

NASA Technical Memorandum 4002

# Preliminary Design and Cost of a 1-Megawatt Solar-Pumped Iodide Laser Space-to-Space Transmission Station

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## Summary

A preliminary conceptual design of a space-based solar-pumped iodide laser emitting 1 MW of laser power for space-to-space power transmission is described. A near-parabolic solar collector focuses sunlight onto the t-C<sub>4</sub>F<sub>9</sub>I (perfluoro-t-butyl iodide) lasant within a transverse flow optical cavity. Using waste heat, a thermal system was designed to supply compressor and auxiliary power. As a result of the particular lasant selection, a standard technology radiator removed the waste heat. The major system components were designed with weight and cost estimates assigned. Although the total system cost is very approximate, the cost comparison of individual system components leads to valuable insights for future research directions. In particular, it was found that laser efficiency was not a dominant cost or weight factor, the dominant factor being the laser cavity and laser transmission optics. The manufacturing cost (no design development testing and evaluation included) was approximately two thirds of the total cost with transportation to orbit the rest. The flowing nonrenewable lasant comprised 20 percent of the total life cycle cost of the system and, thus, was not a major cost factor. The station mass was 92 000 kg without lasant, which would require approximately four shuttle flights to low Earth orbit where an orbital transfer vehicle could transport it to the final altitude of 6378 km.

## 1. Introduction

When planners project man's future in the utilization of space, the missions range from space industries and space laboratories to bases on Mars, lunar mining, and space colonies (ref. 1). Each of these requires extensive use of power and propulsion systems. To provide the large quantities of electric and propulsive power required by intensive development of space, consideration is being given to collecting solar energy, converting it to a laser beam, and transmitting it to space-based users (ref. 2). This concept is termed space-to-space power transmission, and the system essential to this concept is a space laser power station.

The rationale for space power transmission is similar to that for other space power sources. Like a solar photovoltaic power system, a space laser power station would use solar energy as its primary power source. Unlike the photovoltaic system with its large array of solar cells, this power station offers mission flexibility by providing either electricity or power for thermal or electrical propulsion. Large arrays with their stiff structures and stringent controls require each large power consumer to carry much

auxiliary mass to orbit and possibly face difficult deployment or assembly problems. A satellite deriving a large quantity of electric power from a remote space power station would have a small, lightweight, high-efficiency laser-to-electric converter. By dispensing with the large onboard solar collector, the power-receiving spacecraft gains structural simplicity and reduces dynamic control requirements. Without the large array, atmospheric drag can be reduced and much lower altitude operation can be tolerated (ref. 3). Besides possibly reducing the design, control, and launch costs for high-power low Earth orbit (LEO) spacecraft (for example, space factories) using multiple stations, the space power transmission concept offers receivers the potential of having energy constantly available, even when the receiver is in the Earth's shadow (ref. 4). Numerous studies have been performed to explore the feasibility of microwaves (ref. 5) and lasers (refs. 6, 7, and 8) for power transmission in space. Holloway and Garrett (ref. 9) have emphasized space-to-space power transmission and have developed a comparison between major classes of power stations. They conclude, from advanced power station mass and cost comparisons, that direct solar-pumped lasers could be the lightest and least costly system, when compared with microwave, electric discharge laser, and direct nuclear-pumped laser power transmitters. They also concluded that a laser propelled orbital transfer vehicle (OTV) could have substantial cost advantages over the chemical OTV. Thus, the subject of the present study is the design and cost of a direct solar-pumped laser power station.

This study is one step in an iterative process which defines the system implications of the growing body of basic knowledge on solar-pumped lasers, assesses the status of space power station technologies, and guides future fundamental laser research toward developing the enabling technology which may one day lead to space-to-space power transmission. The primary purposes for this study were (1) to further test the feasibility of a direct solar-pumped laser power station by a conceptual design more detailed than in prior studies and (2) to assess the relative importance of the subsystems (their procurement and requirements for transportation, assembly, and support) by developing a preliminary mass and cost estimate.

There are three general classes of solar-pumped lasers—photodissociation, photoexcitation, and black-body lasers. Within each class are two or more candidate lasants, each supported by a different level of knowledge. Organic iodide solar-pumped photodissociation lasers have received more study in recent years than any of the other classes (ref. 10), and

therefore were chosen for this study. The particular lasant, perfluoro-*t*-butyl iodide ( $t\text{-C}_4\text{F}_9\text{I}$ ), was selected because it offered the highest efficiency of conversion of sunlight into laser light and also the highest fraction of lasant reassociation, important for closed-cycle laser systems. Unfortunately, other parameters of the lasant are either unknown or incompletely characterized; thus, assumptions had to be made as indicated in the paper.

A 1-MW power level was chosen for this study because such levels could service several space power consumers. In addition, a range of studies (refs. 3, 8, and 11) suggests that this value is substantially above a lower useful power limit, generally near 100 kW<sub>e</sub>, where onboard photovoltaic power loses its advantage over other power sources. At the high end of the power spectrum, transmitted powers of 10 MW, 100 MW, or more require sizes and masses which substantially exceed current technology and resources. In fact, this preliminary design shows that even a 1-MW space power station would represent a major technical challenge for the national space program.

Since most subsystems or components were not technologically ready in 1987, projections were made for the laser and other subsystems. Rather than performing a final design for each subsystem, physical requirements were determined, and general laws or experience were employed to estimate the size and mass of each, consistent with system constraints. The results of our study were the overall design, the sizes and masses of subsystems, and an energy budget, including thermal, mechanical, electrical, and laser energy.

The power station would orbit the Earth at an altitude of 6378 km (1 Earth radius) with an inclination of 0°, beaming power to user spacecraft orbiting at altitudes greater than 100 km. With several power stations in this mid-altitude orbit, good coverage (ref. 4) of the user spacecraft is provided without requiring extremely long transmission distances, like those necessary from geosynchronous orbit, and without encountering atmospheric drag. Minimizing transmission distances is important because even diffraction-limited laser beams diverge significantly over thousands of kilometers.

Atmospheric drag, at altitudes reachable with the Space Shuttle (<600 km), would be a problem for the power station because it has such a large surface area compared with its mass. The power station would have an orbital lifetime of less than 1 year at an

altitude of 600 km if no drag makeup thrusters were provided. A lifetime of 30 years was used, based on the typical lifetime of Earth power stations, thus the need for higher altitude basing.

The process for positioning and maintaining a solar laser power station is shown in figure 1. Components are manufactured on Earth, launched into LEO by the Space Shuttle, carried to a mid-altitude equatorial orbit by a reusable chemical orbital transfer vehicle (OTV), and then assembled and maintained on orbit. The chemical OTV is space based, but refueled, on demand, from the Shuttle.

Operation and lasant resupply are shown schematically in figure 2. In normal operation, the power station provides utility power to remote users. Infrequently, as a station's *new* lasant supply approaches zero, lasant is manufactured on Earth, carried to low orbit by the Space Shuttle, and loaded into a space-based, laser-powered OTV. A laser-powered OTV is used because of its cost advantage over a chemical OTV and is discussed later. The station's laser beam is diverted to this OTV to power its engines and raise it up to the station. *Used* lasant is returned to Earth by way of the laser OTV and Space Shuttle.

For costing the station, the philosophy was to extrapolate the cost of each subsystem component based on the cost of similar presently available components. Most component costs were defined by the product of an estimated cost per kilogram (called the specific cost) times the mass required for the component. Since design, development, test, and evaluation (DDT&E) costs have fluctuated for high technology projects and since estimating these costs for future technologies is even more highly uncertain, only operating (not DDT&E) costs were included. These costs include manufacturing, transportation to space, assembly, on-orbit operation and maintenance, and lasant resupply for a 30-year operational lifetime. The costs are highly speculative; nevertheless, comparative subsystem costs can give general trends which can guide future research effort.

The following sections summarize the preliminary study. A design section identifies the subsystems and technical rationale employed and the physical characteristics which resulted. The cost section defines the basis of cost estimates, discusses the purchasing cost of each subsystem, and develops a comparative cost table. The discussion section explores the assumptions and implications of the design and costs. The final section summarizes conclusions and defines the major lessons learned from this study.

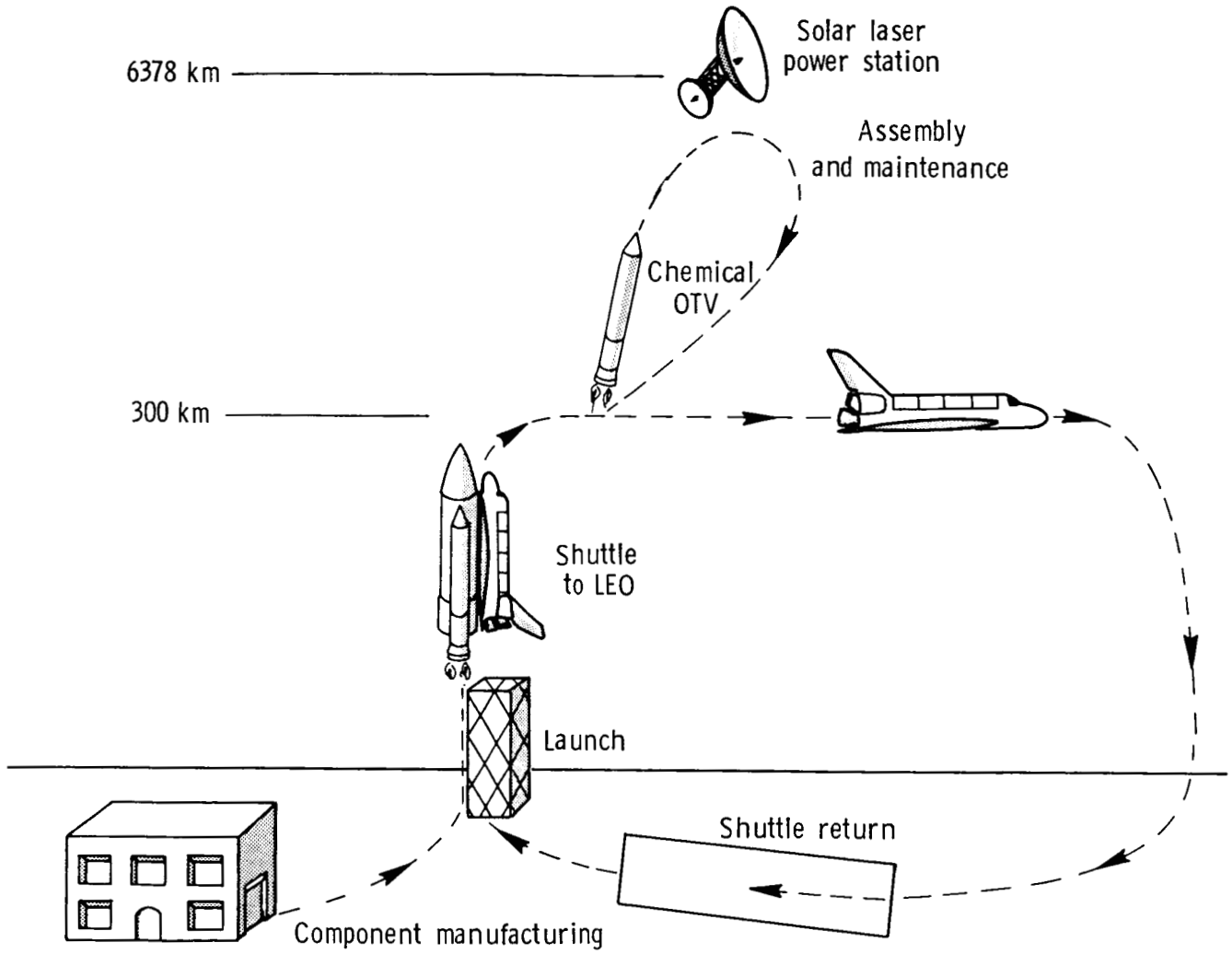


Figure 1. Schematic diagram for space laser assembly.

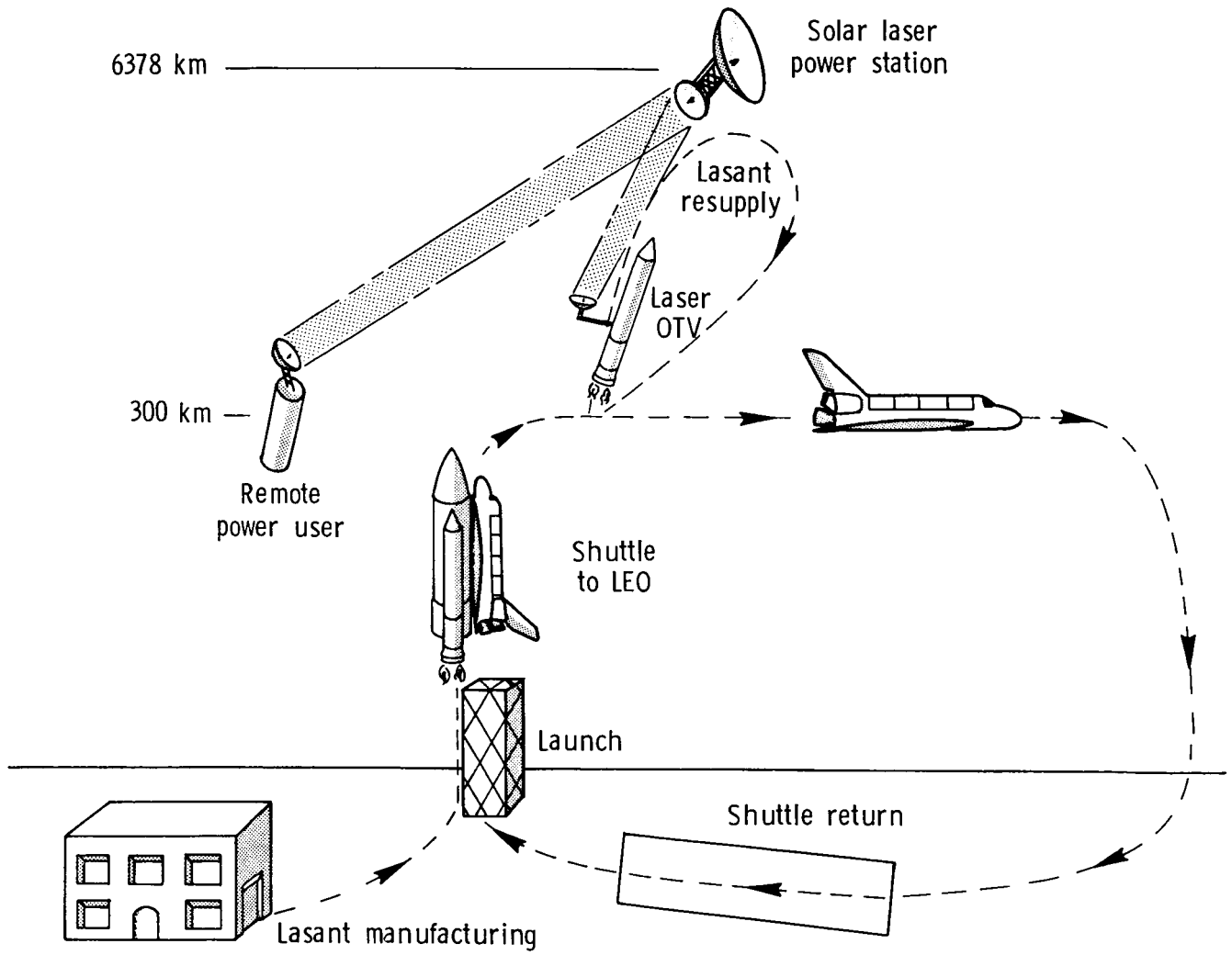


Figure 2. Schematic diagram for operational phase of solar-pumped laser system.

## 2. Design

In its simplest form, as shown in figure 3, a solar-pumped laser power station is composed of a solar concentrator, the laser, a thermal radiator, and transmission optics. In operation, sunlight is reflected by a large solar concentrator (pointed toward the Sun) so that it passes through a focal volume within the laser cavity. Molecules of the gaseous lasant ( $t\text{-C}_4\text{F}_9\text{I}$ ) absorb part of the solar radiation and, in the process, dissociate into  $\text{C}_4\text{F}_9$  radicals and excited I atoms. The atomic iodide lases at  $1.315\ \mu\text{m}$ , producing a 1-MW beam. Almost all of the I atoms recombine with  $\text{C}_4\text{F}_9$  radicals to form lasant molecules that can be reused. A very small fraction of the photodissociated molecules forms  $\text{I}_2$  molecules (a strong quencher of excited I) and  $(\text{C}_4\text{F}_9)_2$  dimers. To avoid the quenching, the  $\text{I}_2$  molecules are removed by flowing the lasant at such a speed that the cavity is flushed before a detrimental concentration of  $\text{I}_2$  is reached. To permit continuous-wave lasing and lasant reuse, a flow system, driven by an axial compressor, provides closed-cycle subsonic

circulation. The gaseous lasant in the flow circuit is kept pure by removing the  $(\text{C}_4\text{F}_9)_2$  and  $\text{I}_2$  and replacing it with fresh  $t\text{-C}_4\text{F}_9\text{I}$ . Four storage tanks are used to store fresh and used lasant.

The gaseous lasant absorbs more solar energy than is converted to laser energy, and this heats the gas. The maximum temperature of the lasant and thus of the entire system must not exceed 500 K. Above that temperature, thermal dissociation of the molecules begins to produce many unexcited I fragments which cannot contribute to lasing but which do form  $\text{I}_2$  molecules that will quench the laser. Some of this thermal energy is extracted by a turbine and used to power the compressor which drives the flow. Also, the turbine provides electrical power for attitude control for communications and for onboard electrical requirements. The rest of the excess energy in the gas is removed by a thermal radiator. The minimum temperature in the system (243 K) was set high enough to avoid condensation of the  $t\text{-C}_4\text{F}_9\text{I}$  lasant and to supply lasant at the appropriate pressure by sublimation.

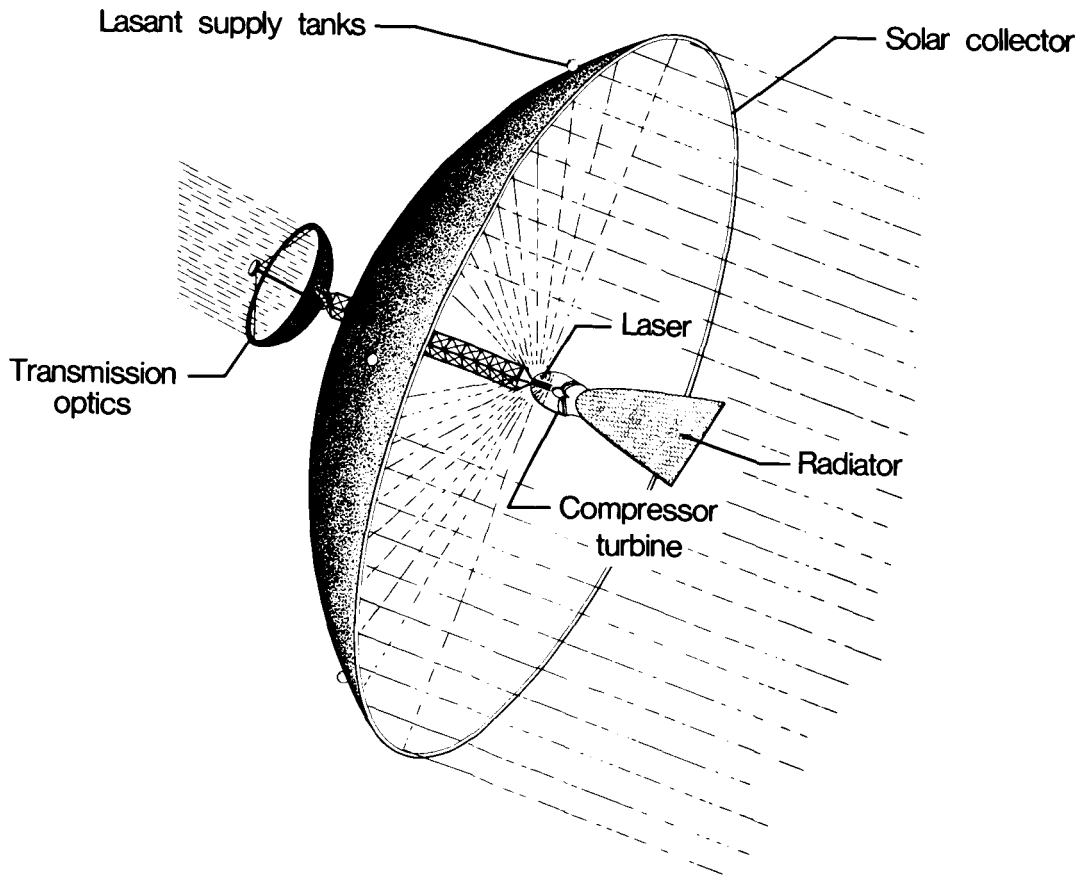


Figure 3. Schematic representation of the solar-pumped laser power station. Axes shown were used to balance the moments of inertia for pointing stability.

The laser beam travels down the open center of a central truss (which supports the laser at the focal point of the solar concentrator) and passes through an aperture in the large mirror of the Cassegrainian transmission system. The transmission system axis can be rotated to direct the laser beam to the user.

### 2.1. Concentrator

The concentrator illustrated in figure 4 is an almost parabolic dish that increasingly deviates from a true parabolic surface at points near its periphery. The effect of the deviation is to increase the focal length of the concentrator continuously with the square root of the dish radius. This variation creates a 10-m elongated focal region perpendicular to the concentrator aperture and 89 to 99 m from the vertex of the dish. The collected solar power is represented in figure 4 by the rays from the reflector to the focal region. The diameter of the dish aperture is 395.3 m. The center portion of the aperture, 62.5 m in diameter, cannot effectively transfer collected solar power to the laser focal volume. Figure 5 is a scaled plot of the intersection of the optical system with a plane through the system's axis. It shows the true relative sizes of the focal region and other optical components.

The annular aperture area collects 162 MW of solar power which is directed to a 14.7-m<sup>3</sup> focal volume that is shaped like the frustum of a right circular cone. The larger diameter of the frustum is 1.84 m and the smaller diameter is 0.85 m. The inside surface area of the dish is 145 395 m<sup>2</sup> which is coated with vacuum-deposited aluminum that has approximately 92 percent reflectivity in the ultraviolet portion of the solar spectrum. The average solar concentration over the surface of the focal volume is 2826 solar constants (1 SC = 1353 W/m<sup>2</sup> at air mass zero).

The weight of the solar collector was extrapolated from the design of Canady and Allen (ref. 12), which used 0.1 kg/m<sup>2</sup> as the weight per unit area. Using 0.148 km<sup>2</sup> as the total surface area, the collector weight becomes 14 800 kg.

### 2.2. Laser Cavity

The laser converts concentrated solar radiation into a coherent optical beam for eventual transmission to the remote user. It employs an optical cavity to generate a large-diameter fundamental mode beam. The diameter of the cavity was matched to the larger diameter of the concentrator focal volume, 1.84 m. Thus, a cylinder of 10 m in length by 1.84 m

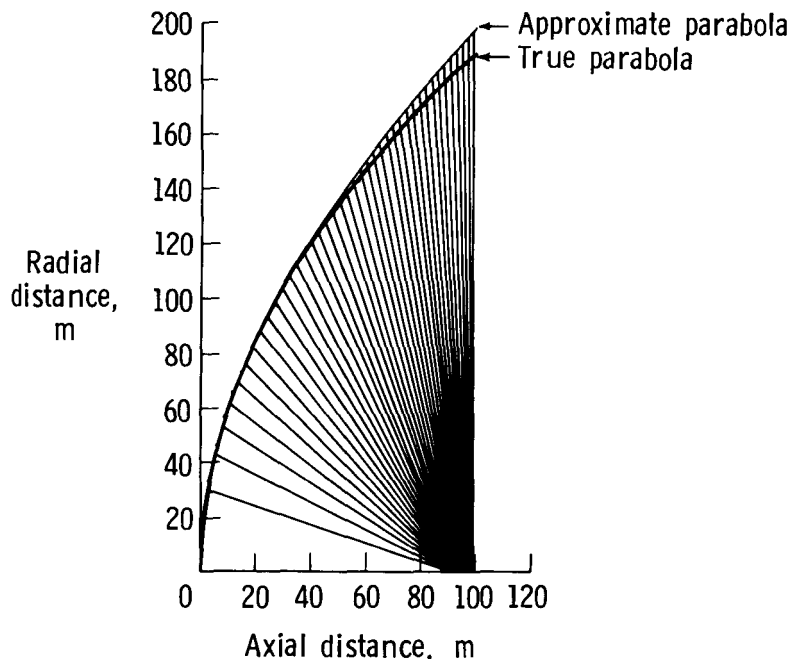


Figure 4. Radial section of solar collector dish with true parabola shown for comparison. Design produces focal volume 10 m in length.



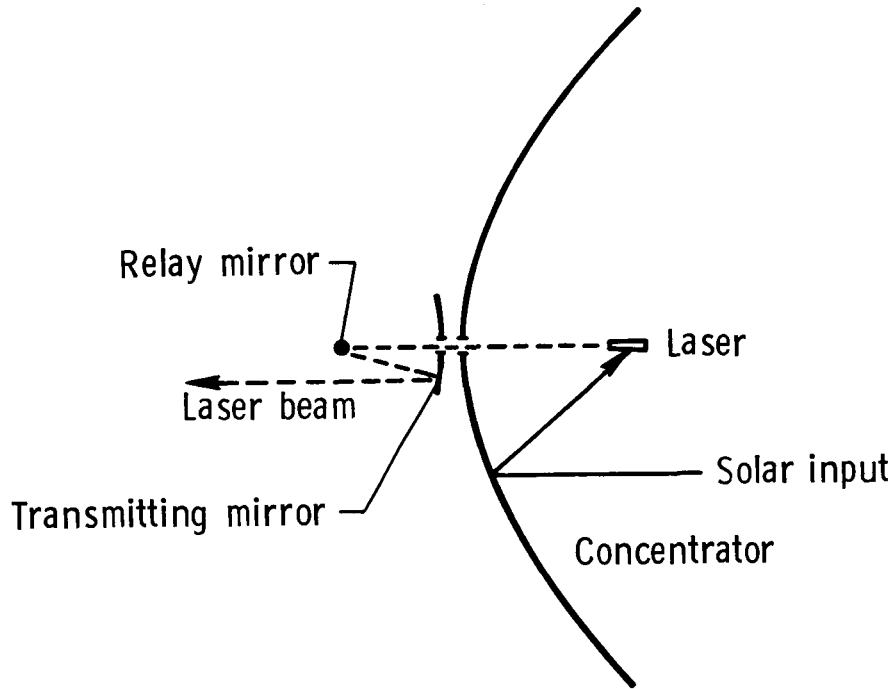


Figure 5. Scale diagram of major system optical components and their position within the system.

in diameter is the active laser region, and this is enclosed by a transparent quartz laser tube of 2-mm thickness. The lasant,  $t\text{-C}_4\text{F}_9\text{I}$ , flows transverse to the length of the tube and absorbs the incident solar radiation in a narrow band near 280 nm. The majority of the concentrated light is not absorbed but is transmitted through the tube and reflected out of the system back into space.

The laser power is defined by the equation

$$P_L = (QE)(A)(C) \int_0^\infty S_0(\lambda) \left(1 - e^{-\sigma(\lambda)Nd}\right) d\lambda \quad (1)$$

where  $QE$  is the quantum efficiency (0.2),  $A$  is the illuminated surface area of the laser tube,  $C$  is the solar concentration,  $S_0(\lambda)$  is the solar spectral intensity distribution, and the last term is the absorbed fraction of the incident solar power. The absorption cross section (ref. 13) is  $\sigma$ ,  $N$  is the number density of  $t\text{-C}_4\text{F}_9\text{I}$  molecules, and  $d$  is the diameter of the laser tube. The absorbed fraction of the incident solar radiation, within the absorption band, is calculated to be 99 percent over a 1.84-m tube diameter at  $10^3$  Pa (7.5 torr) of  $t\text{-C}_4\text{F}_9\text{I}$ . No attempt was made to tailor the energy absorption across the laser cell diameter. Future studies should address the issue of energy deposition and resulting laser beam profile in detail. The relationship between the collected solar

power  $P_c$  and the laser output power  $P_L$  (1 MW) is

$$P_c = \frac{P_L}{(SU)(QE)(CR)(QT)(DS)} \quad (2)$$

where  $SU$  is the solar utilization (0.043),  $QE$  is the quantum efficiency (0.2),  $CR$  is the collector reflectivity (0.92),  $QT$  is the quartz tube transmission (0.92), and  $DS$  is the shading factor of the incident solar light on the laser tube by the gas flow ducts (0.84). For a 1-MW laser, the collected solar power is 162 MW and the solar concentration on the 1.84-m-diameter quartz tube is 2050. The laser tube surface area is larger than the actual focal volume surface area. Therefore, the concentration is larger, or 2826. Solar light that enters the lasant gas is partially absorbed, resulting in 5 MW of solar power being deposited in the gas of which 1 MW is emitted as laser power and 4 MW is released in the gas as heat.

The laser has three components—the quartz tube, the cavity optics, and the lasant gas. The mass of the quartz tube was calculated by using the density of quartz and the volume of a tube 1.84 m in diameter by 10 m long with a 2-mm wall thickness. This resulted in a mass of 1860 kg. The laser cavity optical system was not defined, but based on reference 14, we assumed that the system could be constructed to weigh 1000 kg.

### 2.3. Thermal Cycle

To define an energy budget and to provide the required lasant gas flow through the laser cavity, a thermal cycle was developed. Several thermodynamic cycles were considered; however, from a thermodynamic point of view, one cycle produced net work which was enough to drive the compressor. Most other cycles required the addition of work from an outside source, which is an undesirable characteristic for a self-sustaining power station.

Figure 6 is a thermodynamic pressure-volume ( $P$ - $V$ ) diagram which describes the four major processes of the thermal cycle as (1) heat is added to the lasant in the laser cavity by the absorbed solar radiation at a constant pressure of  $10^3$  Pa (7.5 torr), (2) an isentropic expansion through a turbine produces work as the pressure drops to 550 Pa (4.1 torr), (3) heat is rejected by a radiator at constant gas pressure, and (4) to complete the cycle, the lasant is compressed isentropically to a pressure of  $10^3$  Pa (7.5 torr) before entering the laser cavity. The  $P$ - $V$  diagram of the cycle does not show, for simplicity, the expansion and compression provided by the ducts immediately before and immediately following the laser tube. However, these effects were taken into account in calculating the states of the lasant around the cycle.

Thermal cycle computations were based on continuum gas-flow equations and the appropriate boundary conditions for each segment of the system. Energy interchange was described by the first law of thermodynamics:

$$\dot{Q} = \dot{m} \left[ c_p (T_e - T_i) + \frac{V_e^2 - V_i^2}{2} \right] + \dot{W} \quad (3)$$

where  $\dot{Q}$  is the heat-transfer rate;  $c_p$ , the lasant specific heat at constant pressure;  $T$ , the lasant temperature;  $V$ , the gas velocity; and  $\dot{W}$ , the power transferred. The subscripts  $i$  and  $e$  refer, respectively, to initial and exit characteristics of the gas in one segment of the cycle. The lasant was assumed to be an ideal gas, thus,

$$p = \rho RT \quad (4)$$

where  $p$  is the static pressure,  $\rho$  is the gas density, and  $R$  is the specific gas constant. The mass-flow rate  $\dot{m}$  of the lasant molecules entering ( $i$ ) and leaving ( $e$ ) each segment is (from the conservation of mass):

$$\rho_i A_i V_i = \rho_e A_e V_e = \dot{m} \quad (5)$$

where  $A$  is the duct cross-sectional area. Isentropic approximations were applied to the compressor, the turbine, and the cross-sectional area changes of the ducts. These isentropic flow equations were employed by using a ratio of specific heats of 1.05. Hence, each section of the system was defined by a series of equations describing incoming flow and the exiting flow. The exit conditions from one section were the inlet conditions for the next section.

Heating of the lasant during transverse flow across the cylindrical laser was approximated by

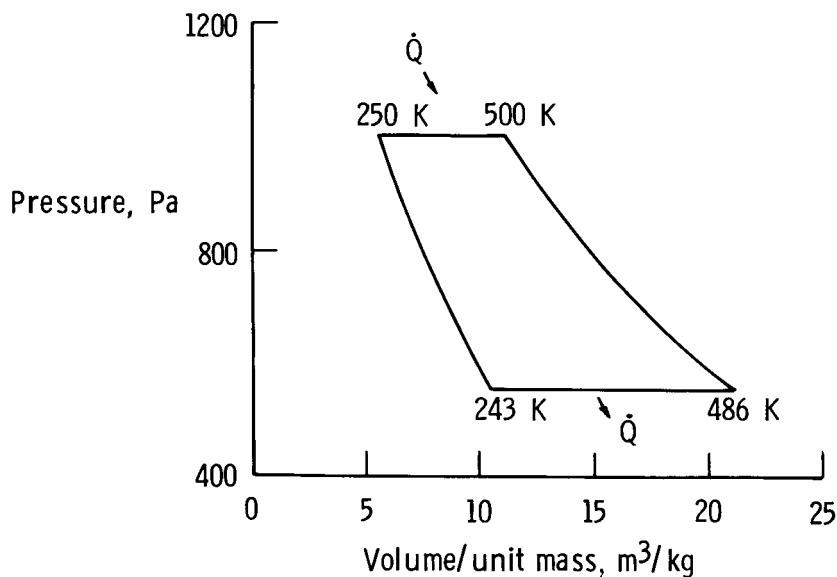


Figure 6.  $P$ - $V$  diagram of laser thermal cycle.

a three-step process: (1) an isentropic expansion, (2) the addition of heat, and (3) an isentropic compression of the flow. This approximation, which simplified the calculations, was the basis for the laser cross section shown in figure 7.

Using input values for  $\dot{Q}$ ,  $c_p$ ,  $T_i$ ,  $T_e$ ,  $A_i$ , and  $A_e$ , equations (3), (4), and (5) were solved simultaneously across the laser tube for  $\dot{m}$ ,  $p_i$ ,  $p_e$ ,  $V_i$ , and  $V_e$ . Gas heating of 4 MW was used for  $\dot{Q}$  based upon the solar collector size and predicted laser output. For the t-C<sub>4</sub>F<sub>9</sub>I lasant, we used  $c_p = 508$  J/kg-K (ref. 15). The inlet temperature was set at  $T_i = 250$  K to be substantially above the temperature for which the t-C<sub>4</sub>F<sub>9</sub>I vapor pressure would provide 10<sup>3</sup> Pa (7.5 torr) in the laser cavity. The design maintained the exit gas temperature at 500 K as discussed

earlier. The inlet and exit cross-sectional areas ( $A_i$  and  $A_e$ ) were determined by the laser cavity size. This size resulted in a mass-flow rate of  $\dot{m} = 31.5$  kg/s with an average velocity across the laser cavity of 15.5 m/s.

Gasdynamic lasers have a reputation for requiring much more power to maintain the flow than is emitted as laser power. Although the laser in this study derives its power to achieve a population inversion from the Sun rather than from high velocity gas expansion, an important concern was to determine if the power required to circulate the lasant could be kept small in comparison with the emitted laser power. For this reason, lasant flow velocity was limited to subsonic speeds everywhere in the system. A limiting Mach number of 0.8 was used to set critical duct sizes.

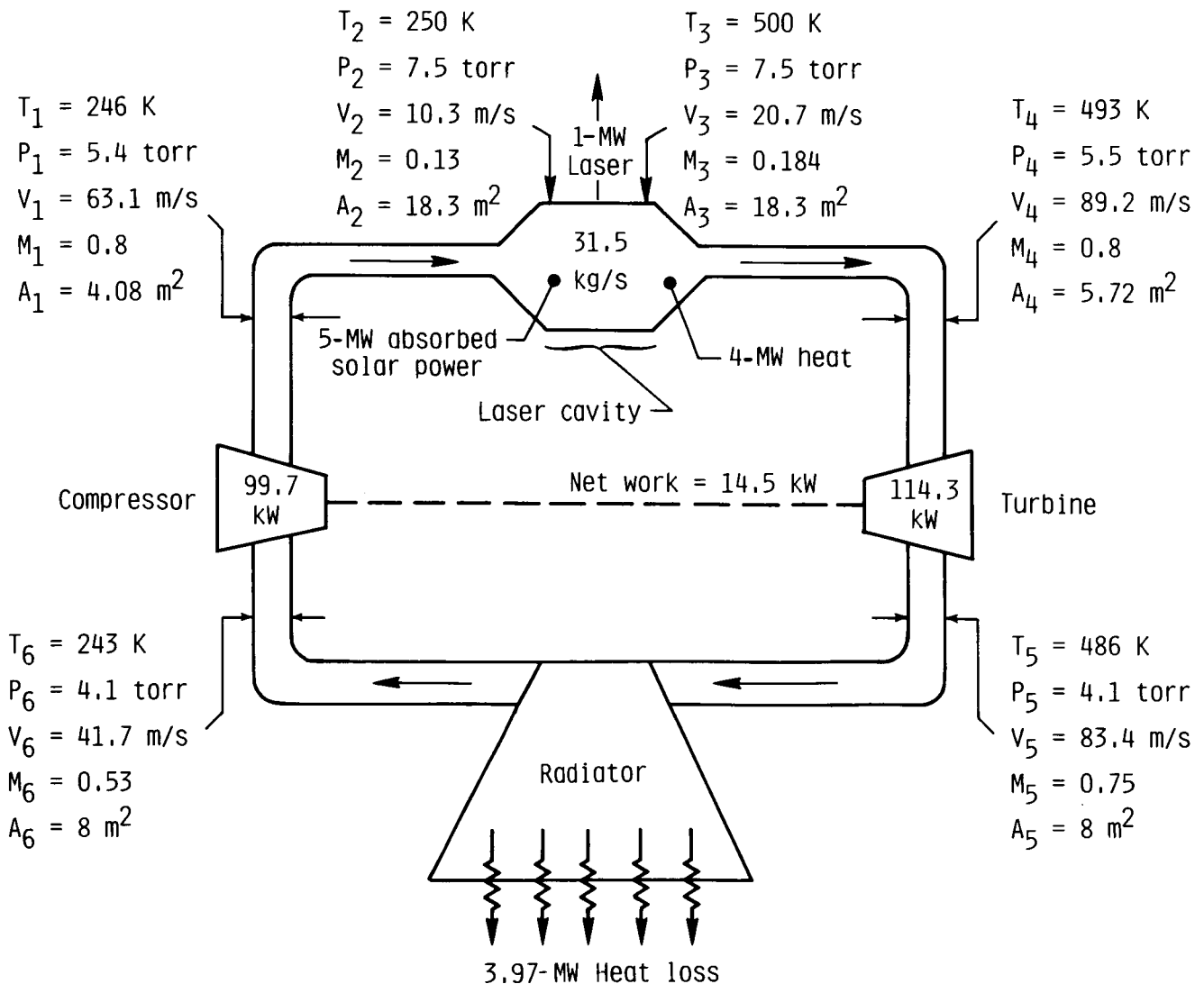


Figure 7. Results of thermal cycle calculation shown at key points around flow cycle.

The turbine and compressor were of special design and are discussed subsequently. Thermal energy was extracted by a 95-percent efficient turbine and much of the mechanical work was used to drive an 86-percent efficient compressor. The compressor required approximately 100 kW to maintain the lasant mass-flow rate. This power is only 10 percent of the emitted laser power; thus, the power required for lasant flow can be kept small in comparison to the laser power. A small amount of turbine power (14.5 kW) was converted to electricity for station service requirements such as the control moment gyroscopes (CMG).

The temperature drop across the turbine was held to a minimum (7 K) to maximize the average temperature of the radiator and thus minimize its area. The radiator, discussed in section 2.3.2, dissipates nearly 4 MW of relatively low quality (low temperature) thermal power. The exit temperature from the radiator was fixed to provide the appropriate lasant vapor pressure. At this location, impurities I<sub>2</sub> and (C<sub>4</sub>F<sub>9</sub>)<sub>2</sub> were removed and the t-C<sub>4</sub>F<sub>9</sub>I was replaced.

Further work needs to be done on the laser cavity flow as well as heat loss around the ducts.

**2.3.1. Compressor and turbine.** The design of the axial compressor and turbine was based on the report of Young and Kelch (ref. 14). The present design incorporates a two-stage compressor to achieve the required 1.32 compression ratio. In their report, the approximate compressor density was found to be 1000 kg/m<sup>3</sup>; thus, by calculating the compressor volume required for the station, an approximate mass was determined. The compressor inlet area was 8 m<sup>2</sup>, and the outlet area was 4.08 m<sup>2</sup>, where the ratio of length to inlet diameter was 0.33 per stage. Thus, the volume of the truncated cone-shaped compressor times this density resulted in a mass of approximately 12 700 kg.

The turbine was treated in a similar manner, where the inlet area was 5.72 m<sup>2</sup> and the outlet area was 8 m<sup>2</sup>. Using the same argument as previously, the mass was found to be approximately 12 200 kg.

**2.3.2. Radiator.** The radiator mass was based on the area necessary to passively radiate the waste heat into space. The area was obtained by equating the rate of heat carried to the radiator by a constant mass flow to the rate of heat lost by radiation to space. Solving for area gives

$$A = \frac{1}{3} \frac{\dot{m} c_p}{\varepsilon \sigma} \left( \frac{1}{T_6^3} - \frac{1}{T_5^3} \right) \quad (6)$$

where  $\dot{m}$  is the lasant mass-flow rate,  $c_p$  is 0.508 kJ/kg-K,  $\varepsilon$  is the radiator emissivity assumed

to be 1, and  $\sigma$  is the Stefan-Boltzmann constant. Using  $T_6 = 243$  K and  $T_5 = 486$  K (fig. 6), the radiator area was calculated to be 5728 m<sup>2</sup>. The radiator mass was found by using the scaling coefficient of 2.7 kg/m<sup>2</sup> (ref. 16), which resulted in a mass of 15 470 kg. The radiator was placed as close as possible to the laser cavity to minimize the gas flow distance. The radiator surface area was not exposed to either direct or reflected solar heating due to the geometrical design. The compressor and turbine were mounted on the edge of the approximately 1-m-thick radiator.

## 2.4. Lasant Storage Tanks

As noted earlier, some lasant was lost due to the less than 100-percent recombination of I and C<sub>4</sub>F<sub>9</sub> radicals to reform t-C<sub>4</sub>F<sub>9</sub>I. The loss rate is equal to the photodissociation rate times the fraction of those molecules which do not recombine into t-C<sub>4</sub>F<sub>9</sub>I. The dissociation rate is  $6.6 \times 10^{24}$  molecules/s. To estimate the lasant loss fraction, a similar loss fraction for i-C<sub>3</sub>F<sub>7</sub>I of  $4.5 \times 10^{-3}$  (ref. 17) was the starting point. J. W. Wilson, from the Langley Research Center, who has experience with both t-C<sub>4</sub>F<sub>9</sub>I and i-C<sub>3</sub>F<sub>7</sub>I, has suggested that the loss rate for t-C<sub>4</sub>F<sub>9</sub>I is perhaps 100 times less than that for i-C<sub>3</sub>F<sub>7</sub>I. Based on this information, it was assumed that the loss fraction of t-C<sub>4</sub>F<sub>9</sub>I is  $4.5 \times 10^{-5}$ .

The laser power station was designed to operate continuously in sunlight but not at all when it was in the Earth's shadow. For an equatorial orbit at an altitude of 6378 km, this amounted to an operational time of  $2.63 \times 10^7$  s/yr. Therefore, the loss rate of lasant was 4490 kg/yr.

Initially, there is a 5-year supply of lasant in the chambers of the storage tanks. After 5 years of operation, all has been converted to unusable lasant and is stored in the *used*-lasant chambers. The laser driven OTV tanker then comes to the power station and removes this lasant and replaces it with fresh lasant. The capacity of the lasant tanks must therefore be twice the volume of the 22 450 kg of t-C<sub>4</sub>F<sub>9</sub>I. The density of t-C<sub>4</sub>F<sub>9</sub>I is not known exactly but is assumed to be 2.06 g/cm<sup>3</sup>, which is the density of n-C<sub>4</sub>F<sub>9</sub>I. At that density, the total (both new and used lasant) volume of all the supply tanks is 21.8 m<sup>3</sup>.

Four supply tanks, each having a volume of 5.45 m<sup>3</sup>, were placed 90° apart on the shaded side of the solar concentrator as shown in figure 3. The tanks were spherical with an outside diameter of 2.18 m. An inner spherical shell, concentric with the outside wall and having a diameter of 1.73 m, separated the tank into two chambers of equal volume. Both tank walls were made of 1-mm-thick aluminum with a thin protective coating to prevent chemical

reactions. The mass of each tank was 67.4 kg when empty and 5680 kg when filled with the lasant. The mass of each concentric pair of tanks was constant throughout the mission, since as fresh lasant is removed from one chamber, an equal mass of unusable lasant was returned to the other chamber.

The mass of the filled storage tanks was substantial, and their location on the power station significantly affected the moments of inertia of the power station. Having the moments of inertia about the three principal axes nearly the same reduced the magnitude of the gravity gradient torques on the power station and therefore the size of the control moment gyroscope needed to keep the concentrator pointed directly at the Sun. After the rest of the power station had been designed, the position along the back of the concentrator which minimized the differences in the moments of inertia was sought. That position was at a radial distance of 149 m from the axis of symmetry of the concentrator.

### 2.5. Control Moment Gyroscope (CMG)

A control moment gyroscope (CMG) was used to keep the power station oriented with the solar concentrator axis pointed directly at the Sun. The CMG was located on the solar concentrator axis between the laser cavity and the radiator. The moments of inertia about the three axes of the laser power station (shown in fig. 3) were  $8.15 \times 10^8$  kg-m<sup>2</sup> about the X-axis,  $8.10 \times 10^8$  kg-m<sup>2</sup> about the Y-axis, and  $8.15 \times 10^8$  kg-m<sup>2</sup> about the Z-axis. It was found that, by using the Articulated Rigid Body Control Dynamics (ARCD) computer program developed by M. L. Heck of Analytical Mechanics Associates, Inc., under contract to the Langley Research Center, a double-gimbal CMG with a mass of approximately 2000 kg and an electrical power requirement of approximately 1 kW was sufficient to maintain proper attitude. Four thrusters on the edge of the concentrator, 191.7 m from the laser axis, were used to desaturate the CMG. These thrusters use about 150 kg of fuel per year, which is 4500 kg over the 30-year lifetime of the power station.

### 2.6. Transmission Optics

Transmission of laser power from the station to the user was dominated by the range and by the size of the transmission and the reception optics. As mentioned previously, the power station altitude was chosen to be approximately 6400 km for the purpose of minimizing both atmospheric drag and the number of power stations necessary for continuous and complete coverage of low Earth orbit (LEO) spacecraft, even taking account of a loss of output from a power

station in the Earth's shadow. From this altitude, the range of transmission from the power station to a LEO spacecraft on the horizon was 11 000 km. A laser receiver dish with a nominal diameter of 1 m was chosen to avoid significant drag effects and to provide a high intensity beam for conversion to electricity or propulsion. With the range, receiver diameter, and laser wavelength selected, major characteristics of the transmission optics on the power station were then defined.

The beam from the laser passes through the vertex of the solar concentrator and enters a Cassegrainian optical transmission system designed for long-range transmission. The Cassegrainian system was composed of two parabolic reflector dishes (fig. 3). The primary reflector is 1.8 m in diameter and is convex toward the beam. This shape causes the incident laser beam to expand to fill the much larger diameter of the secondary (transmitting) parabolic reflector dish which focused the beam at large distances. The diameter of the transmitting dish was 27.6 m, which was the diameter required to put 99 percent of the beam power into a 1-m-diameter spot at a distance of 11 000 km. The vertices of the two dishes were separated by 20 m and their focal points almost coincided at 20.6 m from the transmitter dish. Very small and precise axial translation movement of the primary mirror caused sufficient focal length changes of the transmitting mirror system to compensate for range changes. The surfaces of both dishes had precise optical finishes to limit beam distortion and very highly reflective coatings to minimize mirror heating and maximize power transmission.

The entire Cassegrainian system was hinged at the vertex of the transmitting dish to allow the laser beam to be pointed in any direction within a  $2\pi$ -sr solid angle. Two rotatable wedge prisms located at the transmitter vertex were used to direct the laser beam to the primary mirror when the Cassegrainian system pointed away from the axis of the power station.

The mass of the transmission mirror was calculated by using the scaling coefficient of 40 kg/m<sup>2</sup> derived from Berggren and Lenertz (ref. 18). The area of the transmission dish was 600 m<sup>2</sup>; thus, the transmission optics mass became 24 000 kg.

## 3. Cost

The power station components would be launched to a low Earth orbit (LEO) by the Space Shuttle and then carried to the operational altitude of 6378 km by a chemically propelled orbital transfer vehicle (OTV). There the station would be constructed and produce a 1-MW beam for 30 years. Replenishment

of the lasant every 5 years would be provided by a laser-propelled OTV.

The cost associated with each system component has been estimated. That cost included (1) the cost of purchasing the component from a manufacturer on Earth, (2) the cost of transporting it to the power station site, (3) the cost of assembling it in space and integrating it into the system, and (4) the cost of maintenance and operation over the 30-year lifetime of the power station.

The intention of this cost analysis was to obtain a set of relative cost figures for each component that provides an indication of which components and operations (transportation, assembly, etc.) more significantly affect the cost of the entire station. The actual costs are expected to be less accurate than the cost comparison between individual system components. Thus, emphasis should be placed on the cost ratios and differences between individual components.

The mass of each component was vital to the cost analysis and is shown in table I. Transportation and assembly costs were directly proportional to the component mass. This approach was used because it was a simpler method for estimating the cost of a power station component than making a manufacturing-process cost estimate. By minimizing the number of variables, the relative accuracy of the cost was

expected to be better than the absolute cost accuracy. When available, specific cost (i.e., \$/kg) found in the literature for the manufacturing of similar, but less massive, components was used as the basis for calculating the cost of the power station components. However, in some instances, where no published estimates were available, it was necessary for the authors to estimate specific costs.

The cost of transporting  $C_T$ , a power station component to an equatorial orbit at an altitude of 6378 km, was

$$C_T = (2800 \text{ \$/kg})(m) \quad (7)$$

where  $m$  is the mass of the component in kg. The specific cost of 2800 \$/kg included a launch cost to LEO of 1000 \$/kg and an orbital transfer cost of 1800 \$/kg. The Shuttle specific launch cost was calculated based on a dedicated flight by a U.S. Government user in the year 1980 (ref. 19). The specific orbital transfer cost was calculated by dividing the cost of buying and operating the chemically propelled OTV by the total payload it could deliver to the laser power station altitude during its lifetime (ref. 9). The cost of transporting the 5-year load of fresh lasant to the power station and the load of used lasant

Table I. t-C<sub>4</sub>F<sub>9</sub>I Solar Laser Station System Mass<sup>a</sup>

Collector, kg . . . . .	14 800
Radiator, kg . . . . .	15 470
Laser cavity	
Quartz tube, kg . . . . .	1 860
Laser cavity optics, kg . . . . .	1 000
Laser transmission optics and structure (27.6 m diam.), kg . . . . .	24 000
Gas flow system	
Compressor (2 stage), kg . . . . .	12 700
Turbine, kg . . . . .	12 200
Ducts, kg . . . . .	3 000
t-C <sub>4</sub> F <sub>9</sub> I storage tanks (4 empty tanks), kg . . . . .	270
Attitude control system (CMG and fuel)	
CMG, kg . . . . .	2 000
150 kg fuel/yr, kg . . . . .	<u>4 500</u>
Total mass, kg . . . . .	91 800

<sup>a</sup>Excludes first 5-year lasant supply.

back to the Earth was handled in a different way. The launch phase from Earth to LEO and the final return phase from LEO to Earth would still be done with the Space Shuttle at a cost of 1000 \$/kg, but the orbital transfers between LEO and the power station would be done with a laser-powered OTV using the beam from the laser power station. A laser OTV like that described in reference 8 would require 1.4 percent of the laser power produced by the power station to carry out its refueling missions. To supply the power station with fuel required one-sixth of the OTV lifetime. Thus, one-sixth the cost of a laser OTV must be included in the operational cost of the laser power station.

There were 13 components of the power station. The ten components needed to begin operation were the solar collector, laser, compressor, turbine, radiator, flow system ducts, lasant storage tanks, transmission optics, control moment gyroscope, and the first 5-year supply of lasant. The three components needed to keep the station operating over the following 25 years are the 25-year supply of lasant, the laser-powered OTV (use of one-sixth of its lifetime), and the supply of hydrogen fuel for the laser-powered OTV.

The cost of assembling  $C_A$  a component in space and integrating it into the system was

$$C_A = (400 \text{ \$/kg})(m) \quad (8)$$

where  $m$  is the mass of the component in kilograms. The cost per kilogram for assembly was based on an assembly work rate of 250 kg per crew hour and a cost of \$100 000 per crew hour from reference 20. This assembly cost applied to all the power station components except the lasant and the OTV fuel which, of course, required no assembly.

The cost of maintenance and operation  $C_o$  for each component was assumed to be 10 percent and depends only on its mass and manufacturing cost:

$$C_o = 0.1C_M + 0.1C_A + 0.1C_T \quad (9)$$

where  $C_M$  is the manufacturing cost. Again, this cost applies to all the power station components except the lasant and OTV fuel which require no maintenance.

The manufacturing cost  $C_M$  of each component is discussed under separate headings in the following sections and is shown in table II. The manufacturing cost for the power station components was \$673.4 million. This was 98 percent of the total 30-year manufacturing cost. The total initial laser power station cost was \$1223 million, which was 95 percent of the total 30-year cost of \$1289 million. The largest cost elements of the 30-year power station cost were the transmission optics, the laser tube and optics, and the solar collector.

Table II. t-C<sub>4</sub>F<sub>9</sub>I Laser Power Station Cost

[All costs in millions of dollars; number in box is total power station cost]

Component	Manufacturing unit cost	Assembly cost	Operation and maintenance cost	Launch cost	Total cost
Laser tube and optics	286.0	1.1	29.5	8.0	324.6
Collector	74.3	5.9	12.2	41.4	133.8
Turbine and compressor	21.4	10.0	10.1	69.7	111.2
Ducts and lasant tanks	0.3	1.3	1.0	8.4	11.0
Radiator	8.6	6.2	5.8	43.3	63.9
Transmission optics	240.0	9.6	31.7	67.2	348.5
CMG	42.9	0.8	5.0	6.5	55.2
Lasant for 5 years	0.01	0	0	62.9	62.9
Total	673.4	34.8	95.3	306.4	1111.0
Lasant for 25 years	0.05	0	0	<sup>a</sup> 112.0	112.0
Total (with lasant)	674.0	35.0	95.0	418.0	1223.0
Laser OTV	9.0	0.25	0.98	0.65	10.9
Laser OTV fuel (H <sub>2</sub> ) for 25 yr	0.1	0	0	<sup>a</sup> 54.8	54.9
Total cost	683.0	35.0	96.0	474.0	1289.0

<sup>a</sup>Earth to LEO only.

### 3.1. Collector

The total collector area of 148 000 m<sup>2</sup> was designed to support a 1-MW laser. The mass per unit area of 0.1 kg/m<sup>2</sup> was calculated from the data of references 12 and 21, and the manufacturing specific cost was calculated by using a cost of 502 \$/m<sup>2</sup> (ref. 22). Although lower specific cost data for other collectors (such as inflatable collectors) were found, because of the required life and design complexity, it was believed that 502 \$/m<sup>2</sup> was more reasonable for this collector. Thus, the manufacturing cost for the collector is \$74.3 million. This was 56 percent of the total collector cost of \$133.8 million and 11 percent of the total manufacturing costs for the power station components. The total cost of the collector was 10 percent of the total power station cost.

### 3.2. Laser Tube and Optics

The 10-m-long quartz laser tube and the laser cavity optics have a total mass of 2860 kg and at an assumed specific cost of 100 000 \$/kg, the manufacturing unit cost for the laser cavity and optics was \$286 million (ref. 23). This cost, although high, appears reasonable due to the precision, high-technology nature of these components. This cost was 42 percent of the total manufacturing unit costs for the power station components. The total cost for the laser tube and optics was \$324.6 million. This was 25 percent of the total power station cost.

### 3.3. Transmission Optics

The transmission optics had a mass of 24 000 kg and a cost of 10 000 \$/kg scaled from space telescope cost and weight estimates. These weights and specific costs were based on reflector technology used for the Hubble telescope which was developed by NASA Marshall Space Flight Center. Although the Hubble telescope is designed for low power applications, it is a good approximation to the present application because of the need for long-range transmission diffraction limited optics. The manufacturing cost was \$240 million. This was 36 percent of the total manufacturing cost for the power station components. The total cost for the transmission optics was \$348.5 million. This was 27 percent of the total power station cost. The total cost of the transmission optics was the highest of the power station components.

### 3.4. Turbine and Compressor

The manufacturing cost for the turbine and compressor was calculated by multiplying the estimated specific cost of 100 000 \$/kW by the turbine and compressor power. (Industrial sources would not estimate the cost of our turbine and compressor because

of their large size and complexity.) The assumed specific cost of 100 000 \$/kW was obtained by extrapolation from the cost of a typical gas turbine cycle generator (private communication from the General Electric Company). The manufacturing cost for the turbine and compressor was \$21.4 million, which was 3 percent of the manufacturing cost for the power station components. The total cost for the turbine and compressor is \$111.2 million. This cost is 9 percent of the total power station cost.

### 3.5. Radiator

The area of the radiator needed to radiate waste heat was 5728 m<sup>2</sup>, and at 2.7 kg/m<sup>2</sup> (ref. 16), the radiator had a mass of 15 470 kg. At a specific cost of 1500 \$/m<sup>2</sup> (ref. 16), the manufacturing cost of the radiator was \$8.6 million. This was 1 percent of the total manufacturing cost for the power station components. The total cost for the radiator was \$63.9 million; this was 5 percent of total power station cost.

### 3.6. Ducts and Lasant Tanks

The ducts and the four lasant tanks were made of aluminum and had a mass of 3270 kg. The manufacturing cost of \$0.3 million was calculated by assuming a specific cost of 100 \$/kg since this is typical of a low technology manufacturing process. This was 0.04 percent of the total manufacturing cost for the power station components. The total cost for the ducts and lasant tanks was \$11.0 million. These ducts and tanks were the least costly of the laser power station components, less than 1 percent of the total power station cost.

### 3.7. CMG

The specific cost of the CMG was taken as 6600 \$/kg. (This value was scaled from an MA 2300 double-gimbaled CMG and provided by Bendix Aerospace Sector, Allied Corporation.) At a mass of 6500 kg, the manufacturing cost was \$42.9 million, which was 6 percent of the total manufacturing cost for the power station components. The total cost for the CMG was \$55.2 million. This was 4 percent of the total power station cost.

### 3.8. Lasant

For specially prepared samples of the t-C<sub>4</sub>F<sub>9</sub>I lasant, the cost is approximately 10<sup>5</sup> \$/kg. Other iodide bearing compounds, such as i-C<sub>3</sub>F<sub>7</sub>I that are produced in larger quantities, although not production volume, have a cost of approximately 10<sup>3</sup> \$/kg. In large production quantities the cost should substantially decrease. Therefore, we have assumed a specific



cost of 0.45 \$/kg, which is typical of high production chemicals such as Freon 22 (cost based on tank car loads of Freon 22 and supplied by E. I. du Pont de Nemours & Company). Thus the lasant manufacturing cost is \$0.01 million, and this is less than 0.01 percent of the total manufacturing cost for the power station components. The cost for a 5-year supply of lasant was dominated by the transportation cost of \$62.9 million. The total cost is \$62.9 million or 5 percent of the total power station cost.

### 3.9. Lasant Supply for 25 Years

The lasant manufacturing cost for the remaining 25 years of the power station life is \$0.05 million. The total cost for the lasant was again dominated by the transportation cost—\$112 million. The lasant transportation cost was dominated by the Shuttle cost since a laser-driven OTV will transport it to the power station at negligible cost as seen in section 3.11.

### 3.10. Laser OTV

A laser OTV is assumed to provide transport of the lasant from Shuttle altitude to the power station altitude. The laser OTV had an assumed lifetime of 30 missions, of which only 5 missions are needed to transfer the necessary lasant. Thus, only one-sixth of the laser OTV cost was apportioned to the power station because of the assumption that the other 25 flights would be paid by other users of the laser OTV. The manufacturing cost assumed for the OTV was \$9.0 million. The total cost for the laser OTV (see table II) was \$10.9 million, which is about 1 percent of the total 30-year power station cost.

### 3.11. Laser OTV Fuel

The H<sub>2</sub> fuel for the laser OTV had a manufacturing cost of \$0.1 million. The total cost for the 25-year supply of OTV fuel is \$54.9 million, which was dominated by a transportation cost of \$54.8 million, 99.8 percent of the total laser OTV fuel cost.

## 4. Discussion

### 4.1. Design

Previous studies of laser power transmission generally treated the power station components as blocks whose mass or cost were estimated in order to determine if central power stations could be cost-effective in space. Those studies assumed that the components could be connected and made to work. This study goes a step further in the design of the power station. The size, shape, and location of each component has been specified for a particular laser power

station. The interaction of the components has been investigated to see if indeed they can be connected and integrated into an overall system.

The system was designed so that 160 MW of solar energy was focused on the laser cavity of which 5 MW was absorbed by the t-C<sub>4</sub>F<sub>9</sub>I lasant to produce a 1-MW laser beam and 4 MW of heat to be rejected by a radiator. A specifically shaped concentrator collected and focused that amount of solar energy into a laser cavity designed to match the focal volume. Circulation ducts supplied gaseous lasant for transverse flow through the laser cavity. A compressor maintained the flow, and a turbine extracted power from the heated lasant to drive the compressor and to provide electrical power. The degree to which the ducts shielded the laser cavity from sunlight was taken into account. The temperature of the lasant was kept below that where thermal dissociation becomes a serious problem. The position of all the components was selected to reduce solar shielding, to minimize gas flow path length, and to balance the moments of inertia.

Not all details were considered. More studies would be required to assure that the operation of this power station was indeed feasible. But, to the degree to which this study has proceeded, no insurmountable technical problems have been identified. Thus, this type of laser power station remains a feasible concept.

Of the details not considered in this study, the most important was the design of the laser cavity flow channel where the proper solar absorption and lasant flow must exist. The resulting spatial distribution of excited iodide atoms must produce the lasing modes suitable for long distance transmission. This is an important area for future in-depth analyses of power transmission by solar-pumped gas lasers. Other details not addressed were the structural design of the central truss and the design of rigidizing members in the solar concentrator needed to withstand the torques applied to maintain the proper attitude. Also, space fabrication and assembly of the solar concentrator were not defined.

Two concerns held prior to this study were (1) whether the gas could be circulated fast enough to maintain lasing without requiring unreasonable power levels to maintain the flow, and (2) whether the required solar pointing attitude could be maintained with reasonable electrical and propulsive power. The study showed that the power required for both flow and pointing could be obtained from the heated lasant by a gas turbine.

The mass of the power station, 92 000 kg, was not large. The power station could be carried to LEO with four Space Shuttle flights, if the Shuttle could

carry 23 000 kg per trip. A chemical OTV carried all the power station components to the operating orbit for assembly.

Nearly all the components of the power station were much larger than presently available counterparts and were designed by extrapolation well beyond conservative limits. Technologies still lacking include large compressors for low pressure gases of high molecular weight, very large high power transmission optics, lasant cost-reduction technology, and assembly in space of large space reflectors.

## 4.2. Cost

Although the total costs were quite uncertain, the cost comparison between components should provide some valuable insights to guide future research. No design, development, test, and evaluation costs (DDT&E) were included in our cost analysis; thus, they need to be addressed in future studies.

The costs of the four major operations identified in table II are summarized in table III.

Table III. Operations Relative Cost in Percent

Manufacturing, percent . . . . .	53
Assembly, percent . . . . .	3
Operation and maintenance, percent . . . . .	7
Transportation, percent . . . . .	37

It is often thought that the cost of transporting a system to space was by far the largest cost incurred and that, therefore, the comparative mass of several systems will provide a comparative cost estimate. This study did not support that contention. Transportation costs were estimated to be 37 percent of the total cost of the laser power station, whereas manufacturing costs were estimated to be 53 percent. The costs associated with particular components are given in table IV.

Table IV. Components Relative Cost in Percent

Transmission optics, percent . . . . .	27
Laser cavity and optics, percent . . . . .	25
Total lasant resupply for 25 years, percent . . . . .	14
Solar collector, percent . . . . .	10
Turbine/compressor, percent . . . . .	9
Radiator, percent . . . . .	5
Lasant, percent . . . . .	5
CMG, percent . . . . .	4
Ducts/lasant tanks, percent . . . . .	1

The transmission optics were the most expensive component of the power station. The cost was a result of the size of the transmission optics and

the size depended on the output wavelength of the laser. This suggested that one of the more important characteristics of a laser for power transmission was its wavelength. The laser used in this study had a wavelength of 1.3  $\mu\text{m}$ . If the wavelength were reduced a factor of 2, the cost of the transmission optics would be reduced by a factor of 4, since cost scales with area.

The laser cavity was a high technology component that was expected to be a high cost item no matter what its size because of its complexity. No means of reducing the cost of the laser cavity have been identified.

The cost of lasant resupply could be completely eliminated with a lasant that recombined completely after photodissociation, or with a directly pumped lasant that did not dissociate at all during lasing. Lasants that meet these criteria are known; however, such lasants were not chosen because they all possessed some overwhelming undesirable characteristics. Finding a suitable solar-pumped lasant that is not consumed during lasing is a continuing research objective.

The cost of the collector was not one of the major costs, which means that the laser efficiency was not the most important characteristic of the laser.

The radiator was a minor cost factor because the lasant had the very desirable property of being transparent to wavelengths that do not produce lasing; thus, lasant heating was minimized. The radiator costs would go up if a lasant absorbed much energy at wavelengths that did not contribute to lasing. In searching for a lasant that lases at shorter wavelengths and would not be consumed in the lasing process, one must also consider the transparency of the lasant to radiation not useful to lasing. Lasants that absorb unwanted solar energy may require a higher technology radiator design.

The cost of the CMG's, a minor cost, was determined by the masses of the solar collector and the transmission optics and therefore depends on the efficiency and wavelength of the laser.

Almost all high power lasers will require a circulation system for cooling, whether it is a gas laser, a liquid dye laser, or a cooled solid-state laser. Great cost reductions of the power station will probably not be realized through reductions in the cost of fluid circulating components.

## 5. Concluding Remarks

A preliminary design of a laser power station in Earth orbit did not reveal any major technical problems; thus, this type of power station remains a viable concept for future space applications. Several features of the design indicate conceptual progress:

A nonparabolic concentrating dish was found to provide a focal volume in the shape of a frustum of a long narrow cone which could be matched to a laser optical cavity

A standard-technology radiator of large size was sufficient for the power station thermal management as long as the lasant was transparent to wavelengths that do not produce lasing

Power transmission optics, which provided a 1-m focal diameter at the 11 000-km range, were designed. Technology from other space-mirror applications may help meet the present requirements

The power required to circulate the lasant can be an order of magnitude less than the power emitted by the laser

The power required for pointing a well-balanced power station can be nearly three orders of magnitude less than the power emitted by the laser

The estimated mass of the power station of 92 000 kg without lasant can be less than the payload capability of four Space Shuttle flights

A more detailed design of the laser cavity is needed to fully assess the technical challenge of this key system component

A cost for the system components was determined which enables a relative cost comparison of critical technology areas and thus indicates trends for future research emphasis. The absolute system cost was much less reliable than cost comparisons. Such comparisons indicate

That the laser transmission optics and cavity are the most massive and expensive components

That the manufacturing (and also design development testing and evaluation) of station components could be a greater program component (53 percent) than transporting the station to its operating orbit (37 percent) because the laser and the transmission optics are such high technology and, thus, high cost items

The reusable lasant makes up as little as 20 percent of the life cycle cost of the station

Laser efficiency was not found to be the primary system cost and weight factor

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16. Abstract <p>A preliminary conceptual design of a space-based solar-pumped iodide laser emitting 1 megawatt of laser power for space-to-space power transmission is described. A near parabolic solar collector focuses sunlight onto the t-C<sub>4</sub>F<sub>9</sub>I (perfluoro-t-butyl iodide) lasant within a transverse flow optical cavity. Using waste heat, a thermal system was designed to supply compressor and auxiliary power. System components were designed with weight and cost estimates assigned. Although cost is very approximate, the cost comparison of individual system components leads to valuable insights for future research directions. In particular, it was found that laser efficiency was not a dominant cost or weight factor, the dominant factor being the laser cavity and laser transmission optics. The manufacturing cost (no design development testing and evaluation included) was approximately two thirds of the total cost with transportation to orbit the remainder. The flowing nonrenewable lasant comprised 20 percent of the total life cycle cost of the system and thus was not a major cost factor. The station mass was 92 000 kg without lasant, requiring approximately four shuttle flights to low Earth orbit where an orbital transfer vehicle will transport it to the final altitude of 6378 km.</p>			
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