Advanced Solar Power Systems

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Abstract

Advanced Solar Power, Inc. (ASPI) has developed a demonstration prototype of a point focusing solar power system. The concentrator is a modified Cassegrain system (10th order generalized aspheric mirrors) producing 10,000 suns at the focal point. The integral receiver is an extended, pressurized black-body cavity designed to operate at 700 psi and 503 °F. The system tracks on two axes under microprocessor control. The demonstration prototype has a 4 kilowatt thermal (kWt) mirror mounted on a 40 kWt receiver system and is trailer-mounted (freeway legal) for experimental use.

Because of the patented black-body cavity receiver design, high thermal efficiencies of 80% with aluminimum and 90% with silver on the mirrors are calculated. Energy is transferred directly from photons to the molecules of the working fluid (water). The design system efficiency for this technology is virtually constant in the working range of 350 °F to 2000 °F and 135 psi to 10,000 psi because reradiation is negligible.

Commercial units are sized at 40-50 kWt (highway transportable), 500 kWt (helicopter transportable) and 1 MWt (mirrors manufactured on site). While tooling is expensive, quantity manufacturing is inexpensive and designed to be automated. The 40 kWt to 50 kWt (136,00 to 170,000) units will cost about $20,000 per unit with an available steam engine at a production rate of 300 units per year. A cogeneration version may cost on the order of $2,300 per kilowatt electric (kWe) for 1 to 10 kWe and 120,000 BTU/hr for a thermal load. The 500 kWt to 1 MWt units are estimated to cost $100,000 to $150,000 at a production rate of 500 units/year with the high likelihood of using conventional team turbine generator technology to achieve $600 to $1,000 per kWe of capacity installed cost.

All sizes of ASPS units have the inherent capability of buffer storage of abouat 1 hours of energy collection. Applications for ASPS units range from irrigation pumping, cogeneration and inudstrial process heat to heater/treater operations in oilfields. The larger units are designed to be competitive with fossil fuel as oilfield steam generators, large-scale chemical production, particularly in conjunction with geothermal wells, and electric power production. Since any transparent or translucent working medium can be used, possibilities exist for very efficient systems using helium, air, tolulene or sewage sludge as a working medium.

Introduction

The Advanced Solar Power System (ASPS) uses a technically sophisticated design and extensive tooling to produce very efficient (80-90%) and versatile energy supply equipment which is inexpensive to manufacture and requires little maintenance. The advanced optical design has two 10th order generalized aspheric surfaces in a Cassegrainian configuration which gives outstanding performance and is relatively insensitive to temperature changes, wind loading and manufacturing tolerances have been achieved.

A 4 kilowatt thermal (kWt; 14,000 BTU/hr) freeway transportable demonstration prototype unit has been designed, constructed and tested. The system, illustrated in Figure 1 uses automatic two-axis tracking, focusing and alignment under microprocessor control to give high geometric efficiency and low manufacturing and maintenance costs. The required mechanical motions are provided by hydraulic actuators which have stored energy to provide high power levels for an emergency scram or during high wind conditions. Routine power requirements are very low.

The key to the ASPS is the direct absorption of concentrated sunlight in the working fluid by radiative transfers in a black- body cavity. This heat transfer mechanism is 100% efficient by physical law. Thus the thermodynamic efficiency of the system is determined by the reflectivity of the two mirror surfaces and the transmission of the pressure window surface. Heat losses through the optical cavity walls can be limited by insulation to any desired economic value.

A broad range of temperatures (350 to 2000 deg F) and pressures (0 to 10,000 psi) are efficiently obtainable with this system which makes it very effective for many unique applications. The first commercial prototype ASPS will supply 40 to 50 kWt (136,000 to 170,000 BTU/hr) in the form of high temperature and pressure steam (350 to 700 deg F at 300 to 700 psi).

Basic ASPS Design Concepts

Figure 2 illustrates the basic design concepts underlying the ASPS technology. The key patented element of the ASPS is the black-body cavity receiver where photons are absorbed directly in the working medium. Max Planck's insight in 1899, explained the observed distribution of energy in a black body cavity at temperature T, by limiting permissible energy values to $E_n = nhf$ (Verh.d.D.Phys.Ges. 2, 237 (1900); Ann.d.Physik 4, 553 (1901)).

Albert Einstein developed a sounder mathematical basis for the quantization of matter and radiation (Ann. d. Physik 17, 132 (1905); Phys. Zeits., 18, 121 (1917)). The result of the quantization condition is that energy enclosed in an insulated cavity will always produce a given wavelength and intensity distribution dependent only on the absolute temperature (T) and not on the working fluid or the wall materials.

A typical black-body cavity is externally heated and has black walls and a small exit hole allowing the escape of black body radiation. Based on the principle that almost all optical phenomena are reversible, the ASPS introduces concentrated solar radiation into an enclosed, insulated cavity through a small pressure window. A sophisticated optical system is required to give high concentration ratios (10^4) and keep the entrance aperture area a small part (less than 1%) of the total cavity surface area. The entrance window must be highly transparent to the solar spectrum to prevent local heating. Energy is dispersed down the pressure tube by a turning mirror to prevent hot spots and to prevent direct reflections back out the window for any incoming rays. The walls of the cavity are highly reflective (specular and/or diffuse) to aid wall insulation and to permit preferential absorption of solar photons in the working medium (e.g.,water). All photons are absorbed and reradiated by the medium and cavity walls with a typical time constant of 10^{-8} seconds until the black-body curve for the equilibrium temperature (T) is achieved in less than a microsecond.

By the principle of Conservation of Energy, the radiative transfer of energy from photons to the working fluid is 100% efficient. To prevent direct reflection of sunlight out the entrance aperture, the minimum ray path in the working fluid is designed to be an absorption length for a green photon. This is about 10 feet for tap water. A minimum length for the optical cavity is established since a reflected ray would be attenuated by at least $1/e^2$.

For reradiation to effectively establish thermal equilibrium in the optical cavity, the working fluid must be transparent or translucent to the equilibrium temperature spectrum as well as the solar spectrum. The minimum temperature for tap water appears to be about 350 degrees F. At higher temperatures, equilibrium will be established faster. At lower fluid temperatures, an expanding 350 degree F. bubble is formed at the inside of the entrance window and at the adjacent turning mirror. Since the turning mirror and window do not melt on start- up, this has been demonstrated to be an effective heat transfer mechanism.

Energy, will of course, be reradiated out the entrance aperture. However, since the entrance aperture sees only the suns disk (the optical system is reversible), a net transfer of energy from the cooler cavity to the hotter sun would violate the first and second laws of thermodynamics. The high concentration ratio of 10^4 to 1 also makes reradiation losses negligible. Because no energy must be transported through an absorbing surface (the window is transparent and a thermal insulator) the optical cavity can be insulated as well as desired with cost as the limiting factor. Vacuum insulation in a Dewar construction has been chosen as an economic and convenient insulation method in the 4 kWt demonstration prototype. The microtherm spacers used are effective, but other insulation can be used without compromising the system principles in any way.

To provide precise temperature control of the working fluid without losing sun track, a movable baffle is provided in the optical cavity of the larger systems. This baffle blocks light, which travels in straight lines, but does not block fluid pressure. Since this is not a circulating system the system pressure is set by the feed pump which pumps cold fluid. If more energy is entering the cavity than is being removed, the baffle is moved down the pressure tube, increasing the size and the heat capacity of the cavity and maintaining a constant temperature. If more energy is being removed from the cavity by withdrawing fluid than is entering the cavity from the sun, then the baffle is moved up the tube. This decreases the size of the cavity and the heat capacity while maintaining a constant temperature of the working fluid. In this way, ideal engine or turbine operating conditions can be achieved and the Carnot efficiency of the system can be maximized.

System Efficiency

Because the ASPS has no appreciable reradiation losses, the only significant energy losses are from the two mirror reflections and the reflection at the surface of the pressure window. Because of the steepness of the mirror curves, 25% of the primary mirror intercept area is at ray angles of less than 45°, and a large part of the secondary mirror area has ray angles of less than 45°. Since at acute angles the reflectivity of the aluminum (or silver) layer and the plastic outer surface approaches 1 at the critical angle, for a given wavelength, the total reflectivity exceeds 80% for aluminum and 90% for silver coatings. Use of dichroic coatings could increase these reflectivities but may not be economic. The pressure window does have a dichroic coating which transmits better than 99.5% of the solar spectrum incident in an f/1.0 cone. After energy is inside the window, it is in the black body-cavity and will contribute to the equilibrium temperature by radiation or conduction.

The high vacuum insulation proposed, if properly designed, can give losses of less than 1% per day for a single Dewar design maintained at 10^{-6} Torr. Additional insulation can be added to reduce thermal losses to any desired value. In further testing of the 4 kWt unit, calorimetric analysis will primarily measure the efficiency of the cavity insulation. The reflectivity of the mirrors can easily be measured separately as a function of incident angle and wavelength integrated over the solar spectrum. Tracking efficiency is not a factor because it is either adequate to keep the sun's image on the pressure window or parts of the system melt or burn. However, the calorimetric analysis directly measuring the ratio:

$$\frac{\text{Energy in fluid}}{\text{Direct solar insolation}} = \text{efficiency}$$

will give an easily understood measure of system efficiency.

Moreover, the start-up variations of temperature as a function of position along the tube will give an indication of the working fluid opacity as a function of equilibrium temperature. This is a difficult number to calculate accurately for water and many other fluids, although a lower operating limit of about 350 degrees F. is expected in water.

A unique advantage of the ASPS is the essential independence of thermal efficiency from equilibrium operating temperature or the external environment. Thus the system can be operated to optimize the performance of external devices or processes. The practical upper limit for a fused quartz window operated at pressures to 10,000 psi is about 2,000 degrees F. Crystaline quartz windows would be limited to about 3,000 degrees F.

ASPS Optical System

Conventional telescopes are designed to resolve a point source (star) at infinity and have parabolic prime mirrors as derived by Sir Isaac Newton (1671). A conventional Cassegrain system has a parabolic primary and a hyperbolic secondary to give a more convenient focus for spectrographic studies of stars as derived by N. Cassegrain (1672). However, the sun subtends 1/2 degree of arc at the earth's orbit and is thus not a point source at infinity. This observation is taken into account in the design of the ASPS. The two reflective optical surfaces were designed using the full power of the Optical Researach Associates (ORA) of Pasadena, California proprietary software programs and hardware. The optimized surfaces are given by:

$$Z = \frac{(curv)y^2}{1 + (1-(1+k)\ (curv)^2y^2)^{\frac{1}{2}}} + Ay^4 + By^6 + Cy^8 + Dy^{10}$$

The ORA optical design programs are generally recognized as the best available for systems containing reflective elements.

Figure 3 shows the optical diagram for the 4 kWt ASPS which was constructed using two hyperbolas. The improvement over the conventional design is significant at the edge of the field (sun's rim) which is the area of primary concern. Because the objective is to put light through a hole, the energy distribution in the center of the sun's image is of little concern. The demonstration unit design was limited to conic sections because these simpler equations were presumed to simplify manufacture and testing of the mirrors.

However, the manufacturing and testing methods developed during the fabrication and testing of the demonstration 4 kWt system revealed that using conic sections was not an advantage. Numerically controlled machine tools used to generate the sweep template for constructing mirror molds point fit anyway and can accept the 10th order curve. Conventional testing methods do not work for our very fast systems (4 kWt;f/1, 40 kWt;f/0.8) because there is no prime focus but only a volume defined by rays from the primary mirror. Figure 4 shows the optical diagram 10th order design of the 40 kWt mirrors. The more sophisticated design provides steeper curves with higher reflectivity and more mechanical strength. In addition, this design has a lower obscuration ratio (11.2% - 14.4%) and better manufacturing tolerances.

The obscuration ratio is deliberately kept larger than 10% to permit the use of a plastic secondary mirror rather than the stainless steel secondary originally proposed. Obscuration ratios in the range used also give better manufacturing tolerances. The mirror design is tolerant of the primary environmental effects of temperature changes and wind loading. Temperature increases bring up the rim of the mirror, increasing the curvature and thus shortening the focal length. This effect can be corrected by automatic refocussing. The wind loading changes the pointing of the mirror which can be corrected by the fine-tracking system.

Manufacturing tolerances required for the 4 kWt unit have been achieved and will scale linearly with size for the proposed 40 kWt unit. The key tolerance is 1 milliradian random deviation on the mean slope of the primary mirror. Achievement of this tolerance on the demonstration unit was measured on a Cordax unit and also shown by the optical performance of the complete system. The sun's image on the face of the pressure window was calculated to be 1.1 inches in diameter with the allowable tolerances. The actual diameter was measured to be 1.08 inches.

To provide this superior optical performance at minimum construction and maintenance cost, these mirrors must move as a unit without unpredictable changes in figure. Thus all the materials used in a mirror must have similar coefficients of expansion, the mirror must be damped to avoid standing waves, and it must be of monocoque construction to avoid continuing adjustment. The ASPS mirrors are made of fiberglass and paper honeycomb with a slightly stretched reflective surface of aluminum or silver with a slippery plastic outer protective layer. This lightweight construction is economical because the materials are inexpensive ($1.50/lbd.), fabrication can be automated, there are no labor intensive subassemblies and there is no need for continuing alignment adjustments.

Controls

The ASPS features automatic tracking and focusing under microprocessor control primarily for economic reasons. The coarse tracking system located on the back of the secondary mirror is a simple quadrant detector. The system is constructed using four photo sensors (photo transistors) that are located under diffusing domes (pilot light covers). The sensors detect the shadow cast by a black hat. Since the system optical axis is boresighted to the coase detector equal shadows cast on all four sensors mean the detector is perpendicular to the sun's rays. This sytem will acquire the sun within 180 degrees (2 steradians) and lock on within 15 seconds.

The fine tracking and focusing system looks through 4 quartz fibers at the sun's image on the face of the pressure window. Again this arrangement is a quadrant dectector which centers the image on the window. Additional algorithms are used to minimize the size of the image, thus insuring proper focus. A clock is also contained in the microcomputer permitting rough tracking without a visible sun. This sophisticated but inexpensive control system permits less rigidity in the mount, prime mirror and secondary mirror support (spider) than a conventional telescope drive would require This results in enormous savings in system weight and cost. Maintenance is also greatly reduced since there are no manual adjustments required for changing environmental or operating conditions.

The microcomputer also performs critical performance monitoring and remote control from any location with a communication link (e.g., telephone). Energy production is monitored for billing purposes and tampering with the unit could be detected. Whenever dangerous temperatures or pressures are measured or sun-track is lost, the unit is programmed to scram by rotating 90 degrees off the sun within 5 seconds. If the unit is not moved off the sun within 15 seconds, of course parts of the system burn or melt. Strain gauges will be used to sense excessive wind loading and instruct the control software to move the unit into a zenith stow position.

Mount

An equatorial mount as illustrated in Figure 5, is the most economic design for the limited support requirements of the ASPS. The sun position is well known as the earth rotates daily about its inclined (23 - 1/2 degrees) polar axis and completes a yearly elliptical orbit around the sun. The daily rotation is most efficiently accomplished about an axis parallel to the earth's axis (i.e., a north-south axis inclined at the latitude angle). The seasonal variations then require a 23 1/2 degree inclination range perpendicular to this axis.

Because the ASPS needs a long absorption path in the working fluid, a cylindrical receiver reaching from the ground to the Cassegrainian focus is our efficient collection vessel. The pressure tube provides a very rigid axis of rotation inclined at the latitude angle without additional expense. The system is designed to operate in up to hurricane force (65 mph) winds and to survive in a stowed position (horizontal) for winds of 150 mph. The mirrors are fabricated to meet military requirements for wind survival since the technology used was developed for military use. The horizontal stow position is chosen to give negative lift: the Bernoulli forces are down. Thus hurricane winds would tend to force the stowed mirror into the ground. Since the mount is strong in compression, only superficial damage to the unit would be anticipated.

Hydraulic actuators are used for tracking and focusing functions because they are effective, reliable and economical. Minimal power is required for routine tracking and focusing. On the 4 kWt demonstration prototype, a small (0.1 HP) electric pump intermittently replenishes an accumulator tank which stores energy. Hence, large instantaneous power demands can be met for emergency scram functions, rapid solar acquisition after losing track, and slewing to the stow position in case of high winds. Additionally, the fluid characteristics of a hydraulic system can absorb mechanical shocks generated by wind gusts, also provide desired damping in the tracking and focusing functions and prevent "hunting".

The pressure tube receiver is inclined at the latitude angle with the north end raised in the northern hemisphere. Since the mirror must clear the ground at sunrise and sunset, there is substantial ground clearance which would permit other land uses such as farming beneath the collectors. The support structures can be made adaptable to the installation location and terrain. Flat land is not required and installation on top of buidlings appears to be economic. The supporting piers must be adequate to counter the wind shear forces generated by the drag coefficient of the mirrors in hurricane force winds; otherwise, pier materials can be selected on a cost basis.

Applications

Commercial units of the ASPS are sized for transportability and effectiveness for particular applications. The smallest practical unit produces 40 kWt with a round mirror and 50 kWt with a square mirror (see Figure 5). The mirrors are transportable in two sections over the interstate highway system without a special permit. With a production volume of at least one unit per day, 300 units per year, direct costs with an available steam engine are estimated to be about $20,000.

A cogeneration version of the ASPS would provide 20% of the available power (10 kilowatt electric; kWe) for electrical generation or pumping and 70% of the power for thermal loads at an estimated cost of about $2,300 per kWe of capacity with 120,000 BTU per hour of commercial grade steam as a byproduct. Such a system would be competitive with diesel electric systems and oil field boilers operating in remote areas. Installation costs are minimal in large part because only two piers are required on a north-south axis.

Economics of scale can be achieved through other ASPS unit designs that would produce 500 kWt with a direct insolation of 1 kW per square meter. In this case, the prime mirrors are helicopter transportable at a reasonable cost. This system was originally designed for solar thermal oil recovery (STEOR) applications. Each unit would produce 1.7 Million BTU per hour of steam at any desired temperature and pressure; however, it is desirable to operate the ASPS at or above the critical point (705 ^{o} F, 3204 psi). Thus a cogeneration system producing 150 kWe along with 1.2 Million BTU per hour of 500 ^{o} F. steam is feasible and very attractive. System costs at production rates of one per day are estimated to be on the order of $100,000 per system. This gives a cost of approximately $667 per kWe of capacity for electrical generation. The same system with a variety of operating parameters is economic for industrial process heat and cogeneration applications.

The largest sized units economically producible with our patented technology appear to be 130 feet in diameter with an output of 1 MWt. With the mirrors produced on site in quantities of 500 or more, the steam producing system is estimated to cost $150,000 per unit. The installed cost of a large electrical generation plant would be in the range of $600 to $1,000 per kWe of capacity.

These large 1 MWt units are also useful for large-scale chemical production, particularly in conjunction with geothermal wells. Because any transparent or translucent working medium can be used, possibilities exist for very efficient systems using helium, air, toluene and sewage sludge as a working medium. As a final point, all sizes of ASPS units have inherent buffer storage of about 1 hour of energy collection. Constant temperature and pressure steam storage is also available at a 50% system cost increase for 24 hours of energy collection storage.

Figure 1

ASPCO DEMONSTRATION UNIT SCHEMATIC

THIS UNIT IS TRAILER MOUNTED AND FREEWAY TRANSPORTABLE WITHOUT PERMITS FOR EASE OF FIELD TESTING. THE MIRRORS COLLECT 1/10TH THE ENERGY OF THE FIRST COMMERCIAL INDUSTRIAL SOLAR STEAM UNIT.

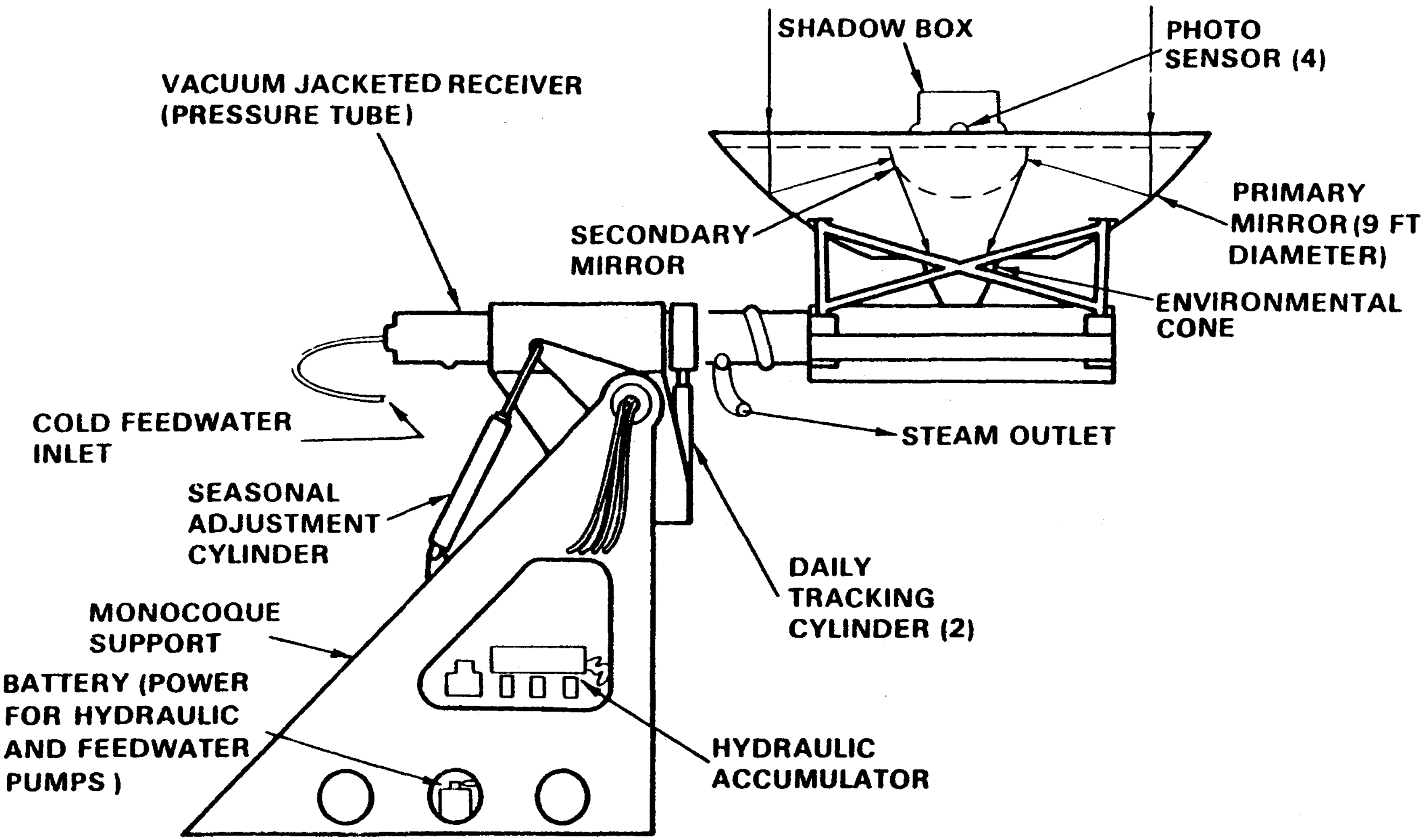


Figure 2

BASIC CONCEPTS OF THE ASPCO TWO AXIS TRACKING AND FOCUSING INDUSTRIAL SOLAR STEAM SYSTEM

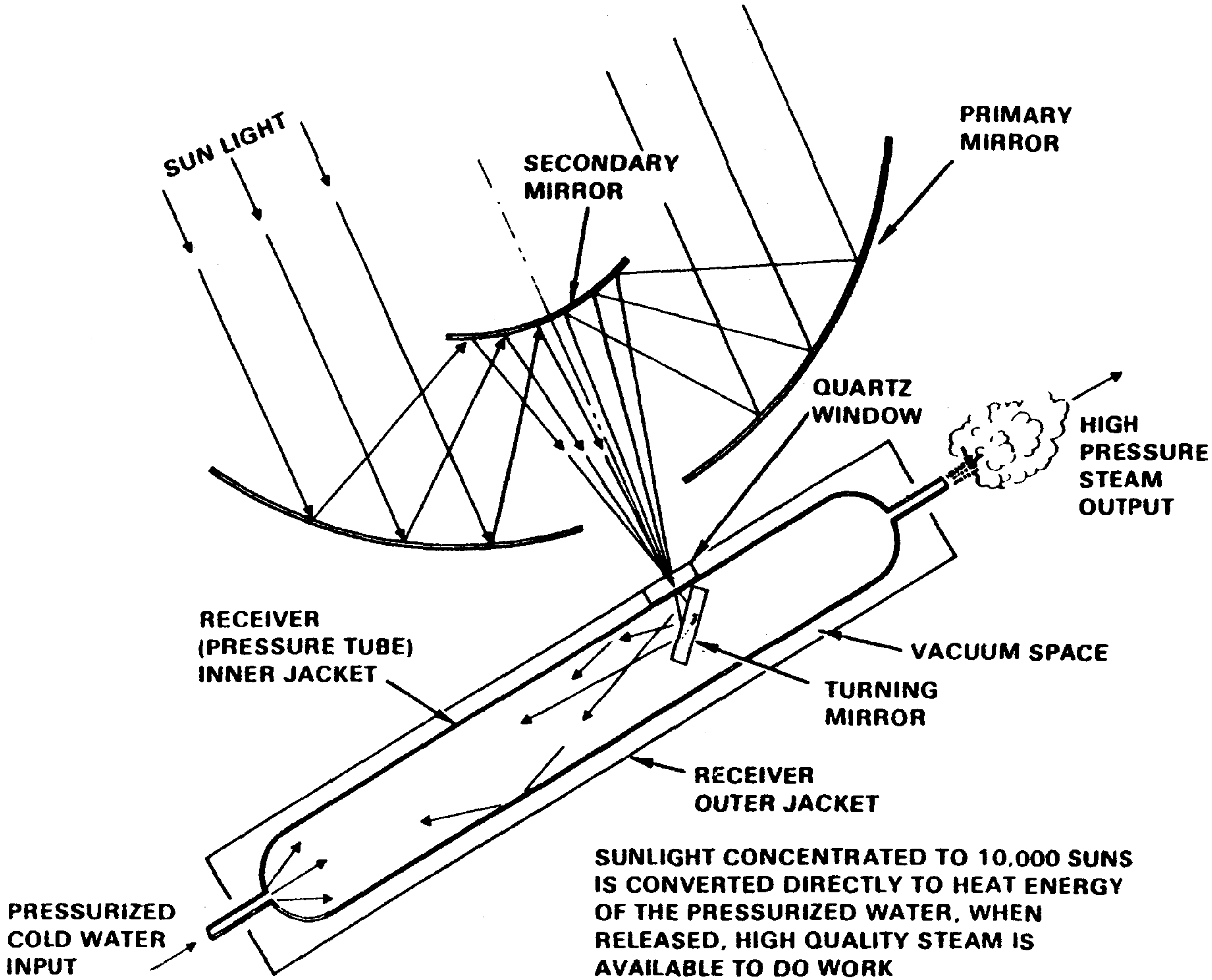
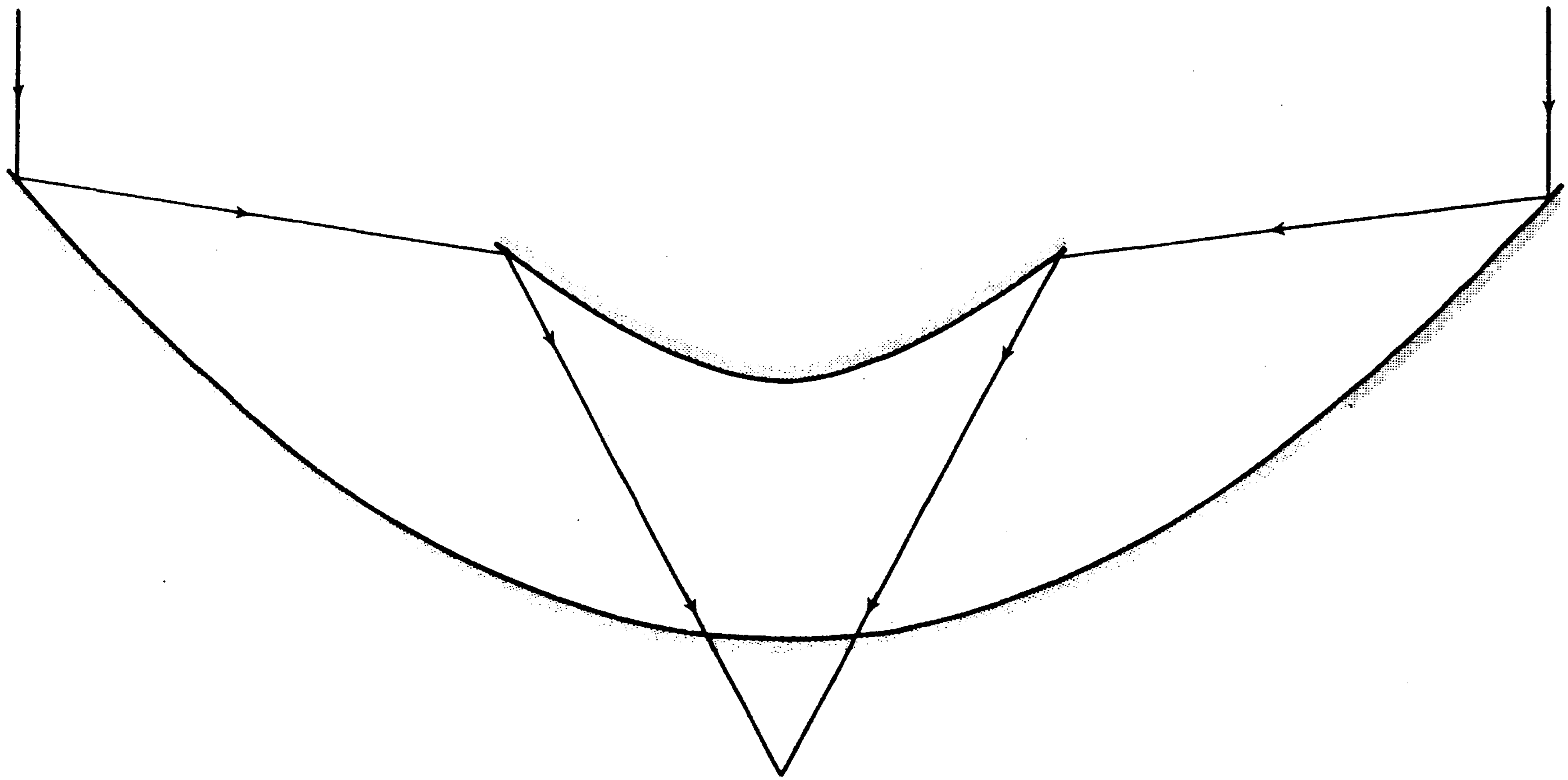
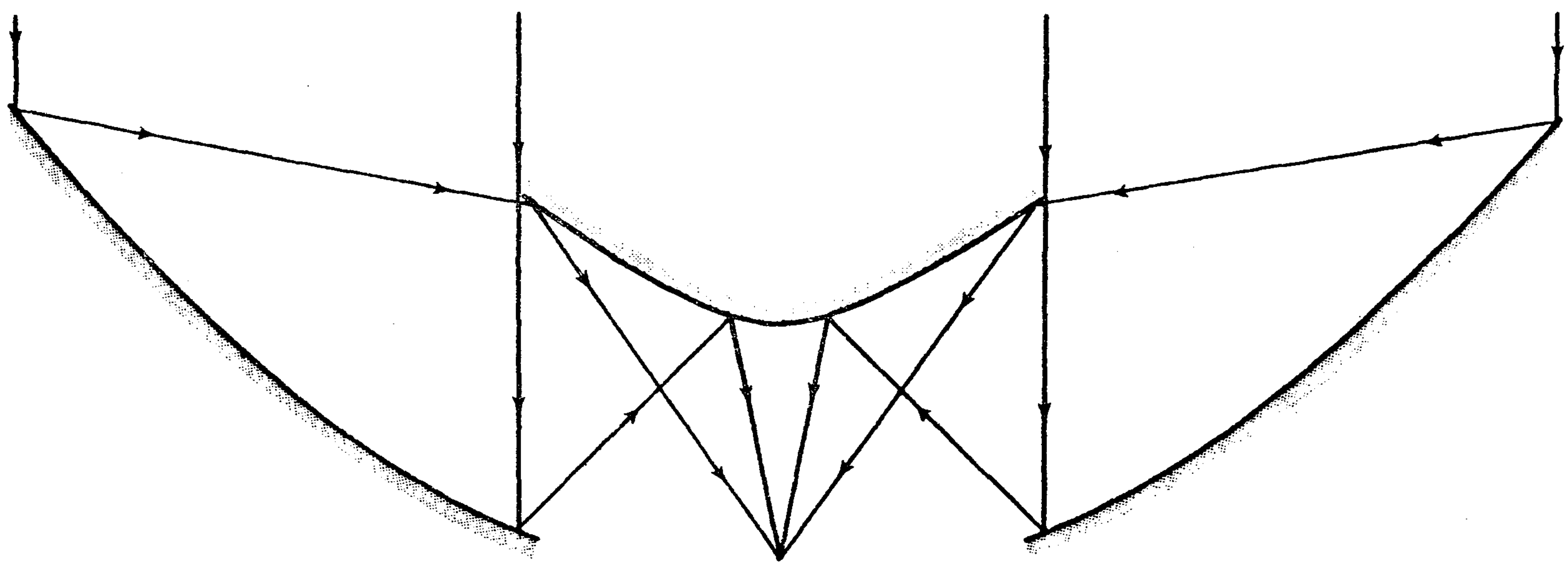


FIGURE 3



4 kW DEMONSTRATION MIRROR

FIGURE 4



40 kW SYSTEM MIRROR

Figure 5

ASPS COMMERCIAL PROTOTYPE DESIGN SCHEMATIC

THIS IS A LOW-COST TWO-PIER GROUND SUPPORT MOUNTED UNIT PERMITTING SEASONAL AND DAILY TRACKING BY USING HYDRAULIC MOTORS. THE PRIMARY IS 28 FEET IN DIAMETER COLLECTING 40 kwt (136,000 BTU/HR) OF ENERGY TO PRODUCE HIGH QUALITY STEAM FOR 'INDUSTRIAL PROCESS HEAT AND ELECTRIC POWER PRODUCTION.