE	0	0	150	123	84
AIRPLANE COST (EACH)	13.5 $M	23.6 $M	17.0 $M	18.3 $M	30.3 $M
SATELLITE COST (EACH)	0	0	650.4 $M	711.0 $M	1007.6 $M
AIRPLANE CREW PAY/FLIGHT	$2077	$2077	$2077	$2077	$2077
AIRPLANE MAINT. COST/FLIGHT	$2523	$4417	$2808	$3139	$4970
AIRPLANE FUEL WT./FLIGHT (kg)	29809	51336	8022	9298	14145

PERTINENT RESULTS

- LASER POWERED AIRPLANE FLIGHT SYSTEM PAYOFF TIME
  - ASSUMING SYN. KEROSENE COST OF $1.0/GALLON
  - PAYOFF TIME = INCREASED SYS. COST/FUEL COST SAVED/YEAR

1. 35 YEARS WITH LASER STRETCH AIRPLANE
2. 40 YEARS WITH LASER JUMBO AIRPLANE
3. 45 YEARS WITH LASER STANDARD AIRPLANE

- ENERGY PAYBACK

1. 2.9 YEARS FOR LASER STANDARD AIRPLANE
2. 2.59 YEARS FOR LASER STRETCH AIRPLANE
3. 2.65 YEARS FOR LASER JUMBO AIRPLANE

CONCLUSIONS

- A LSPS USING THE CO_2 LASER CAN BE CONSTRUCTED IN SPACE AT A REASONABLE COST WITH EXISTING AND PROJECTED TECHNOLOGY

- REQUIRED LASER POINTING AND TRACKING ACCURACIES ARE TECHNICALLY FEASIBLE

- WITHIN THE ACCURACIES OF THE ANALYSIS THE COST OF THE LASER AIRPLANE SYSTEM IS ECONOMICALLY COMPETITIVE WITH AN ADVANCED KEROSENE AIRPLANE SYSTEM

- DOMINANT COST OF THE LASER-POWERED FLIGHT TRANSPORTATION SYSTEM IS THE LSPS

- THE LASER FLIGHT SYSTEM HAS AN ENERGY PAYBACK OF LESS THAN THREE (3) YEARS

RECOMMENDATIONS

- DETAILED OPTIMIZATION STUDIES SHOULD BE PERFORMED FOCUSING ON DESIGNING THE MOST SUITABLE LASER FLIGHT TRANSPORTATION SYSTEM (CONTRACTOR RECOMMENDATION)

- LeRC MISSION ANALYSIS COULD NOT DISMISS CONCEPT BUT QUESTIONED PRACTICALITY

- THIS CONCEPT AND STUDY RESULTS SHOULD BE MAINTAINED FOR FUTURE CONSIDERATION

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PARTICIPANTS

R. W. Bercaw	NASA Lewis Research Center Mail Stop 500-125 21000 Brookpark Road Cleveland, OH 44135
E. J. Conway	NASA Langley Research Center Mail Stop 160 Hampton, VA 23665
R. J. De Young	NASA Langley Research Center Mail Stop 160 Hampton, VA 23665
R. E. English	NASA Lewis Research Center Mail Stop 500-125 21000 Brookpark Road Cleveland, OH 44135
D. J. Flood	NASA Headquarters Code RTS-6 Washington, DC 20546
L. B. Garrett	NASA Langley Research Center Mail Stop 364 Hampton, VA 23665
R. A. Gualdoni	NASA Headquarters Code RSS-5 Washington, DC 20546
D. H. Humes	NASA Langley Research Center Mail Stop 160 Hampton, VA 23665
L. W. Jones	Marshall Space Flight Center Code EP24 Marshall Space Flight Center, AL 35812
R. B. Lancashire	NASA Lewis Research Center Mail Stop 500-210 21000 Brookpark Road Cleveland, OH 44135
L. P. Randolph	NASA Headquarters Code RTS-6 Washington, DC 20546
G. D. Walberg	NASA Langley Research Center Mail Stop 367 Hampton, VA 23665

ATTENDEES

NASA Langley Research Center
Hampton, VA 23665

NASA Langley Employees:

M. D. Williams	(M.S. 160)
N. W. Jalufka	(M.S. 160)
W. E. Meador	(M.S. 160)
W. R. Weaver	(M.S. 160)
W. R. Hook	(M.S. 364)
D. R. McFarland	(M.S. 160)
J. W. Wilson	(M.S. 160)
W. J. Friesen	(M.S. 160)

NASA Langley Contractors:

J. H. Lee	(M.S. 160)
B. T. Smith	(M.S. 160)
E. Kamaratos	(M.S. 160)

1. Report No. NASA CP-2214	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SPACE LASER POWER TRANSMISSION SYSTEM STUDIES		5. Report Date February 1982
		6. Performing Organization Code 506-55-13-01
7. Author(s) M. D. Williams and E. J. Conway, editors		8. Performing Organization Report No. L-15030
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Conference Publication
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A Symposium on Space Laser Power Transmission System Studies was held at NASA Langley Research Center, October 14-15, 1981. The objective of the symposium was to review previous NASA system studies in the areas of space laser power generation, transmission, and utilization. This publication is a collection of abstracts, viewgraphs (some with comments), and articles that summarize the state of laser power transmission studies. The presentations were reviews of studies done previously for the U.S. Government. The studies cover such areas as applications, laser systems, transmission systems, conversion systems, and laser propulsion concepts.

17. Key Words (Suggested by Author(s)) Laser power transmission Laser power conversion		18. Distribution Statement Unclassified - Unlimited Subject Category 36	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 214	22. Price* A10

For sale by the National Technical Information Service, Springfield, Virginia 22161

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