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NEW ENERGY CONVERSION TECHNIQUES IN SPACE, APPLICABLE TO PROPULSION*†

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ABSTRACT

The powering of aircraft with laser energy from a solar power satellite may be a promising new approach to the critical problem of the rising cost of fuel for aircraft transportation systems. The result is a nearly fuelless, pollution-free flight transportation system which is cost-competitive with the fuel-conservative airplane of the future. The major components of this flight system include a laser power satellite, relay satellites, laser-powered turbofans and a conventional airframe. The relay satellites are orbiting optical systems which intercept the beam from a power satellite and refocus and redirect the beam to its next target.

INTRODUCTION

The dramatic, nearly prohibitive increase in the cost of aviation kerosene illustrates one of the major problems currently facing aircraft designers. This new design constraint has become a dominating factor in the consideration of future aircraft transportation systems. Even with the advanced technology projected for future aircraft, substantial amounts of fossil fuels must be consumed and, as these fuels become even more scarce, the operating costs of conventional flight transportation systems may very well rise to forbidding levels.[1]

The powering of an aircraft with laser energy beamed from a solar power satellite may be a promising new solution to the aircraft transportation fuel requirement, creating the possibility of a virtually pollution-free global air transportation system based on an inexhaustible energy resource. This

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*The concept of laser-powered aircraft propulsion has been previously discussed by the author. Papers were presented at the AIAA Aircraft Systems & Technology Conference (AIAA 78-1484), Los Angeles, CA, August 1978; the GCL Symposium, Brussels, Belgium, September 1978; the Delft University of Technology, Delft, The Netherlands, September 1978; and the AAS 25th Anniversary Conference, October-November 1978, Houston, TX. A similar paper was published in Astronautics & Aeronautics (17:41-49, 1979).

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paper will examine the potential of the laser-powered air transportation system as an approach which nearly eliminates fossil fuel requirements in aircraft transportation.

The system, described in the following sections, largely confines itself, as a first step, to near-term technology. For example, existing laser concepts and solar energy conversion systems are employed in conjunction with a modified conventional aircraft and propulsion system flying a standard flight profile. It is apparent that the cost of kerosene will rise in the near future to levels where such a system will become competitive even under these constraints. Moreover, the authors feel that these results invite continued studies in which the introduction of new technology and special design approaches are employed. Such studies offer the potential of making the laser-powered aircraft flight system economically superior as a major transportation system.

A laser-powered flight transportation system (Fig. 1) would involve beaming infrared laser energy from a solar power satellite, via a relay satellite, to a flying aircraft in which the laser energy is collected and converted into thermal energy for use by the aircraft propulsion system. Since laser-powered aircraft would be indirectly energized by solar energy, a laser flight system has the potential of saving significant amounts of fuel. For a 5500 km transcontinental range and a payload of 196 passengers (18,140 kg), a transonic laser airplane would require 40 MW of laser power and in each flight would save 31,400 liters (8300 gallons) over a similar fuel efficient kerosene airplane. Advances in laser aircraft propulsion may result in vehicles capable of hypersonic velocities which could serve as Air Breathing Launch Vehicles (ABLV). Several different laser aircraft concepts have already been proposed, as indicated in Table I.

An important part of laser aircraft systems is the Space Laser Power System, i.e., the laser power satellites and relay satellites.[2,3] The laser power satellites resemble microwave solar power satellites, except that a closed-cycle laser system is used instead of a microwave generator system. The relay satellites are orbiting optical systems which intercept the beam from the power satellite, correct beam distortions and refocus and redirect the beam to a flying laser aircraft or another receiver. Since the mass and the cost of a Space Laser Power System overshadow those of the aircraft, an analysis of any laser-powered flight transportation system must include an assessment of the Space Laser Power System.

Laser-powered flight transportation is an excellent example of the multi-mission capability of the Space Laser Power System. Because of its short wavelength, a laser beam can be focused to small spot sizes at very long transmission ranges. Small spot sizes result in small, high power density receivers that can be mirrors for a relay network, high temperature engines for electrical power generation, or compact propulsion units that can be integrated into an airframe. A relay network would enable the heavy laser power satellites to be deployed in a low Earth sun-synchronous orbit, avoiding the transportation costs to geosynchronous orbit, while still retaining a worldwide distribution capability.

In this article laser-powered ABLV's are introduced and then followed by a discussion of laser-powered commercial jet transports.

AIR BREATHING LAUNCH VEHICLES

The laser-powered ABLV combines the high specific impulse of an air breathing propulsion system with the high temperature potential of a laser heat engine. The projected kerosene and hydrogen fueled ramjets have a specific impulse on the order of 1000 seconds, approximately the same as a laser rocket. A. Kantrowitz and R. Rosa proposed that focused laser radiation be used to heat the ingested air to extremely high temperatures, resulting in a ramjet with even higher specific impulses.[4] An ABLV teamed with a Space Laser Power System, i.e., a space-borne energy source, results in a more flexible boost trajectory and a more gradual acceleration than the rigid rectilinear trajectory with a 10 g acceleration of the proposed laser rocket and the ground based laser system.[5] Unfortunately, ramjets cannot produce static thrust and an alternative engine cycle may be needed. L. Myrabo's laser-driven rotary pulse jet is one of several interesting and clever possibilities.[6] Myrabo's device is a pulsed system made quasi-steady by rotating a set of propulsion units.

An extensive system study is needed to fully assess the potential of these concepts. The relatively advanced technology requirements of ABLV's do not permit such an analysis at this time. The laser-powered commercial jet transportation system, however, is based on near-term technology, and hence is described in much greater detail, with a particular emphasis on the system cost.

LASER-POWERED FLIGHT TRANSPORTATION SYSTEM

This particular laser-powered flight transportation system involves a Space Laser Power System and a fleet of conventional aircraft, each equipped with laser driven turbofans (Figs. 1 and 2). In the Space Laser Power System, the laser power satellite is deployed in a low earth, sun-synchronous orbit and converts solar radiation into infra-red laser energy which is beamed to a relay satellite. The relay satellite is deployed in an elliptical orbit and redirects the beam towards the next target which is either a cruising airplane or another relay. At the airplane, the laser energy is converted into thermal energy, which is used to drive the engines. The aircraft engines are modified kerosene burning turbofans with a laser powered heat exchanger placed ahead of the combustor so that either kerosene or laser radiation can be used as an energy source. The airframe is a modification of a Boeing design for a fuel conservative air transport --the "Terminal Area Compatible/Energy" (TAC/E) airplane.[7]

It must be emphasized that untried technology is avoided as far as possible in this analysis. This laser-powered flight transportation system is based on available and near-term projected technology, and the major subsystems are direct modifications of existing designs.

The flight profile chosen for the laser-powered airplane (Fig. 3) is the same as that of a conventional kerosene burning airplane. The laser flight system is completely compatible with existing airports and air traffic control systems. The laser airplane will take off and climb to an altitude of 9 kilometers using kerosene power alone. Upon reaching cruising altitude, the laser power satellite and relay satellites will begin tracking the airplane. When a secure tracking lock is achieved, the laser will be activated and the beam will be directed to the receptor area of the airplane. At this point the airplane will fly on laser power alone with the kerosene flow shut off. Using only laser power, the airplane will continue to cruise to its destination. Prior to descent, the kerosene flow will be turned on. When full kerosene power is restored, the laser will be diverted away to another waiting laser airplane. Using only kerosene, the laser aircraft will descend and land in a conventional manner. In the case of an interruption of laser power, the airplane will have an emergency kerosene reserve for a 930 kilometer cruising range.

The practicality of a laser-powered flight transportation system is measured by its system cost and depends heavily on whether or not the fuel savings will offset the high capital cost of the Space Laser Power System. These costs are a reflection of the particular configuration that we have chosen: power satellites, relay satellites, and a specific laser airplane design. This configuration evolved from a consideration of the available technology and a rough optimization of the spacecraft deployment strategy. Within this sytem framework, each subsystem (i.e., components of the power satellite, relays, and airplanes) was in turn designed for minimum cost.

The following sections of this paper will discuss the important aspects of each major component of the laser-powered flight transportation system, with an emphasis on obtaining a realistic cost estimate. The analysis is initiated by the preliminary design of a laser-powered turbofan and the suggested modification of a Boeing TAC/E airframe. Next, the laser power satellite and relay satellites are designed to meet the airplane laser power and receiver area requirements. The total laser flight system cost is then calculated using these component costs and compared against an advanced kerosene flight system.

LASER TURBOFAN

The laser turbofan is comprised of two major components: a heat exchanger which converts laser radiation into useful thermal energy, and conventional turbomachinery(Fig. 4). The laser turbofans are installed in a common housing or propulsion pod. Mounted on top of the propulsion pod is a 15 meter diameter receiver which focuses and directs the laser beam into a heat exchanger placed inside a blackbody cavity with a 5 meter diameter opening. Once inside the cavity, the laser beam is processed by a system of mirrors and light pipes into an intensity distribution that illuminates the interior of the heat exchanger tubes. Reflection and re-radiative losses are held to 3 MW because of the blackbody cavity design. Compressor air passing over the outside of these thin circular tubes is heated by cross flow convection and passed to the turbine. In order to keep the heat exchanger pressure drop small, the inlet flow Mach number is kept low, $M = 0.05$.

The laser receiver must be covered with a thin transparent window in order to minimize skin friction and prevent the establishment of convective flows inside the blackbody cavity and concentrator. Such a laser receiver window could be fabricated by mounting a set of window elements in a mosaic frame with the air pressure behind the window approximately equal to that of the external air flow. Sapphire-like substances are suitable window materials due to their good infrared transmission, high mechanical strength, thermal stability and insensitivity to thermal shock.

The resulting heat exchanger is relatively light, amounting to only 45% of the uninstalled gas turbine weight. Relatively compact heat exchangers can be designed because the laser energy can be focused in a manner leading to almost constant (high) wall temperature throughout the entire length of the heat exchanger. The heat exchanger weight was estimated as the total tube weight. This, however, ignores headers and other miscellaneous equipment which should not increase the airplane weight by more than few percent. The material chosen for this heat exchanger design is a nickel-chromium iron alloy.[8]

The laser turbofan is equipped with a combustor in tandem with the heat exchanger to facilitate the two modes of operation, kerosene and laser. Under kerosene power, the turbine inlet temperature ranges from 1560°K at sea level static to 1420°K at high altitudes, similar to those of the conventional Boeing TAC/E airplane. Under laser power the turbine inlet temperature is 1100°K. Higher turbine inlet temperatures could be obtained by increasing the heat exchanger size; however, the additional thrust gained by these higher temperatures is offset by the weight penalty of a larger heat exchanger. Material limitations restrict the wall temperature to less than 1300°K.

MODIFIED AIRCRAFT

The basic airframe used in this report is an example of Boeing's design for a fuel conservative aircraft, the TAC/E airplane (Fig. 5). In order to share the same laser receiver the laser turbofans are grouped together in a common propulsion pod. The three engine propulsion pod is placed above the center of the fuselage in a manner resembling Boeing's AWACS design (Fig. 6) requiring, of course, a substantial structural re-design. The calculated laser airplane cruise lift to drag ratio is 14.6. Applying this same method to the baseline Boeing TAC/E airplane, the resulting lift to drag ratio is 17.4, which agrees with Boeing's estimate of 17.5.[7] Due to the large laser receiver, a more optimal aircraft configuration might integrate the laser receiver completely into the airframe.

The airplane costs, i.e., the manufacturing costs, crew pay and maintenance costs, were derived from Boeing's analysis of the TAC/E airplane.[7] Since the heat exchanger mass is small in comparison to the airframe mass, the manufacturing costs of the laser airplane and kerosene airplane are similar.

LASER POWER SATELLITE

One possible design for a 42 MW output laser power satellite is shown in

Fig. 7. A solar-powered thermal engine generates electrical power for the closed-cycle supersonic electric discharge CO laser. An adaptive optical system employing active controls to remove beam aberrations aims and focuses the laser radiation. The three major satellite subsystems, the Electrical Power Supply, the Closed-Cycle Laser and the Optics, are detailed in the following sections. The mass and cost estimates of the resulting laser power satellite are also described in later sections.

ELECTRICAL POWER SUPPLY

Electrical power is generated using a regenerative Brayton cycle thermal engine with a cycle efficiency of 38%. More advanced thermal engines, such as the Potassium Rankine Cycle[9,10] and the Energy Exchanger Cycle[11], may be used in the future. Photovoltaic power cells are probably unacceptable in low earth sun-synchronous orbits due to the severe radiation degradation from exposure to the Van Allen Belts.

LASER SYSTEMS

Both the CO and CO_2 lasers were considered in this study. However, optical considerations favored the shorter wavelength of CO radiation. Due to beam diffraction, a CO laser ($\lambda = 5\ \mu m$) requires a 30 m diameter transmitter aperture for a 10 m diameter spot at a 20,000 kilometer range, whereas a CO_2 laser ($\lambda = 10.6\ \mu m$) requires a 60 m diameter aperture. As suggested by Mann,[12] an electric to laser open-cycle conversion efficiency of 60% was used. After taking into account the energy needs of the refrigeration and recirculation equipment, the final closed-cycle conversion efficiency reduces to 25%.

The heaviest components of a closed cycle CO laser are the heat exchangers, radiators, the supersonic diffuser and ducting, which collectively amount to 85% of the total subsystem mass. Since most of the laser components are similar to those used in existing thermal engines, the manufacturing cost of a closed cycle laser device should correspond to that of these same thermal engines. Consequently, the manufacturing cost of the laser subsystem is adjusted to be \$500/kg, which is about 35% higher than the cost of a high bypass turbofan (\$368/kg)[7].

OPTICS

Using Coherent Optical Adaptive Techniques (COAT)[13], a sophisticated optical system directs the laser radiation to the proper receiver and maintains beam coherence. The transmitting aperture expands the narrow beam from the laser device and corrects for any beam distortions. In this design a Cassegrain aperture configuration using a large concave primary mirror and a small convex secondary mirror is employed (Fig. 8). On the secondary mirror, error sensors measure beam distortions and instruct the primary mirror to change its shape in order to provide the necessary phase corrections. The primary mirror surface is composed of small mirror plates supported by fine actuators on a reaction structure which in turn is supported on a truss structure by coarse actuators. The combination of these actuators and mirror segments conforms the primary mirror to the desired shape.

The primary mirror has a 30 m diameter and the secondary mirror has a 0.6 m diameter. The technical feasibility of a 30 m diameter lightweight adaptive mirror for space has already been explored by R. Berggren and G. Lenertz of Itek Corporation.[14] Allowing for diffraction, 0.05 microradian beam jitter and $\lambda/20$ wavefront error, a 30 m diameter transmitter can focus the 5 micron CO laser radiation to an 8.5 m diameter spot size at a range of 20,000 kilometers. This results in a 15m aircraft receiver diameter which is large enough to capture the beam, including jitter.

In order to center the laser spot on the receiver area, submicroradian pointing and tracking accuracies are needed. For a receiver diameter D of 15 meters and a range R of 20,000 kilometers, a tracking resolution $\delta\theta < D/2R \approx 0.4$ microradians is required. With active interaction between the transmitter and receiver units this requirement can be met. Each receiver unit will be equipped with a feedback telemetry system to communicate positioning and beam quality information back to the transmitter. Experiments at Lockheed have already demonstrated a beam stabilization of better than 1 microradian.[2] Conventional space systems already achieve 0.10 to 0.01 microradian tracking accuracies.[15]

Only 5 percent of the laser beam is lost during propagation. Due to the lack of CO and H_2O at high altitudes, the vertical atmospheric transmission of CO laser radiation from space to an airplane at a 9 km altitude is calculated to be 99%, using the atmospheric absorption coefficients from McClatchey.[16] Besides atmospheric absorption and scattering, other losses occur in imperfect relay mirrors and in the truncation of a Hermite Gaussian beam by a finite receiver size.

The heaviest optical components are the primary mirror, the transmitter structure and the control moment gyroscopes, totaling approximately 95% of the optical system mass. Since production models of large scale space optics do not exist, the first unit manufacturing costs were parametized for $1,000 to $3,000 per kilogram, comparable to the cost of similar complex equipment.

POWER SATELLITE MASS AND COST SUMMARY

The laser power satellite mass and cost distribution are shown in Fig. 9. The total power satellite mass is 671,500 kg. The thermal engine electrical power supply is the heaviest subsystem at 74% of the total satellite mass. The closed cycle laser and the optical system are respectively 18% and 8% of the total satellite mass.

The cost analysis includes DDT&E costs (Development, Design, Testing & Engineering), manufacturing costs, space transportation costs, space assembly costs and maintenance costs. The DDT&E costs average $3,500/kg. The first unit manufacturing costs were calculated, using the cost structure described in the previous sections. Then, in order to find the mass production costs, an 85% learning curve was applied to the first unit power satellite cost. Using a Heavy Lift Launch Vehicle, the space transportation cost to a low sun-synchronous orbit is $47/kg.[2] P. Glaser has suggested a space assembly cost of $30/kg.[17] The maintenance cost is calculated on the assumption that during its 30 year lifetime, 10% of the laser power satellite will be replaced. An interest rate of 6% per year was applied to the initial procurement costs (DDT&E, manufacturing, space transportation and space assembly costs), to account for the penalties of such a large capital investment. Interest rates for large tax-free capital investments are currently 6% per year for tax-free systems over a thirty year life. (Taxable import-export investments handled by the U.S. World Bank are charged an interest between 8% and 9% per year.) The initial procurement costs were assumed to be repaid over the entire lifetime of the power satellite in a series of equal annual payments. All costs are in constant 1978 dollars.

In spite of its relatively small mass, the transmitting optical system is the most expensive subsystem of the power satellite because of its high technology and precision design requirements. Due to its low Earth orbit, the space transportation costs are only 20% of the initial procurement costs as opposed to 45% for geosynchronous deployment. The total cost of each power satellite is $170 million, assuming a $2,000/kg optics cost.

RELAY SATELLITES

Relay satellites intercept the beam from a space laser power satellite, correct outgoing beam aberrations, refocus the beam and direct it to the next target. Lockheed's concept of a relay satellite with two Cassegrain optical systems, one for receiving and another for transmitting, is shown in Fig. 10. The primary receiver mirror captures the incoming beam and directs it to transfer mirrors where beam jitter is removed. Inside the spacecraft, these transfer mirrors guide the beam to the primary transmitter mirror which corrects beam distortions, focuses and redirects the beam. The relay's optical systems are designed to be very similar to those of the laser power satellite. The transmitter and receiver primary mirrors and secondary mirrors have the same respective dimensions as the Cassegrain transmitter on the laser power satellite. Almost 90% of the relay satellite's total mass is involved with optics; the remainder is associated with spacecraft housekeeping functions.

The relay satellite cost analysis is very similar to that of the laser power satellite. Due to the different orbital requirements (elliptical rather than sun-synchronous), the space transportation cost was assumed to be $97/kg. Since each relay could be launched as a completed unit from earth, space assembly costs were ignored. As with the power satellite, the first unit manufacturing cost of optics were parametized from $1,000/kg to $3,000/kg.

In spite of their small size and mass (each relay weighs only 12% of the power satellite weight), relay satellites are inherently very expensive due to the high cost of optics. Depending on the cost of optics, the relay costs range from 25% to 50% of the power satellite cost. A mass and cost summary of a relay satellite is displayed in Fig. 11. The total mass and cost of each relay are 77,500 kg and $66 million respectively, assuming a $2,000/kg optics cost.

SPACECRAFT DEPLOYMENT

Past studies by Lockheed[2,3] indicate that space laser systems are very effective when teamed with relay satellites. For example, in applications requiring small near-earth laser receivers, a geosynchronous laser power satellite requires large transmitter apertures, excessive space transportation costs and very demanding pointing and tracking accuracies. For a laser-powered flight system, a more suitable, though not necessarily optimal, spacecraft deployment strategy would be to place the laser power satellites in a low sun-synchronous orbit and to place the relays in an elliptical orbit. The low sun-synchronous orbit is a nearly polar orbit that avoids the earth's shadow and leads to significant reductions in space transportation costs compared to those of geosynchronous deployment. The large angular inclination and very high apogee over the northern hemisphere of the relay elliptical orbit result in long loiter times over the northern hemisphere.

For example, power satellites in a 1500 km altitude circular sun-synchronous orbit at a 97° inclination to the equator would beam laser energy to relay satellites in a 4 hour elliptical orbit with a 500 km perigee and a 12,300 km apogee at a 63.4° inclination (Fig. 2). Each relay is over the northern hemisphere from 0.5 until 3.5 hours past its perigee. The relays can be used effectively in the northern hemisphere for 75% of its orbital period. Eight relays in this same orbit spaced 45° apart can provide full time coverage of the northern hemisphere. However, only six of the eight relays would be over the northern hemisphere at any given moment. For simplicity, a strategy of one power satellite and one relay per flying airplane was chosen. Thus, if an airplane flies 3 times per day and averages 8 hours per flight, then 6 power satellites, 8 relay satellites and 6 airplanes can handle 18 flights per day. Boeing's analysis of the TAC/E airplane assumed a fleet of 300 airplanes. Following Boeing's example, a fleet of 300 airplanes was selected for this study. Consequently, 300 power satellites and 400 relay satellites are also needed.

FLIGHT SYSTEM COST ANALYSIS

In this cost analysis a control group, the kerosene airplane fleet, and an experimental group, the laser airplane fleet, are both subjected to the same mission models. This technique minimizes the need to make an absolute determination of the actual system cost. Instead, relative costs determine the system's effectiveness.

The standard mission models are an 18,140 kg payload for each airplane to be delivered over ranges of 5500 km and 7500 km. The laser flight system consists of a fleet of 300 laser power transmitters, 400 relay satellites and 300 airplanes. The kerosene flight system consists of a fleet of only 300 airplanes. Each airplane flies 3 times a day with each flight lasting approximately 8 hours. A 30 year lifetime is assumed for the aircraft and spacecraft. Since the actual future cost of kerosene is unknown, the fuel costs were parametized from 26¢/liter to $1.05/liter.

The cost effectiveness of the laser flight system is measured by the break-even fuel cost which is the cost of kerosene at which the annual cost of the laser airplane fleet equals the annual cost of the kerosene airplane system. If the manufacturing cost of optics is $2,000/kg, then the break-even fuel cost is 52¢/liter ($2/gal) for a 5500 kilometer range. For a 7500 kilometer range the break-even fuel cost is 36¢/liter ($1.40 gal). The anticipated cost of synthetic kerosene is expected to be about 40¢/liter ($1.50/gal). Despite the large amounts of rocket propellant consumed in delivering the power satellites and relays to orbit, the energy content of the kerosene saved by the laser airplane system will equal the total energy cost of the space system in a little more than a year of operation.

Fig. 12 depicts the subsystem cost distribution for both the laser and kerosene airplane systems at a fuel cost of 40¢/liter and a range of 7500 km. The spacecraft costs, which include those of both the relays and power satellites, are the dominant cost of the laser flight system. The fuel costs dominate the kerosene flight system. In a laser-powered transportation system the fuel costs are traded for spacecraft costs. This high percentage of spacecraft costs is due primarily to the interest on the large capital investments and the high manufacturing cost of optics. Even at a 6% per year interest rate, the spacecraft costs are nearly twice those without interest.

The above analysis indicates that a laser-powered flight transportation is cost effective in comparison to tomorrow's advanced kerosene airplanes. This conclusion is very dependent on the following assumptions: high fuel costs, advancements in technology, a mature space industry and system operation at very high utilization rates. Without these assumptions, a laser flight system would probably be economically unjustified.

IMPACT OF INCREASED FUEL COSTS

A laser flight system becomes economically competitive with a kerosene flight system only when the cost of the fuel saved is comparable to the initial procurement cost (including interest) of a Space Laser Power System. The competitive edge occurs at fuel prices of about 40¢/liter. Oil price increases are inevitable and the actual future cost of kerosene will probably depend on the price of synthetic oil which is estimated by DOE to be about 40¢/liter. Improvements in laser and optics technology will make laser propulsion economically competitive at a lower kerosene cost.

ADVANCEMENTS IN TECHNOLOGY

The cost effectiveness of the laser flight system also hinges on the required advancements in technology. The technology required for the airplane is well within reach. The technology required for the laser power satellites and relay satellites is far more demanding.

The amount of new technology incorporated into the airplane is minimal. Both the airframe and rotating turbomachinery are of conventional design. The only new components are the heat exchanger and the receiving optics. However, as previously shown, such a laser to fluid heat exchanger can be fabricated in a conventional manner. The most difficult problem is that of designing compact receiver optics small enough to fit inside an aerodynamically streamlined container but big enough to intercept a 10 meter diameter laser beam.

Most of the new technology is designed into the laser power satellites and relay satellites. Many of the important spacecraft components have yet to be built. Even though high power lasers and optics are already in existence, none of these devices have a sufficiently high performance which would permit the construction of a low cost Space Laser Power System. Each of the laser and optical components is based on small scale laboratory experiments, prototypes and paper designs.

A low cost Space Laser Power System requires a high efficiency laser which is capable of continuous operation and is scalable to high power levels. The electrically excited CO laser and CO_2 laser are both capable of continuous operation at high power levels. The laser used in this report is a 42 megawatt CO laser with an open-cycle electric to laser efficiency of 60%. Small scale experimental CO lasers have reached 63% open cycle conversion efficiency[12], but an efficient, continuous wave, megawatt size CO laser still does not exist at this early date. The CO_2 laser which is the most developed high power gas laser has already reached megawatt sizes and promises an open cycle efficiency of 30%.[18]

The development of inexpensive high power optics is anticipated; however, this task is far from easy. For example, laser windows and the small mirrors must withstand continuous exposure to high power laser fluxes, often necessitating active cooling mechanisms. Large mirrors are needed for long range focusing to the desired small spot sizes. Adaptive optics, employing error sensors and mirror surface actuators, should provide phase correction and survive the harsh high power laser environment. The transmitting optical system is required to point and track a small target at very long ranges. Furthermore, all these requirements must be accompanied by high reliability.

In addition to these stringent technical requirements, these optical systems would have to be manufactured at a reasonable cost, probably as low as $2,000/kg. Even if these devices exist today, using present day manufacturing techniques, the cost of optics would be prohibitively expensive. The successful manufacture of low cost, high power optics depends on the development of advanced mass production techniques which in turn will form the basis of a mature optics industry.

Since this flight system features a laser power transmission system, particular emphasis is placed on the technology of lasers and optics. This does not mean that the technology requirements for the other spacecraft components are trivial. Questions pertaining to the technical feasibility of large scale space structures and space transportation systems have been already addressed by the various studies on microwave solar power satellites available in the literature.

A MATURE SPACE INDUSTRY

The spacecraft manufacturing, transportation and assembly costs were derived from recent microwave solar power satellite studies which assume fleet sizes (50 or more power satellites) and a mature space industry. Current projections call for the deployment of at least sixty 10 GW microwave solar power satellites at a rate of 1 to 4 each year.[9,10] For a laser flight system, a fleet of 300 laser power satellites and 400 relays is proposed. In order to build a fleet of laser and/or microwave power satellites, a mature space industry is needed. Such an industry will be capable of constructing large quantities of spacecraft components at low cost by using advanced manufacturing techniques, mass production techniques, learning curves, economies to scale, etc. This industry would also include an armada of boosters, space tugs and space assembly facilities in addition to the ground based factories. (The spacecraft components will be manufactured in ground based factories and the final assembly will occur in space.)

The size of such a mature space industry should not be underestimated. The Space Laser Power System needed for a commercial jet transportation system requires the production and delivery into orbit of approximately 230 million kilograms of spacecraft within a 1 to 2 year period, which is equivalent to the mass of 3500 kerosene powered jet transports. A fleet of 10 GW microwave solar power satellites (80 million kg/satellite) has the mass equivalent of 75,000 jet transports. In comparison, the existing American aerospace industry is capable of producing less than 1,000 jet transports a year.

While the size of a mature space industry seems forbidding, any new alternative energy source will require a massive industry of its own. For example, if coal-derived synthetic oil becomes a new energy source, then the size of the coal gasification industry, i.e., gasification plants, additional mining facilities, railroads, etc., may equal or exceed the size and cost of a mature space industry.

Furthermore, any new energy source is capital intensive and consequently must be operated at a very high utilization rate. Unlike ground solar systems, space solar power systems can operate continuously round the clock. Here, we have assumed that the laser-powered airplanes are flying almost 24 hours each day of the year, resulting in the nearly continuous use of the Space Laser Power System. The proposed microwave solar power satellites for electrical power generation would be deployed in a geosynchronous orbit and would operate 99% of the year. Lockheed's laser power satellites for electrical power generation would be deployed in a sun-synchronous orbit and would operate continuously.

SYSTEM SAFETY

While the radiation intensity at the aircraft receiver is less than 30 watts per cm^2, a protective system must be provided both for the airplane and terrestrial inhabitants. This protection requires a system which permits the laser power to be switched on only when a secure tracking lock onto the heat exchanger receptor of the airplane exists. Thus, any failure to properly track the aircraft would automatically shut down the laser, and the aircraft would revert to kerosene power until a secure lock is re-established. Since the signal travel time to the relay satellite is only about 40 milliseconds at the farthest tracking distance, it should be possible to terminate the laser beam in less than 100 milliseconds if tracking is disrupted. The upper surface of the airplane can be easily designed to withstand this brief exposure to moderate intensities. Moreover, standard airplane window materials are opaque to both CO_2 and CO laser radiation so that the crew and passengers are never exposed to radiation.

Flight paths would be arranged so that no airplane would fly into a laser beam. In the event when another airplane accidentally intrudes into the beam path, the interruption of the beam will automatically trip a laser cutoff mechanism.

Since corresponding protection for terrestrial inhabitants is not possible, there still exists the rare possibility that someone may be so positioned as to look in the direction of the laser transmitter at the moment of a tracking lock failure. In clear weather conditions much of the radiation may reach the ground. Since the beam (15m in diameter) sweeps the ground at roughly 960 km/hr, the maximum energy deposited near the beam center is about 1 Joule/cm^2. While this is considerably less than the threshold for skin burns (6 Joules/cm^2), it is twice the dose tolerable for corneal eye damage.[19] The brief exposure allowed by the feedback safety system minimizes the possibility of contact. The large scale transportation network considered here would expose less than 10^{-8} of the Earth's surface each year to radiation doses about the threshold for eye damage, assuming as high as 1 miss per 100 missions. In addition,flight paths can be selected that will avoid populated areas. Taking into account the rarity of tracking failure, the rarity of perfect optical transmission conditions, and the additional rarity of someone looking directly into the laser beam, the probability of eye damage is reduced to an infinitesimal level.

The use of a power satellite-relay combination also enhances the overall system reliability. For example, the failure of any given power satellite or relay would not require an additional margin of fuel reserve since laser power could be restored by switching to another operating unit. Collateral safety effects, such as reduced fuel load on take-off, enhances the aircraft's safety.

ENVIRONMENTAL EFFECTS

A laser-powered aircraft is a long range transportation system with a minimal pollution impact on the atmosphere. The turbofan involves an engine in which heat is transferred to the engine airflow by convection instead of combustion.

Consequently, the usual combustion products, such as nitric oxides, water vapor and carbon dioxide, are absent from the laser turbofan exhaust. Moreoever, at the CO and CO_2 laser frequencies and at power levels on the order of 30 W/cm^2, there is no interaction with the ionosphere and thus no effect on the ozone level. Launch effluents are small when compared to the emissions from a whole fleet of kerosene airplanes. Rocket engines also burn relatively clean; exhaust products are normally only CO_2 and H_2O.

PROGRAM DEVELOPMENT

The high capital investment requirements of this flight system demand that the technology and associated risks be assessed in a step by step research and development program. In the beginning a small RPV could be energized by a system of existing welding lasers and tracking systems stationed on the ground. This would be the first free flight demonstration of laser propulsion and would also be the first fuelless airplane. The next step may involve space shuttle deployed relay satellites and a ground based laser, probably located on top of a mountain, such as Mauna Loa in Hawaii, allowing relatively efficient atmospheric beam transmission from ground to relays. This laser system would be used to power small jet aircraft. The large scale prototype spacecrafts and jet transport could then follow with confidence.

FUTURE POTENTIAL

In the above studies the authors, in order to make a preliminary economic assessment, have confined themselves to technology which they feel can be justified as a reasonable extension of existing or near-term technology. This may be an unduly severe constraint considering the time-span for the introduction of such a program, and serves only as the basis for illustrating the technical viability of such a scheme.

Research and development programs are active in the area of new concepts in both laser development and solar energy conversion. For example, there is a significant effort in much shorter ($\approx 2\ \mu m$) lasers of high efficiency. An outstanding example is the "free electron laser," which promises, in principle, high efficiency conversion from electrical energy to laser energy at wavelengths which could be optimized for such a flight system.[20] In examining the cost structure of our satellites, it can be seen that reducing the wavelength from about 5 microns to 2 microns would have a first order impact in reducing the cost. Other approaches to high efficiency lasing systems are also being studied. For example, the solar pumped laser concept offers the potential of a large increase in efficiency of the conversion of solar radiation into laser energy.[21] Studies are under way at the University of Washington which indicate that the efficiency of energy conversion in space using proper advanced technology may be significantly increased.[11] Therefore, the authors feel that there are a number of technical approaches which would permit the utilization of a satellite strategy which can dramatically reduce the operating cost of the system.

In limiting themselves to existing aircraft and engine technology, the authors again penalized the system unnecessarily. An optimal airplane flying in optimal strategy for laser propulsion could significantly reduce the laser power requirements. For example, since the airplane is not burdened by a large parasitic mass of fuel during take-off, a new flight strategy should be introduced which would allow aircraft to climb more rapidly. The altitude constraints, which were optimized for a kerosene airplane, certainly do not represent an optimal flight strategy for such an aircraft. With an aircraft and engine designed around such a transportation system, there is little reason to believe that the operating altitude of this aircraft could approach that of the SST, resulting again in further cruise economies.

The very existence of laser power satellites suggests that these systems can be used also as part of a space transportation system, acting in a synergistic way to reduce the boost cost of such systems.[22]

These are but a few of the options that should be examined to determine the ultimate potential of this system. This paper, therefore, represents only an introductory examination of the general feasibility and appears in itself to be encouraging enough to warrant such explorations.

CONCLUSIONS

A laser-powered flight transportation system is only one of many possible uses of a Space Laser Power System. This article has explored the possibility of using laser propulsion for an air-breathing booster and a commercial jet transport. If all the assumptions made here are true, then a laser-powered commercial jet transportation system will be cost competitive with an advanced fuel efficient kerosene flight system.

As pointed out earlier, the economic justification of any solar power satellite depends primarily on the establishment of a very large and mature space industry. Such an industry can only be sustained by a correspondingly large market. Due to its multi-mission capability, the Space Laser Power System has the potential for a market that includes air and space transportation, electrical power generation, high temperature chemical processing (such as coal gasification), hydrogen production, and material processing. Once the mature space industry is established for the construction of small power satellites for a laser flight system, these same industrial facilities could also be used, for example, for the construction of larger laser power satellites for electrical power generation and space propulsion.

The laser flight system, like many other space laser concepts, can be incorporated directly into our existing technology base. As shown, laser airplanes are incorporated with existing airport systems. A laser heat engine may even replace a coal-fired boiler of an electrical power plant, while still retaining the same turbomachinery and power distribution lines.

In the long run, advancements in technology will result in high efficiency, low cost Space Laser Power Systems. These advanced space laser systems combined with the unique advantages of relay capability and multi-mission capability will then play a vital role in the development of solar power satellites and solar-powered flight transportation systems.

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TABLE I - LASER-POWERED AIRCRAFT CONCEPTS

AUTHOR	YEAR	VEHICLE	PROPULSION	CONVERSION SYSTEM
KANTROWITZ & ROSA[4]	1974	HYPERSONIC AIRFRAME	RAMJET	ALKALI SEED/INVERSE BREMSSTRAHLUNG
L.N. MYRABO[6]	1976	LAUNCH VEHICLE	MHD FANJET	BREAKDOWN/INVERSE BREMSSTRAHLUNG
BARCHUKOV, et al.[23]	1976	LAUNCH VEHICLE	LASER AIRJET	BREAKDOWN/SHOCK WAVE
BEKEY, et al.[24]	1976	JET TRANSPORTS	TURBOFAN	FOCUSED LASER RADIATION
R.J. WEBER[25]	1976	JET TRANSPORTS	TURBOFAN	LIQUID METAL HEAT EXCHANGER
L.N. MYRABO[6]	1978	LAUNCH VEHICLE	ROTARY PULSE JET	BREAKDOWN/INVERSE BREMSSTRAHLUNG
HERTZBERG, et al.[1]	1978	JET TRANSPORT	TURBOFAN	LASER TO AIR HEAT EXCHANGER

LASER POWERED FLIGHT TRANSPORTATION SYSTEM

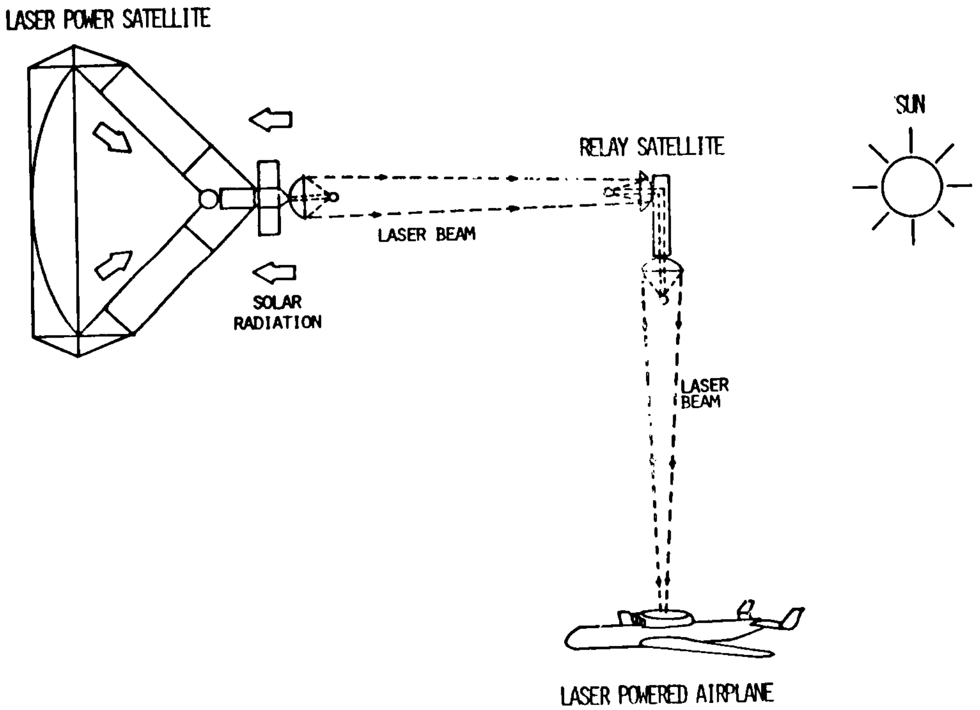


FIGURE 1

SPACECRAFT DEPLOYMENT STRATEGY

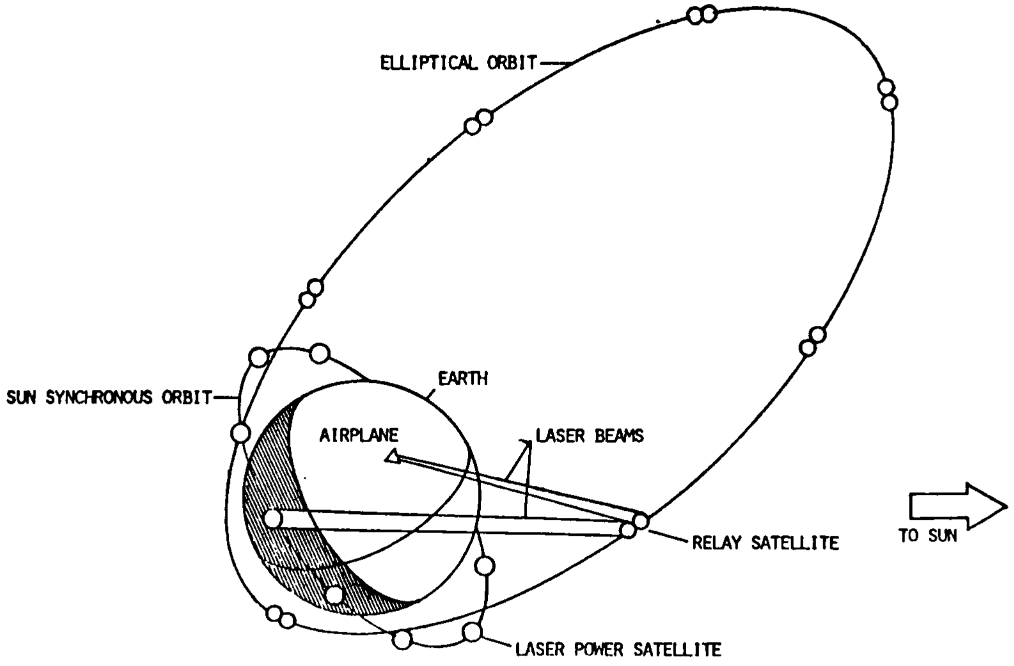


FIGURE 2

LASER POWERED AIRPLANE FLIGHT PROFILE

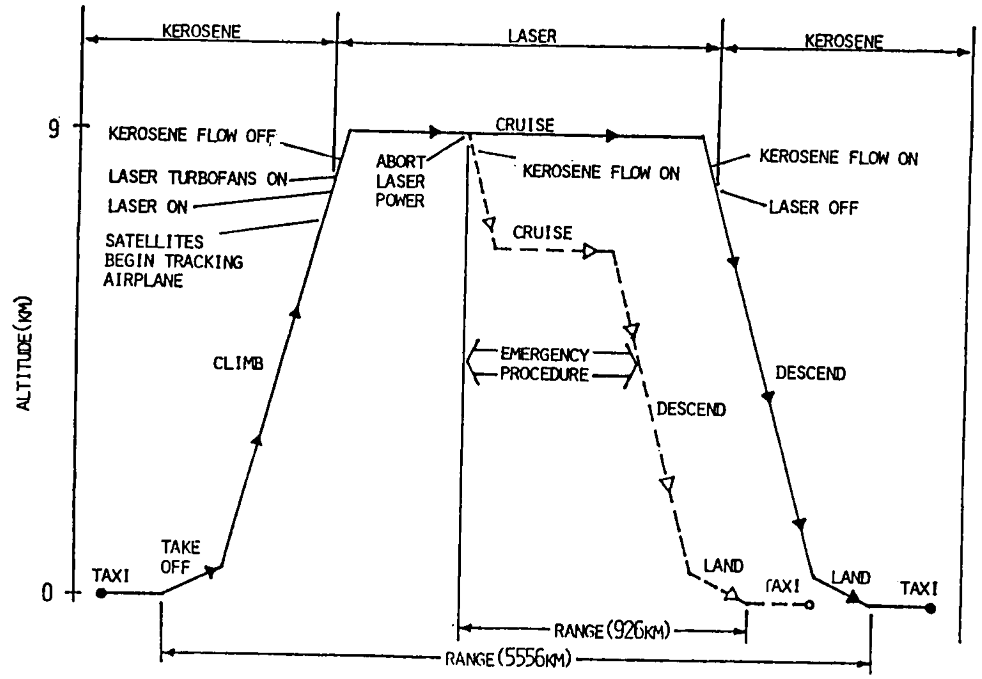


FIGURE 3

LASER-POWERED TURBOFAN

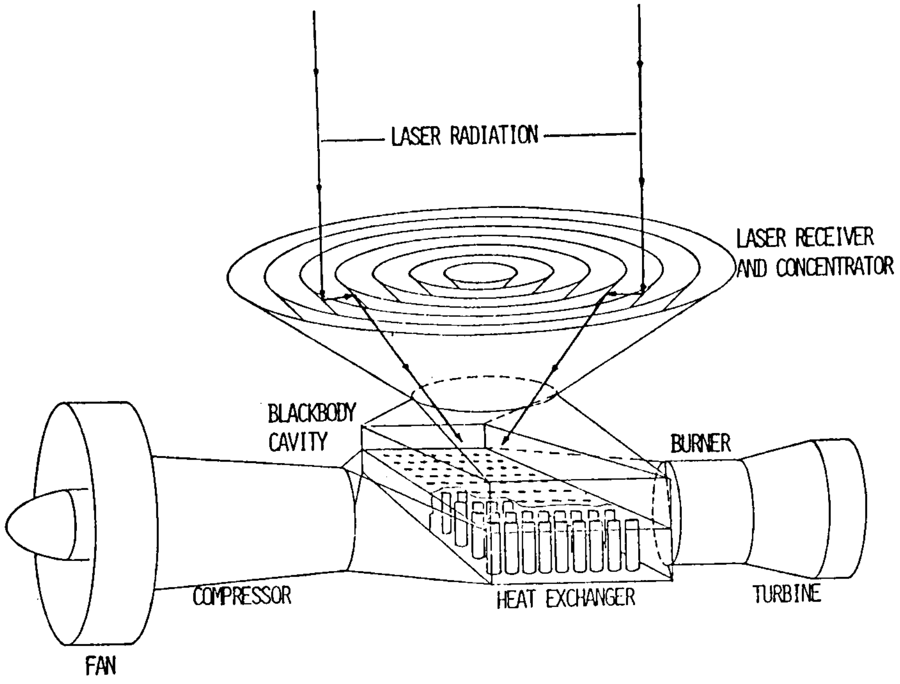


FIGURE 4

KEROSENE POWERED AIRPLANE (BOEING TAC/E AIRPLANE)

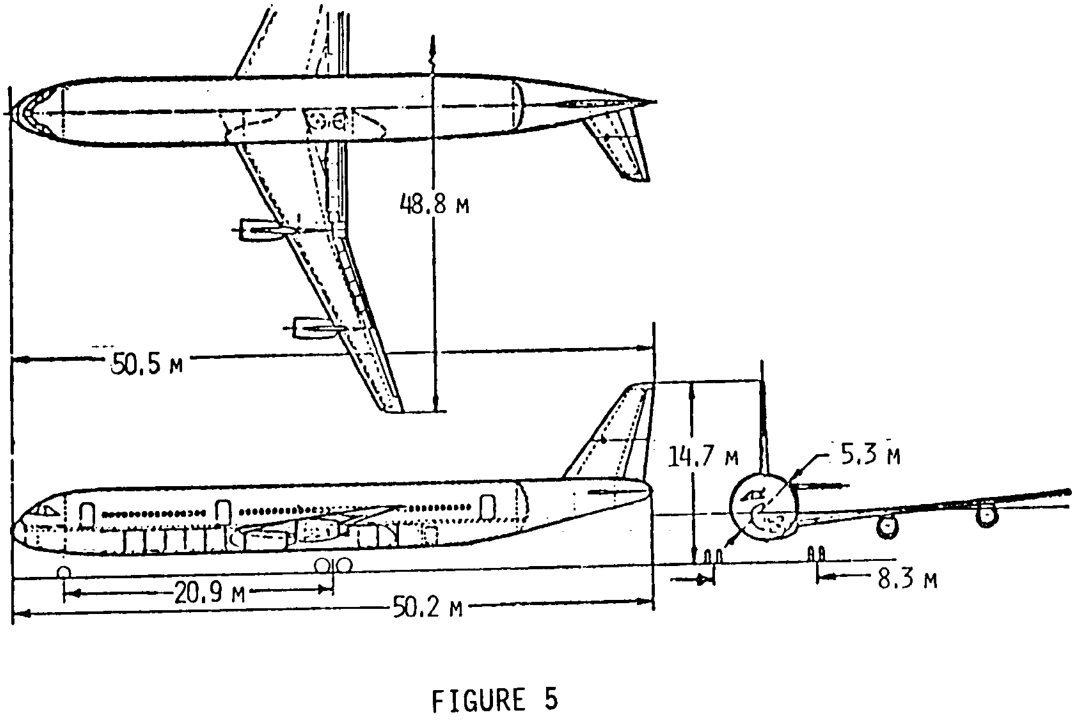


FIGURE 5

LASER POWERED AIRPLANE - BASELINE CONFIGURATION

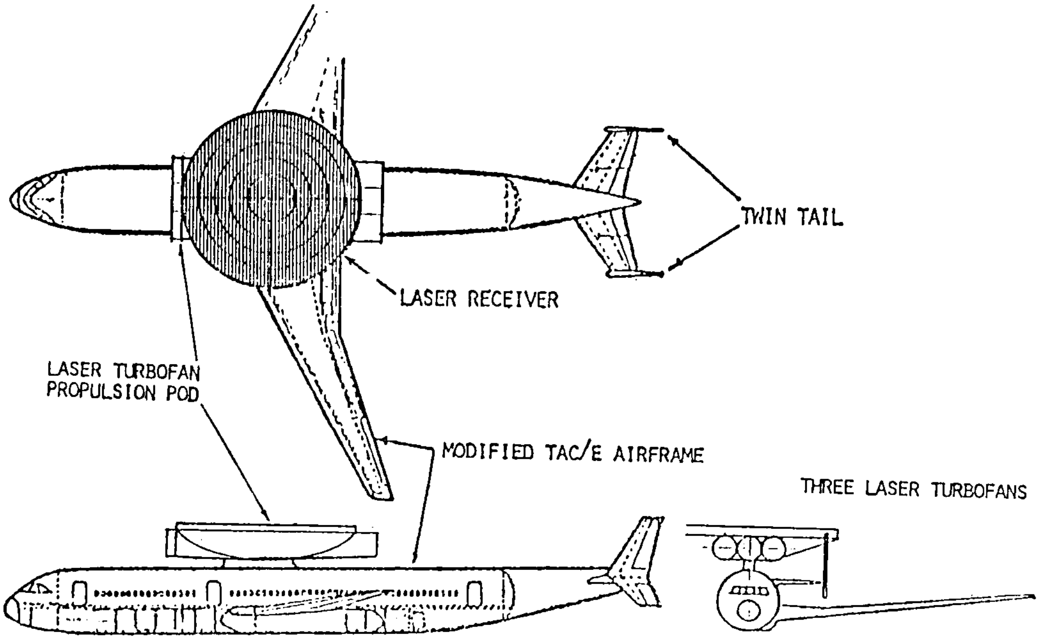


FIGURE 6

CARBON MONOXIDE LASER POWER SATELLITE - 42 MW OUTPUT POWER

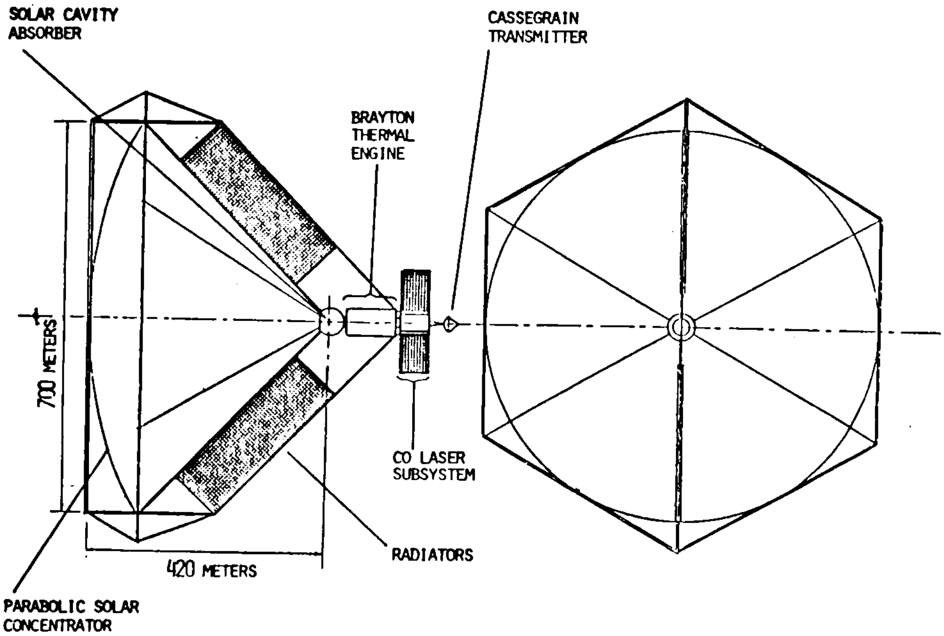


FIGURE 7

CASSEGRAIN TRANSMITTER SUBSYSTEM

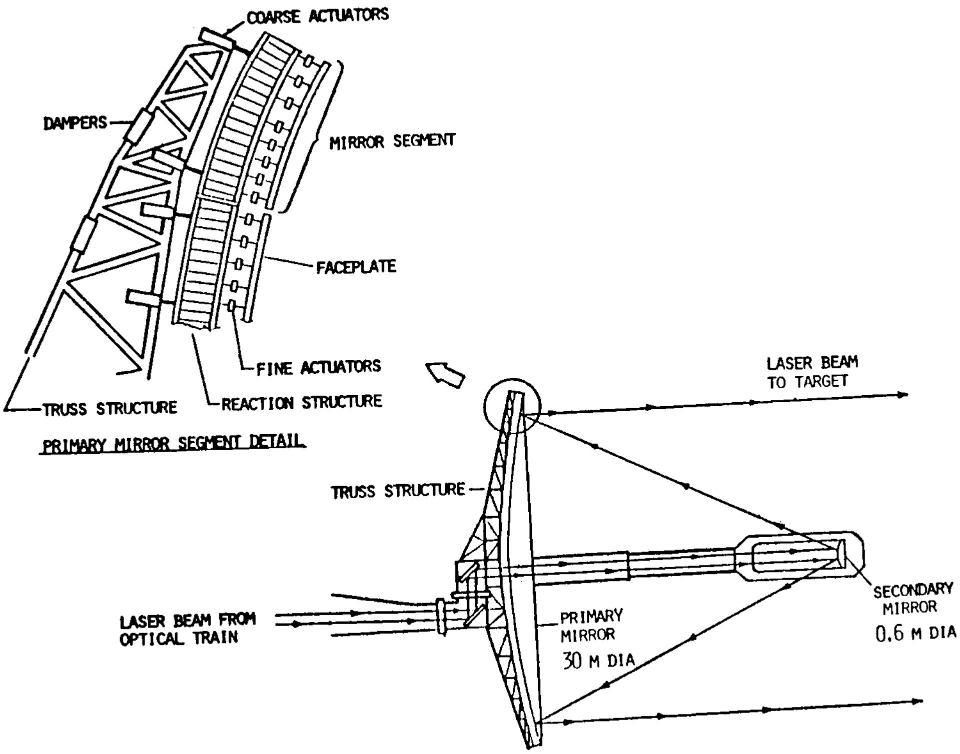
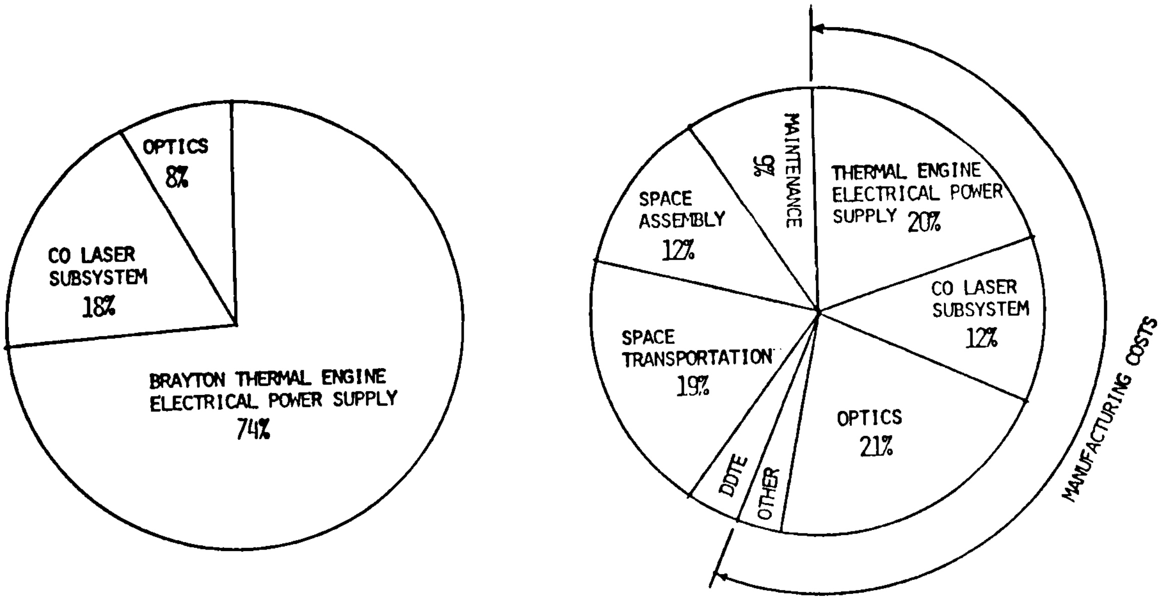


FIGURE 8

LASER POWER SATELLITE MASS AND COST DISTRIBUTION



TOTAL MASS 671500 KG.

TOTAL COST $170.4 MILLION

FIGURE 9

RELAY SATELLITE CONFIGURATION

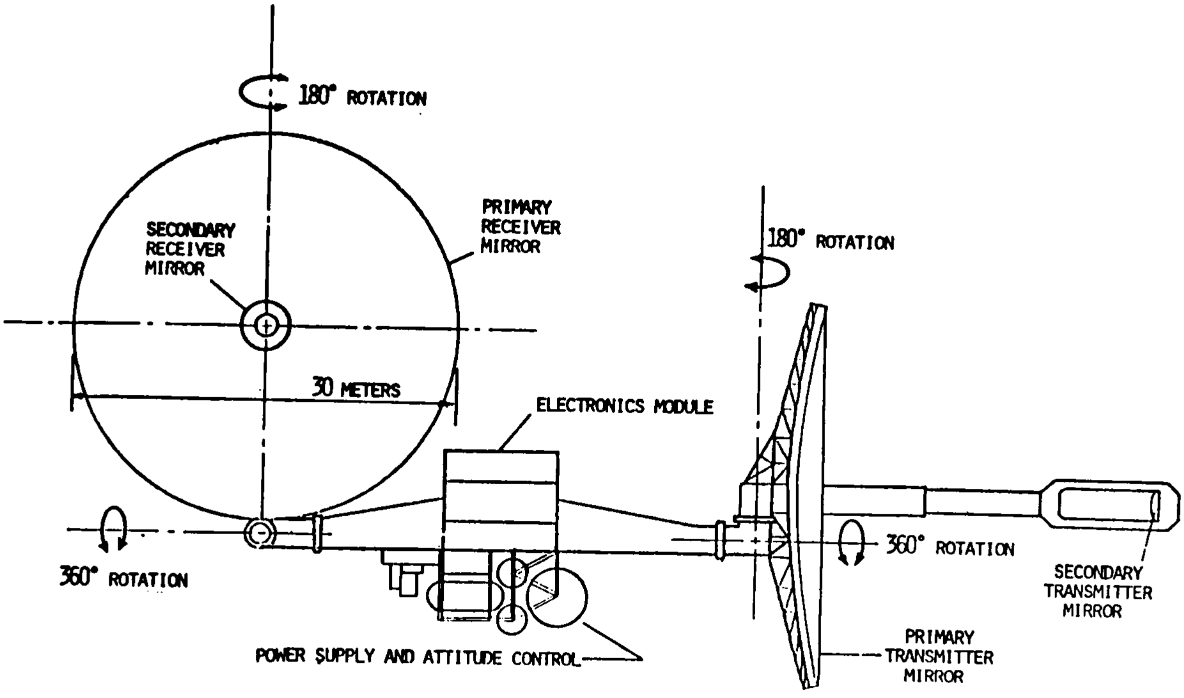
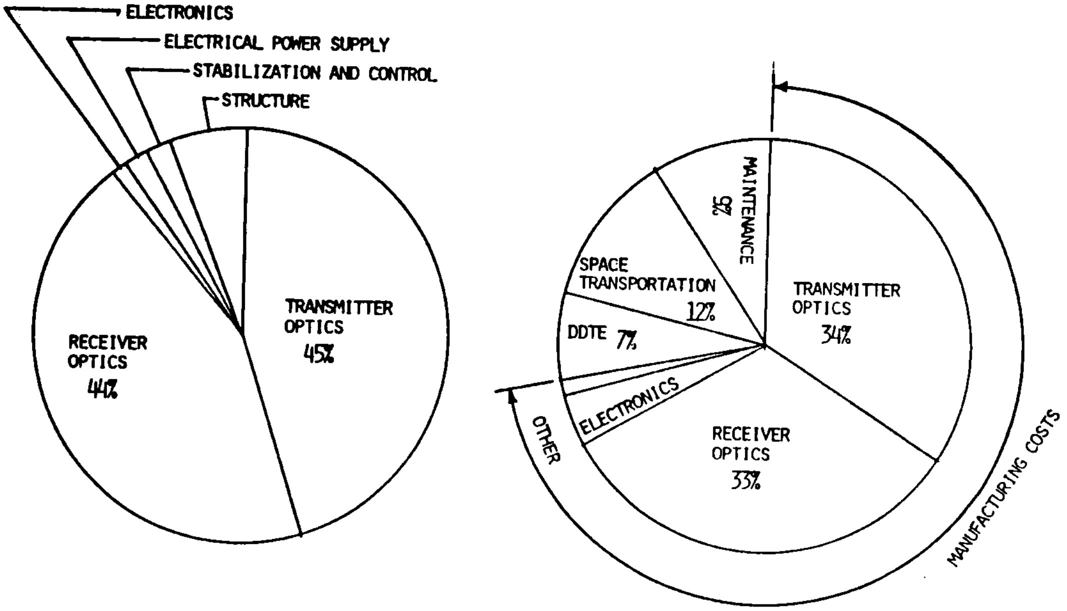


FIGURE 10

RELAY SATELLITE MASS AND COST DISTRIBUTION

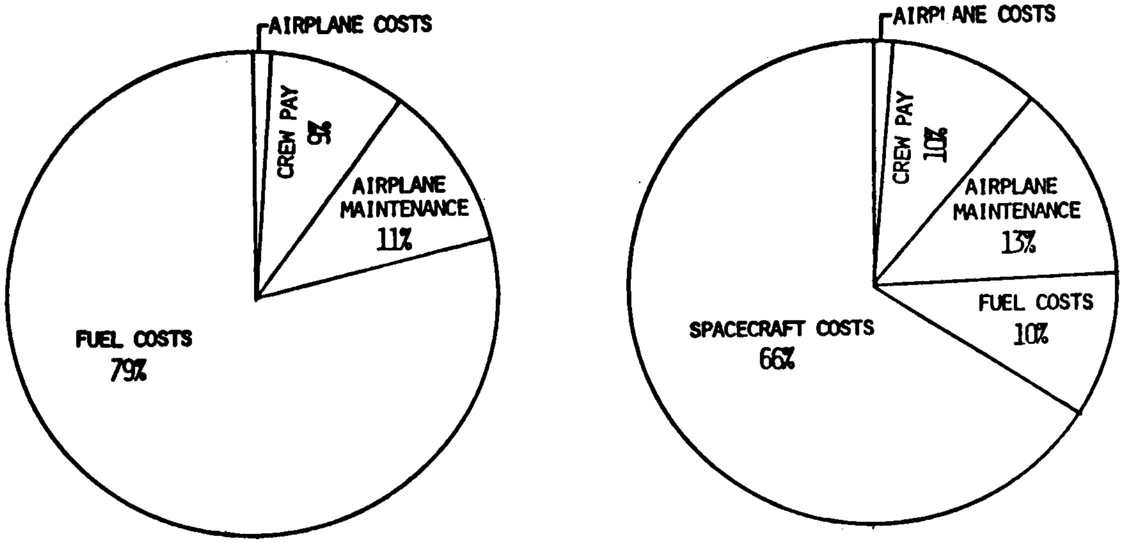


TOTAL MASS 77450 KG.

TOTAL COST $65.8 MILLION

FIGURE 11

KEROSENE FLIGHT SYSTEM AND LASER FLIGHT SYSTEM COST DISTRIBUTION AT 40¢/LITER FUEL COST AND A 7500 KM RANGE



KEROSENE FLIGHT SYSTEM COST $1.43/KG-PAYLOAD

LASER FLIGHT SYSTEM COST $1.36/KG-PAYLOAD

FIGURE 12