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HIGH TEMPERATURES FROM THE SUN:

A GUIDE TO SOLAR THERMAL TECHNOLOGY

William B. Stine

November 1986

This report was prepared for the U.S. Department of Energy under contract with the Solar Energy Research Institute.

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Preface

The research and development (R&D) described in this document was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology (STT) Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates the solar flux by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point- and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 m in diameter track the sun on two axes and use mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1,500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve each system concept through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to ensure a successful program.

This report describes the development of solar thermal technology by looking at the fundamental principles of solar thermal components and systems, discussing the technical issues that drive or limit their development, and describing their evolution to its current state. It is written for those who want to understand the solar thermal conversion process. The reader should realize that many concepts here are highly simplified so that only the major points are emphasized. Much detailed engineering, mathematics, and physics underlies this simplicity.

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SUMMARY AND INTRODUCTION

Background

The long-term energy needs of the United States and the world will require the development of renewable energy resources. In the short term, this nation has an adequate supply of coal and oil, but this will not always be true. Eventually, alternative sources of energy will be required. More than half of the nation's energy needs could be supplied by the sun's radiation. It is continuous, nonpolluting, and free.

The high standard of living in the United States depends on using large amounts of energy in various forms. The United States, with only 6% of the world's population, uses about half the world's energy. In 1984 the United States used 76 quads (i.e., 76×10^{15} Btu or 80×10^{18} J) of energy. This was 4% more than in 1983 and indicates that consumption is rising again after the brief decline resulting from OPEC oil embargoes.

Oil provides 41% of the energy consumed in the United States, natural gas provides 24%, coal 22%, and nuclear about 5%. Renewable forms of energy, mostly hydro power but including wood, geothermal, and solar, provide the remaining 8%. Until very recently, oil and gas were the major contributors in the United States but the use of coal has increased because supplies of oil and gas are more limited (Figure 1).

Experts[1,2] estimate that there is sufficient oil to last the world for only about 35 to 60 years and enough natural gas for about 55 years[2]. Recently the United States learned the hazards of reliance on imported oil. If all oil imports were cut off, domestic reserves (excluding oil-shale) would last only 8-10 years[3].

In the United States, the industrial sector uses the most energy—about 38% of the 76 quad total. The residential and commercial sector (houses and stores) uses 35% and the remaining 27% is used for surface and air transportation.

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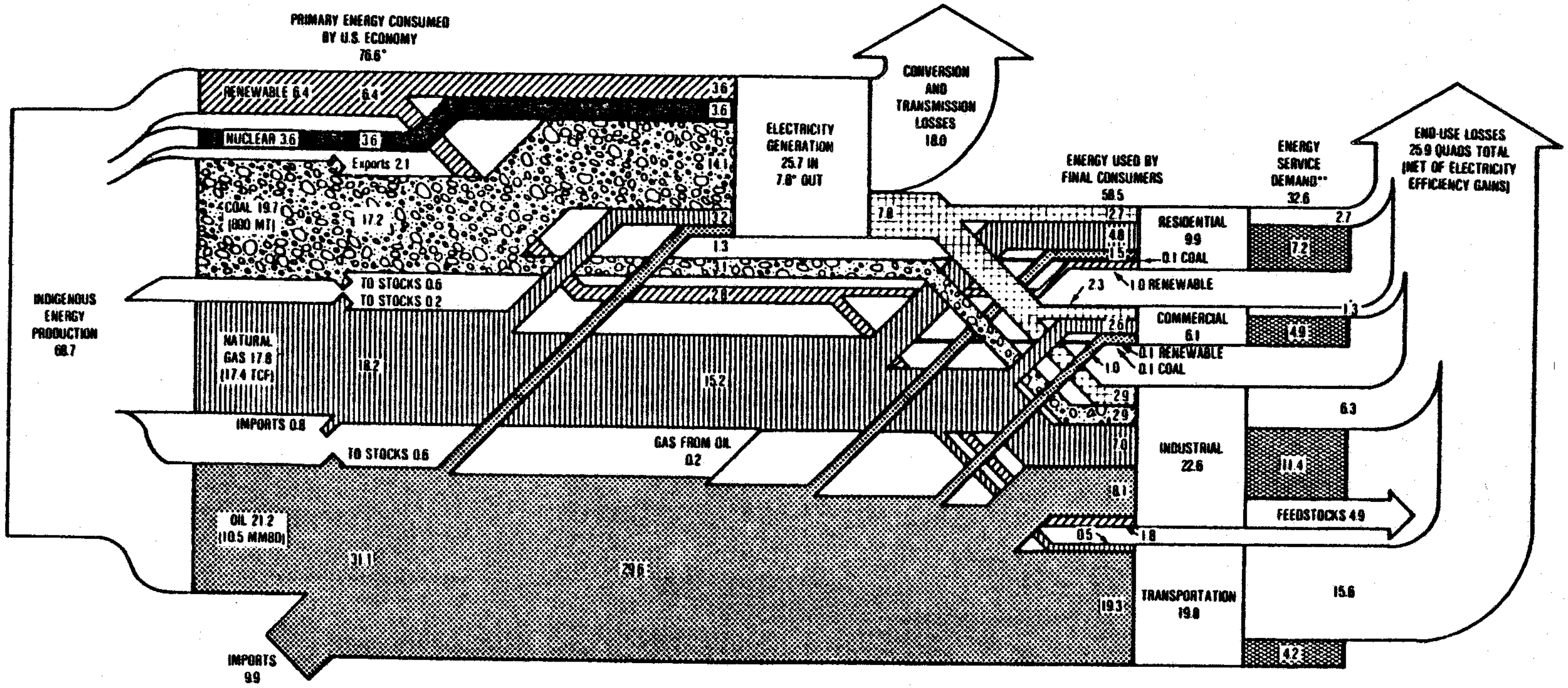
[1] *U.S. News and World Report*, May 27, 1985.

[2] *World Energy Outlook*, Chevron Corporation, June 1985.

[3] *U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 1984 Annual Report*, DOE/EIA-0216 (84).



* INCLUDES 0.1 QUADS OF IMPORTED HYDROELECTRIC POWER.

** INCLUDES 4.9 QUADS OF ENERGY RESOURCES USED AS FEEDSTOCKS FOR THE MANUFACTURE OF NON-ENERGY MATERIALS. BASED ON END-USE EFFICIENCIES FROM 1980 BROOKHAVEN DATA.

Figure 1. United States energy source and uses in 1984 (quadrillion Btu)

Most of the fuel used for transportation is derived from petroleum. Even with conservation, our petroleum consumption is large, and it is imperative to assure its continued availability. An emerging scenario is to supplement petroleum used in the other energy-use sectors with solar and coal, so that petroleum can be diverted to the transportation sector where it is less easily replaced.

The United States has enough coal to last for several centuries at the present rate of consumption. But coal must be mined and, like oil and gas, emits particulates and sulfur compounds. Also, like oil and gas, coal when it is burned produces nitrogen oxides (NO_x), a major component of 'smog.' Burning of fuels also substantially adds to the carbon dioxide (CO_2) level in the atmosphere, which is thought to be causing an increase in global temperature with consequent climate and sea level changes. In the long term, we obviously need to reduce the combustion of fuels.

The sun represents a virtually limitless source of useful energy. In contrast to the 76 quads of energy used by the United States in 1984, 44,000 quads of solar energy fell on the continental United States that same year and in every year since the beginning of time. Using this solar energy promises a significant contribution to the nation's energy supply.

What is Solar Thermal Technology?

Solar thermal technology converts the sun's radiation into useful products such as electricity, fuels, and heat by first concentrating the sun's radiation so that high temperatures can be attained, and then converting this radiation to high temperature heat (Figure 2). Although equally important, other forms of solar energy conversion such as the direct conversion to electricity by photovoltaic processes, or providing building or hot water heating (or cooling) through low temperature flat-plate collector systems are not included when we speak here of solar thermal systems.

The market potential of solar thermal technology is immense since it can provide electricity for large population centers as well as for small, modular applications not connected to a large power grid. Also, industrial process heat can be supplied over a wide range of temperatures for a variety of industrial uses.

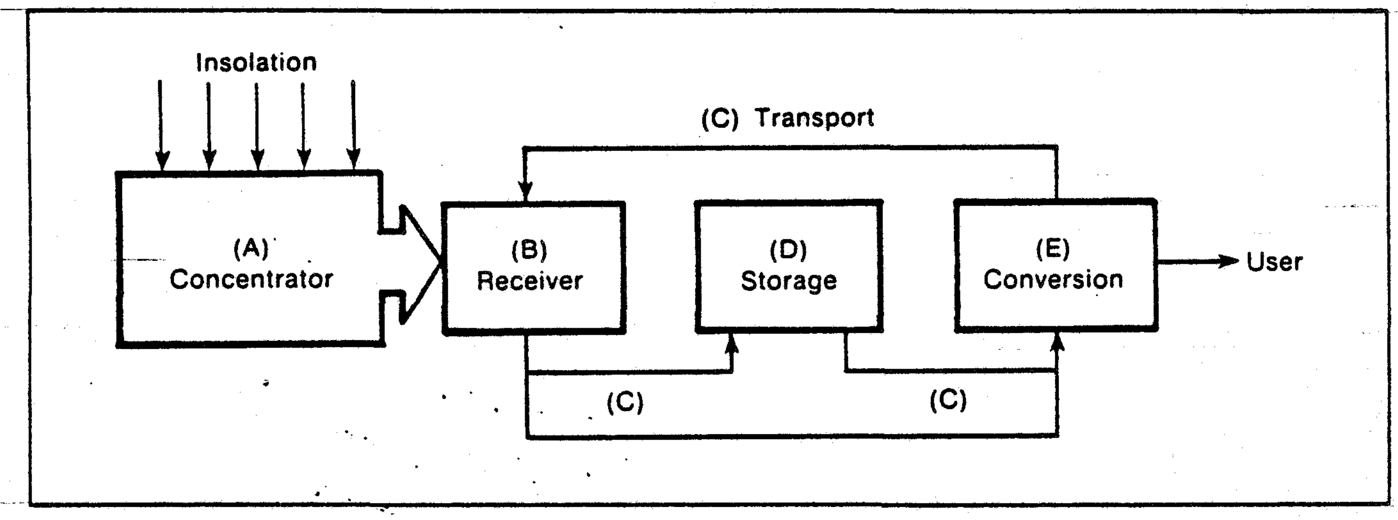


Figure 2. Solar Thermal System. Solar thermal systems convert the sun's radiation to useful products (such as electricity, fuels, or direct heat) by way of a thermal process. The basic elements of any solar thermal design are (A) the tracking optics used to concentrate the sun's energy, (B) the receiver which converts the photon energy to heat in a fluid, (C) transport piping to transfer the fluid to (D) storage for later use or directly to (E) the conversion device which uses the solar heat to produce the user's product.

Figure 1 shows that almost 34% of our current energy resources are used to make electricity, and 26% goes to the industrial sector, much of which is used to generate process heat. Energy from solar thermal systems could displace a large portion of these mostly nonrenewable resources.

Solar thermal energy has been proven technically feasible at a series of experimental installations and its costs have decreased dramatically. Performance has increased steadily in the last decade and projections lead to economic competitiveness with fossil fuels and other renewables in the mid- to late-1990s.

In the future, solar thermal systems will produce transportable fuels and high-value chemicals. These can be easily transported long distances from the solar site. This will extend the use of solar energy into the transportation sector, and displace the use of fossil fuels and electricity for these purposes.

DOE Involvement - In recent years, the U.S. Department of Energy (DOE) Solar Thermal Technology Program has commissioned research and development (R&D) studies and feasibility experiments for the production of high temperature thermal energy, as a possible option to using fossil fuels. Since 1975 this program has carried out the development of the three types of concentrating collector concepts: parabolic troughs, parabolic dishes, and central receivers. The program emphasizes R&D to reduce system cost and increase system efficiency and reliability. Additional program activities include research to prove the feasibility of new concepts that can be cost-competitive over the entire temperature range.

To perform R&D activities in support of the fundamental program goal, Sandia National Laboratories at Albuquerque, New Mexico, and the Solar Energy Research Institute at Golden, Colorado, are combining their talents with the special expertise and facilities of various universities and of the solar industry. The program goal is to deliver solar-derived electrical energy at 5¢/kWh and heat at 3.1¢/kWh ($9/MBtu) or lower (1984 dollars).

History

Solar power, as well as space and water heating technologies, has been evolving for thousands of years. The Chinese, Greeks, and Romans developed curved mirrors that concentrate the sun's rays onto an object with enough intensity to make it burst into flames in seconds. In 700 B.C. the holy virgins who reportedly tended the sacred fire at the Temple of Vesta in ancient Rome lighted the alter fire with the "pure flame" of the sun. Legend tells that in 212 B.C. Archimedes had his soldiers use their polished shields as 'burning mirrors' to set fire to the sails of the invading Roman ships at Syracuse.

Knowledge of 'burning mirrors' disappeared from European culture during the Dark Ages, but resurfaced during the Renaissance when Leonardo de Vinci proposed to build a parabolic mirror four miles wide. It wasn't until the 1800s that extensive efforts were made to use solar energy for power production. Many of the first solar motors were developed by Augustin Mouchot, perhaps the most famous of which was his 20 m^2 parabolic concentrating reflector that powered a steam driven printing press at the 1878 World's Fair in Paris.

One of the most successful leaders of the recent turn-of-the-century solar movement was Aubrey Eneas. In 1901 his 60 m^2 focusing collector in the shape of a truncated cone received a great deal of public exposure when it was used to operate a 10-hp solar steam engine for a water pump at the Cawston Ostrich Farm in Pasadena, California. Although Eneas' Solar Motor Company sold several of these solar pumps, their high price and susceptibility to damage from the environment deterred most potential buyers.

Frank Shuman, an American engineer, developed a more practical solar-driven hydraulic pump. In 1913 he successfully demonstrated the use of a 50-hp solar engine for pumping irrigation water from the Nile River at Meaki, Egypt. This device, which he designed with the aid of C.V. Boys, used a 1233 m^2 field of long parabolic troughs that focused solar radiation onto a central pipe. The outbreak of World War I disrupted plans to expand the use of the Shuman sun plant. With the increasing availability of low-cost oil and natural gas, there was minimal activity in the field of solar power until 1950 except for the use of solar hot water, particularly in Florida and California, during the 1930s and 1940s.

Several solar furnaces were constructed in the 1950s and 1960s in France, Japan, and the United States. The French and U.S. furnaces were developed to simulate the thermal radiation environment produced by a nuclear explosion. Because of widespread interest in solar thermal power systems, research funds were allocated for the development of earth-bound solar electric power and process heat systems following the Middle-East oil embargo in 1973. Since then efforts have concentrated on making solar power more economic to compete with lower priced fossil fuels.

CHAPTER 1 - BASIC CONCEPTS OF SOLAR THERMAL TECHNOLOGY

To use energy from the sun effectively, we must know the amount of solar energy available, design and test appropriate hardware to perform this task, and develop strategies to control the energy collection system that optimizes its output. The Solar Thermal Technology Program has provided research and hardware development in these areas. In this section we will look at how different solar thermal energy systems work and how the technology developed to its present state.

Comparison of Solar Thermal Technologies

Solar thermal technology has evolved into concentration on three distinct types of concentrating collectors: the parabolic trough, the parabolic dish, and the central receiver. Each one of these technologies will be discussed in the sections that follow.

The parabolic trough is a concentrator formed by taking a parabola and moving it linearly along an axis perpendicular to the curve (Figure 3). The focus is a line; therefore, it is called a line-focus concentrator. Parabolic troughs operate at lower temperatures than the other two types of concentrators. Temperatures below 650°F (343°C) are considered optimum because of the line-focusing geometry of the parabolic trough that causes it to have a lower concentration ratio than most parabolic dishes or a central receiver. As a result, the operating temperature (defined by the application) must remain low so that the collector does not lose most of the energy it receives.

The best applications for parabolic trough systems seem to be providing process heat in the form of steam or hot heat transfer fluids. There are large industrial demands for heat from 300° to 500°F (150° to 260°C), which matches the lower operating temperatures of the parabolic trough.

The parabolic dish is a concentrating solar collector formed by taking a parabolic curve and rotating it about its axis to form a shape called a paraboloid (Figure 4). All parallel rays entering the aperture along the axis will be focused to a single point. Therefore, the designation point-focus is used to classify this type of concentrator. Many current point-focus designs are not a continuous paraboloid, but individually aimed flat or slightly curved facets mounted on a frame. Since the end result is approximately the same, no distinction will be made between these designs when discussing their operation.

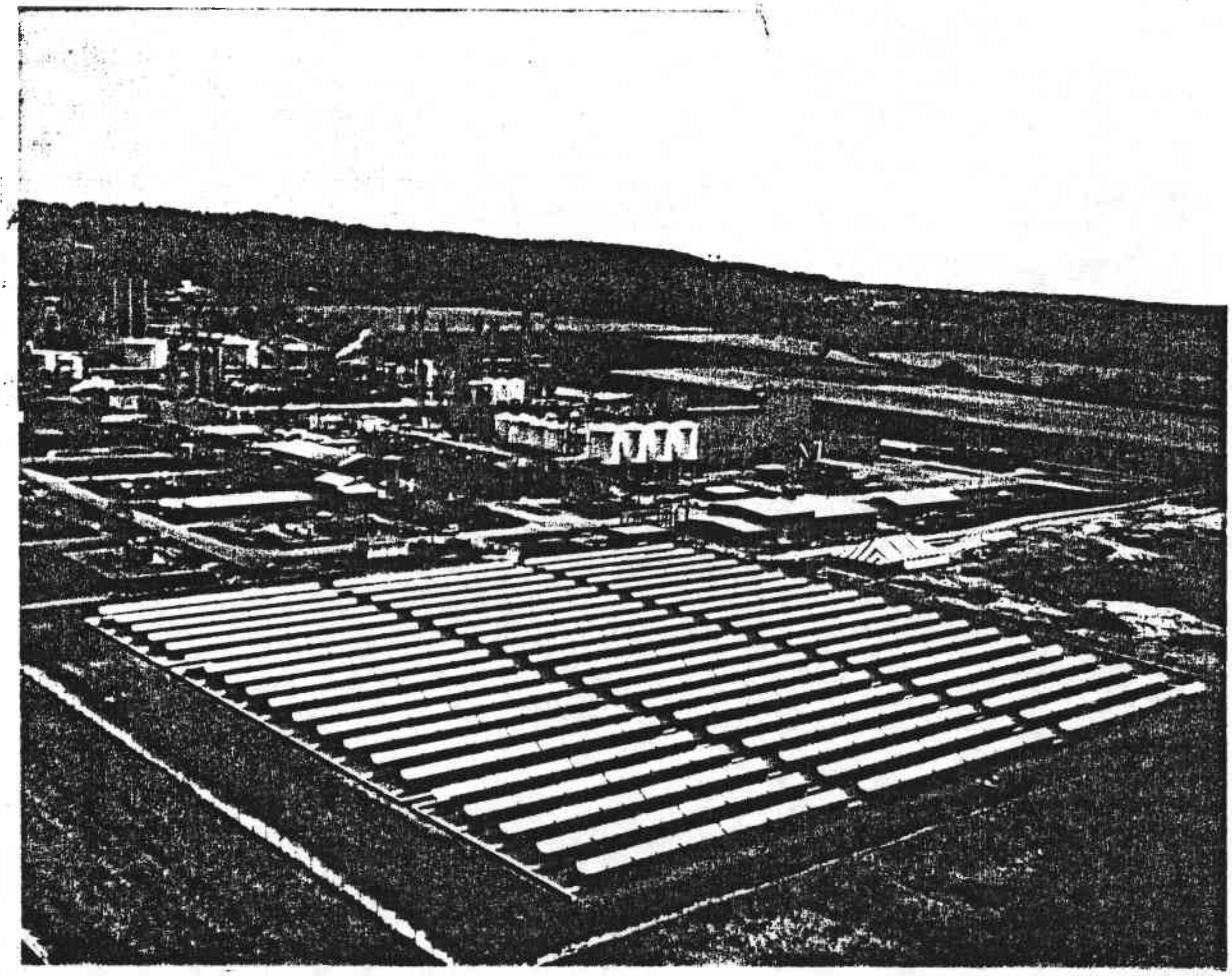
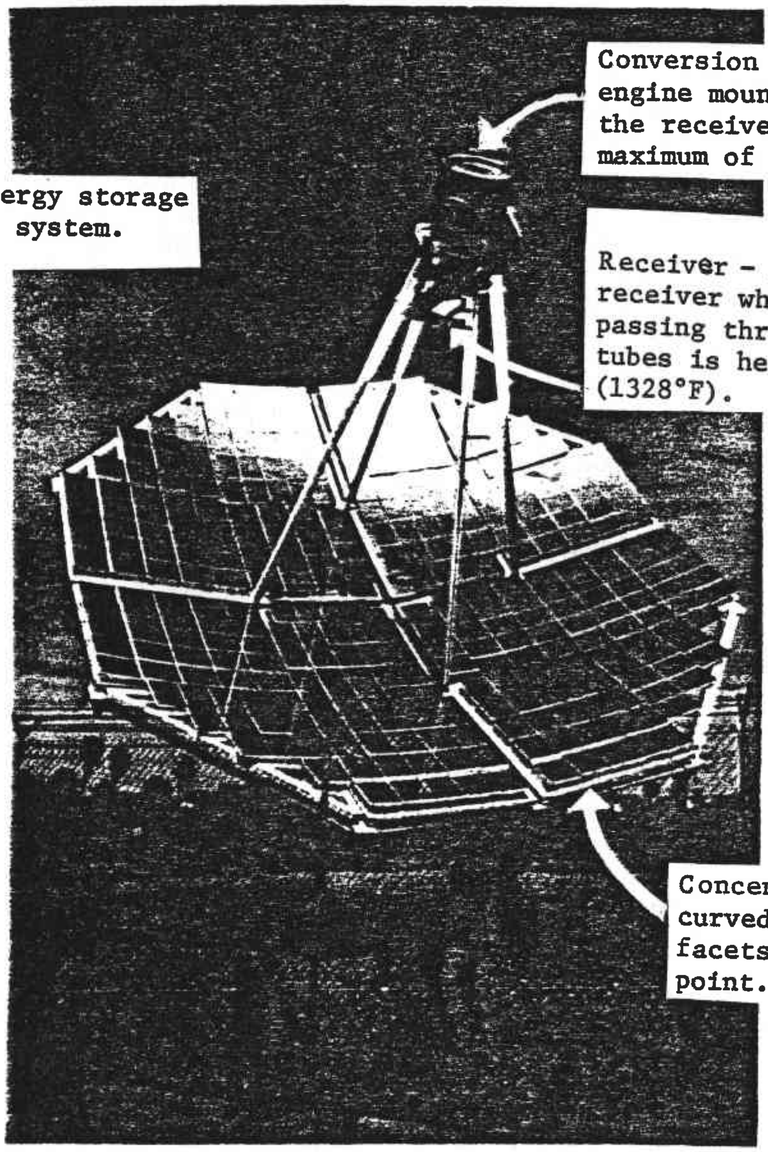


Figure 3. A typical parabolic trough system



Conversion - A Stirling engine mounted just behind the receiver, produces a maximum of 23 kW of electricity.

Storage - No energy storage is used in this system.

Receiver - A cavity receiver where hydrogen passing through very small tubes is heated to 720°C (1328°F).

Concentrator - 82 slightly curved silver-glass mirror facets all aimed at a single point.

Figure 4. A typical parabolic dish system

The best applications for a parabolic dish system appear to be the production of electrical power because power conversion efficiency increases with temperature and advantage can be taken of the higher temperature capabilities of these collection systems.

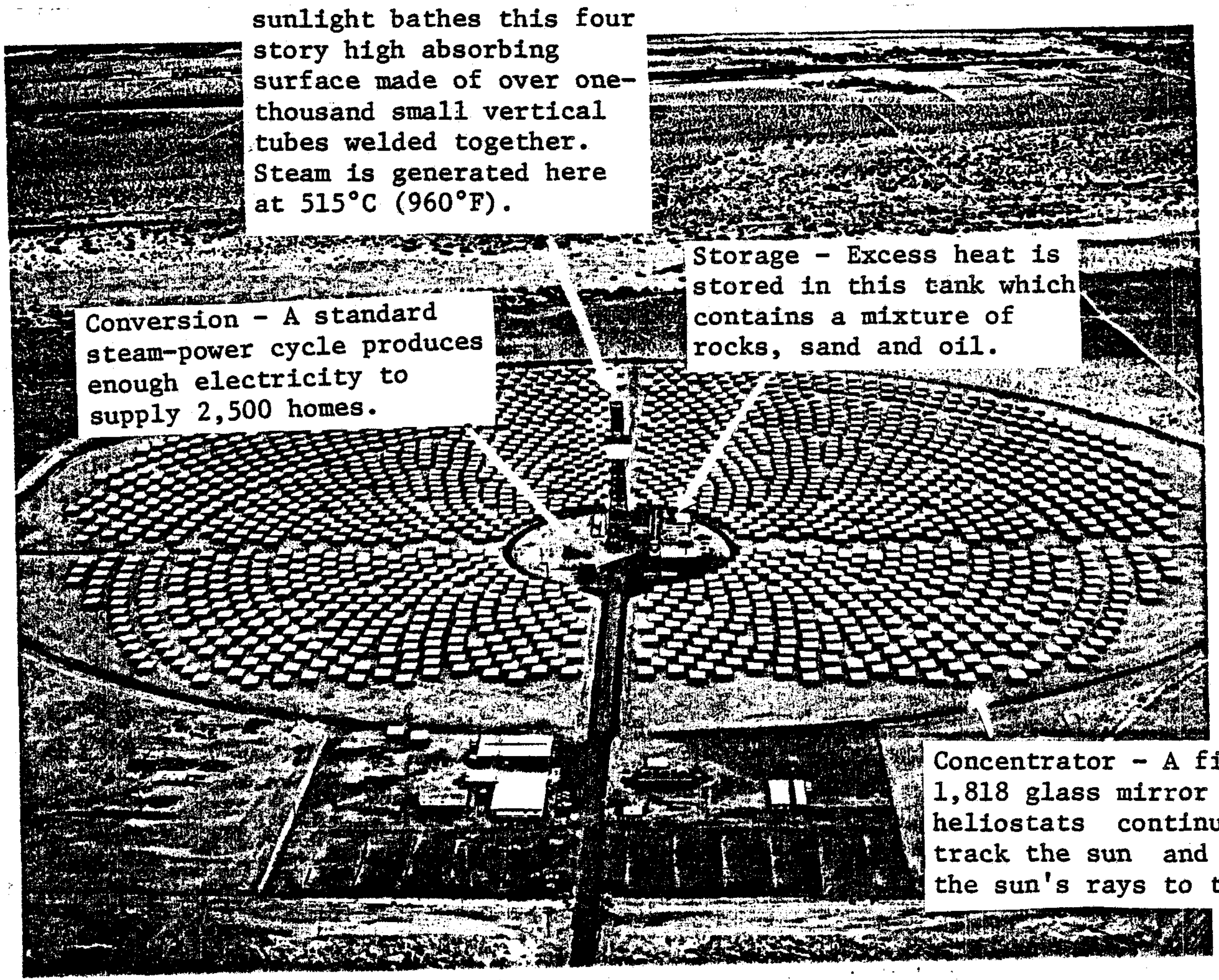
The central receiver solar collector system consists of a field of many movable mirrors, called heliostats, spaced over a large area, which reflect sunlight onto a single receiver at the top of a tall tower (Figures 5 and 6). The surface of the receiver is heated as it absorbs the reflected radiation, which in turn heats a fluid. This fluid may be either an intermediate heat transfer fluid or the power cycle working fluid boiled directly in the receiver. In most central receiver systems envisioned today, the heated fluid is pumped down the tower and used to drive a steam Rankine power cycle just as fossil fuel or nuclear-generated heat is used in other power plants.

The economically optimum size of a central receiver system is usually larger than troughs and dishes, but is still small compared to fossil or nuclear power plants. Since these systems also operate at high temperatures, this has led the central receiver technology toward large central electrical power production systems of 100-200 MW.

Parabolic dishes have the special capability of providing small, self-contained, high-efficiency electrical power generation modules (25-50 kW). These can be rapidly installed at locations where there is a demand for power. The amount of power required can be met by installing a given number of modules. When the demand increases, modules can be added to the site.

Because of their high temperature capabilities and modularity, parabolic dishes or small central receivers are readily applied to industrial total energy systems where electricity, process steam, and cooling are all provided from a single solar energy system using a cascaded power cycle. The high temperature capabilities of both dishes and central receivers make them suitable for extremely high temperature applications (1000°-1500°C), such as producing fuels or high value chemicals. These processes may use either the high temperature heat or the high photon flux available at the focus.

Storage of thermal collected energy is relatively easy and inexpensive for all three solar collection technologies. This is unlike direct conversion energy technologies such as



Receiver - Reflected sunlight bathes this four story high absorbing surface made of over one-thousand small vertical tubes welded together. Steam is generated here at 515°C (960°F).

Storage - Excess heat is stored in this tank which contains a mixture of rocks, sand and oil.

Conversion - A standard steam-power cycle produces enough electricity to supply 2,500 homes.

Concentrator - A field of 1,818 glass mirror heliostats continuously track the sun and reflect the sun's rays to the receiver

Figure 5. A typical central receiver system

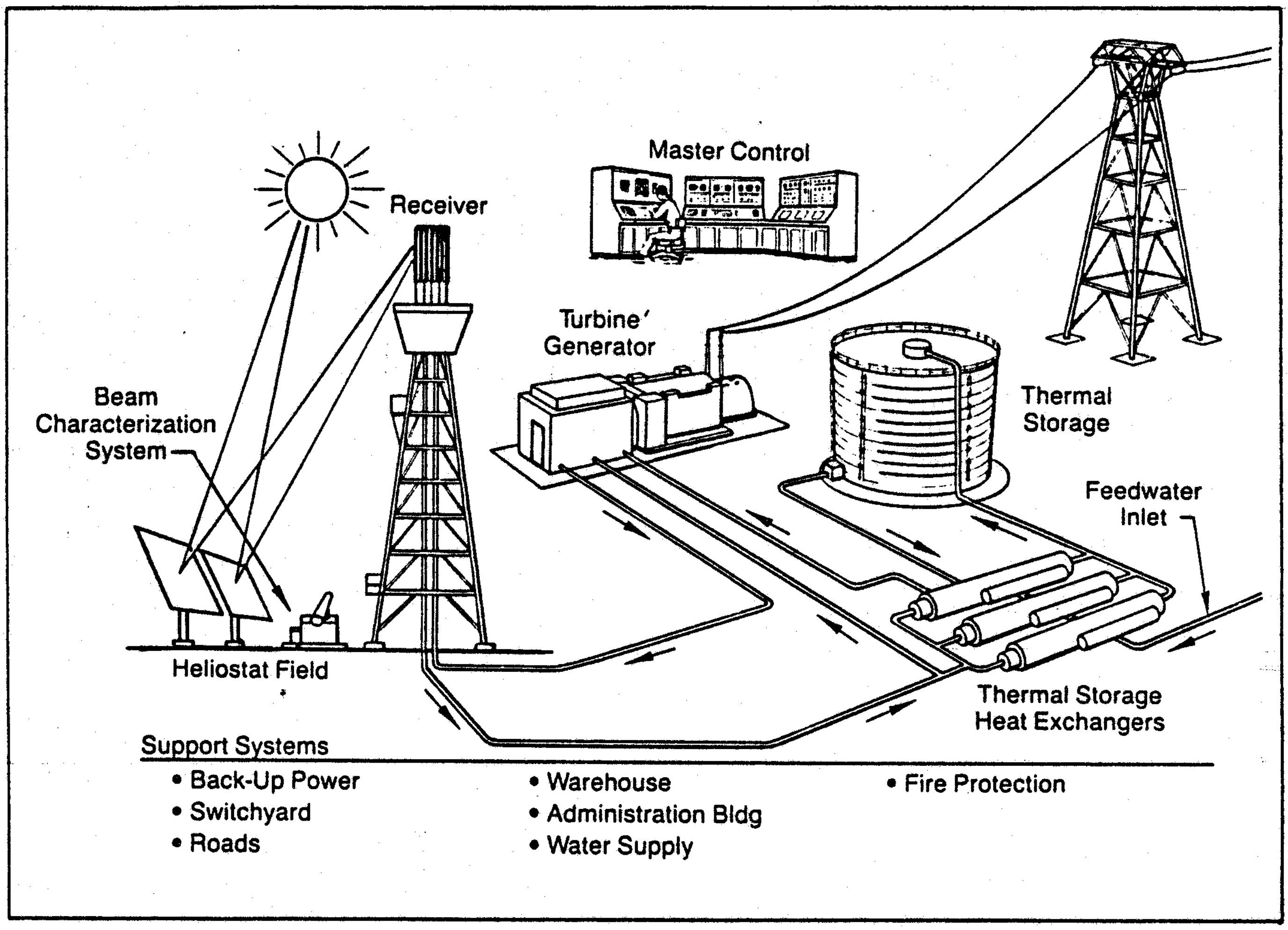


Figure 6. Solar thermal central receiver system

photovoltaic cells or windmills, where storage of electricity is expensive and difficult. Storage makes possible solar energy systems that can supply energy at the times required by industrial users or the electric power industry.

The Fundamental Solar Collection Equation

A simple energy balance equation governs the performance of any solar energy collection system and guides the design of new systems. In this report, we will discuss the many aspects of solar energy system design and will refer to the underlying theory that drives the system design.

In a solar thermal system, the sun's radiant energy is first converted into thermal energy or heat. Most of the new technology centers around optimizing this conversion. Once this useful thermal energy has been obtained, it is transferred from the solar system either for direct use or converted into a more valuable form of energy, usually electricity (but possibly fuels or chemicals).

The fundamental solar collection equation defines the instantaneous performance of the system. Although a solar energy system must be designed to have high instantaneous performance at a peak design condition, a more important parameter is how the system performs over a long time as the insolation, angle of incidence, and the ambient temperature change. Averaged over a year, this is called the annualized system efficiency and depends on the location and 'typical year' analyzed. As a general rule, a system with high instantaneous system efficiency will also have a high annualized system efficiency.

The rate of useful energy collected by a solar energy system (Q_{useful}) can be described with a simple equation stating that the useful energy collected by a solar collector field equals the amount of solar energy reaching the receiver, minus the heat loss. The rate of energy reaching the receiver depends on the amount of solar energy available, the size of the concentrator, and a number of parameters describing the loss of this energy on its way to be absorbed by the receiver. Heat loss is separated into convection heat loss (in the middle) and radiation heat loss (on the right-hand side). These show that the rate of heat loss increases as the area of the receiver or its temperature increase.

$$Q_{useful} = I_{b,n}A_{app}\cos\theta_i(\rho\Phi\tau\alpha) - A_{rec}[U(T_{rec} - T_{amb}) + \sigma F(T_{rec}^4 - T_{amb}^4)]$$

where the symbols are defined as:

α - receiver absorptance (the fraction of energy absorbed)(always less than one)

ρ - concentrator surface reflectance (the fraction of incident energy reflected by the reflective surface) (always less than one)

τ - transmittance of anything between the reflector and receiver such as air or a cover sheet(the fraction of energy transmitted) (always less than one)

Φ - capture factor (the fraction of energy leaving the reflector that falls on or into the receiver) (always less than one)

A_{app} - area of the concentrator aperture (opening)

A_{rec} - area of the receiver aperture or surface

$\cos\theta_i$ - cosine of the angle of incidence (i is the angle between the sun's rays and a line perpendicular to the collector or heliostat aperture)(always less than one)

σ - the Steffan-Boltzmann constant

F - equivalent conductance (combines the ability of a surface to lose energy by radiation with the ability of the surroundings to accept this energy)

$I_{b,n}$ - beam normal insolation (rate of solar energy per unit area coming directly from the sun's disc at the collector location

T_{rec} - receiver operating temperature (must be absolute temperature when raised to the fourth power)

T_{amb} - ambient temperature (must be absolute temperature when raised to the fourth power)

U - overall heat loss coefficient (describes the amount of heat that can be carried away by air currents generated within and around the receiver. It depends on the receiver geometry, its temperature, the wind, and the amount of insulation used).

What the the Fundamental Solar Collection Equation says is that the amount of useful energy collected by a solar collector is, at most, equal to the beam normal insolation falling on the collector(s), can be increased by making the collector or collector field larger, and is reduced by a number of factors (since ρ, Φ, τ, and α are always less than one).

Throughout this report, we will show how the different solar thermal technologies are striving to change and optimize one or more of these parameters to increase the performance of a system design.

The Solar Resource

Before designing a solar thermal energy system, we must understand a lot about the energy coming from the sun. Although we have all experienced the warmth of the sun and its cycles, we must obtain considerable technical information about its energy and the clouds which block or modify its output in order to develop optimum collection systems. Considerable effort is being expended to define just how much solar energy is available in the United States.

Insolation - The rate of energy falling on a unit surface area is called the 'insolation.' The usual units for insolation are watts per square meter (W/m^2); however, Table 1 lists insolation units that are also used.

Table 1. Insolation Units in Common Use

unit	to convert to W/m^2 multiply by
$Btu/(hr\ ft^2)$	3.152
Langleys/min	697.3
$cal/(cm^2\ min)$	697.3

Radiation coming directly from the sun is called 'beam' radiation because the rays come from what appears to be a small area. Since the sun is far away, these rays are almost parallel. On a clear day, the sun's disc has an apparent size of approximately 1/2 degree. Beam radiation can be assumed to be parallel rays coming from the center of the sun's disk. The important insolation value to solar thermal system design is the 'beam normal' insolation. This is the amount of beam radiation falling on a surface normal (perpendicular) to the sun's rays.

In the fundamental solar collection equation, the term $I_{b,n}$ represents the beam normal insolation. It can be seen that the amount of useful energy collected by a collector or collector field is directly proportional to the amount of beam normal insolation reaching the collector.

Some of the beam normal insolation reaching the outer atmosphere of the earth is deflected on its path through the atmosphere. This scattered radiation, which reaches the observer from anywhere in the sky other than from the sun's disk, is called 'diffuse insolation.'

A second source of diffuse insolation that may fall on a solar collector is the insolation reflected from the ground surrounding a collector. This reflection can occur when the collector is oriented in any direction other than horizontal. Because most collectors used in solar thermal systems are highly concentrating, though, generally only beam normal insolation is of interest. Considerable effort has been expended on obtaining and compiling data on the beam normal resource.

The National Weather Service is expending continued effort to develop highly calibrated data stations throughout the country and compile the recorded data into forms useful to system and component designers (Figure 7).

Cosine Effect - The maximum amount of insolation passes into a collector or heliostat aperture when it is perpendicular to the rays of the sun. For this case, the angle of incidence θ is 0° and the cosine of that angle is one. If the aperture of the collector or heliostat does not point toward the sun, the angle of incidence is greater than 0°, which reduces the amount of energy being collected or reflected. This reduction is called the cosine effect (Figure 8).

To keep a collector aperture or heliostat pointing toward the sun at all times, it must be 'tracked' about two independent axes. Some types of collectors have either fixed

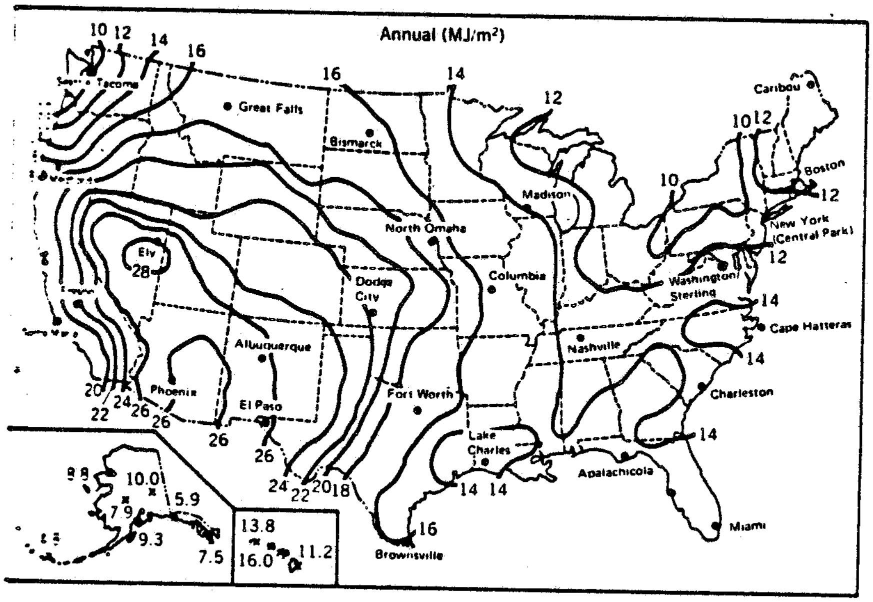


Figure 7. Annual average daily beam (direct) normal irradiation in the United States (MJ/m^2)

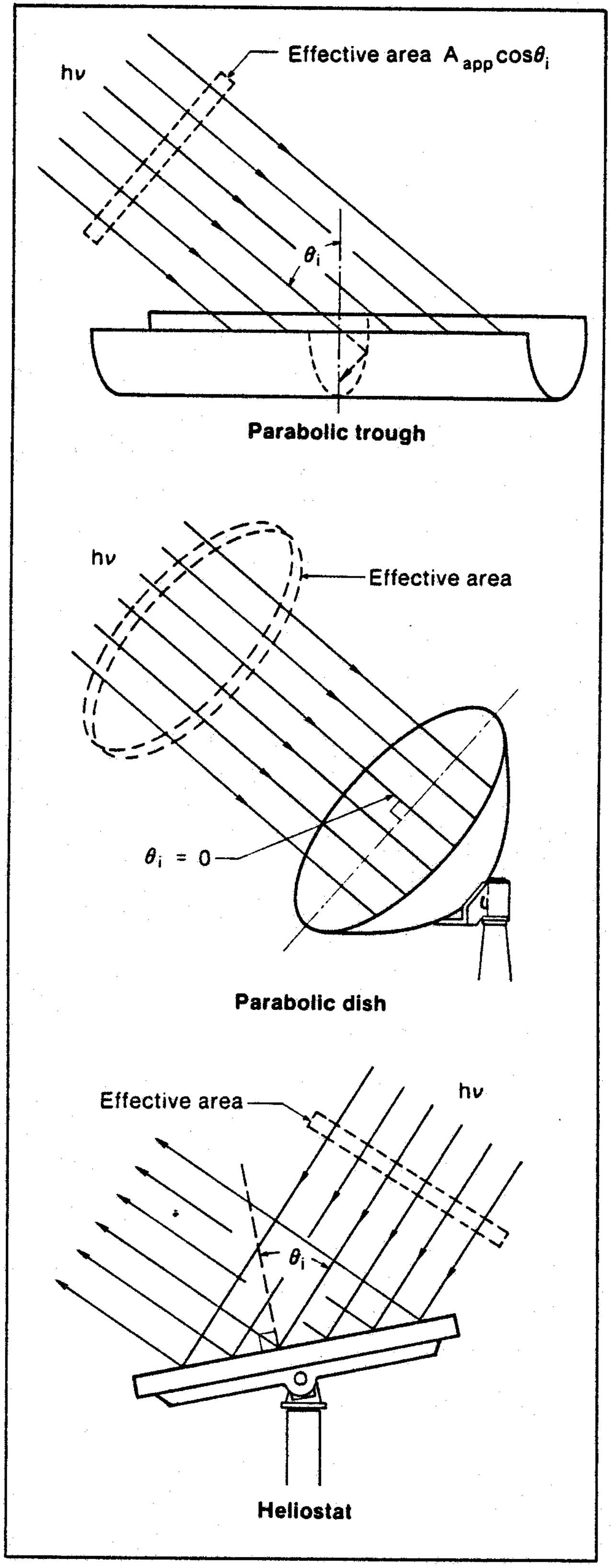


Figure 8. The cosine effect

apertures or apertures which only track about one axis when following the sun. For these collectors, the term cos i is usually less than one, causing a reduction in the useful energy collection area.

The cosine effect changes as the sun moves across the sky during the day, and as these angles change over the year. The effect depends on the orientation of the collector and the location. The cosine effect is largest for designs where the aperture remains fixed. For these, the cosine loss is large in the mornings and evenings when the beam normal insolation is low. Therefore the energy loss due to the cosine effect must be considered in conjunction with the insolation available. The cosine loss for some of the more common schemes for tracking concentrating collectors are shown in Table 2 with their average cosine effects. Typical weather data were used to generate these numbers.

Table 2. Cosine Effects for Different Orientations
(Yearly average for Albuquerque, NM, TMY data[4])

Orientation	Average cos θ_i
2-axis tracking	1.00
1-axis tracking, horizontal N/S	0.87
1-axis tracking, horizontal E/W	0.78
Fixed, tilted to latitude angle	0.72
Fixed, horizontal	0.61

Irradiation - So far we have been discussing the instantaneous amounts of energy coming from the sun. However, when designing a solar thermal system, it is most important to know how much useful energy will be delivered over a period of time like a day, month, or year. The parameter defining the solar energy delivered over a period of time is the irradiation. Irradiation is simply the sum of energy falling on a surface over a specified period of time. For solar thermal collectors, we are mostly interested in the beam normal irradiation.

Although beam normal irradiation data have not been measured regularly at many locations, a data base of beam normal irradiation has been developed from weather measurements taken all over the country. The accompanying map gives the beam normal irradiation for an average day for a 'typical' year over the United States. This data base is considered by many investigators to be inaccurate and a program is currently underway to improve it.

Sources of Data - The primary solar irradiation data base available to designers today is the Typical Meteorological Year (TMY) data base. This is a full year compilation of hour-by-hour insolation and other weather data for 248 sites in the United States. The 'typical' year is a compilation of typical months derived from approximately 23 years of data. This data base is available on computer readable magnetic tapes from the National Oceanic and Atmospheric Administration (NOAA) and has been summarized in two manuals noted in Appendix C.

Without a good definition of $I_{b,n}$, our energy resource, the useful energy derived from a solar thermal system cannot be accurately predicted or evaluated.

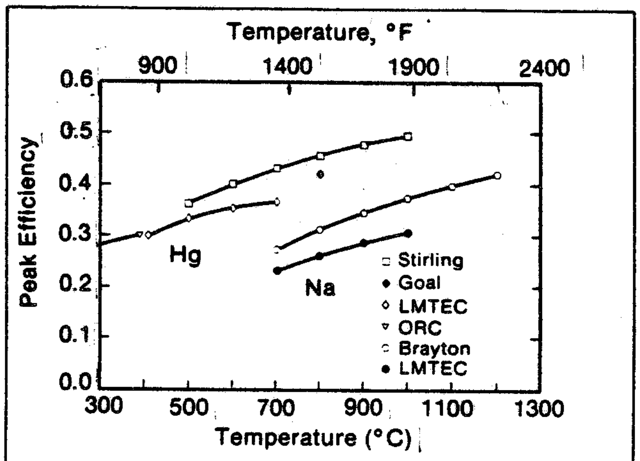
Why Concentrating Collectors?

Solar thermal applications demand high temperatures to produce either electricity or process steam for industry. High temperatures are required because the efficiency of electricity generation increases with temperature, and most industrial applications for heat are well above the boiling point of water. However, as operating temperature increases, heat loss from the solar collector also increases, resulting in lower energy collection efficiency. When high temperatures are required from a solar collector, the sunlight must be concentrated to reduce the heated portion of the receiver and counter the effect of the high temperature (Figure 9).

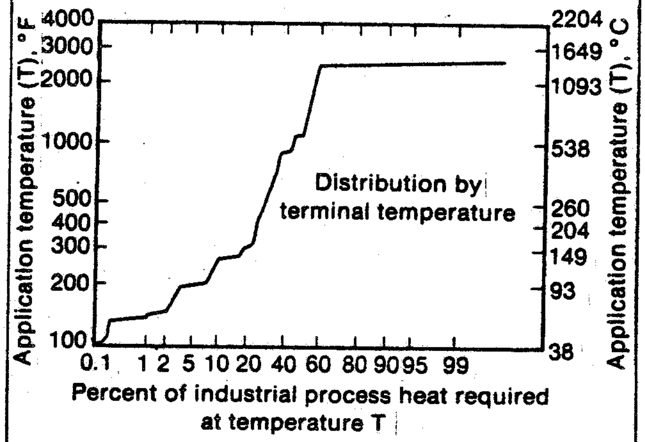
All collectors used in solar thermal systems are concentrating collectors, therefore, the solar energy is collected through a large aperture area A_{app} and reflected to a smaller receiver area A_{rec} where it is absorbed and converted to heat. The reason for this can be seen by looking at the fundamental solar collection equation.

$$Q_{useful} = I_{b,n} A_{app} \cos \theta_i \; (\rho\Phi\tau\alpha) - A_{rec}[U(T_{rec} - T_{amb}) + \rho F(T_{rec}^4 - T_{amb}^4)]$$

Because solar thermal systems operate at relatively high temperatures, the temperature difference $T_{rec} - T_{amb}$ is large. This results in high heat losses, which therefore reduces Q_{useful}. To compensate for this, concentrating optics permit A_{rec} to be reduced without reducing A_{app}. The extent to which the receiver area is reduced relative to the aperture area is called the geometric concentration ratio defined as the ratio A_{app}/A_{rec} (Figure 10). The concepts described below are all designed to provide a receiver area



Peak Engine Performance



Process Heat Temperature Requirements

Figure 9. Temperatures required for solar thermal applications

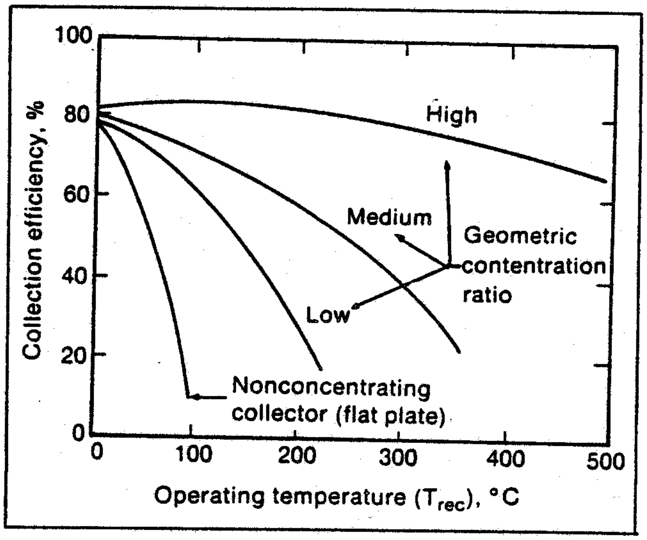


Figure 10. Effect of concentration ratio on collection efficiency (insolation is the same for each curve)

that is smaller than the aperture area and thereby reduce heat loss from the receiver at high temperatures.

The Concentrator

The part of a solar collector that intercepts and reflects the sun's rays from a large area to a smaller area is the concentrator. The parameters affected by the design of the concentrator are highlighted in the fundamental solar collection equation above. The remaining parameters are functions of the design of the receiver or the weather and will be discussed later.

Parabolic Reflectors - The surface of the parabola is shaped so that all rays of light parallel to the parabola's axis reflect from the surface through a single point, the focal point. Figure 11 shows a diagram of the parabola with the primary elements labeled.

The rim angle or focus-to-diameter f/d ratio defines the curvature of the parabola and the relative location of its focus. Parabola for solar applications have rim angles from very small to beyond 90°. The sketch shows a family of parabola with the same aperture diameter but different rim angles. At small rim angles there is little difference between a parabola and a sphere. Sometimes spherical surfaces are used to approximate parabolic surfaces since they are easier to produce, especially with stretched membranes.

Parabola with small rim angles are used when the reflected radiation is to pass into a cavity receiver, whereas larger rim angles are best when the reflected radiation bathes an external surface receiver. These types of receivers will be discussed further under the section on Receivers.

Very large rim angles (more than about 90°) are not cost effective since, as seen in Figure 12, large amounts of reflector surface and structure are required to provide small amounts of aperture area A_{app} near the edge of the concentrator. Very small rim angles on the other hand result in the focus being far away from the reflective surface. The reflective surface must be accurately manufactured to minimize the spread of the reflected beam over this long distance so that a large A_{rec} with resulting high heat loss is not required.

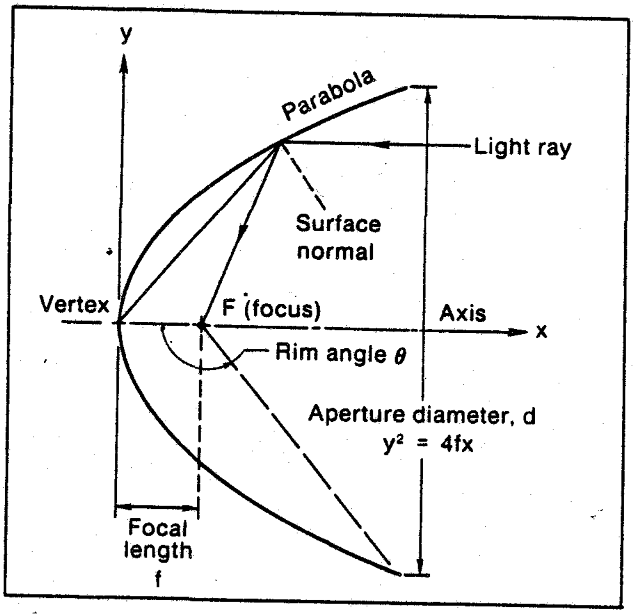
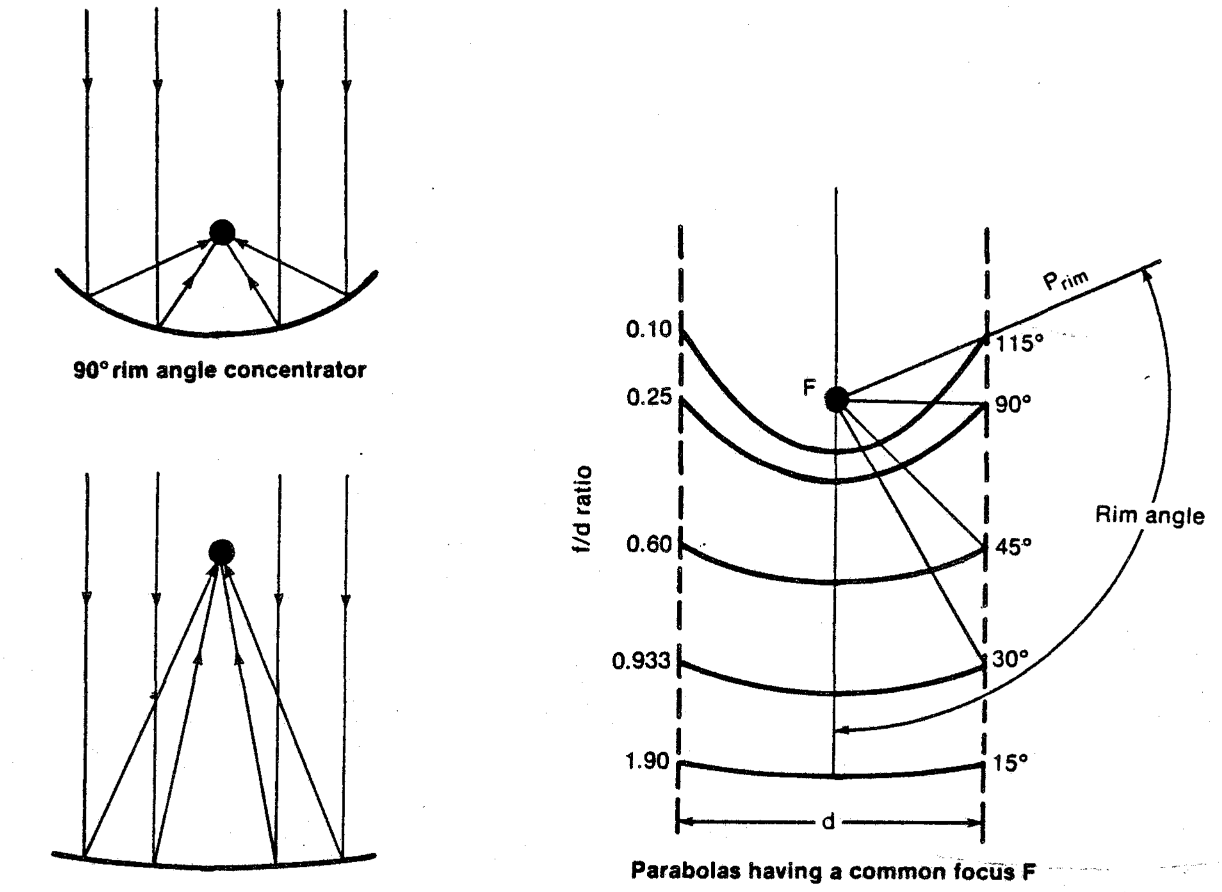


Figure 11. The parabola



90° rim angle concentrator

15° rim angle concentrator

Parabolas having a common focus F and the same aperture diameter

Note how the focal length increases as rim angle decreases.

Figure 12. Parabolas having a common focus F and the same aperture diameter (note how the focal length increases as rim angle decreases)

Segmented Reflectors - Instead of using a parabolic shape to concentrate the sun's rays, small, movable reflectors may be placed on a large surface and each one aimed so that a ray coming from the sun is reflected to a fixed point in space. This concept forms the basis of the central receiver collector where it permits the ground to be used to support the reflective surfaces rather than using a large, movable structure to support the reflective surface. The movable mirror segments are called heliostats (Figure 13).

The use of segmented optics to simplify the structure of a concentrating collector adds two optical problems to the design of the collector. First, since the surface must be aimed halfway between the sun and the focus point, there is a varying cosine loss which reduces the amount of energy reflected off of each segment. Secondly, adjacent segments will both block incident rays and shadow reflected rays.

Concentration of sunlight using segmented optics also provides a reduction in A_{rec} in the fundamental solar collection equation. With flat reflectors, the minimum size of the focus, and therefore A_{rec}, is limited by the minimum size of the segment. To compensate for this, a single heliostat is broken down into smaller segments and these canted (aimed) toward the focus. The segments may also be slightly curved to give them a long focal length parabolic shape.

Spherical Reflectors - A third type of concentrating optics is that based on a spherical reflective surface rather than a parabolic one. Spherical concentrators do not focus to a single focal point as do parabolic concentrators. Spherical bowl concentrators, with the concave (inside) surface being reflective, focus the sun's rays along the radial line parallel to the rays.

Refractive Concentrators - A completely different method to concentrate the sun's rays is by using a lens. Here, parallel rays are bent inward as they pass through a medium different from air (usually glass or plastic). Glass lenses are too massive for solar thermal applications. Since concentration depends only on the angle of the surface where light enters and leaves the lens and not on its thickness, thin lenses can be made by successively reducing the thickness of the material between the surfaces. This results in a 'saw-tooth' cross section, called a Fresnel lens, which can be molded in the form of a thin sheet of plastic. Large, lightweight plastic Fresnel type lenses have been developed and used in some concentrating collectors.

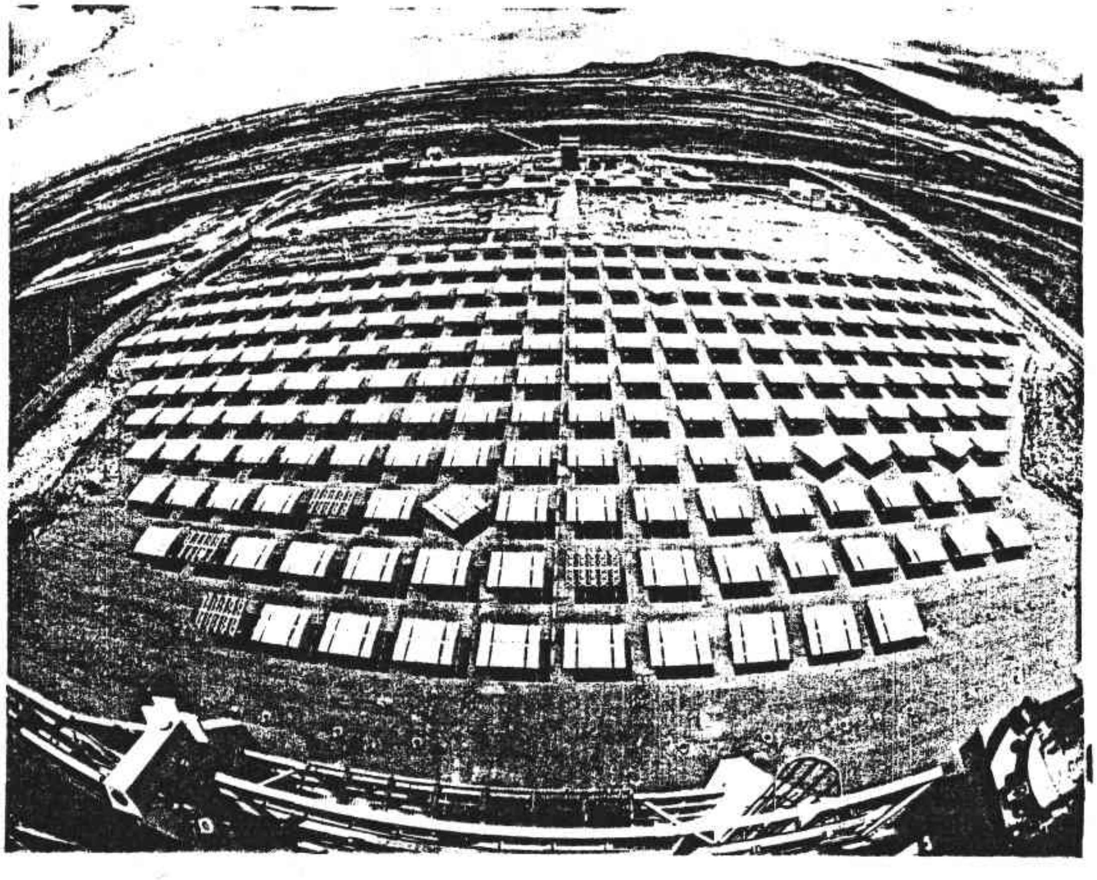


Figure 13. A heliostat field

Optical Errors - A number of optical errors can result in a deviation from the theoretical optics discussed above. Some of these errors are random and result in spreading of the optical image of the sun at the focus. Reducing these errors usually means increasing the cost of the concentrator and therefore represent one of the major trade-offs in the design of solar thermal systems.

Even the best concentrator surfaces deviate from the ideal curve to which they were manufactured. These deviations are called slope errors and are measured in milliradians (mrad) of angle that the actual slope deviates from true. In general, the higher the cost of the optical surface, the smaller the error. Well-manufactured parabolic concentrator surfaces may have an average slope error of about 2.5 mrad.

A second source of optical error is from the reflective surface itself. When a beam of parallel rays hits an optical surface, part of the reflected beam is diffused. This is called non-specular reflectance. Polished aluminum diffuses incident radiation to a greater extent than back-surface, silvered glass mirrors.

Two optical alignment errors dislocate the focus from the true focus: the mechanical error of not positioning the receiver at the true focus and the tracking error of not having the concentrator pointed directly at the sun.

One last 'error' that cannot be changed with increased concentrator manufacturing quality is the sun's width. Because the sun is not a point-source giving parallel rays, the reflected image spreads in a cone of approximately 0.5° (8.7 mrad). This acts just like the errors discussed above, and spreads the reflected radiation at the focus.

The effect of optical errors on collector performance is represented in the fundamental solar collection equation by the capture factor Φ, which represents the fraction of the reflected beam that enters the receiver. This parameter is a function of both the optical quality of the concentrator, and the size and type of receiver. The more spread-out the reflected beam at the focus, the more difficult it is to capture in a receiver of given size. The radiation not entering the receiver is 'spilled' around the outside of the receiver and is called spillage.

The Receiver

The function of the receiver is to intercept and absorb the reflected radiation from the concentrator, transferring the thermal energy to either a heat transfer fluid (to carry heat somewhere else) or directly to the power cycle's working fluid.

Considering the fundamental solar collection equation, the parameters that are affected by the receiver design are highlighted. The receiver operating temperature T_{rec} is determined in the design of the rest of the solar energy utilization system. The remaining parameters are functions of the design of the concentrator or the weather.

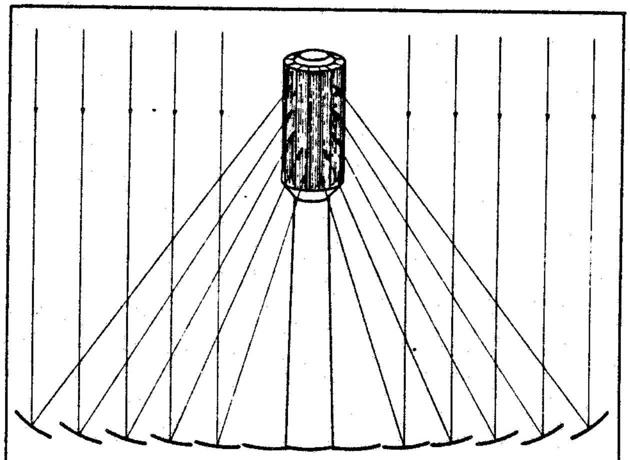
$$Q_{useful} = I_{b,n}A_{app}\cos\theta_i(\rho\Phi\tau\alpha) - A_{rec}[U(T_{rec} - T_{amb}) + \sigma F(T_{rec}^4 - T_{amb}^4)]$$

Two receivers are used in solar thermal concentrators: external or omni-directional receivers and cavity receivers (Figure 14). External receivers are absorbing surfaces that are in direct view of the reflector and depend on direct absorption of radiation. Cavity receivers, on the other hand, have a smaller aperture (opening) through which reflected radiation must pass. Once the radiation is captured inside the cavity, internal reflections ensure that most of it is absorbed on the internal absorbing surface.

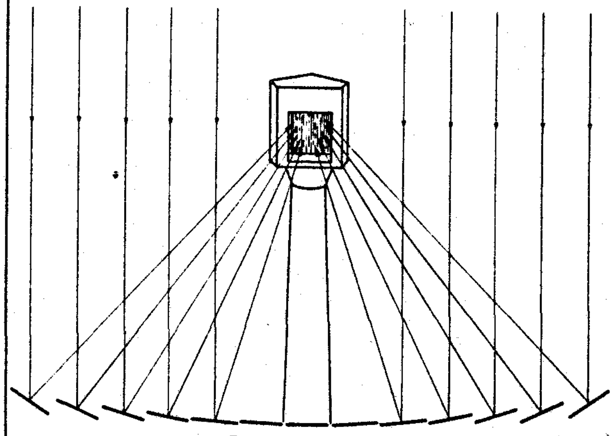
Since external receivers absorb radiation from all directions, concentrators matched to them may have wide rim angles of approximately 90°. When cavity receivers are used with dishes, rim angles of approximately 45° are optimum since the aperture of the cavity must increase with large rim angles.

The receiver should be made as small as possible to minimize heat loss, but not so small that much of the reflected energy spills past it. In the fundamental solar collection equation a small receiver area A_{rec} increases the useful energy derived from a collector. However, as the receiver is made smaller, the capture factor Φ starts decreasing. The receiver must be large enough to capture most of the radiation reflected to the focus.

To increase the capture factor Φ without increasing the size of the aperture of a cavity receiver, secondary concentrators have been used at the receiver aperture. These are highly reflective, trumpet-shaped surfaces that capture reflected radiation from a wide area and reflect it down through the cavity receiver aperture (Figure 15).



External receiver



Cavity receiver

Figure 14. External and cavity receivers

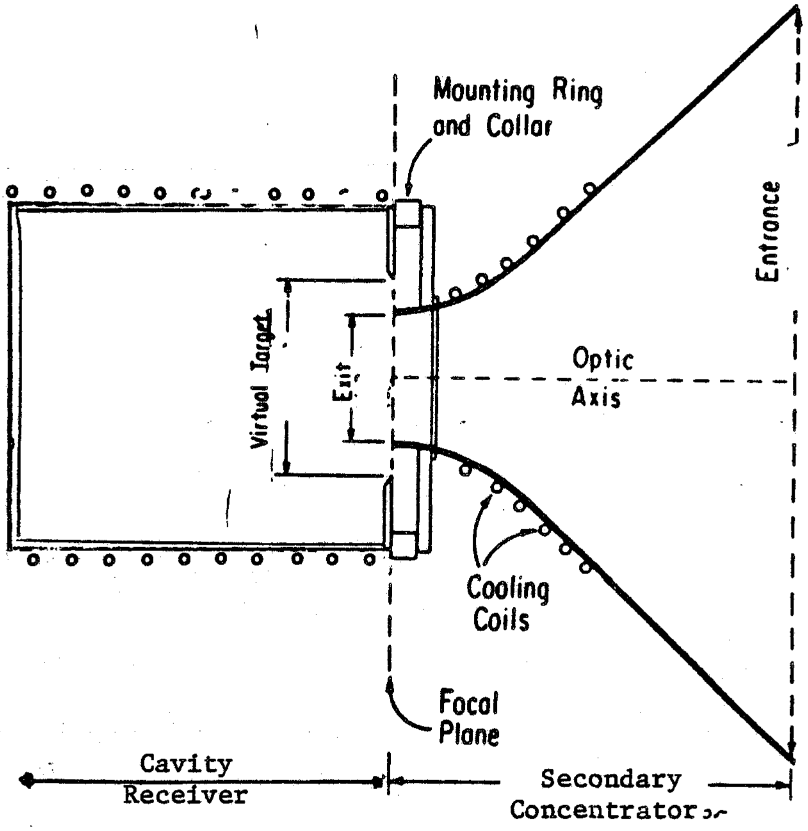


Figure 15. A secondary concentrator being used with a cavity receiver

For a given concentrator-receiver type there is an optimum receiver area. Sizing the receiver incrementally larger would let out more energy than would be gained; sizing it incrementally smaller would block more reflected energy from coming in than the energy loss being saved.

Convective or radiative heat loss is usually less from a cavity. These are the two major terms in the overall heat loss coefficient U. The convective loss portion of this term is also affected by the local wind velocity. This effect, and the entire convective portion of the loss term can be reduced by putting a glass cover sheet around the external absorbing surface or at the aperture of a cavity receiver. This reduces the value of U, but adds a transmittance term τ. Transmittance is simply the fraction of energy which gets through the cover. For clean glass, the value of this term should be above 0.9.

CHAPTER 2 - THE PARABOLIC TROUGH

Of the three solar thermal technologies, the parabolic trough is simplest to fabricate. It is made by bending a sheet of reflective material into a parabolic shape. Support structure is built to hold this curvature. A black metal tube, usually covered with a larger diameter glass tube, is placed along the focal line as the receiver. When the parabola is pointed toward the sun, parallel rays incident on the reflector are reflected onto the receiver tube.

Parabolic trough technology is the most mature of the solar thermal technologies because of considerable experience with the systems and the development of a small commercial industry to produce and market these systems (Figure 16).

Technical Issues - Because of the line-focusing geometry, parabolic troughs inherently have a lower concentration ratio than point-focusing concentrators such as parabolic dishes and central receivers. Since A_{rec} can not be made small (relative to A_{app}) in the fundamental solar collection equation, troughs are not as efficient at high temperature and therefore have to be less costly to compete with dishes or central receivers.

Concentrator

Because the parabolic trough is parabolic in only two dimensions, it only has to track about a single axis (the focal line axis) to keep the sun's rays focused. When only tracked about one axis, the focal line or tracking axis is normally kept parallel to the ground.

Technical Issues - When tracked about a single axis, the aperture of the trough is not pointed directly at the sun most of the time. Because of this, the cosine loss term cos θ_i of the fundamental solar collection equation is less than 1.0.

The tracking axis of a parabolic trough is usually horizontal and oriented either east-west or north-south. The cosine loss from these fields is different. With east-west orientation, the full aperture always faces the sun at noontime. In the morning and evening, the angle between the sun's rays and the aperture is large and cosine losses are high. North-south oriented troughs usually have their highest cosine loss at noon and directly face the sun when it is due east (mornings) or due west (evenings).

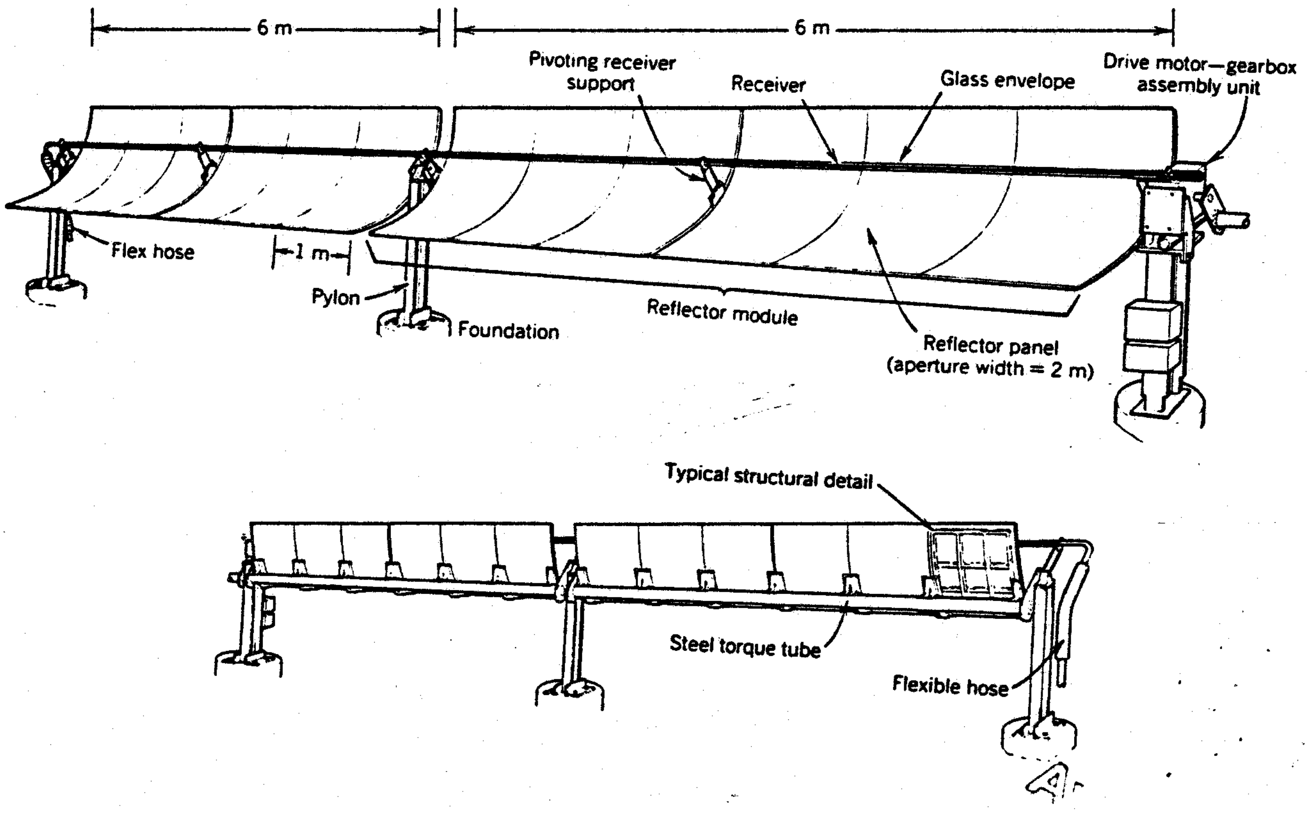


Figure 16. Parabolic trough subsystem - half drive string shown

Over the period of a year, a north-south trough field usually collects slightly more energy than an east-west field. However, a north-south trough field collects a lot of energy in the summer and much less in the winter. The east-west field collects more energy in the winter than a north-south field and less in the summer, providing a more constant yearly output. The choice of orientation usually depends on the application and whether more energy is needed in the summer than the winter.

Parabolic troughs may be tracked about two axes and if so, the aperture is always pointed at the sun and cosine loss is eliminated. However, considerably more piping must be installed to connect the collectors for a two-axis system. This increases the heat loss and cost of the system. It also adds considerably to the collector support structure and complexity of the tracking mechanism. It is a general consensus that the added expense and heat loss from two-axis tracking is not worth the performance gained from reduced cosine losses.

The type of receiver defines the rim angle of the trough. When a receiver is used that absorbs energy coming from any direction, such as a tube receiver, the rim angle can be increased to increase the concentration ratio. As rim angle increases however, more and more reflective surface is required to increase the aperture area by a given amount because the reflective surface is at steep angles to the incoming rays. This requires large amounts of reflector surface and structure to attain a small increase in concentration ratio. Rim angles of approximately 90° are considered optimum for parabolic troughs.

Small rim angle troughs are possible, but the reflective surface and the long receiver support structure require extremely accurate manufacturing tolerances. Small rim angles are used when flat surface or cavity receivers are used, but this is not common for troughs.

Troughs are built in modules that are supported from the ground by simple pedestals at either end. If the span between supports is long, the cost of installing and coupling them will be reduced. Also, wider apertures make the spacing between rows greater, reducing the installation cost. Current trough technology produces modules that span 20 ft (6 m) lengths and can be 6-16 ft (2-5 m) wide.

Receiver

The receiver of a parabolic trough is linear. Usually a tube with a high absorptance coating is placed along the focal line to form an external-surface receiver. The size of the tube, and therefore the concentration ratio, is determined by the size of the reflected sun image and the manufacturing tolerances of the trough.

Concentration ratios are inherently lower for troughs than for parabolic dishes. This lower ratio is because insolation reflected to a small area on the receiver comes from a strip on the parabolic reflective surface rather than from all directions as with the parabolic dish. Concentration ratios of 40-60 are typical for troughs.

Technical Issues - The surface of the receiver is typically plated with a selective coating that has a high absorptance for solar radiation but a low emittance for thermal radiation loss. A popular coating of this type is called black chrome. With this type of surface, more energy can be collected as is seen in the fundamental solar collection equation because the absorptance α is high, while the the equivalent conductance F is low.

A problem related to receiver performance is degradation of the selective coating. When initially applied, this coating gives the tube a high absorptance (around 0.9) and a low radiation loss (emittance around 0.2). However, over long periods, the optical performance has been found to degrade. Research is continuing on the factors involved, believed to be in the plating process and corrosion of the substrate.

A glass cover-tube is usually placed around the receiver tube to reduce the convective heat loss from the receiver tube, thereby further reducing heat loss U (Figure 17). A disadvantage of the glass cover-tube is that the reflected light from the concentrator must pass through the glass to reach the absorber, adding transmittance loss (τ in the fundamental solar collection equation). When the glass is clean, this term is approximately 0.9.

One way to further reduce convective heat loss from the receiver tube and thereby increase collector performance is to evacuate the space between the glass cover tube and the receiver tube. Although a simple concept, this has proven difficult to accomplish.

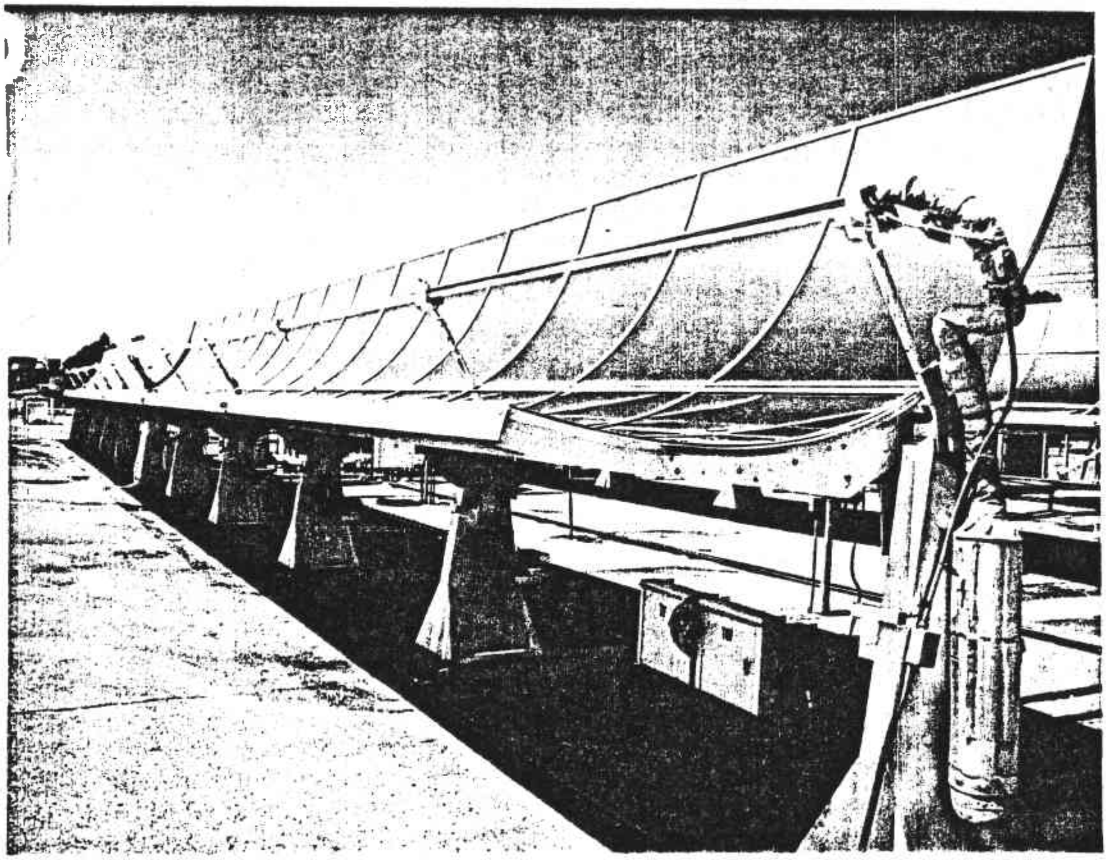


Figure 17. Glass-enclosed receiver tube

A constant mechanical problem with parabolic trough installations has been the failure of flexible hoses used to connect the moving receiver tubes to fixed piping. Flex hoses are used between each rigid length of trough modules, connected to a single tracking drive motor. This is done to make the motion of these "drive strings" independent. They are also used at the ends of each full string to connect the receiver tubes to the manifold piping that carries heat transfer fluid to and from the collector field.

Recent work on using rotary joints instead of flex hoses has shown promise in eliminating this problem. Attempts at designing the trough so that the concentrator tracks about a fixed receiver have been unsuccessful due to the considerable unbalanced load of the concentrator.

Trough Evolution

Because the technology of manufacturing parabolic troughs and designing systems incorporating them is more mature than for the other types of collection, many fundamental technological issues have been solved, resulting in the designs discussed. Peak efficiencies (insolation to useful thermal energy conversion) have risen from less than 50% to over 65% and operating temperatures are now range from 600° to 650°F (315° to 345°C). However, effort is still being directed toward reducing unit costs and increasing the performance and reliability of the collectors.

One method of reducing the cost of trough or any collector being manufactured is through mass production. Generally, the cost decreases as the quantity of collectors produced increases. Parabolic trough designs have evolved from small-aperture, one-at-a-time production modules with high labor intensity, to large-aperture designs that can use mass production techniques.

To enhance the mass production capabilities of parabolic troughs, a study of mass manufacturing techniques revealed numerous techniques that promise considerable price reductions as production rates increase (Figure 18). One such technique involves using a stamped ribbed sheet metal panel to provide a rigid parabolic substructure onto which a glass reflector is bonded. Another mass production approach involves the use of rigid mirrored glass, sagged into a parabolic shape and supported by a light-weight structure.

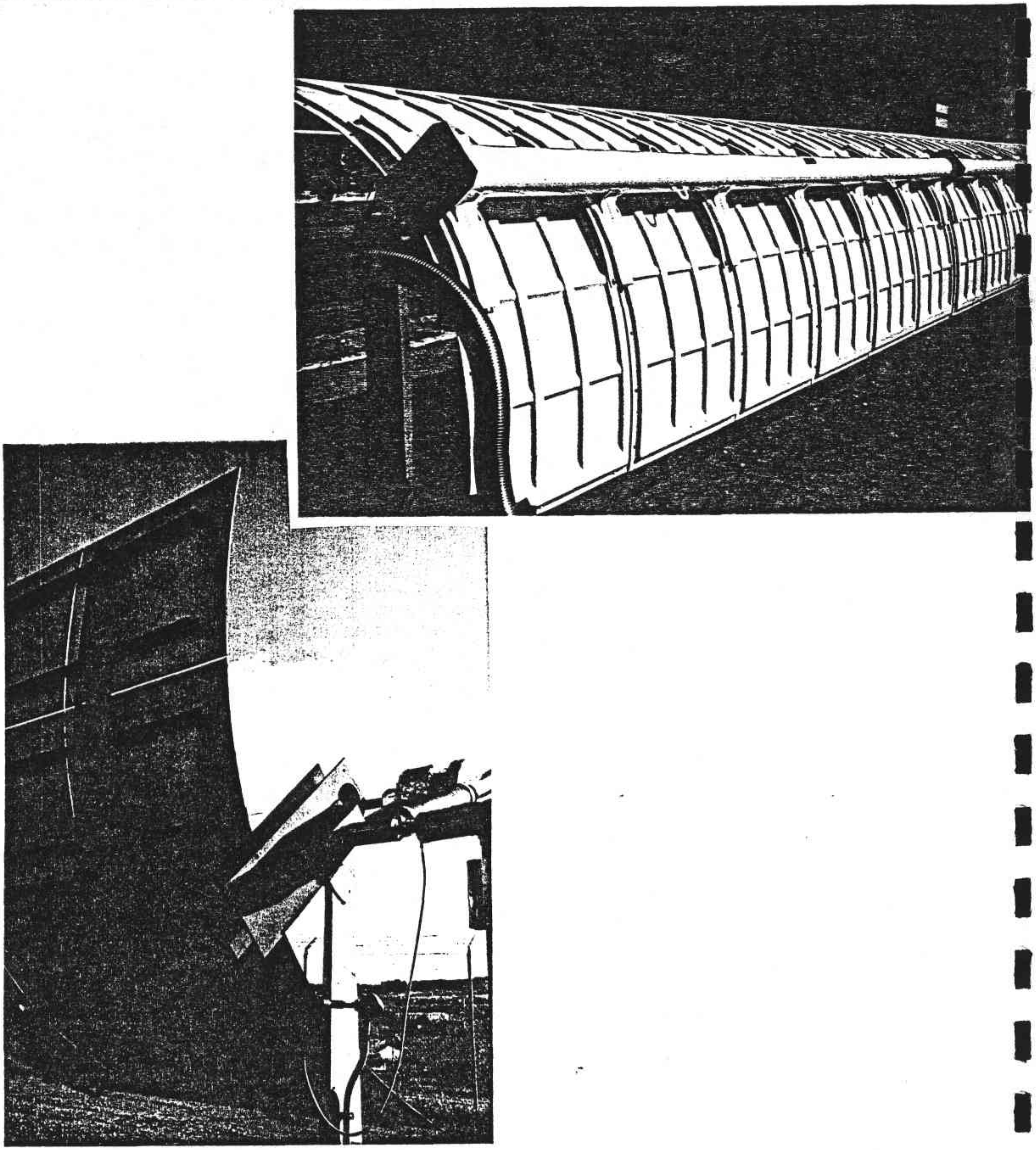


Figure 18. A stamped ribbed sheet metal parabolic trough and a sagged glass parabolic trough.

System Experience

A number of parabolic trough solar thermal systems have been built and tested throughout the United States (Figure 19). Most of these systems provide process steam to an industrial host rather than generating electricity. They displace fossil fuels such as oil or natural gas as the energy source for producing steam are being operated, with fields of parabolic troughs having total aperture areas of from 5,400 to 54,000 ft^2 (500 to 5,000 m^2). Most of these systems supply process steam from 300° to 400°F (150° to 200°C).

The most current example of power production using parabolic troughs is the Solar Electric Generating Station (SEGS) at Daggett, California (Figure 20). Built entirely with private financing, units I and II are currently operating and produce a maximum gross electrical power output of 42 MW_e. The collector field consists of sagged glass parabolic troughs with evacuated cover-glass receivers. An oil-based heat transfer fluid is used along with a two-tank thermal storage to extend the operating period. This system is now being expanded and when complete will produce 104 MW_e with a 7,180,000 ft^2 (667,000 m^2) field of parabolic trough collectors.

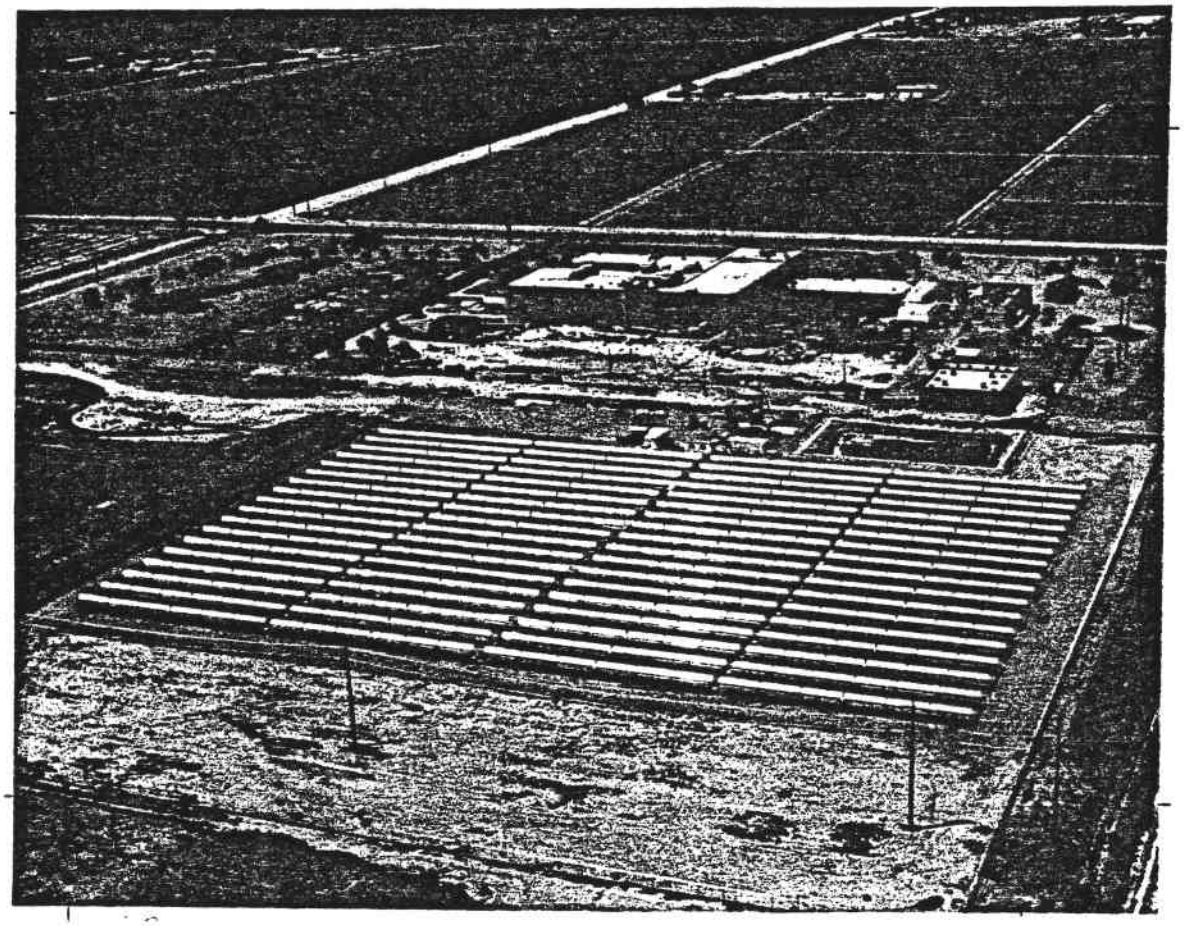


Figure 19. Trough industrial process heat experiment at the USS Chemical Company, Haverhill, Ohio

Figure 20. The Solar Electric Generating Station (SEGS) at Daggett, California

CHAPTER 3 - THE PARABOLIC DISH

Concentrators

A parabolic dish must always point directly toward the sun for proper focusing (Figure 21). Therefore, there is no cosine loss (cos Φ in the fundamental solar collection equation) to reduce the collector performance because the angle of incidence Φ is always zero. To maintain a focus, the dish must be tracked about two axes. Most tracking schemes fall into one of two categories; a azimuth/elevation (az-el) or polar (sometimes called equatorial).

Azimuth/elevation tracking provides for movement about an axis perpendicular to the ground and another parallel to it. Polar tracking uses a tracking axis aligned with the earth's axis of rotation called the polar axis, and the other perpendicular to it called the declination axis. The advantage of polar tracking is that the movement about the polar axis is constant at 15° of rotation per hour and movement about the declination axis is usually negligible over a day.

A special consideration in selecting the reflective material for a dish is that the surface curvature is compound (in two dimensions) and the rim angles are usually around 45° requiring significant bending of the material. This results in mechanical and bonding problems when large flat glass mirrors are bent into the proper shape and bonded on supporting surfaces. To overcome this difficulty, early parabolic dish technology has been driven toward the use of smaller reflective segments called facets for many applications (Figure 22).

Technical Issues - Because the parabolic dish has the potential for small receiver aperture area at high solar concentration, they may be operated at high temperatures without loosing too much energy (given by the two right-hand terms in the fundamental solar collection equation). Therefore, dishes are prime candidates for running high efficiency power cycles to make electricity.

To obtain the high concentration required for high temperature operation, the quality of the optical surfaces and the accuracy of the parabolic curve must be good. Likewise, the tracking system must be accurate to maintain alignment of the concentrator.

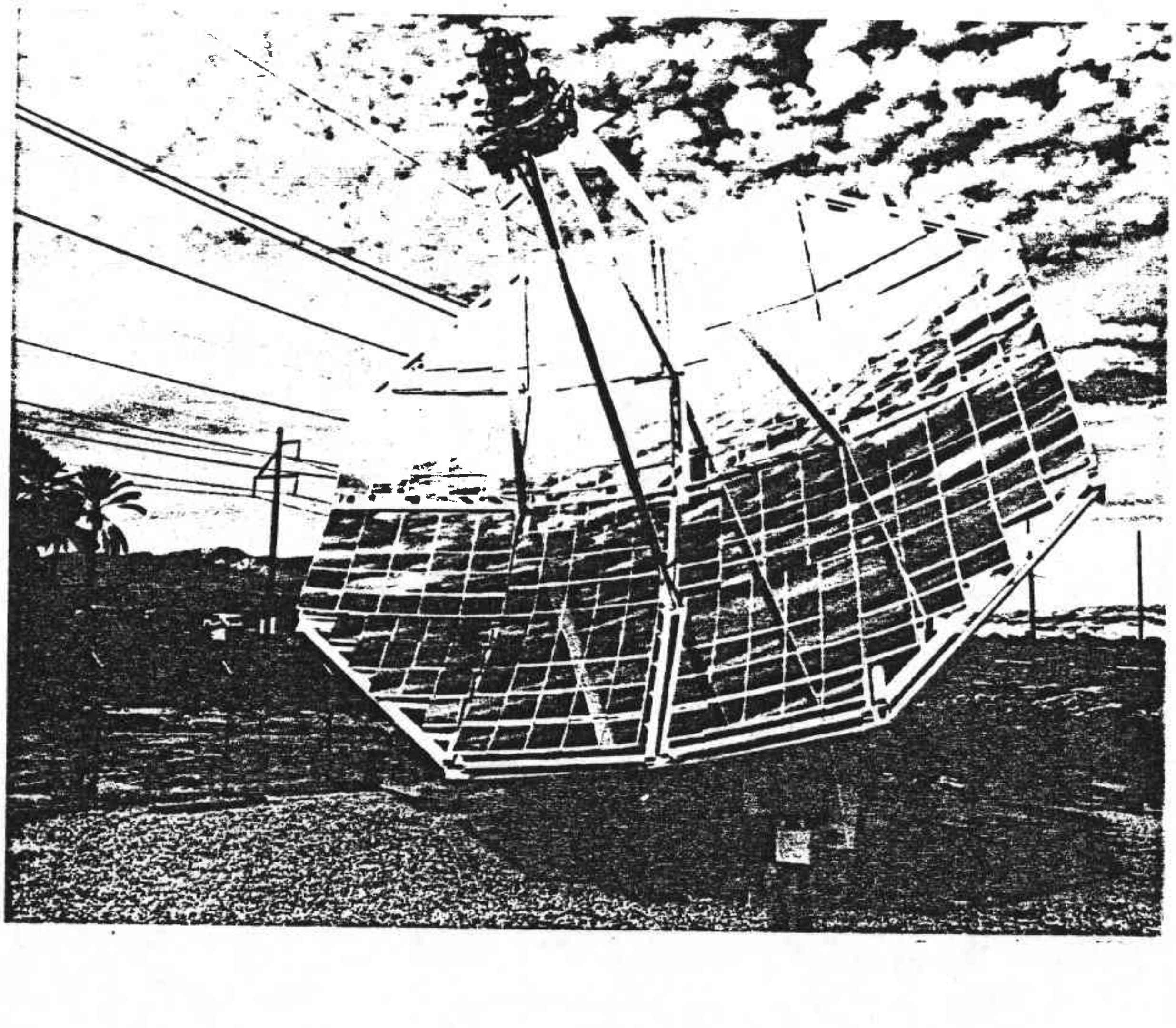


Figure 21. Parabolic dish with a receiver/engine mounted at the focus

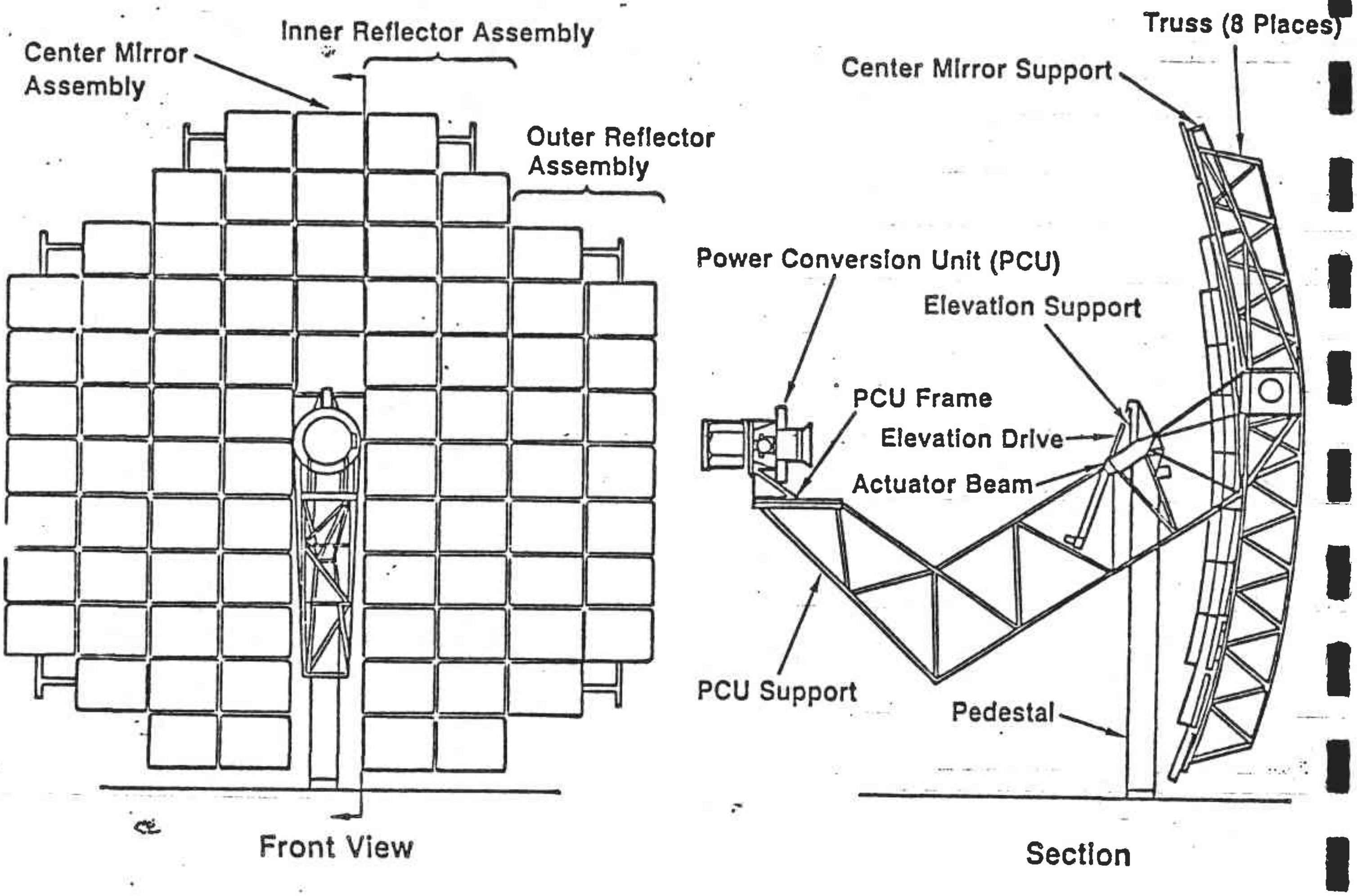


Figure 22. Faceted parabolic dish concentrator with engine at focus

Component Evolution - Many styles of concentrator construction have been proposed and tried during the solar thermal development program (Figure 23). Early dish concentrators used slightly curved glass mirror facets on a lightweight supporting structure where each facet was individually adjusted to focus on the receiver. These were found to be expensive to manufacture and labor-intensive to install. Stamped metal dishes and dishes with mosaic flat mirrors forming the reflective surface have also been tried.

In many designs, the paraboloid is divided into a number of pie-shaped segments called gores. These have a long radius of curvature, which enhance their manufacture and the application of reflective materials. Gores have been made from laminated balsa wood, foam glass and stamped sheet metal rib-and-skin construction (Figure 24).

To bypass many of the difficulties mentioned above, a movable-slat dish was built to test the concept of tracking individual segments of an aperture to maintain a point focus (Figure 25). The tracking elements are rotatable slats of individually aimed mirrors. These slats are mounted on a two-plane, lightweight supporting structure that is tracked about the azimuth axis. Although the dish is not parabolic, focus at a point is maintained by separately tracking the support structure and the slats. This type of concentrator is being used for solar applications because of the relative ease with which the aperture area size can be increased for large power applications.

A completely different type of point-focus concentrator uses the principle of refraction rather than reflection to direct the sun's rays toward a focal point (Figure 26). Large lenses similar to magnifying glasses are heavy and difficult to fabricate. However, since concentration depends only on the angle at which light enters and exits a refracting device, the thickness of a concentrating lens can be reduced by successively reducing the thickness of the refractive material in a plane parallel to the incoming light. This results in a 'saw-tooth' cross section, called a Fresnel lens, which can be molded in the surface of a thin sheet of plastic.

This type of concentrator has the advantage of its focus being near the base of the concentrator, permitting easier support of the weight of the receiver and engine. It also has greater tolerance for tracking and surface slope errors.

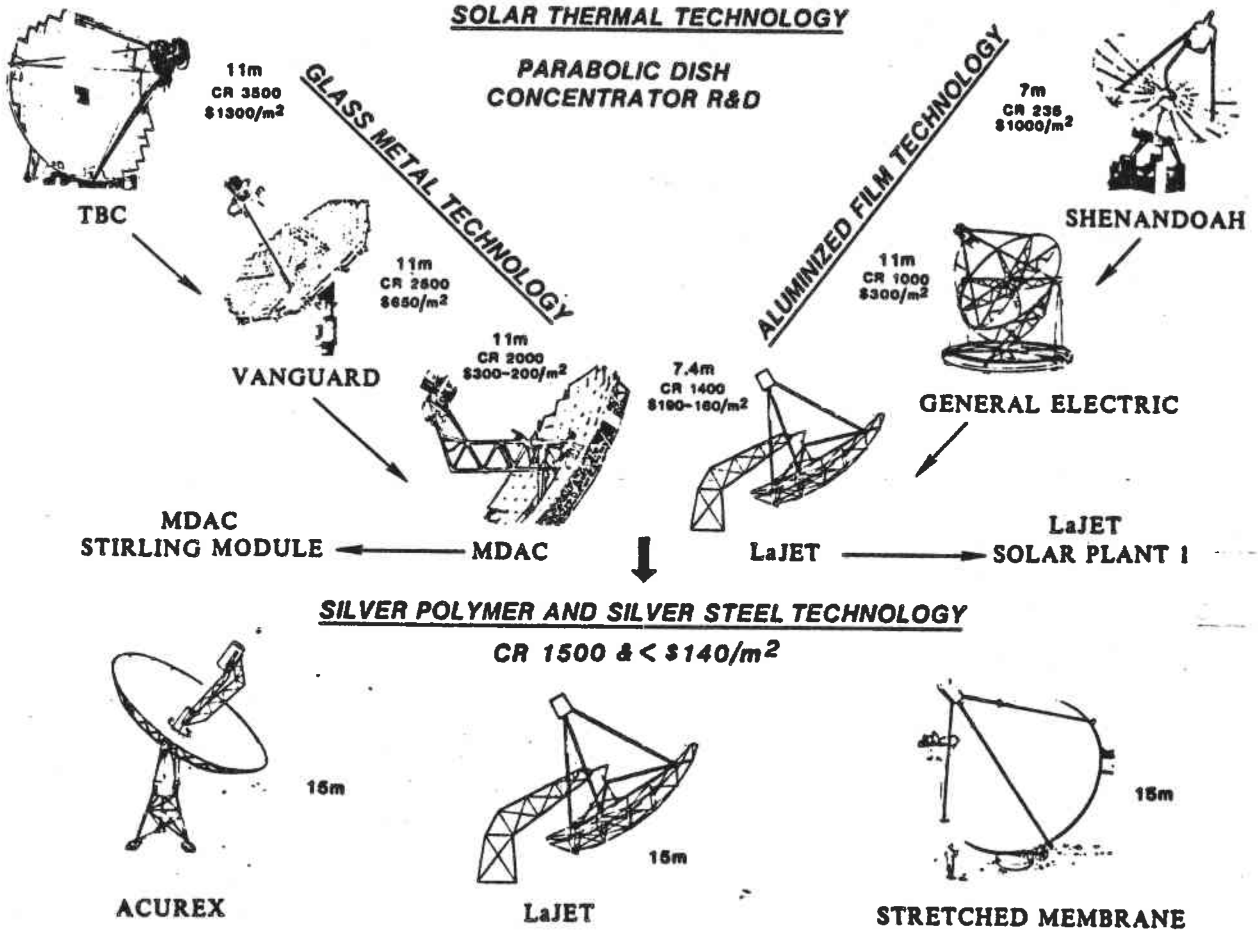


Figure 23. Evolution of the parabolic dish solar concentrator

ACUREX DISH ELECTRIC SYSTEM

S-1292

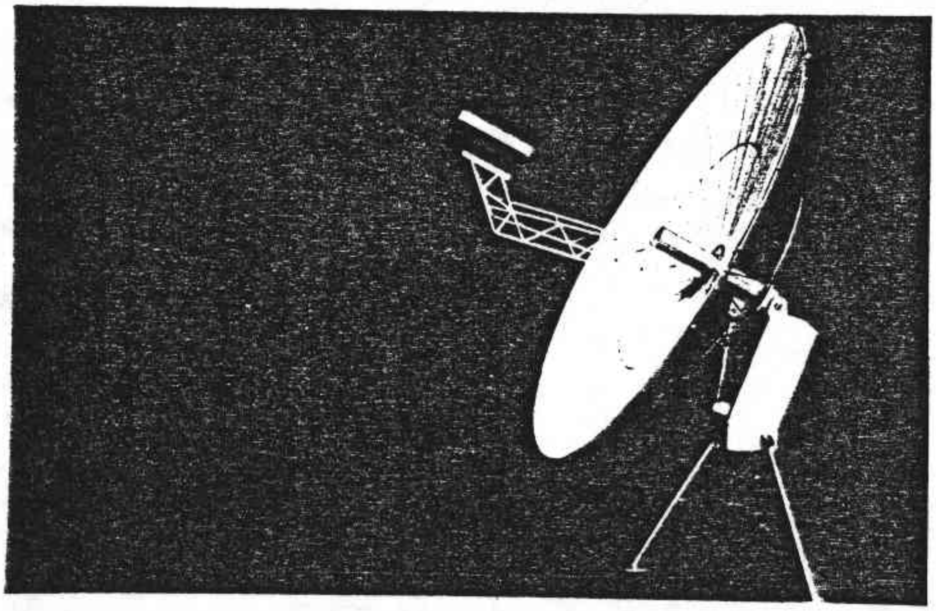


Figure 24. Dish electric system with stamped sheet-metal gore construction

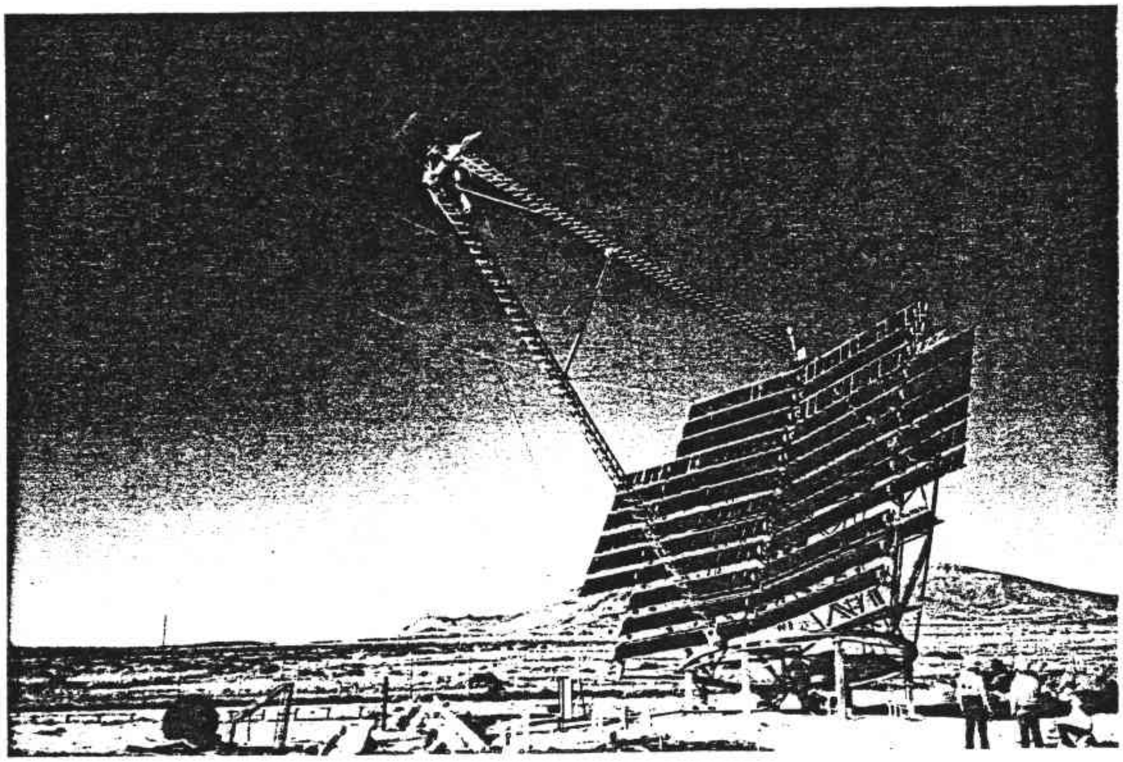
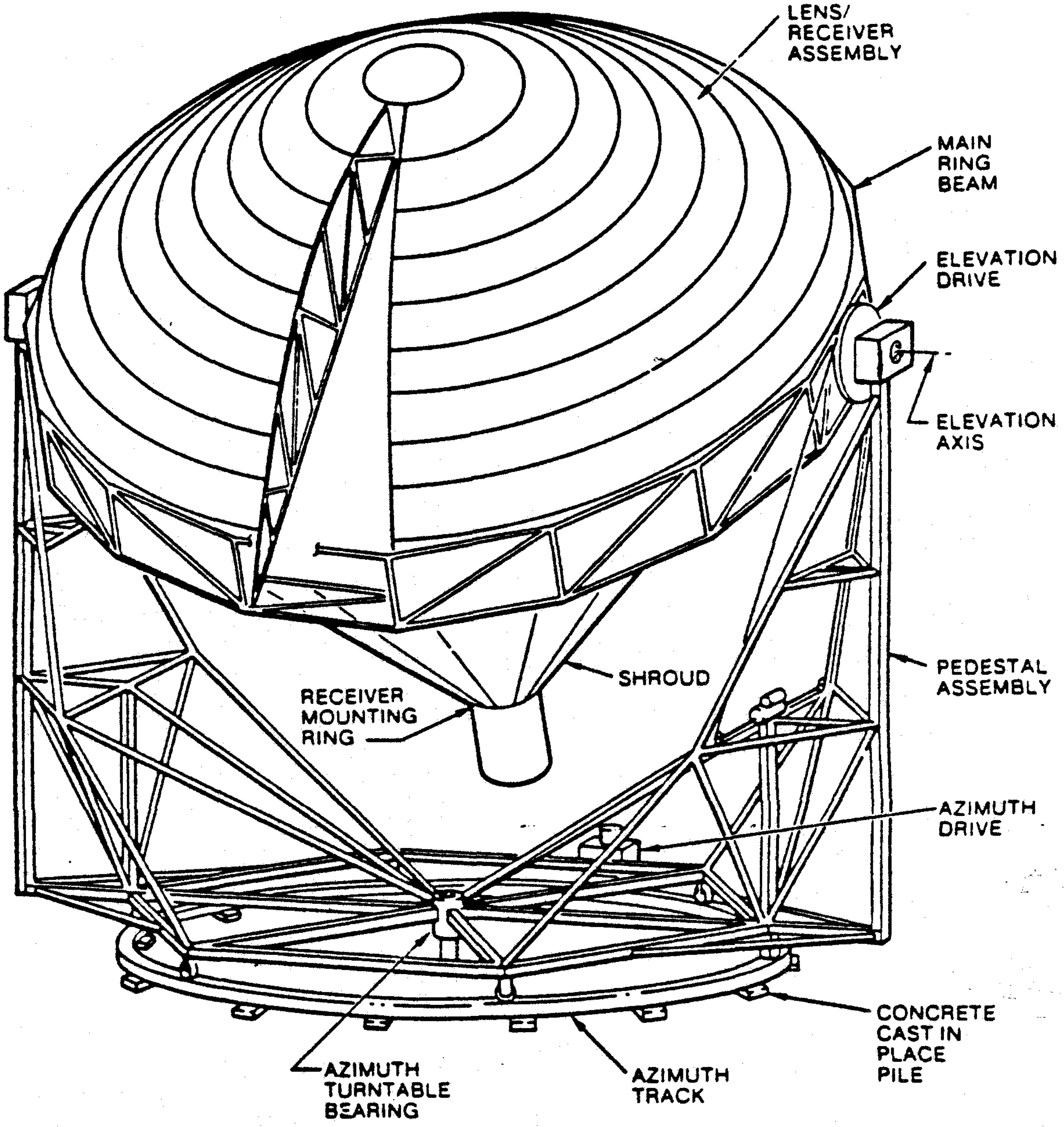


Figure 25. Movable facet point-focus concentrator

INNOVATIVE POINT FOCUS FRESNEL LENS CONCENTRATOR
(14 METER DIAMETER, 1500X GCR, 116 KW-THERMAL)



ENTECH, INC.

Figure 26. Point-focus Fresnel lens concentrator

Because of the difficulties of fabricating larger and larger dishes to reduce unit and operating costs, numerous concepts use individually focused facets mounted on a tracking lightweight supporting structure. One such design known as the stretched-membrane point-focus concentrator, uses a pair of stretched plastic films (one being reflective) over a hoop (Figure 27). The airspace between the membranes is partially evacuated so that the reflective membrane assumes a quasi-spherical shape. At small curvatures, there is very little optical difference between a sphere and a parabola, and therefore the sun's radiation hitting the reflector is reflected to a point. One or more of these stretched-membrane facets are installed on a tracking, lightweight supporting structure, and a point-focus concentrator results. A significant advantage of this concept, which is presently under development, is its simplicity and low cost.

Receiver/Engines

The receiver absorbs the reflected sunlight and heats a fluid. If the dish is designed to produce electricity, the power conversion cycle (engine) can be placed near the focus, allowing short heat transmission paths from receiver to engine. Because the engine and the receiver form the same module for these applications, most of the discussion below will be on these packages.

Cavity receivers are used with parabolic dish concentrators because of their low overall heat loss rate (low U and small A_{rec} in the fundamental solar collection equation) at high operating temperatures T_{rec}. Concentrated radiation entering the aperture spreads out inside the cavity and is absorbed on the internal walls where heat is transferred to the heat transfer fluid. Reflected or reradiated energy is reabsorbed on the cavity walls, and heat loss due to convection currents is reduced.

Most cavity receiver designs do not use a cover window at the aperture of the receiver thereby eliminating the transmittance τ term. Studies show that when cavities are tipped at an angle as in solar applications, the convection loss could be reduced. Covering the cavity aperture with a window to further reduce losses is only required at high temperatures. The high flux at the aperture make their survivability questionable and the added cost has so far made this approach unfeasible.

Like the other types of solar collectors, the size of the receiver aperture affects the capture factor (Φ in the fundamental solar collection equation). A large receiver

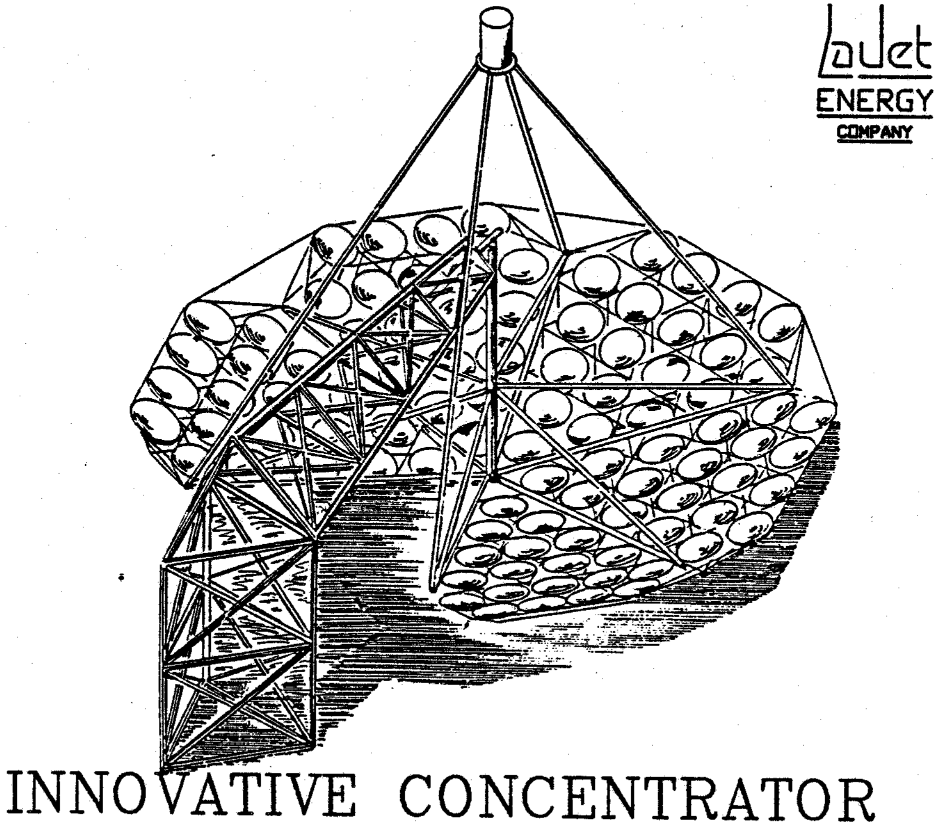


Figure 27. Parabolic dish with stretched-membrane facets

aperture increases the percentage of reflected energy captured. However, a large aperture area A_{rec} increases the heat lost from the receiver. Because the spread of reflected radiation at the focus is a function of the concentrator surface and tracking accuracy, there is always an important design cost trade-off in balancing these factors.

Some cavity receiver designs used with dish concentrators incorporate a small amount of thermal storage called buffer storage. One design incorporates a mass of copper to form the cavity wall, and the other incorporates a phase-change material in the cavity wall. Either design, when heated to operating temperature, will retain heat for times when a cloud passes over the collector and insolation is reduced (Figure 28).

Small engines are placed adjacent to the receiver in many applications. These engines are approximately 25-50 kWe to match the capabilities of the concentrator. Three types of engines have been or are being considered for application to dish concentrators; the Rankine cycle (both steam and organic working fluids), the Stirling cycle (both kinematic and free-piston) and the Brayton cycle (Figures 29 and 30). The Brayton cycle system has lower performance and is not currently being pursued.

Technical Issues - The overriding design issue for the dish receiver is to economically raise the operating temperature so the attached engine can perform more efficiently. This must be optimized to the receiver efficiency which decreases at high temperatures. Parabolic dish concentrators have the potential for operating at very high temperatures (above 1000°C or 1830°F) and therefore supply heat to high performance engines.

Because the concentrated solar flux at the focus of a dish concentrator is very high, extremely high heat transfer rates are necessary at the absorbing surfaces. Often the heat transfer surfaces must be placed away from the focal point in a location where the flux has diffused to a larger area. Since this increases the size of the receiver and therefore its heat losses, attempts are being made to design compact receivers with high heat transfer rates from the absorber to the heat transfer fluid. One concept is to use heat pipe technology where liquid sodium is vaporized in a chamber just behind the absorbing surface of the cavity (Figure 31). It is then condensed on the tubes containing the engine's working fluid.

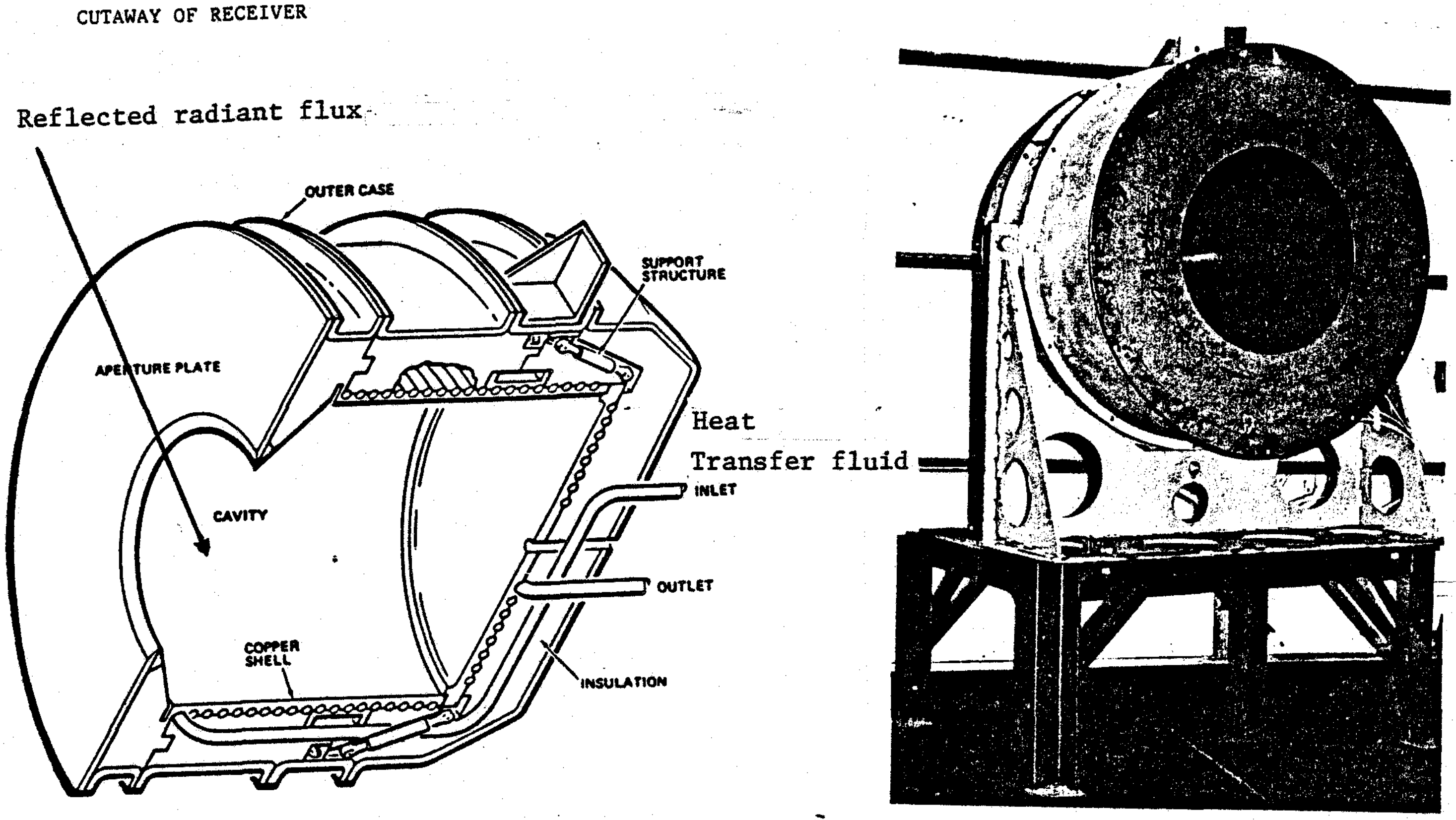


Figure 28. Cavity receiver with copper mass buffer storage

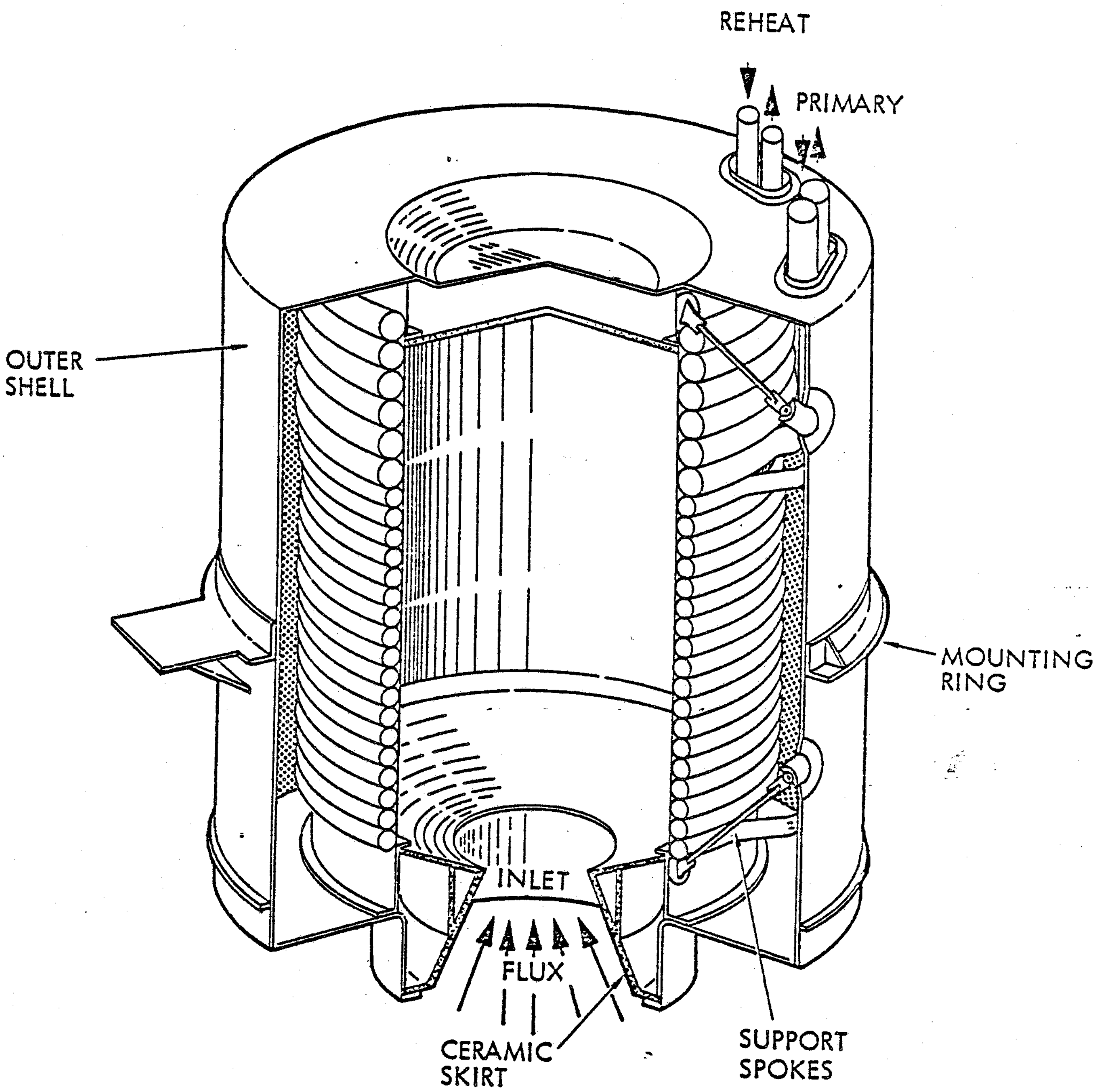


Figure 29. A cavity receiver for Rankine cycle applications

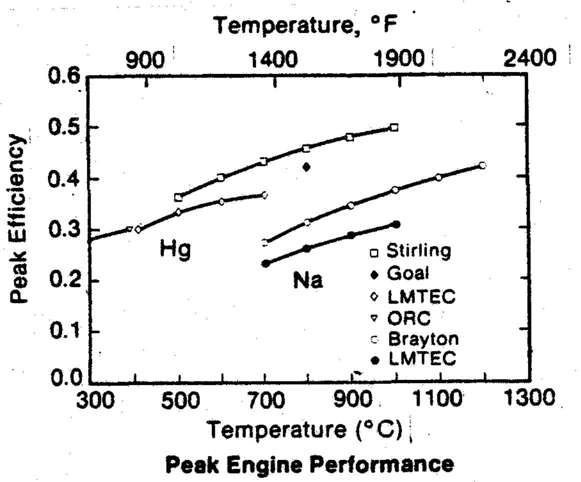


Figure 30. Advanced engine performance potential for Rankine, Stirling, Brayton, and combined Brayton/Rankine cycles

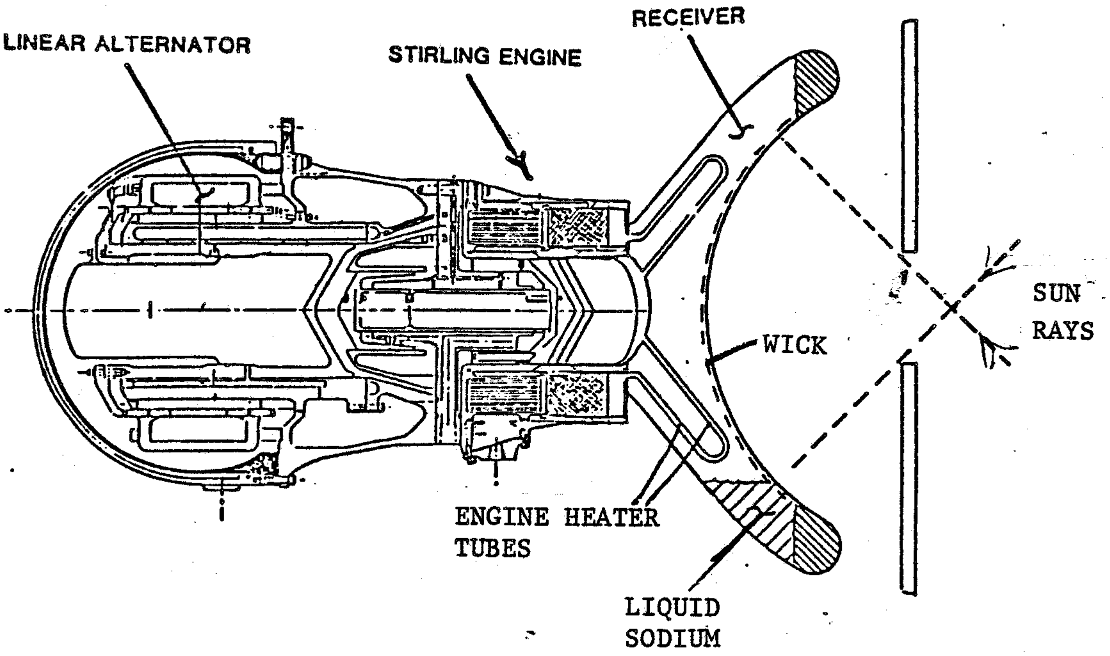


Figure 31. Cavity receiver using heat-pipe technology adjacent to a Stirling engine

A problem of cavity receivers is that if the tracking system fails while the collector is in focus, the high flux focal point passes across the front of the receiver. This is called "walk-off" because the focus moves across the receiver at the rate of one degree every four minutes. Techniques of emergency defocusing of the concentrator have been employed. An alternative is to use refractory materials to protect the receiver.

With concentrating dish technology, another issue is finding the best method of transmission of the high quality (high temperature) collected energy to its end-use point. As discussed previously, high temperature collection techniques are effectively used when electricity is the end product. With electrical generation at each dish module, the output can be connected to the end-use point by wire. An alternative is to pipe high-temperature heat transfer fluid from each dish module to a central steam Rankine cycle electrical production facility or process heat application.

Receiver/Heat Engine Evolution - Receiver/heat engine design technology is aimed at using the high temperatures from a dish solar concentrator.

A small 25-kWe Rankine cycle using an organic working fluid and connected directly to a cavity receiver has been developed and tested (Figure 32). The cycle uses toluene (a petroleum-based fluid much like paint thinner) as its working fluid. Toluene was chosen over steam, the traditional working fluid for Rankine cycles, because of its high molecular weight that makes the design of high efficiency, small power turbines feasible. The cycle operates at a temperature of 750°F (400°C) and has a cycle (heat to power) efficiency of 28%.

The engine design incorporates a high speed alternator built on the same shaft as the turbine and the pump. Heat is rejected from the cycle through a fan-cooled condenser located adjacent to the engine. A copper shell forms the inner walls of the cavity receiver. This provides a small buffer-storage for heat when clouds reduce the insolation. A tube carrying toluene is wrapped around the outside of this shell where the toluene working fluid vaporizes.

Two different engine designs using the Stirling cycle are being developed and tested as receiver/engine modules. One style uses pistons directly connected to a crankshaft or swashplate providing mechanical power to a rotating shaft driving a rotating alternator. This type of Stirling engine is called a kinematic Stirling engine. The other style is

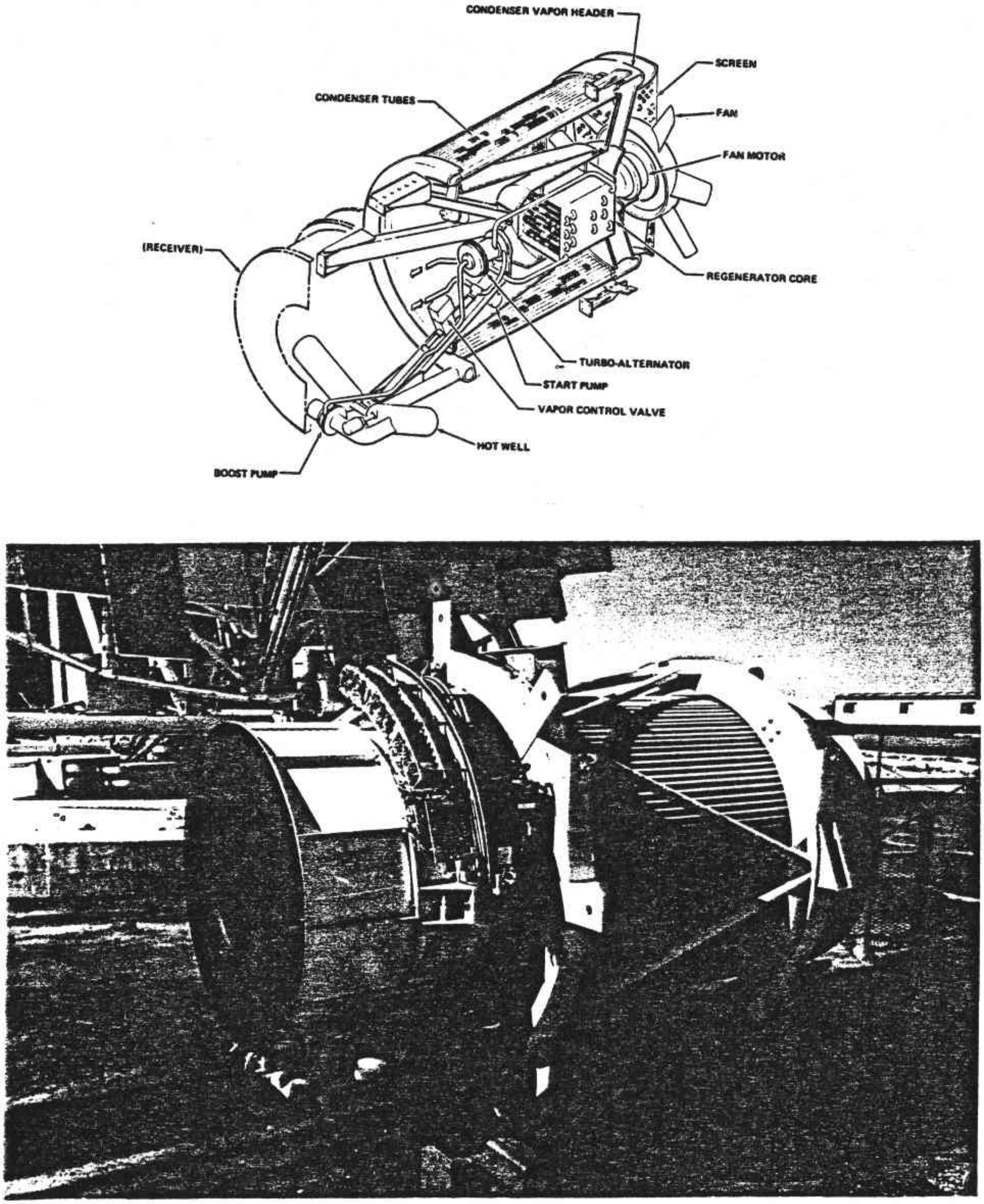


Figure 32. A 25 kWe organic Rankine cycle receiver module

called a free-piston Stirling engine, which uses a piston that is free to bounce back and forth on 'gas springs' located at either end of the cylinder with no mechanical connections. A linear alternator can be built into the piston unit to produce electricity from the back-and-forth motion or a hydraulic converter can be used to transmit this energy to drive an electric alternator.

A 25-kWe kinematic Stirling engine mated with a cavity receiver has undergone extensive testing and is being marketed (Figure 33). This engine is a four-cylinder engine using hydrogen as the working fluid. The engine operates at a temperature of 1330°F (720°C) at a cycle efficiency of 40%.

An important issue with the kinematic Stirling engine designs is the longevity of the linear or rotary gas and oil seals located where the shaft work is transferred from the piston portion of the engine to the crankcase. These seals, although not expensive, require that the engine be disassembled for their replacement. Extension of the lifetime of these seals to periods acceptable for remote site daily power generation is proceeding.

Free-piston Stirling engines only have two moving parts (the displacer and the power piston) and show promise for long lifetime with low maintenance requirements. Small free-piston Stirling engines have been operated and show promise; however, they are still in the design and development phase (Figure 34). Since the entire engine contains the working gas and only electrical power leads penetrate the case, gas sealing problems are minimized. Larger (25 kWe) engines are still in their early stages of development but show promise.

Brayton cycle engines have been considered for application to solar thermal energy conversion. These engines, constructed similar to a small jet aircraft engine, use concentrated solar energy to heat the compressed gas before it expands through the turbine. These engines typically have the advantage of low maintenance and long life.

For solar applications, Brayton cycle engines are considered as having long-term potential only and are not under current development. This is because of the high temperatures (800°-1400°C or 1500°-2500°F) required to operate these engines at high efficiencies. In order to operate at these temperatures, materials currently used in solar receivers cannot be used and the development of high temperature materials, probably ceramics, will be required.

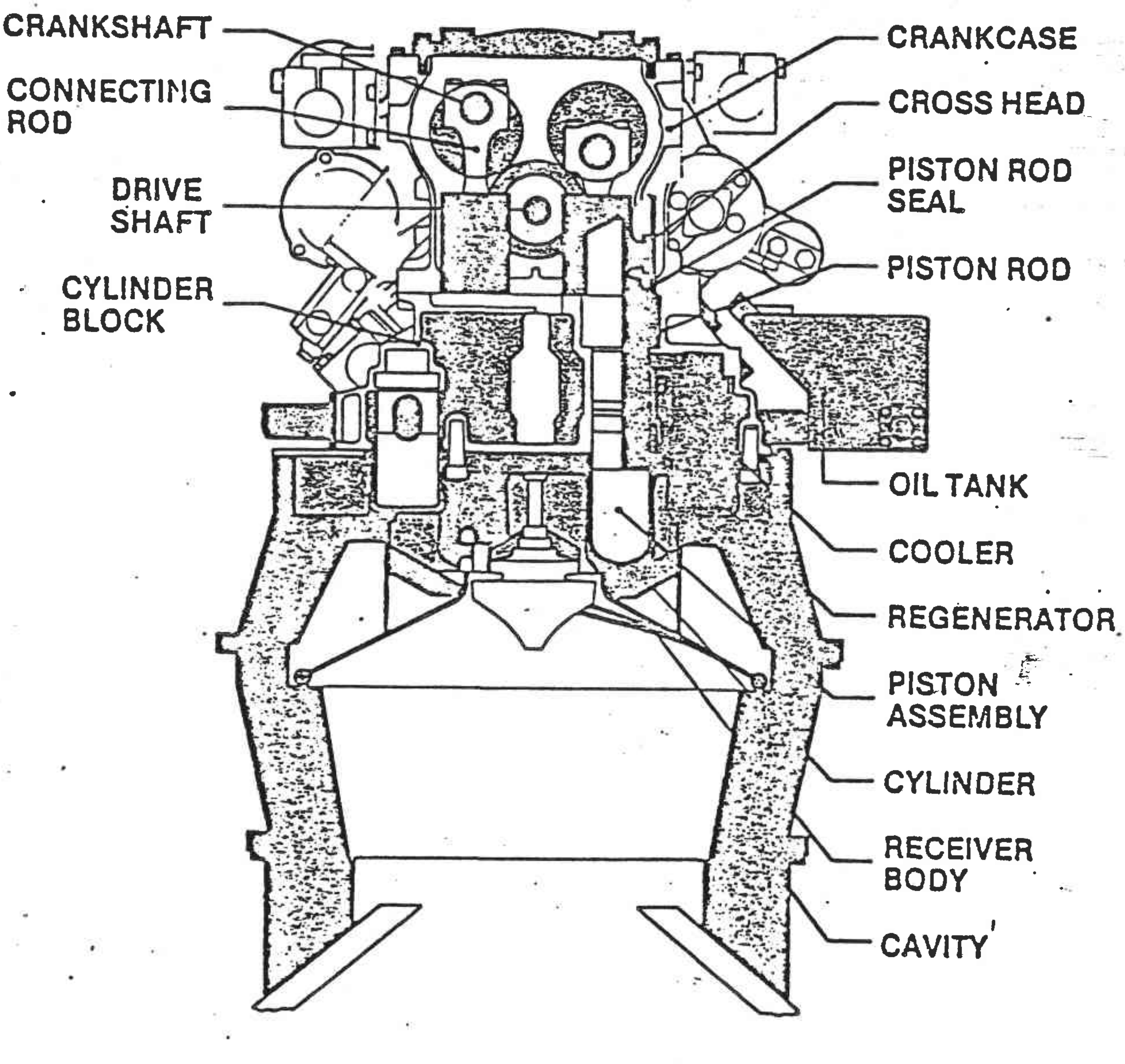


Figure 33. A 25 kWe kinematic Stirling engine

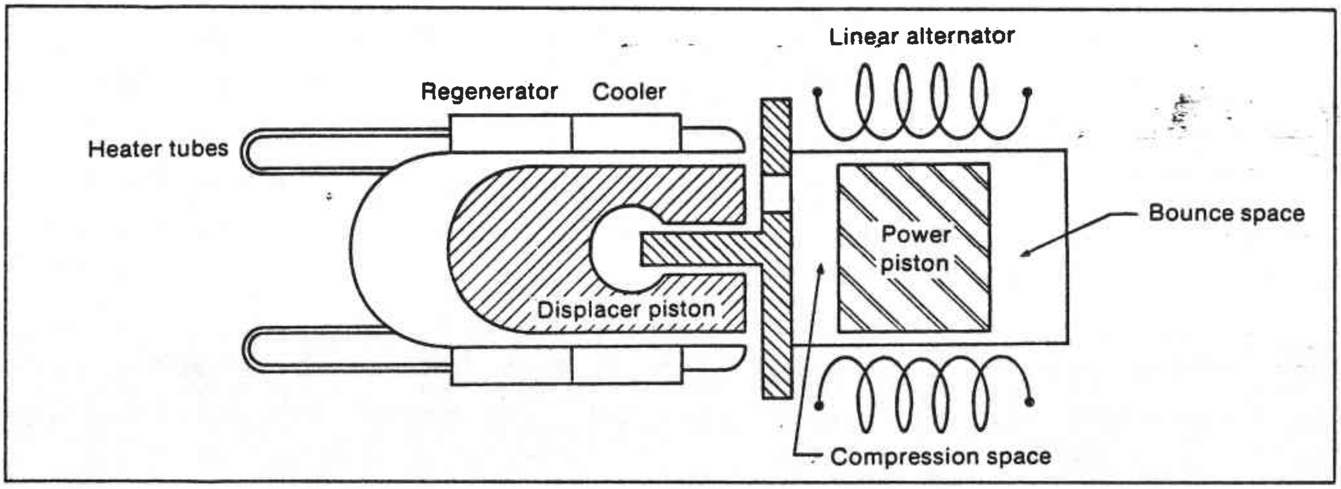


Figure 34. Schematic of a free-piston Stirling engine

System Experience - Three major dish system evaluation experiments are currently being made. These include the Solar Total Energy Project at Shenandoah, Georgia; the LaJet commercial thermal power generation system at Warner Springs, California; and the two Small Communities Experiments currently undergoing final hardware preparation.

The Solar Total Energy Project at Shenandoah, Georgia, includes a field of 114 parabolic dish collectors with a total aperture area of 46,845 ft^2 (4,352 m^2) that supplies 750°F (400°C) heat to a central steam Rankine power generation cycle (Figures 35 and 36). This cycle, operating at 720°F (382°C), produces up to 400 kWe, 1380 lb/hr (626 kg/hr) of 100 psi (700 kPa) process steam and 468 kWt (113 tons) of air conditioning for the adjacent Bleyle Knitwear factory. The system has a solar-to-total energy conversion efficiency of approximately 15%.

The 23-ft (7-m) diameter parabolic dish collectors are made of stamped aluminum gores with an aluminized plastic film applied to the reflective surface. The collectors are tracked about their polar and declination axes. A cavity receiver with the absorbing surface a coil of tubing wound in a 'beehive' shape is used. Solar heat is transferred to a silicon-based heat transfer fluid at temperatures up to 750°F (399°C) and the heated fluid from each collector is pumped through insulated piping to the central total energy cycle.

Solar Plant One is a privately financed electric power production facility located in Warner Springs, California (Figure 37). It comprises a field of 700 stretched-membrane dish collectors having a total aperture area of 311,500 ft^2 (28,940 m^2). Superheated steam at 750°F (400°C) is generated in the collector receivers and piped to a central Rankine cycle that produces 4.9 MWe under peak insolation conditions. This represents a peak solar-to-electric efficiency of 17%.

Each collector incorporates twenty-four 5.0 ft (1.5 m) diameter stretched membrane facets mounted on a lightweight supporting structure. An aluminized plastic film is used for the membranes with a slight vacuum between the membranes to provide for focusing. The entire structure tracks about the polar and declination axis. Cavity receivers are used which have a 10 in. (0.25 m) diameter aperture and incorporate a small amount of phase-change salt that provides buffer storage for the system.

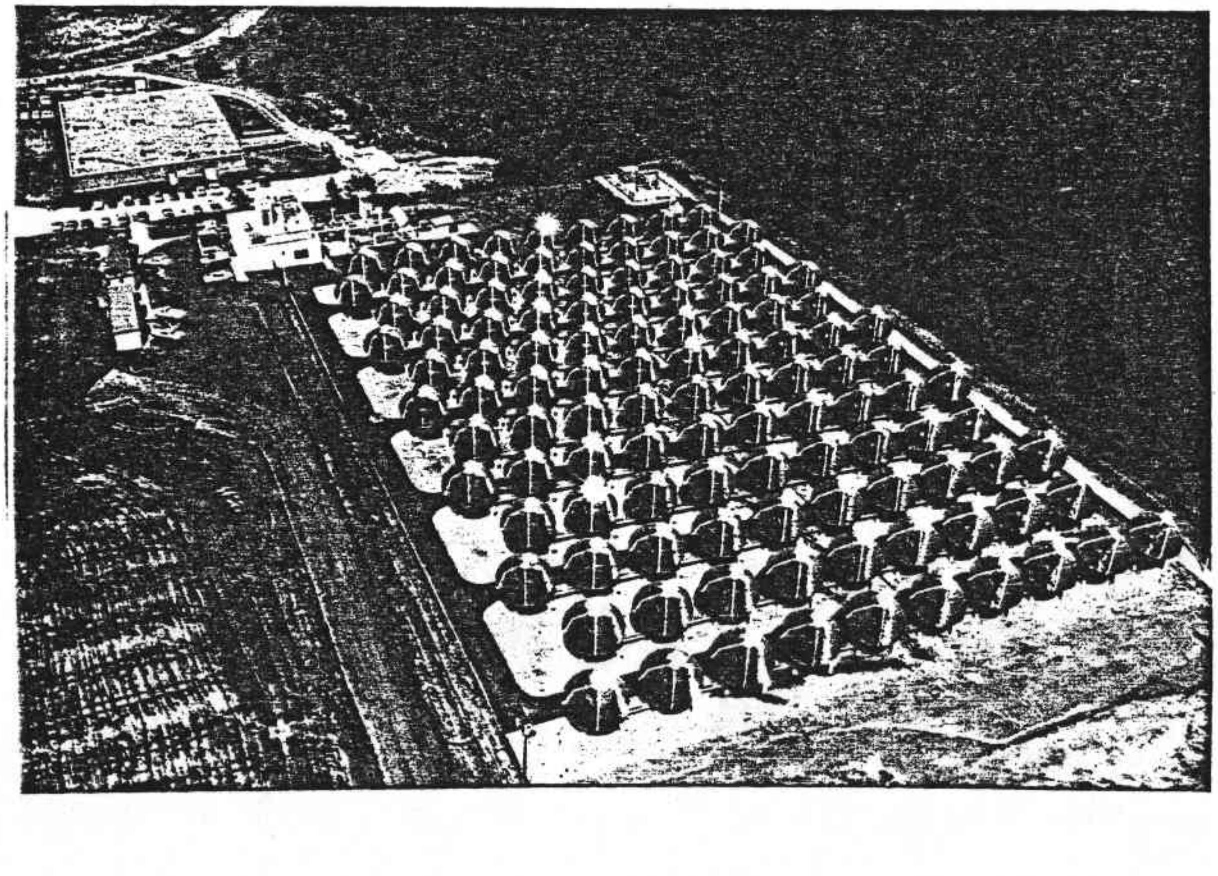


Figure 35. Solar Total Energy Project at Shenandoah, Georgia

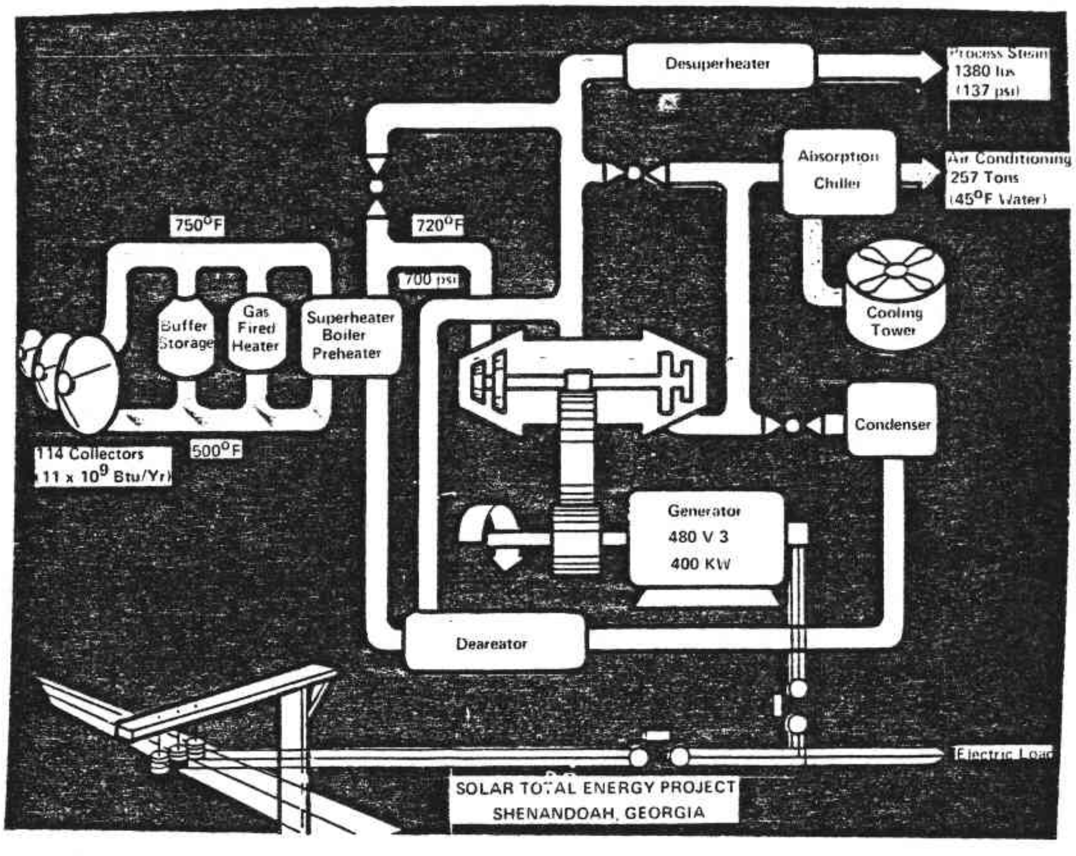


Figure 36. Schematic diagram of the Solar Total Energy Project

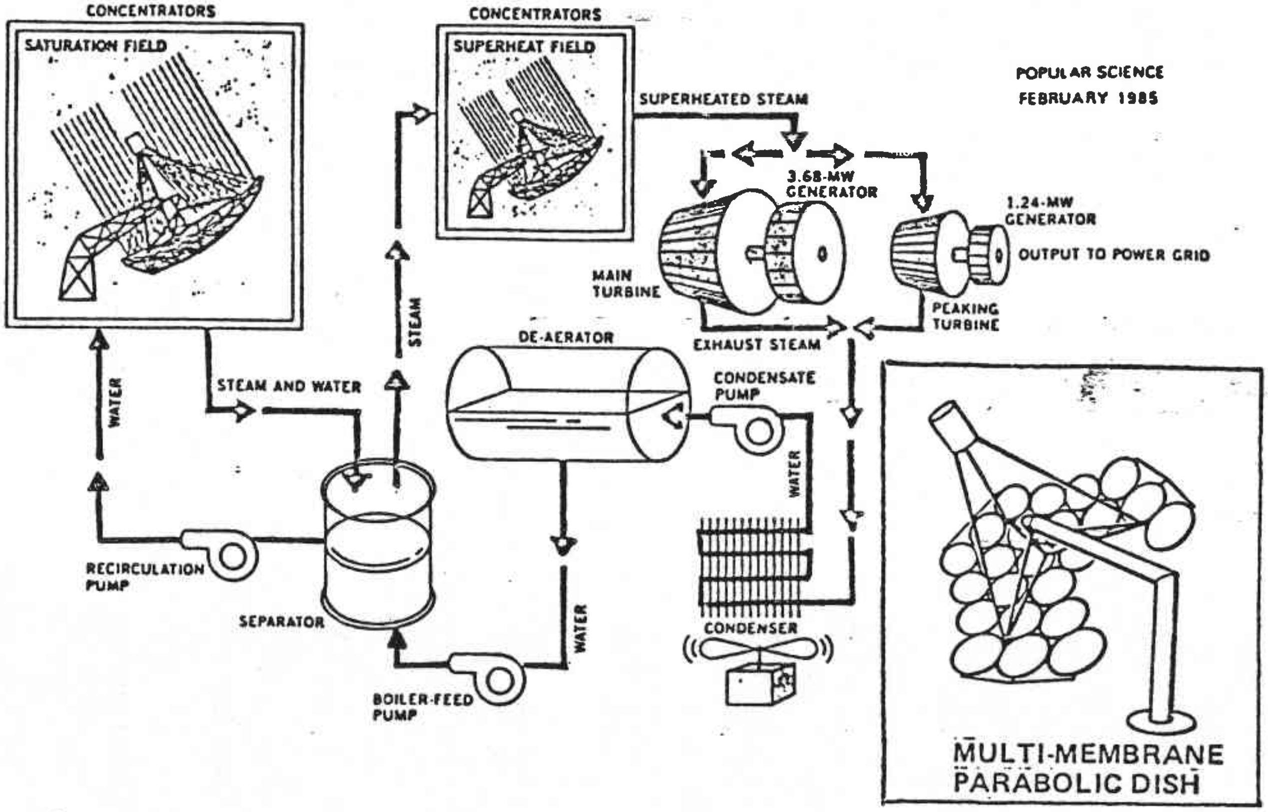


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Figure 37. Flow chart for Solar Plant One

Two experiments using receiver/heat engine modules are in the initial to mid- phases of completion. Called the Small Community Solar Experiments, they are small solar electrical power systems that supply electricity at sites not adequately serviced by the utility grid.

The first of these will be at Osage City, Kansas, where a field of four, square, 1722 ft^2 (160 m^2) movable-slat, point-focus concentrators, each with a receiver incorporating the organic Rankine cycle (discussed above), will provide a maximum of 100 kWe (Figure 38). The receiver has an aperture diameter of 15 in. (0.38 m) and operates at 750°F (400°C). The system is expected to have an overall solar-to-electric conversion efficiency of 16%.

The second experiment at Molokai, Hawaii, will provide 250 KWe. Here again, movable-slat point-focus concentrators will be used. Five 3,230 ft^2 (300 m^2) concentrators are proposed for this project, with thermal receivers that will supply steam to five 50-kWe reciprocating steam engine/generator sets located on the ground adjacent to each concentrator. These concentrators will be almost twice the size and have a different tracking design than those to be used for the Osage City Experiment.

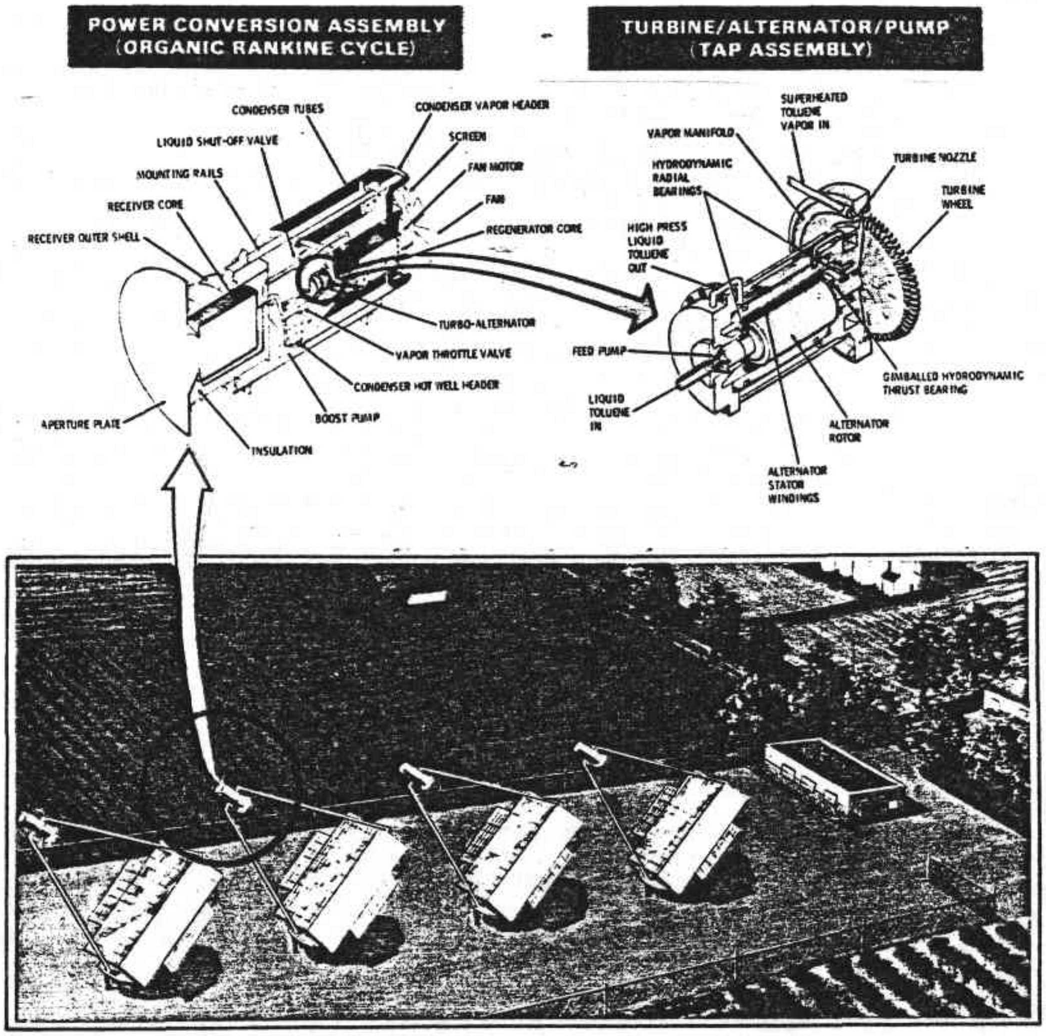


Figure 38. Concentrators and power conversion modules for small community solar experiment at Osage City, Kansas

CHAPTER 4 - THE CENTRAL RECEIVER

The steam Rankine cycle uses traditional electrical power generation technology. Steam is normally produced in a steam generator and expanded through a turbine driving an electrical generator. After leaving the turbine, heat is removed from the now low pressure steam by a condenser (cooled by a cooling tower or other means) and the condensed water is recirculated to the steam generator.

Heliostat Field Design

The segmented optics of a central receiver are similar to the parabolic optics of the concentrators described above. Heliostats, the primary concentrator elements, are positioned on the ground around the base of the receiver tower. Each heliostat is individually aimed so that it reflects the sun's rays to a spot on the receiver. The heliostat surface points halfway between the sun and the receiver, since the incident angle equals the reflection angle.

Heliostats must not be located too close together. How tightly packed heliostats can be is defined not only by mechanical interference requirements but also by shadowing and blocking considerations. One heliostat can shadow the incoming rays to an adjacent heliostat and another can block the reflected rays from reaching the receiver (Figure 39).

To have enough aperture area for the required system energy output, heliostats are spread out from and around the receiver tower. Considerable thought has been directed toward the optimum heliostat field layout. The primary trade-offs are between raising the height of the receiver tower to 'flatten out' the heliostats, spacing heliostats farther apart or installing more heliostats because of their reduced active area. Each alternative raises the cost of the collection system.

As previously described, the two types of receivers for central receiver collectors are external and cavity receivers (Figure 40). While the external receiver can accept reflected sunlight from all directions including from heliostats to the south of the receiver (which typically have high cosine losses), cavity receivers only accept reflections from heliostats located within a narrow included angle to the front of the

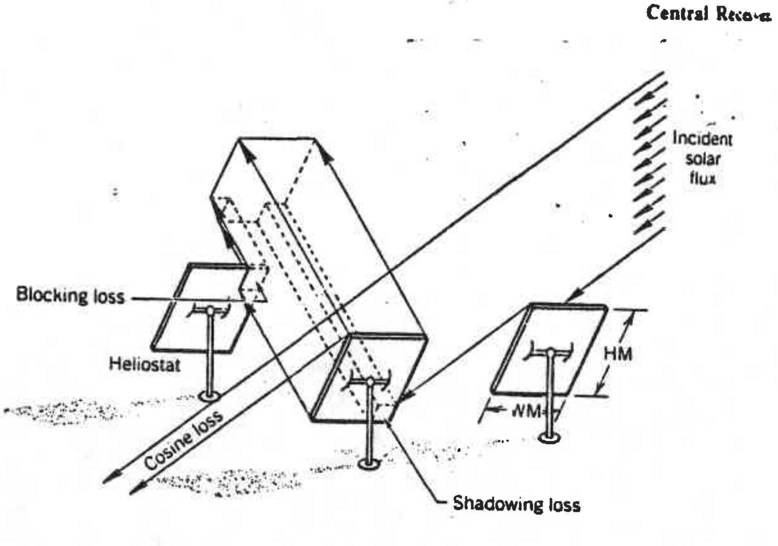
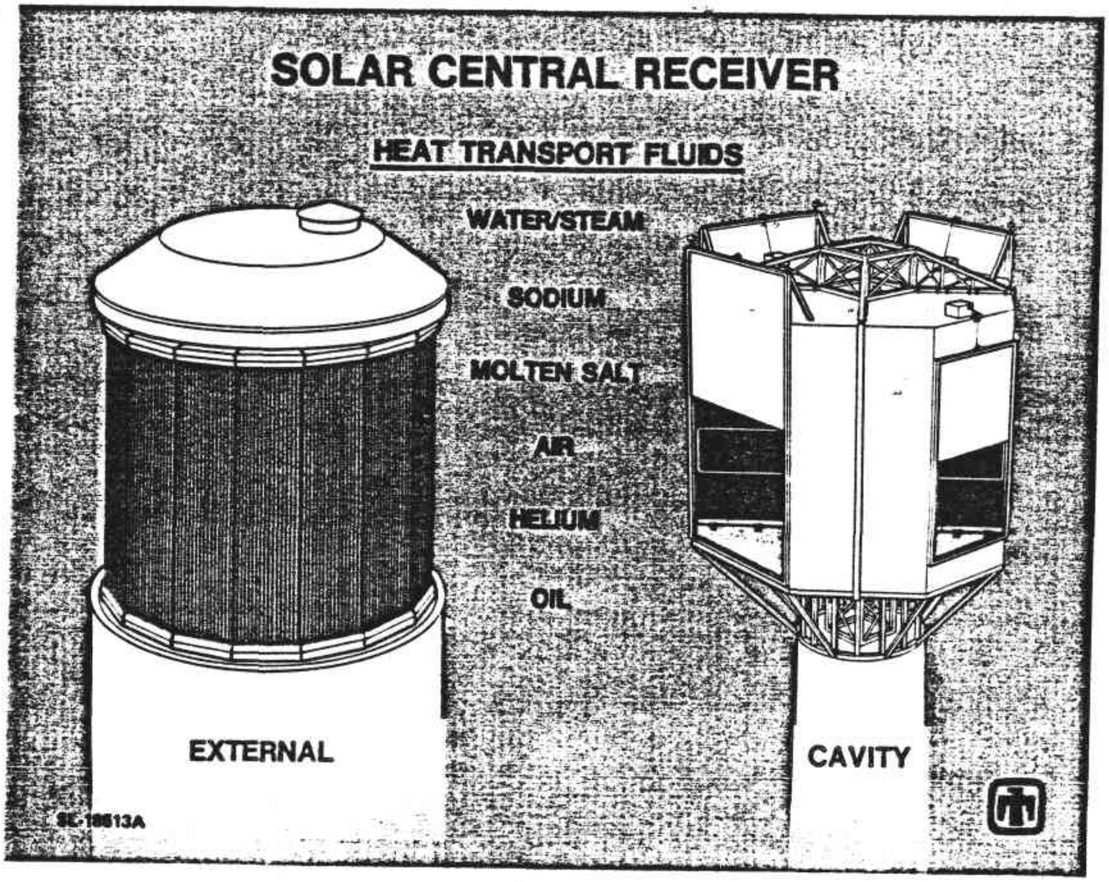


Figure 39. Shadowing and blocking loss of solar flux



SOLAR CENTRAL RECEIVER

HEAT TRANSPORT FLUIDS

WATER/STEAM
SODIUM
MOLTEN SALT
AIR
HELIUM
OIL

Figure 40. Two types of central receivers

receiver (Figure 41). A north pie-shaped field will have considerably less cosine loss than a surrounding field.

Heliostats

The heliostat is the fundamental concentrator unit of a central receiver system. It is also a major cost item in any central receiver design. The thrust of the Solar Thermal Program has been to increase the size and reduce the weight of these units while maintaining their performance. This does two things, it reduces the total number of heliostats in a given application and reduces the cost of each heliostat per unit area.

A typical heliostat consists of a reflective surface on a frame that is moved up and down (elevation) and around its base (azimuth) by small motors (Figure 42). The entire structure is mounted on a pedestal that is set firmly into the ground.

Technical Issues - The performance of a heliostat field encompasses many of the parameters defined in the fundamental solar collection equation. They are:

A_{app} - area of the concentrator aperture
$\cos \theta_i$ - cosine of the angle of incidence
ρ - concentrator surface reflectance
Φ - capture factor

For central receivers, the concentrator aperture area is generally taken as the heliostat surface area multiplied by the number of heliostats. This is appreciably less than the land area covered by the heliostat field. The energy output is proportional to the total reflective area of heliostats.

The effective surface area of a heliostat is reduced by the cosine effect (Figure 43). Because a heliostat is never aimed directly at the sun, the area on which the sunlight falls is reduced by the cosine of the angle between the heliostat pointing direction and the sun. This angle is different for each heliostat in the field and varies with time. The term $\cos \theta_i$ in the fundamental solar collection equation reflects the average cosine 'loss' in system performance.

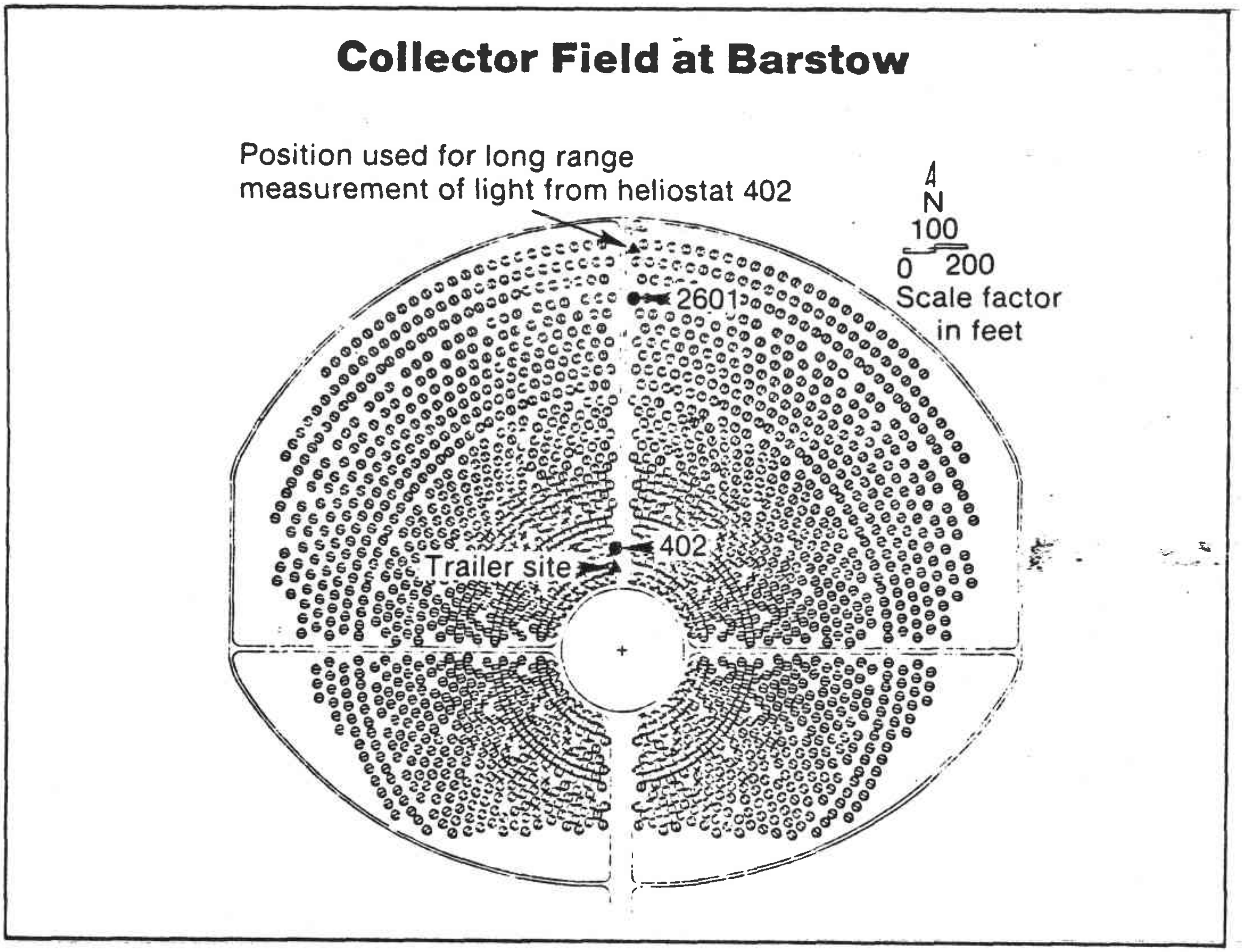


Figure 41. Heliostat field lay-out

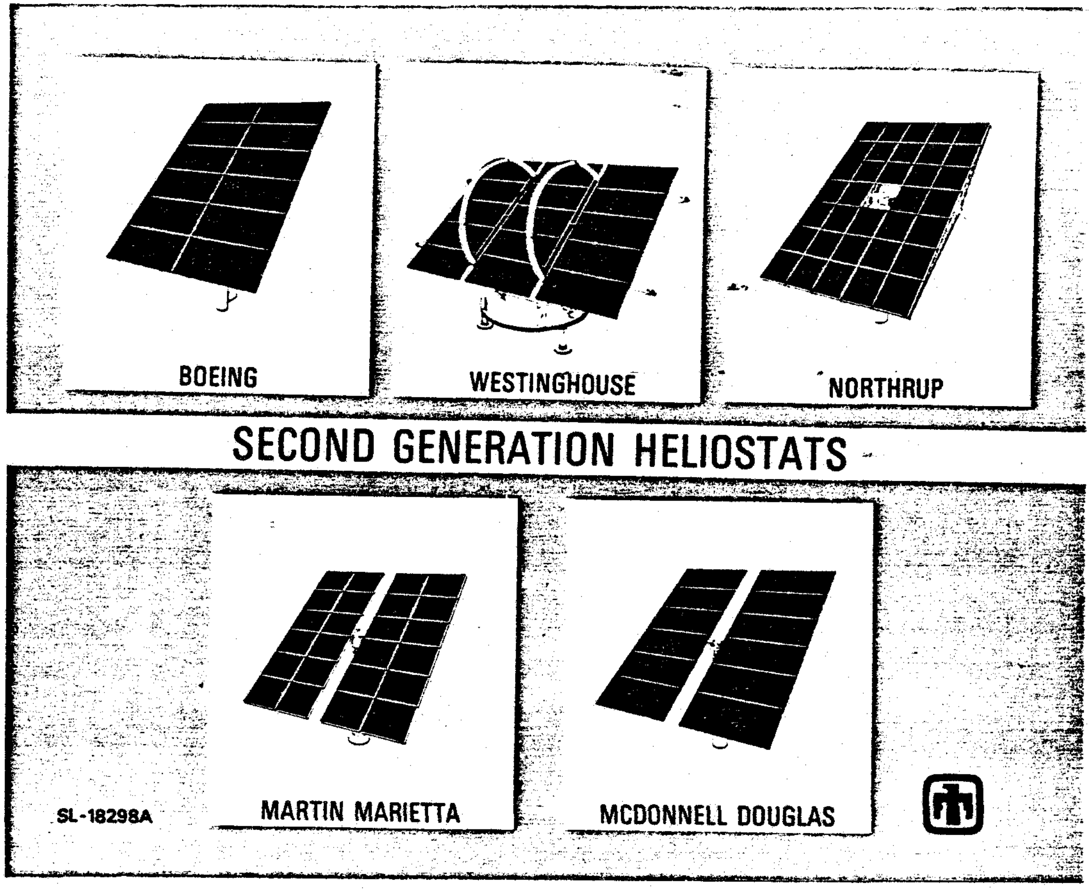
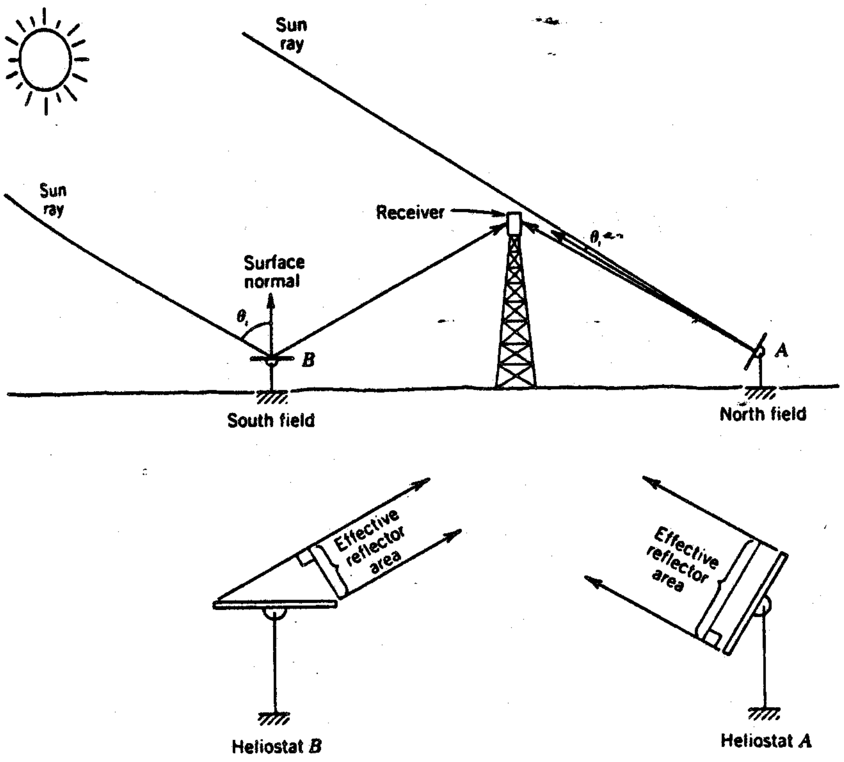


Figure 42. Typical heliostats



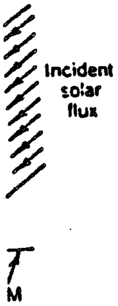


Figure 43. The cosine effect for two heliostats in opposite directions from the tower. For the noontime sun condition shown, heliostat A in the north field has a much greater cosine efficiency than does heliostat B.

Heliostat surfaces of high reflectance ρ are used, similar to any concentrating collector. Washing is necessary to remove dirt accumulations so this value is maximized.

A final factor in heliostat design is the capture factor Φ of the receiver. This parameter is a function of both the heliostat design and the receiver design. It is a goal of heliostat design to make the beam that reaches the receiver as small and accurately directed as possible to reduce spillage of light from the receiver. The amount of spillage is a function of the accuracy of the heliostat surface, its distance from the receiver, and the accuracy of the heliostat pointing system.

Heliostat Evolution - A major thrust in heliostat development is to increase the size and reduce the weight per unit of reflective surface area. Weight in general indicates the amount of materials used and therefore the cost. If the weight of the mirror panel can be reduced, the tracking drive can be made smaller along with all of the support structure required to hold the panel in position. Glass mirrors have typically been used as the reflective surface but to reduce the weight of the reflector panel, reflective plastic films are being developed to replace glass.

For the Solar One heliostat, back-surface glass mirrors are bonded to a substrate backing forming a slightly concave surface for the mirror module. These mirrors are then supported on a frame that is attached to a torque tube which attaches to the drive motors. In the most recent heliostat technology, an attempt is being made to integrate the reflective surface into the overall structure (Figure 44). This eliminates the supporting structure and torque tube and permits a lighter weight reflector.

Figure 45 shows the path of heliostat development from the first design used in Sandia National Lab's Central Receiver Test Facility (CRTF) to designs that are currently being fabricated and tested.

Stressed-membrane heliostats hold promise for providing units with large reflecting surfaces (Figure 46). Design studies have indicated that a 50%-75% reduction in weight and a 50% cut in cost is possible. Sheets of thin metal are mounted to a support ring and either pre-stressed or pulled backwards by a small vacuum to focus the drum-head reflective surface to a small region on the receiver. The membrane is made of thin aluminum or stainless steel, with a silver reflective surface.

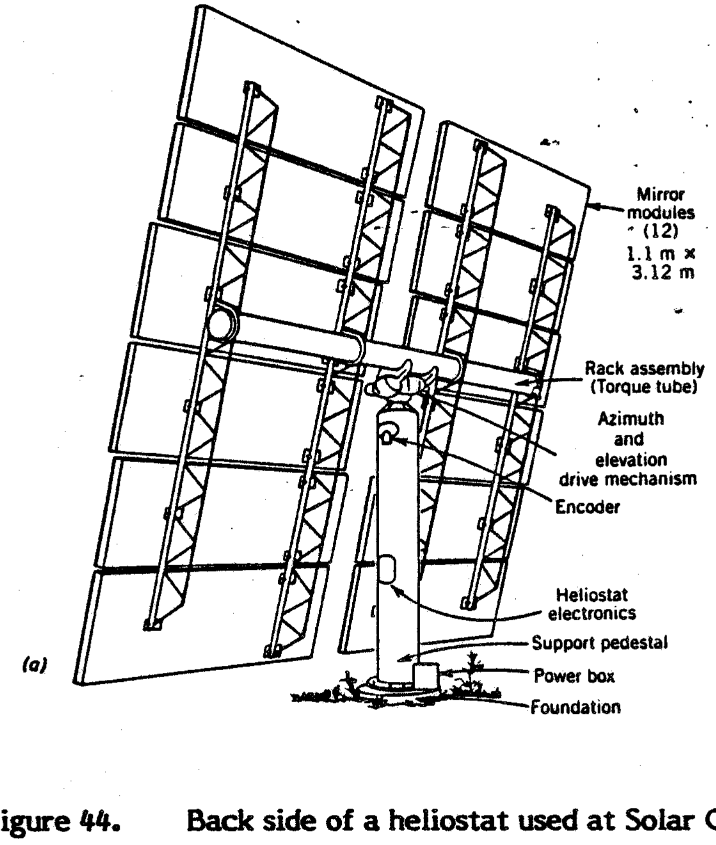


Figure 44. Back side of a heliostat used at Solar One

Concentrators

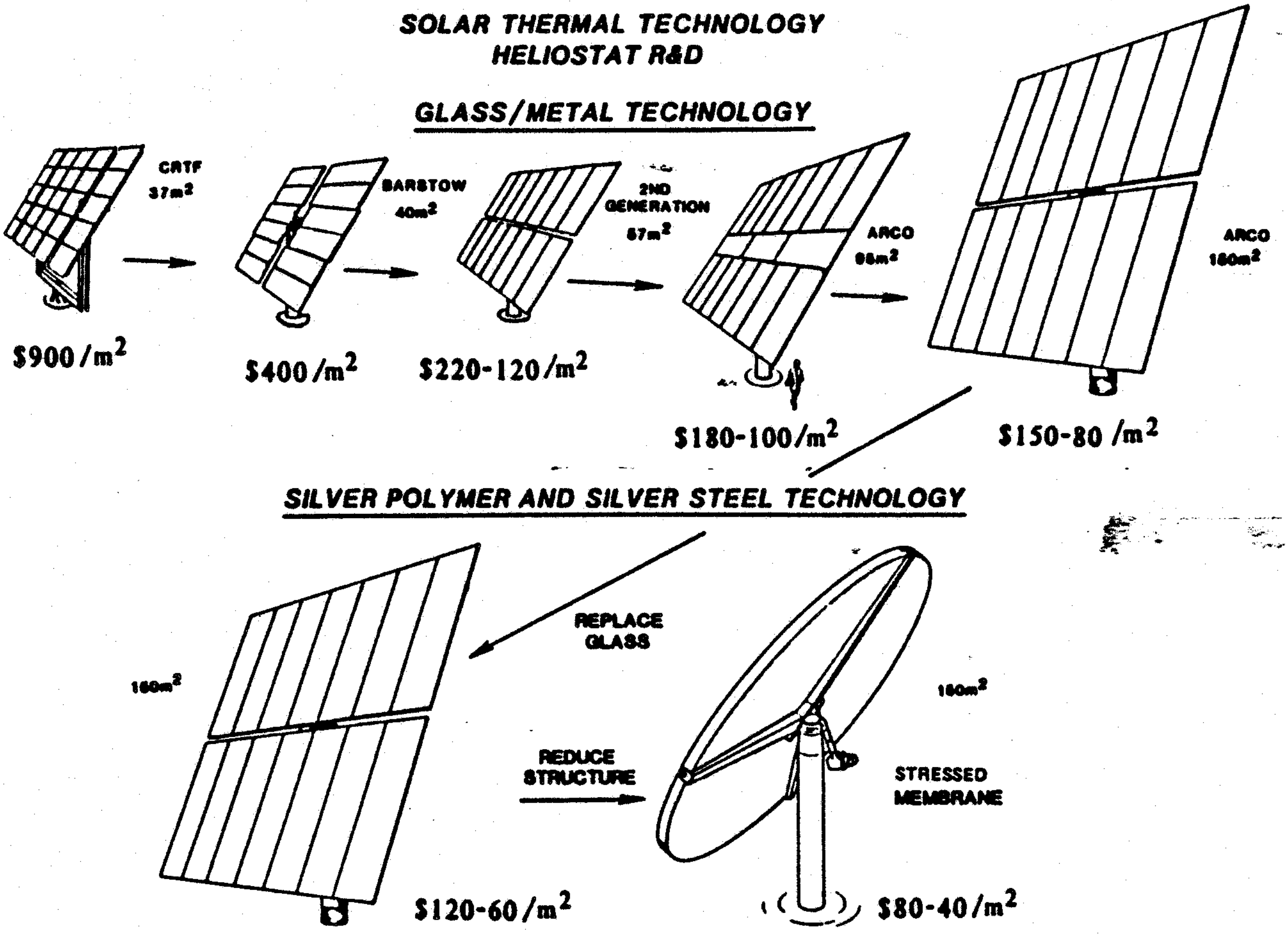


Figure 45. Development of heliostat technology

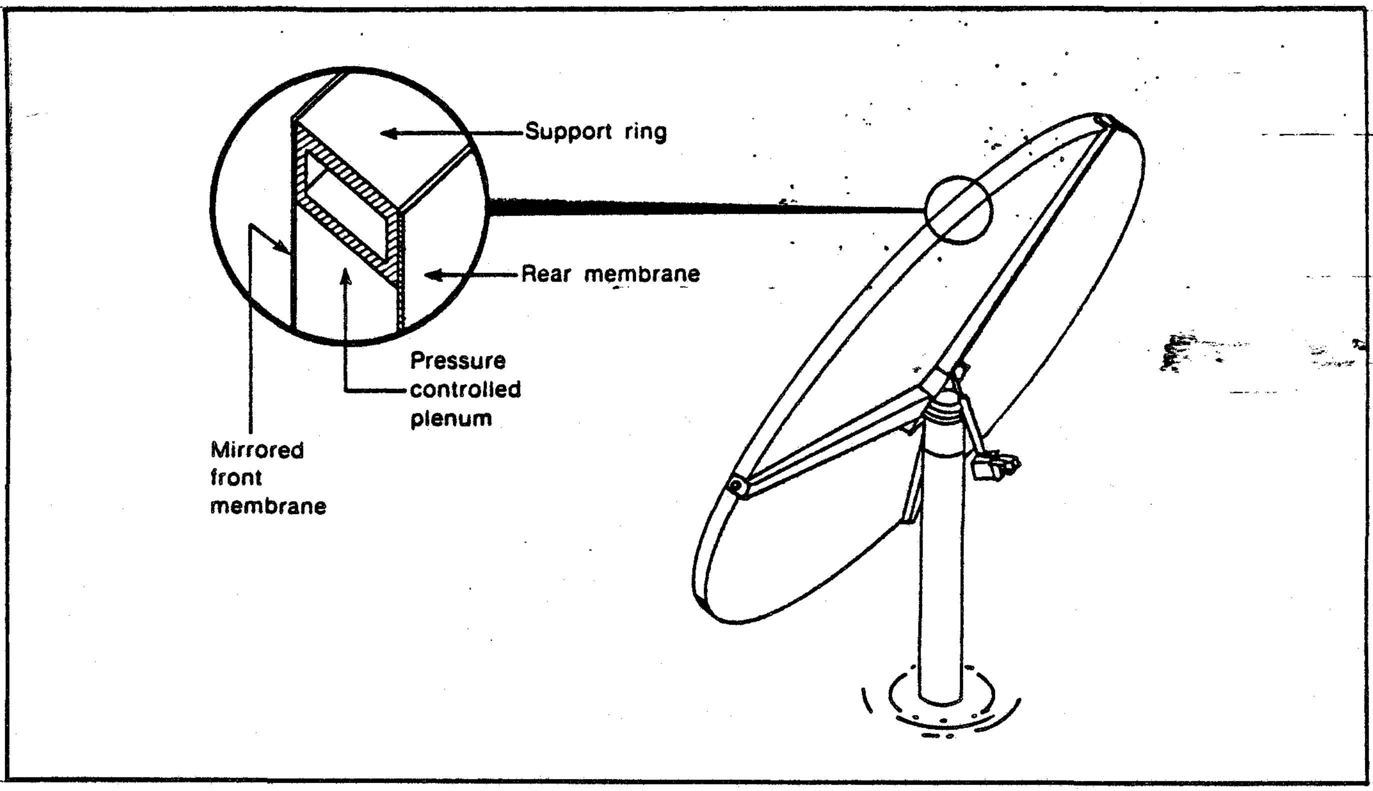


Figure 46. A stressed-membrane heliostat

Receivers

Although the heliostat field represents the greatest cost in central receiver applications, the receiver introduces the greatest technical challenge. The purpose of the receiver is to intercept and absorb concentrated solar radiation reflected from the heliostat field and to transfer most of it to the heat transport fluid.

Technical Issues - The performance of the entire system is directly affected by the performance of the receiver. The following parameters in the fundamental solar collection equation are part of the receiver design, and receiver technology development is directed toward optimizing them:

Φ - capture factor (affected by both heliostat field and receiver design)
A_{rec} - area of the receiver aperture or surface
F - equivalent conductance
T_{rec} - receiver operating temperature
U - overall convective heat loss coefficient

The power cycle performance is directly related to the temperature at which it can receive heat. It can be seen in the fundamental solar collection equation that raising the receiver operating temperature reduces solar collection efficiency. It is a goal of receiver technology development to design receivers that operate efficiently at high temperatures.

A large difference between receiver temperature and ambient temperature requires that the receiver aperture area A_{rec}, the overall convective heat transfer coefficient U, and the equivalent conductance F be small. This is done by making the receiver as small as possible, and in some designs, placing it inside an insulated cavity to reduce convective and radiation losses without having large spillage losses.

The capture factor Φ is affected by both the heliostat field and the receiver. Poor heliostats with large surface and tracking tolerances, placed far away from the receiver, will produce a large image of the sun at the receiver. In order to capture most of this energy, the receiver area must be large. However, large receivers have high thermal losses. There is always a major trade-off between the size of the receiver, thermal losses, and the quality of the heliostat field. The capture factor Φ, an indicator of the amount of spillage, is probably the most illusive parameter in central receiver design because it governs the interaction between receiver and heliostat field design. One other optical parameter affecting the design of a receiver is the receiver absorptance α.

The overall convective heat loss coefficient U is a combination of conductive and convective heat losses (Figure 47). Both losses increase with temperature difference. Convective loss may be reduced by using a cavity design rather than an external design. This also reduces the radiative loss by making the effective radiator area smaller. Conduction loss is a function of how large the heated area is, and the amount of insulation between these surfaces and the outside air.

Receiver Evolution - Experimental receivers have been designed, built, and tested using water/steam, molten salt, liquid sodium, and air as the heat-transfer fluids. Most of these receivers operate at temperatures less than 1100°F (600°C) with efficiencies between 75% and 90%. This temperature is not an inherent limit of the central receiver but an industry standard for power generation using steam.

Receiver research and development activities have been focused on finding the best cost/performance receivers for 1100°F (600°C) systems that produce electricity through coupling with Rankine-cycle steam turbines or intermediate temperature industrial process heat generation.

The Solar One receiver is an external receiver located at the top of a tower (Figure 48). The top of the receiver is about 300 ft (90 m) above the ground. The absorbing surface is 45 ft (13.7 m) high and 23 ft (7 m) in diameter. This surface is made up of 1,680 - 0.5 in. (12.7 mm) diameter heavy-walled Inconel-800 tubes. The tubes are welded into 24 panels of 70 tubes each and coated with a black paint to enhance their absorptance. The six south-facing panels serve as preheat panels and are connected in series with the remaining 18 panels. Water is pumped vertically through these latter panels, with boiling taking place approximately halfway up the tubes. The steam is superheated to 960°F (516°C) during the remainder of its passage to the top of the receiver.

In 1980, a 5-MWt molten salt receiver was built and tested at the Central Receiver Test Facility in Albuquerque (Figure 49). The receiver heats a salt mixture entering at 550°F (288°C) up to 1050°F (566°C). The mixture of 60% $NaNO_3$ and 40% KNO_3 by weight, is forced through 18 serpentine passes of tubes that have an overall active area of 13 by

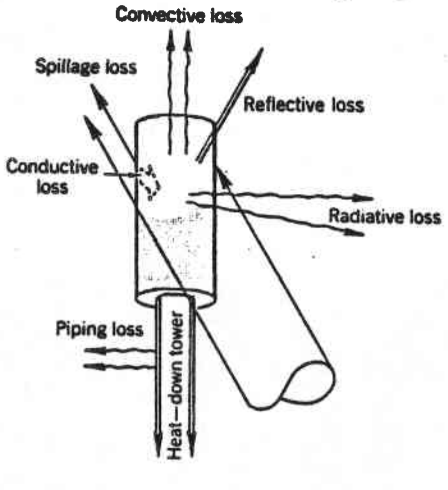


Figure 47. Receiver heat-loss modes

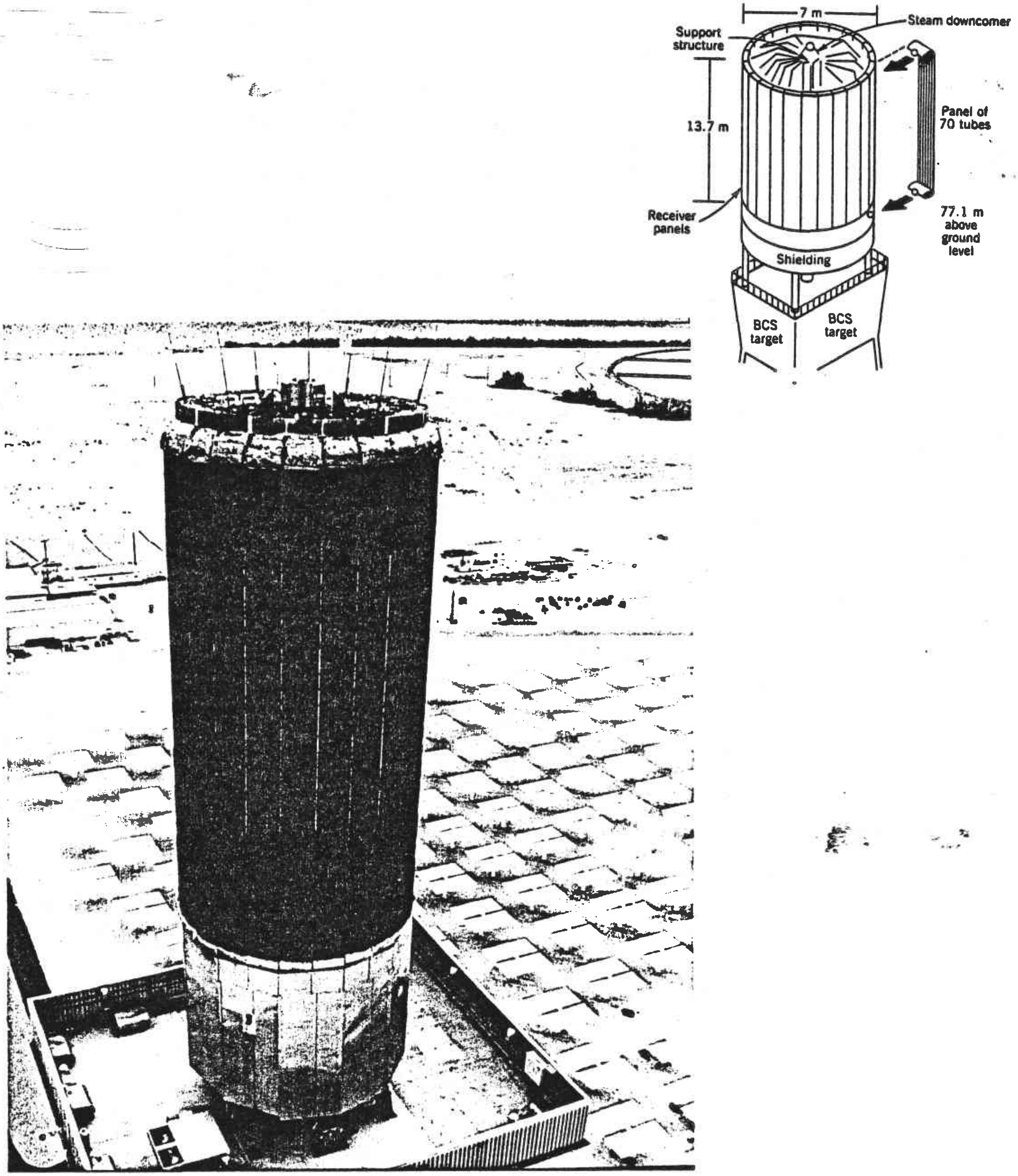


Figure 48. The Solar One external receiver

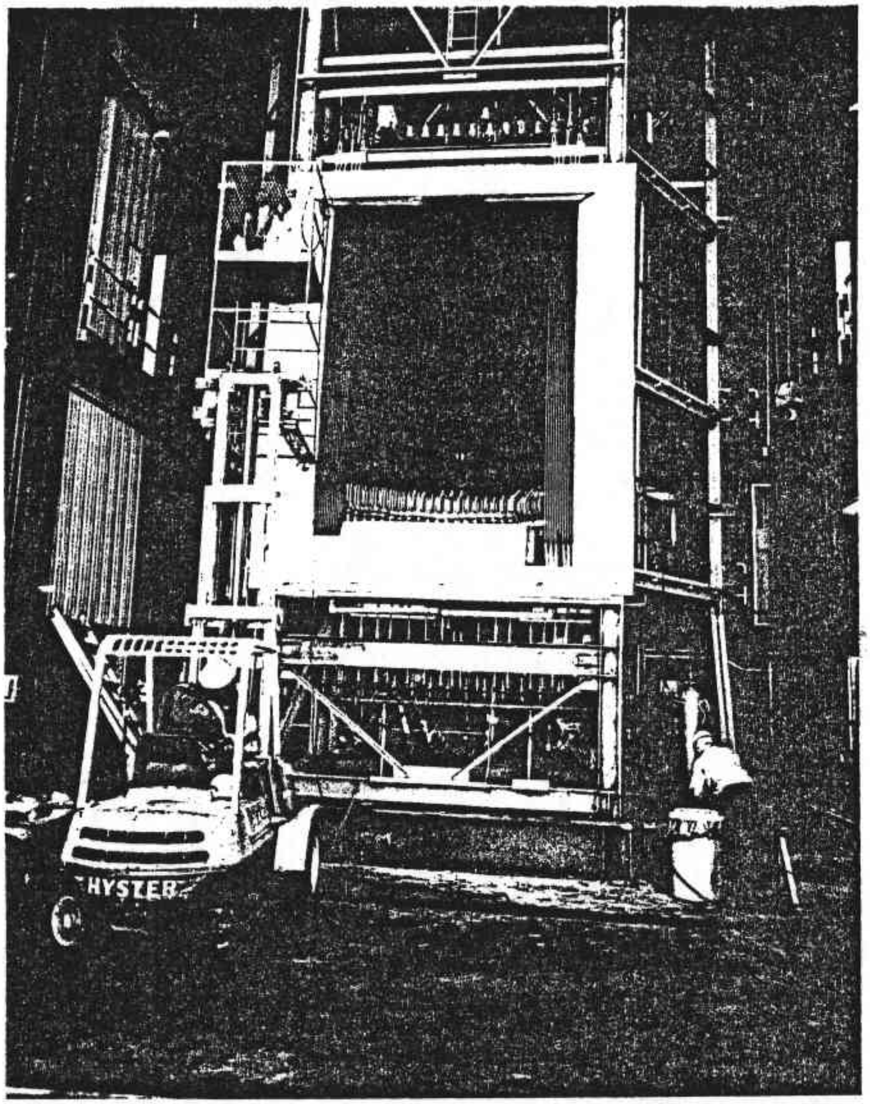


Figure 49. The 5 MWt molten salt cavity receiver (shown with insulating doors partially closed)

18 ft (4 by 5.5 m). Over 500 hours of testing were completed, resulting in a sunlight-to-thermal efficiency of the receiver of 85%.

Molten salts have the advantage that they remain liquid at the operating temperature (1050°F or 566°C) with a low vapor pressure. This means that receivers can have a small surface area since the heat transfer from absorber surface to salt is high. Also, the molten salt can be stored directly in insulated tanks that do not have to withstand high pressures. Although expensive relative to water, molten salt mixtures are less expensive than other alternatives such as liquid sodium discussed below. Disadvantages include the need for a heat exchange loop with steam for the power cycle, and problems associated with the mixture freezing at temperatures above ambient.

A sodium-cooled experimental receiver has also been tested at the Central Receiver Test Facility in Albuquerque. The objectives of the test included providing a proof-of-principle test of sodium-cooled receiver panels, gaining practical fabrication and operating experience, and establishing the capability to build commercial panels. The receiver consists of three 21-tube panels made of 0.5 in. (12 mm) outer diameter 316-stainless steel tubing. The panels operate in parallel and each panel has an independent control valve. The receiver has been operated in a solar flux density greater than 1.5 MW/m^2 at an outlet temperature of 1100°F (593°C).

Sodium has the advantage of providing an extremely high heat transfer rate away from the absorbing surface. This permits high heat flux rates on the receiver, which enables it to be sized smaller, reducing heat loss. As with molten salts, sodium is an excellent thermal energy storage medium and has a low vapor pressure. However, it is more expensive than salt and is hazardous when it comes in contact with water or air.

A liquid sodium receiver is currently in operation at the International Energy Agency project in Almeria, Spain. This receiver has an aperture area of 105 m^2 (9.7 m^2) and operates at a temperature of 986°F (530°C) and approximately 45 psi (4 bar).

System Experience

Solar One - Solar One is the first large-scale application of the central receiver concept for electrical power generation. Located just outside Barstow, California, in the Mojave Desert, the plant produces a peak output of 10 MWe of electricity for the central power grid.

The plant has been in operation since 1984, the first year as a test bed and subsequent years as a commercial Southern California Edison power station (Figure 50). As of December 1985, the plant has recorded the following milestones:

Maximum instantaneous power output:	10.8 MW_e
Maximum energy generated in a day:	82.6 MWh_e
Maximum energy generated in a week:	456 MWh_e
Maximum energy generated in a month:	1,756 MWh_e
Maximum energy generated in a year:	8,803 MWh_e

These statistics indicate that Solar One performs according to its design specifications and operates reliably.

A surround field of 1818 individually tracked heliostats has a total reflective aperture area of 765,700 ft^2 (71,130 m^2). The field is asymmetrical with 1240 heliostats located north of the tower and 578 located south of the tower where cosine losses are greater.

A single heliostat has a reflective surface area of 421 ft^2 (39.1 m^2) consisting of 12 slightly concave panels. These panels consist of a back-surface glass mirror bonded to a honeycomb core that is bonded and sealed to a steel enclosure pan.

High pressure water is pumped into the bottom of the receiver, vaporizes, and is superheated to 960°F (516°C) as it passes up the individual tubes. The steam is piped down the tower and to a conventional steam Rankine cycle power plant that operates at a cycle efficiency of 35%.

A mixed-media thermal energy storage is incorporated into the system to extend its time of operation by approximately 4 hours at reduced power levels (Figure 51). The 118,800 ft^3 (3,360 m^3) storage tank is filled with approximately 1 in. (25 mm) granite rock with the spaces between filled with sand. The tank is then filled with a petroleum-based heat transfer oil that is pumped in and out, exchanging heat with the steam from the receiver, or producing steam to operate the power cycle. Because of temperature limitations of the heat transfer oil and the temperature drop caused by transferring heat to and from the oil, the steam produced from stored heat is only at 525°F (274°C), resulting in lower cycle efficiency and therefore less power output.

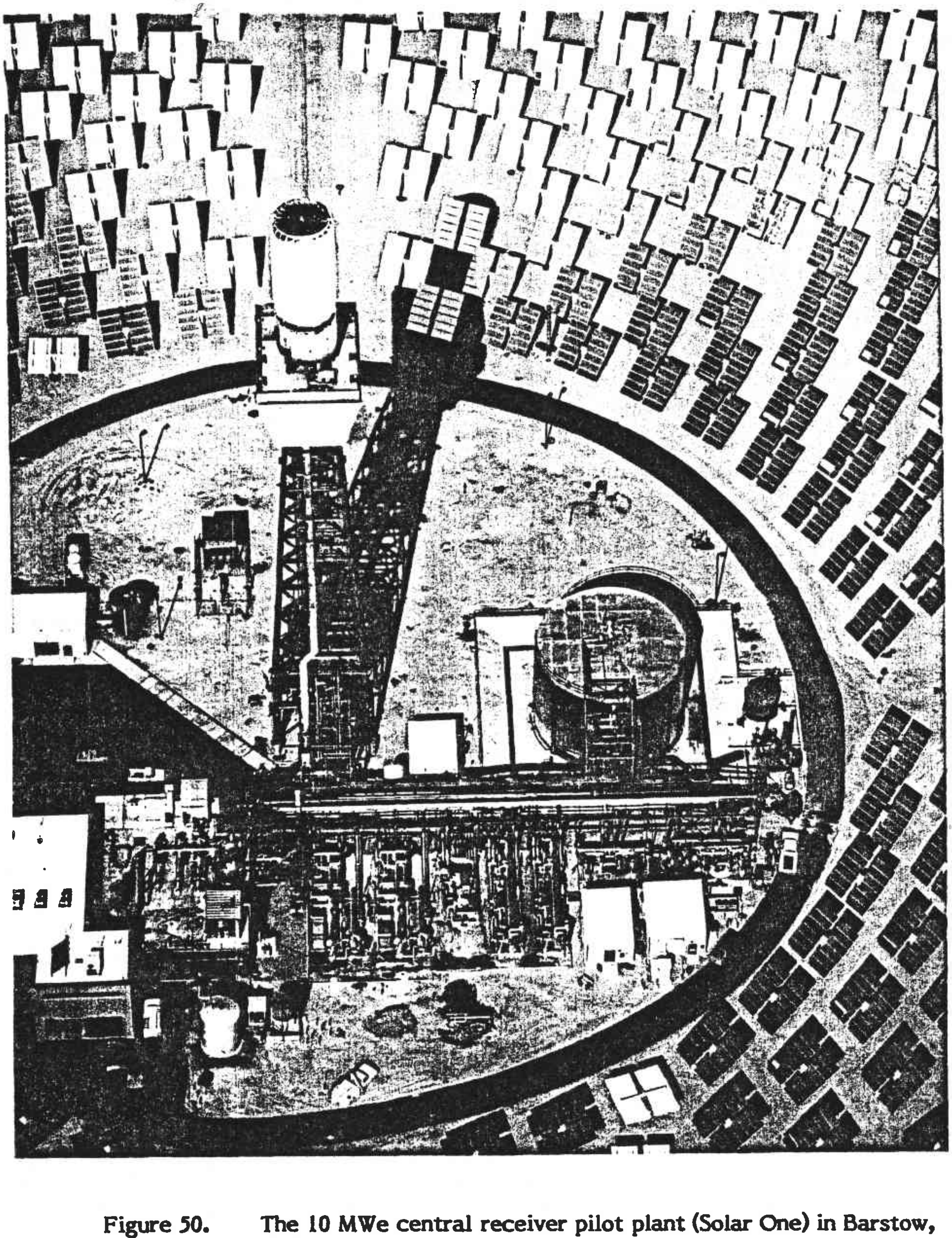


Figure 50. The 10 MWe central receiver pilot plant (Solar One) in Barstow, California

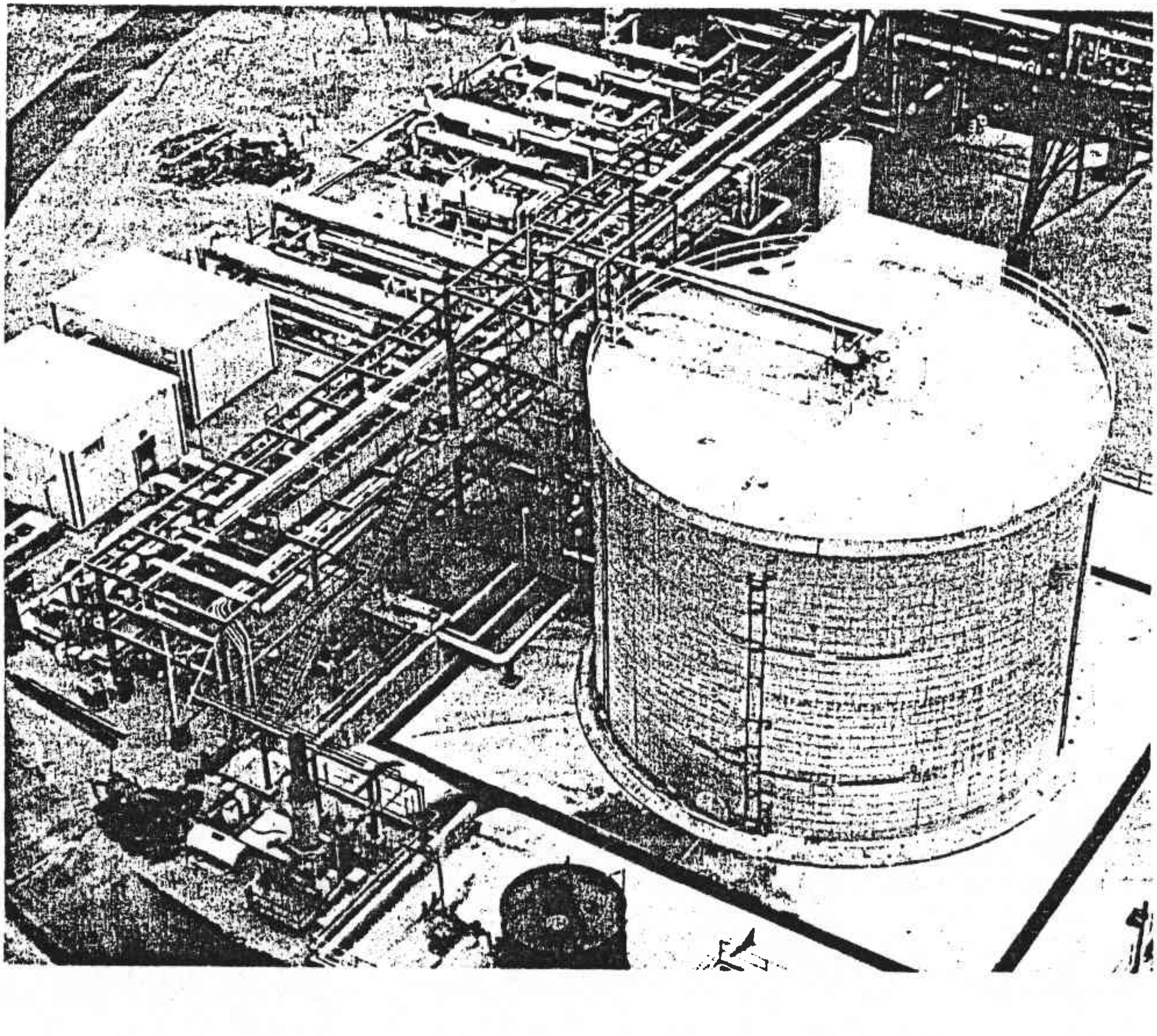


Figure 51. Solar One's mixed-media thermal storage unit

IEA SSPS Project in Almeria, Spain - Two central receiver systems are in operation at the International Energy Agency (IEA) Small Solar Power Systems (SSPS) project test site in Almeria, Spain. This project, funded by many nations, has the goal of testing solar thermal technologies to determine their applicability for commercial power generation. Two central receiver systems are currently being tested in addition to other solar technologies.

One system, the CSEA-1 project, uses 300-423 ft^2 (40 m^2) heliostats to boil water in the receiver 197 ft (60 m) above ground level. Steam is produced at 980°F (525°C). The maximum electrical output of the system is 1 MW_e. Thermal energy is stored in a two-tank thermal storage system containing a molten salt mixture at 645°F (340°C).

The second central receiver system is an experimental liquid sodium system. Here 93-423 ft^2 (40 m^2) heliostats concentrate sunlight on a liquid sodium receiver 141 ft (43 m) above the ground. Liquid sodium is heated to 986°F at 45 psi (530°C at 4 bar). Enough hot sodium for two hours of full power operation is stored at the collection temperature in a two-tank storage. A second loop producing steam at (500°C, 100 bar) operates a commercial steam turbine to produce a maximum net electrical output of 500 kW.

CHAPTER 5 - COMMON SYSTEM TECHNOLOGIES

Although parabolic troughs, dishes, and central receivers differ in design and application, five areas of common technology development are discussed in this chapter: reflective surfaces, heat transfer fluids, thermal storage, energy transport, and system economics.

Reflective Surfaces

Most concentrators used for solar thermal systems depend on a reflective surface to concentrate the sun's rays to a smaller area. The fundamental solar collection equation shows that the performance of a concentrating collector is directly proportional to the reflectance ρ of the mirrored surface.

$$Q_{useful} = I_{b,n} A_{app} \cos \theta_i \ (\rho \Phi \tau \alpha) - A_{rec}[U(T_{rec} - T_{amb}) + \sigma F(T_{rec}^4 - T_{amb}^4)]$$

It was also shown that the factor Φ is affected by the microscopic quality of the reflective surface finish because surface specularity is one cause of the spreading of beams being reflected from a concentrator.

Technical Issues - Mirrors used in solar concentrators are either polished metal surfaces or back-surface (second-surface) mirrors. Aluminum is the only example of the first type because a thin transparent oxide forms on the surface, giving it good weatherability characteristics. Back-surface mirrors are made by applying a reflective surface to the back of a protective sheet of glass or plastic. The protective sheet must transmit a large percentage of the light that passes through it because a reflected beam must pass through it twice, once to reach the reflective surface and once more to leave.

Most reflective surfaces used in solar thermal collectors are metals. Under laboratory conditions, polished silver has the highest reflectance for solar energy of any metal surface. Aluminum reflects all the solar spectrum but does not have the same high level of reflectance. Although common in the automotive industry, chromium plating has a relatively low reflectance and is not suitable for solar concentrators.

In addition to increasing the reflectance of the surface, some of the technical issues driving the development of reflective surface technology are related to the design of the concentrator. Since large areas must be covered by reflective material, the cost of the reflective material must be low to keep the cost of the concentrator down. If a lightweight reflective material is used, the cost of the reflective surface support structure can be less.

The concentrator designer has two choices when making the curved reflective surfaces. One is to use flat reflective sheets such as silvered glass mirror sheet, and bend and adhere them onto a curved sub-surface or frame. The second is to fabricate the curved surface out of metal or plastic, and then apply thin sheets of reflective film onto this surface.

Because concentrating collectors require a curved reflective surface, the reflective surface must be bent without inducing high residual stresses. Parabolic trough reflective surfaces are simple curves so that flat sheets need only be bent in one dimension. Parabolic dish surfaces are compound curves and reflective surfaces must be bent about two axes (compound curvature). Heliostats have been made of a number of slightly canted mirror segments, each segment being pulled into a compound curve having a very long radius of curvature.

Two other technical issues in the development of reflective surfaces relate to the service life of the surface. Because solar collectors are outside for tens of years and are expected to perform without significant degradation, reflective surfaces must meet very severe weatherability criteria. Problems with ultraviolet radiation degradation, moisture, sandstorm, and hail damage are important.

Evolution - The first reflective surface that found widespread use in solar thermal concentrators was thin, polished aluminum sheets. These sheets are available in large sizes, relatively inexpensive and capable of withstanding some adverse climatic environmental conditions. The major disadvantage is its low specular (nonscattering) reflectance, which is about 70%.

Back-surface silvered glass mirrors with protective copper plate and paint on the outside of the thin silver coating have been used in bathrooms and other common applications for many years. However, the glass from which these mirrors are made is thick, making it difficult to bend, and of low transmittance because of the iron in the glass. The resulting mirror does not make use of the almost 98% reflectance of the silver plating because the light has to pass twice through thick, low transmittance glass.

In an attempt to maintain the high weatherability characteristics of the glass back-surface mirror but increase its applicability to solar applications, thin-glass mirrors have been developed. The glasses used for this application are usually iron-free so that they do not absorb strongly in the solar spectrum.

Problems with back-surface mirrors currently being studied include the relief of residual stresses after the mirror has been bent, and corrosion of the silver coating due to imperfections in the edge seal and back protective coating. In addition, the mirrors are brittle, heavy, and expensive.

Aluminized plastic films have been developed for solar applications. Different types of plastic films with aluminum sputtered onto the back surface have been used for many years for solar concentrator reflective surfaces. Although plastics degrade after long exposures to the ultraviolet radiation of the sun, stabilizers have been added to the plastics to effectively slow the degradation.

Recently, a silvered plastic film having a high reflectance has been introduced and promises to be the reflective surface of choice for many new designs. The silvered plastic offers the same high reflectance as silvered glass mirrors (greater than 90%), yet add only a fraction of the cost. In addition, it is much lighter and not brittle as is glass. This allows additional cost savings in the concentrator support structure. However, a major drawback of metalized plastic films is that they can not be mechanically washed like glass. Soil resistant, hard coatings are being developed, and less abrasive washing techniques are being studied. High-pressure sprays are one example.

Heat Transfer Fluids

In concentrating solar collectors, an intense beam of concentrated solar energy is absorbed on a metal or ceramic surface. The heat transfer fluid carries this heat away from this surface as fast as possible (so that it will not melt or crack) and transports it to where the energy is used.

Technical Issues - The heat flux into the receiver and the flow rate at which this fluid is pumped through the receiver passages defines the temperature at which it leaves the receiver; a higher flow rate reduces the fluid outlet temperature and a slower flow increases this temperature for a given heat flux.

A most important consideration in the selection of the heat transfer fluid is the temperature/pressure relationship required for it to remain a liquid. For example, water must be pressurized at least to 1,000 psia (6.9 MPa) to remain a liquid at 550°F (288°C) and to 3,000 psi (20.7 MPa) to remain a liquid at 700°F (371°C). If the heat transfer fluid must be maintained at a high pressure, the receiver and all connecting piping must be thick-walled. In addition to increasing the cost of the receiver, the heat transfer across thick walls is poor and more energy is needed to restart in the morning (most of which is lost overnight) because of the excessive heat capacity of the entire system (Figure 52).

Just as there are system performance and cost savings when the same fluid is used for heat transfer and the power cycle, similar savings can be realized if the heat transfer fluid is also the thermal energy storage fluid. For a heat transfer fluid to make a good storage fluid, it must be inexpensive and have a large capacity to hold heat.

Petroleum-based and silicone-based heat transfer oils are used in many solar thermal applications. The major incentive to use these is their low vapor pressure at high temperatures. Many do not reach the 15 psi (103 kPa) pressure vessel limit until their temperature is 600°F (315°C) or more. The maximum temperature at which these oils can be operated ranges between 650° and 750°F (345° and 400°C) depending on the particular oil. Above this limit, the oils will break down and choke or plug the receiver tubing.

For high-temperature solar thermal applications, new heat transfer fluid technology is being developed. Two candidate heat transfer fluids are molten salts and liquid metals. With these fluids, operating temperatures of over 700°F (370°C) can be attained with small, thin-walled receiver absorber surfaces.

Molten salts are currently being evaluated as a heat transfer fluid in a solar thermal test loop at the Central Receiver Test Facility in Albuquerque, New Mexico. Mixtures of 60% $NaNO_3$ and 40% KNO_3 by weight are being considered for applications at 1050°F (565°C) and above. Even at this high temperature the pressure of the salt mixture is low. Because of this low pressure, the heated salt can be used as a storage media.

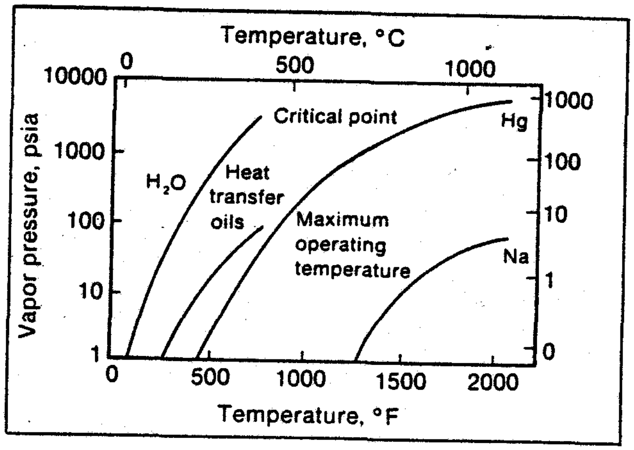


Figure 52. Vapor pressure of heat transfer fluids (note logarithmetric pressure scale)

A disadvantage of molten salt mixtures is that they freeze when well above ambient temperature. To compensate for this, piping and components must be either highly insulated or heat traced with electrical heating elements so that the system does not freeze during overnight or extended period shutdown.

Low melting point liquid metals have low vapor pressures at high temperatures as do molten salts. Currently, liquid sodium is being evaluated as a heat transfer fluid for central receiver systems and parabolic dish applications. Freezing of sodium upon shutdown is a problem.

A central receiver system utilizing liquid sodium is operating at the International Energy Agency project in Almeria, Spain. Operating temperature for this application is 1040°F (560°C).

Parabolic dish applications have been proposed that use sodium heat pipes in conjunction with Stirling engines. Liquid sodium is boiled in the back wall of a cavity receiver and the vapor is condensed on the outside surface of the engine's heater tubes. This application is designed to provide high heat transfer rates at a temperature of 1470°F (800°C) (Figure 53).

Thermal Storage

The simplicity of storing thermal energy makes solar thermal technologies more capable than other alternative energy technologies of meeting the demands of industry and electrical power production. Extra thermal energy, collected while the sun shines, can be used during cloudy periods and at night.

The role that thermal storage plays in a solar thermal system is defined by the size of the storage. Small amounts of storage to smooth out control of a solar thermal system is called buffer storage and keeps the system operating for tens of minutes during times when clouds temporarily obscure the sun. Somewhat larger storage can be used to extend the period of system operation to meet the end of the demand schedule. An even larger size can provide overnight storage, which can be used for early morning start-up.

Technical Issues - Storage requires that extra collectors be installed in a solar thermal system so that excess energy is collected at peak insolation conditions. If collectors are

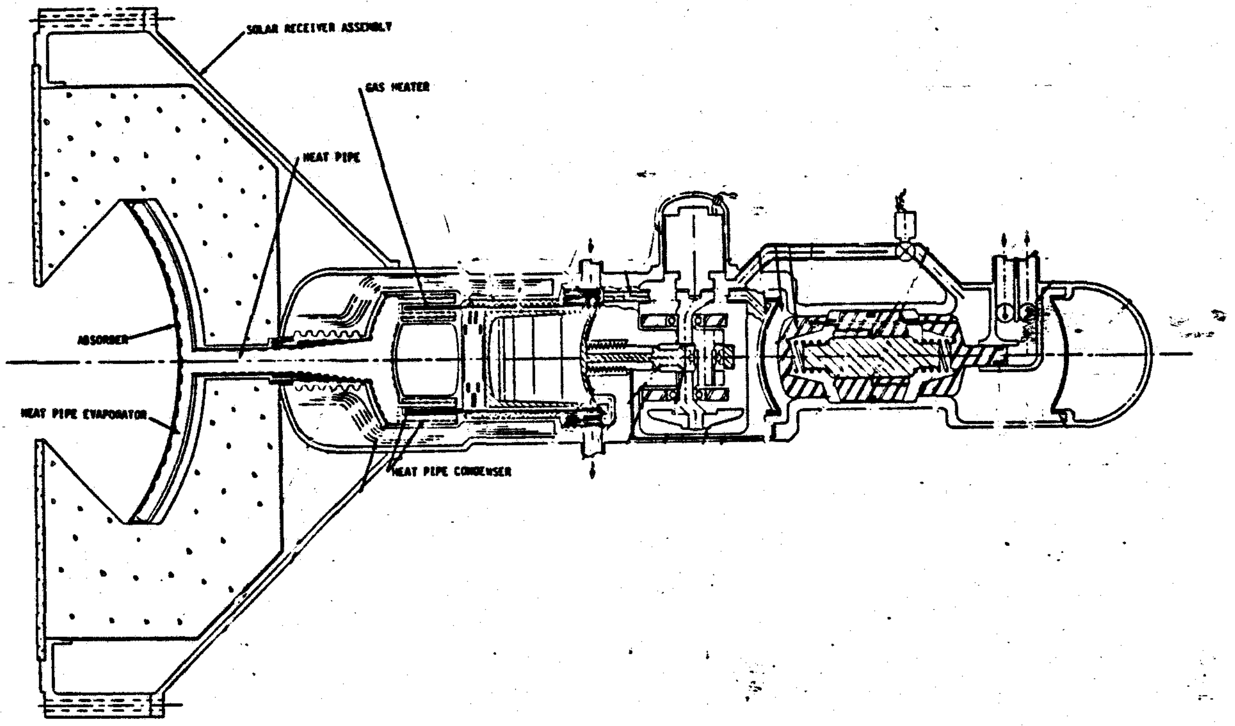


Figure 53. A sodium heat pipe receiver connected to a free piston Stirling engine

a major cost item in the system, the cost of storage must be very low to make the cost of electricity generated from the stored energy reasonable. Because the cost of the concentrator field is a major component of any solar thermal system, the most important technical issue in designing storage is its cost.

Stored energy is always more expensive than energy supplied directly from solar collectors because its cost must include both the cost of collecting the energy and of storing it. Although most solar thermal systems incorporate some thermal energy storage for control purposes, large amounts of storage won't be used in system designs until the cost of fossil fuels exceeds the combined cost of collection and storage.

An alternative to thermal energy storage is hybridization. A hybrid system can operate on either solar energy or some fossil fuel such as natural gas or fuel oil. The capital cost of hybridizing a solar thermal system is only the cost of adding a commercial auxiliary heater. The cost of added concentrator area and thermal energy storage must be less than the costs of the auxiliary heater and the fossil fuel used. It is generally believed that significant amounts of thermal energy storage will not become competitive until the costs of fossil fuel make hybridization the more expensive alternative.

The second technical issue underlying the design of thermal energy storage is the separation of temperature. The heated portion of the storage must not mix with or lose heat to the cooled part of the storage. For example, if hot fluid is put into a tank that contains cool fluid, the whole tank becomes luke-warm. Luke-warm fluid is less valuable for making electricity or for converting to process heat. Because of this, much design effort has been expended in the design of liquid storage systems to keep the cool 'used' fluid separate from the solar heated fluid.

Most solar thermal systems use sensible heat storage where energy is stored by heating up the storage medium. Other types that hold promise for smaller, less expensive systems are those that use latent heat storage where heat is stored at constant temperature as the medium changes phase from solid to liquid.

Current Technology - The hot fluid is kept separate from the cold fluid by several methods, the simplest being to have two tanks (Figure 54). At the start of the day, all the storage fluid is in the cold tank and the hot tank is empty. As the day progresses, fluid heated in the solar field is pumped into the hot storage tank. By the end of the day,

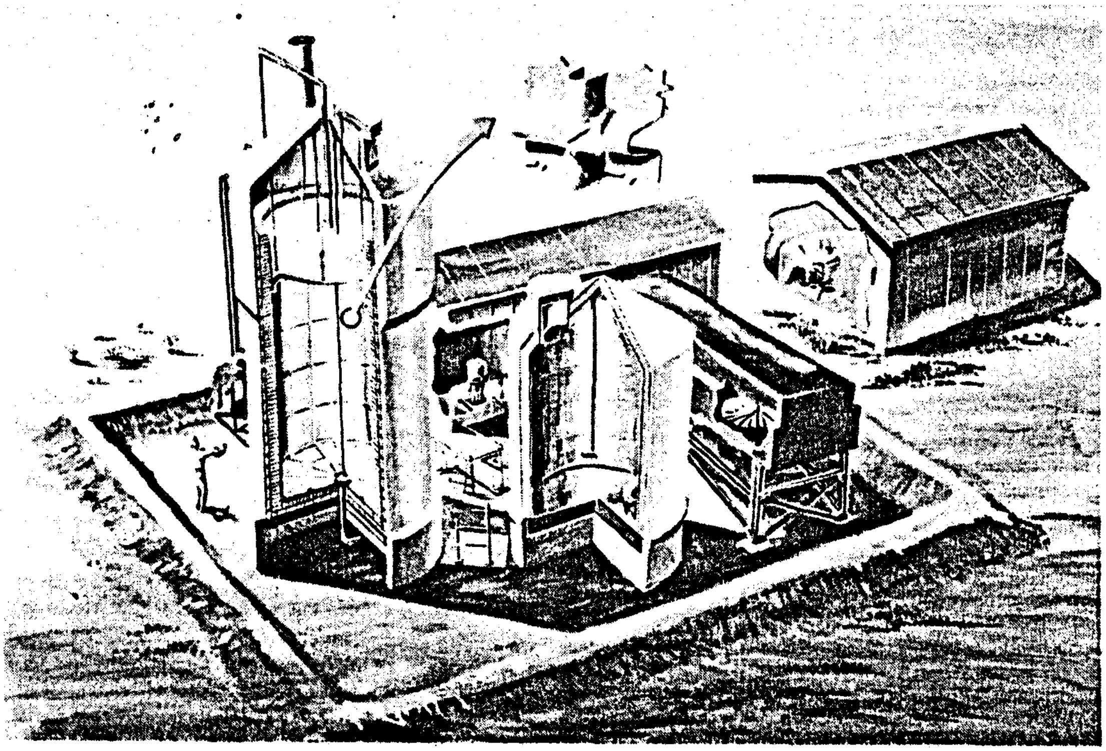


Figure 54. Two-tank molten salt storage

the cold tank is empty, and the hot tank is full. The obvious disadvantage of this method is that there must be twice as much tank volume as there is storage fluid. Since the tank is typically a significant portion of the storage cost, the cost of this system is high.

Multi-tank storage can reduce the excess tankage required but adds to the complexity of the system. If three tanks are used and two initially filled with cold fluid while two are filled with hot fluid at the end of the day, only 50% more tankage is required. Breaking the total tank volume down into more and more segments reduces the excess volume required.

The type of storage used in home hot water heaters is called thermocline storage and depends on the density difference between the hot and cold fluids to keep them from mixing. During storage, hot fluid enters the tank at the top and cold fluid is withdrawn from the bottom. When discharging, this flow process is reversed with cold fluid being pumped in the bottom and hot fluid withdrawn from the top. This type of storage has been used in many solar thermal systems. Tanks must have approximately a 5:1 ratio between height and diameter, and flow diffusers must be installed so that when fluid is added to the tank, it enters with a low velocity.

Solids such as pebbles or chunks of iron can be used as storage media and the thermocline is formed by the heat transfer process between the heat transfer fluid and the solid. Reverse flow must be used as with thermocline storage. The storage used at Solar One in Barstow, California, is a mixed media storage in which a bed of pebbles and sand are filled with heat transfer oil and the oil pumped in or out to supply or withdraw heat from the bed.

Many different storage media have been used or considered for use in solar thermal systems. Water is inexpensive but its high vapor pressure requires heavy tanks. Heat transfer oils are probably the most common media because they can be stored at close to ambient pressure. However, they are expensive and only hold about half as much heat as an equivalent volume of water. Rocks are inexpensive but have not been widely used because of the impurities they add and the chemical reactions that occur with some fluids.

Most of the high temperature heat transfer fluids discussed above can also be used as storage media. The low vapor pressure of molten salt mixtures or liquid sodium make their tankage design relatively easy. Molten salt mixtures are generally preferred because of their lower cost (Figure 55). One problem in storage tank design is the high temperature that must be sustained at the foundation. An alternative being explored is to cool the tank base with water to reduce the temperature and heat transferred into the ground. This is required with storage temperatures above 600°C (1,110°F)

Energy Transport

Since incident solar energy is dispersed over a large area, it must be concentrated and transported to the point of end use. In most solar thermal systems, energy is transported in insulated pipes from the receiver to the point of use. Parabolic trough and dish systems have their receivers distributed over a wide area. When thermal energy is to be transported to a central power plant or factory, insulated piping with associated heat loss is used for this purpose. Central receivers use optical transmission of energy to the single receiver from which thermal energy is transported to its end use.

If the collector field can not be located adjacent to the power cycle or heat usage point, considerable loss of thermal energy can occur in the transport of heated fluid. This loss occurs not only because of the steady-state heat transfer out through the insulation, but also during morning start-up where the entire mass of piping must be heated to operating temperature after an overnight cool-down.

One scheme to avoid these losses is to generate electricity at the receiver, eliminating the intermediate transport of thermal energy. This concept is currently used with many parabolic dishes as discussed previously. Another concept, called thermochemical energy transport, makes use of reversible endothermic/exothermic chemical reactions to store and then release heat in chemical bonds. Transport of the chemicals takes place at ambient temperature, thus eliminating thermal energy losses.

Two relatively simple endothermic/exothermic reactions are being considered for solar thermal applications. Their high theoretical energy densities and ambient temperature storage make this type of transport a possibility.

$$SO_2 + 1/2O_2 \overset{\text{heat}}{\leftrightarrow} SO_3$$

and

$$2H_2 + CO_2 \overset{\text{heat}}{\leftrightarrow} CH_4 + O_2 \quad .$$

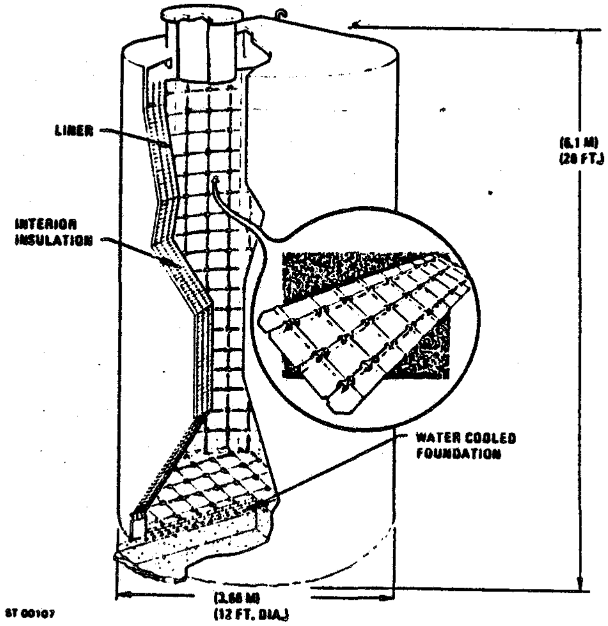


Figure 55. Molten salt subsystem research experiment hot tank

With either of these reactions, concentrated solar energy provides the heat to drive the endothermic reaction in one direction. The products are transported at ambient temperature to the point of thermal energy demand where the reverse exothermic reaction takes place over a catalytic reactor. This type of energy transport cycle can be either open- or closed-loop, depending upon the chemical system (Figures 56 and 57).

System Economics

The fundamental issue driving any solar thermal development is the cost of energy produced by the system. This cost is governed by (1) the initial cost of the system (capital cost), (2) the operating cost of the system, and (3) the useful energy generated by the system. It is found as follows:

$$\text{cost of energy produced} = \frac{\text{initial cost of system discounted over its lifetime} + \text{yearly operating and maintenance costs}}{\text{amount of energy produced in a year}}$$

As an example, if a solar thermal system initially cost $3,000,000 to construct, $80,000 per year to operate and maintain, and produced 3,000,000 kWhe each year, the cost of the energy produced can be calculated.

First, the initial plant cost must be 'discounted.' Discounting, a technique fundamental to economic analysis, will find the monthly or yearly payments required to 'buy' the plant initially. The dollar amount of these payments depends on the length of time they are to be paid, and the interest rate at which money can be borrowed. It is calculated the same way monthly payments are determined when buying a car or a house; part to pay back the capital borrowed, and part as interest on the remaining amount of capital.

To 'buy' a $3,000,000 solar thermal plant, the payments would be $318,238 per year for 30 years if the interest rate is 10%. This value was found by using the standard compound interest annuity formula. The cost of energy produced by this solar thermal plant can now be calculated as:

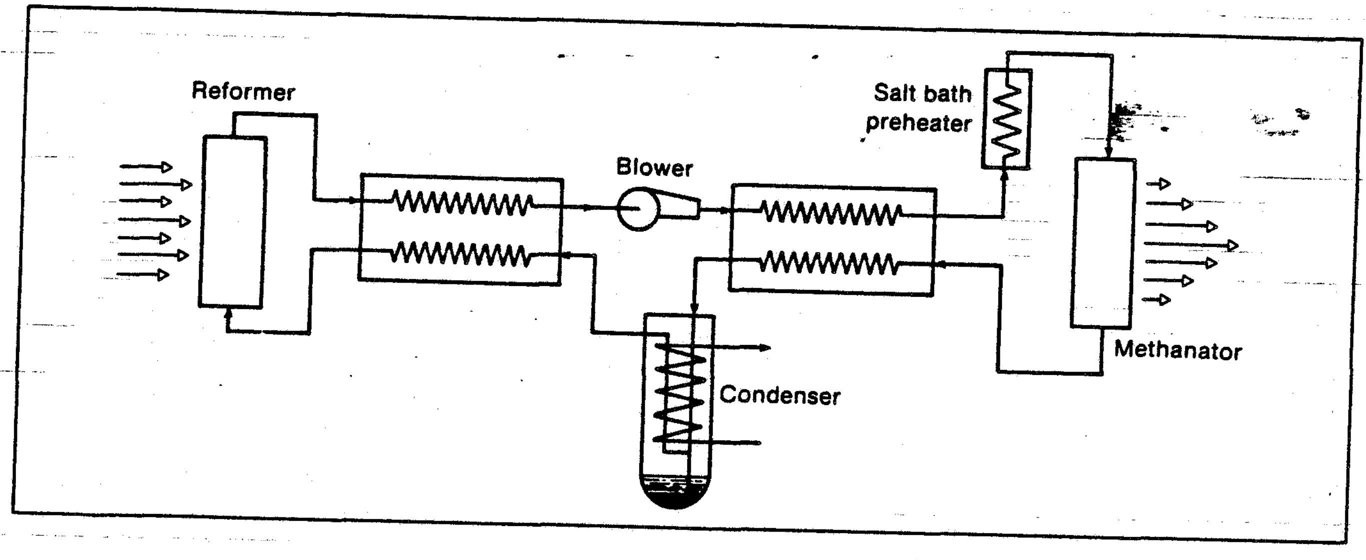


Figure 56. Schematic of closed-loop CO_2 reforming and methanation storage

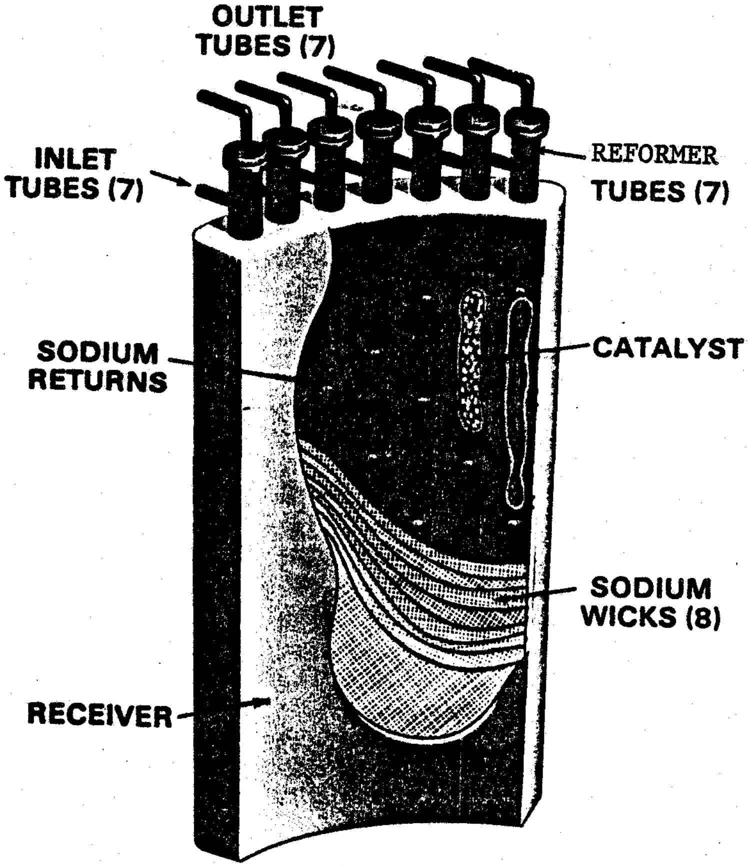


Figure 57. Experimental reformer receiver panel incoporating sodium heat pipe heat transfer

$$\text{cost of energy produced} = \frac{\$318{,}238 + \$80{,}000}{3{,}000{,}000\ \text{kWh}_e} = 13¢/\text{kWh}_e$$

A full economic analysis is more complex; however, the same techniques are used. The complexity lies in determining the values of the numbers, including all of the cost factors, and accounting for the time when they occur.

Much of the Solar Thermal Technology Program discussed so far is directed toward developing new technology to lower the costs in the numerator of the expression above. The fundamental solar collection equation, evaluated over a full year of insolation values at the desired location, determines the denominator.

Economic Analysis Techniques - Many different parameters are used to determine the economic viability of solar thermal project investments. These are (1) life-cycle costing, (2) discounted cash flow, (3) rate of return, (4) payback period, (5) annual energy savings/capital expenses, and (5) net present value. In practice, several of these parameters may be used simultaneously because of their individual strengths and weaknesses.

Solar thermal energy systems usually involve a higher capital and installation cost and a lower operating cost than conventional energy systems. In addition to these differences, economic analysis must be tailored to the type of system and the market where the system competes with conventional energy technology. Methods of cost calculations must also account for the different types of investors: corporations who will include the cost of energy into the price of their product, utilities who must compete for cash with a regulated income structure, and governments (federal, state, or local) who have different constraints.

Because dollars today are worth more to the lender than dollars in the future (not only as a result of inflation, but also because of the loss of interest that could be gained in the interim), costs and revenues must be brought back to some fixed time in a full economic analysis. This is called the 'present value' approach. These costs and revenues may then be averaged over the lifetime of the system as in the example above, to determine the levelized cost of energy produced.

Life-cycle Costing -- Life-cycle cost methodology is a good approach for taking into account both the higher initial capital cost of a solar thermal system, and the reduced operating cost (zero or minimal fuel cost) over its lifetime.

The life-cycle cost approach is based on determining the amount and time of positive and negative cash flows associated with acquisition, installation, and operation of the system over its lifetime. Life-cycle costs are computed using the present value approach. With this approach, all costs are estimated over a system's lifetime (using appropriate escalation) and then 'discounted' to an equivalent value of cost today (the 'present value'). The effect of inflation must be considered in this analysis.

Typical of the costs that must be considered are: the interest on money borrowed (from lenders or from company equity) to buy plant equipment and for construction (these payments start years before the plant starts operating), depreciation, tax liabilities, insurance, auxiliary fuel costs, operating costs, and maintenance costs. Some costs occur initially and some late in the operating period of the system. An equivalent present value must be found for each. The sum of these present values is the life-cycle cost of the solar thermal plant. The present value of all revenues from the plant must at least balance this cost to make the system economically viable.

New Directions

Instead of producing process heat or electricity from concentrated solar energy, the possibility of producing fuels that can be transported at ambient temperature to the point of use, or high value chemicals that require significant input energy is being considered. Producing fuels makes sense because they can be stored at high energy densities and can be transported, extending the use of solar energy to other applications such as transportation. Likewise, producing chemicals is worth considering because many are of very high economic value and are energy intensive. Also, there may be synthesis mechanisms unique to solar applications that will provide a strong economic incentive or produce chemicals that are very difficult to produce using conventional techniques. Three unique capabilities of concentrated sunlight as an energy source can be used: direct absorption of high energy photons to initiate chemical reaction, rapid heating of liquids and solids to produce high value products, and heating materials to very high temperatures in an atmosphere free of waste products.

Photochemical reactions make effective use of only those photons above a certain threshold energy to directly drive a chemical reaction. This threshold energy is specific to a chemical system. A significant research challenge is to define desirable chemical reactions that make efficient use of the concentrated sunlight. One very desirable reaction is to split water into its constituents: hydrogen and oxygen (Figure 58).

Hydrogen is a very high energy transportable fuel that can be oxidized back to water with release of energy in a low pollution cycle. Alternatively, hydrogen can be combined with carbon to manufacture almost any desired hydrocarbon fuel or chemical. The potential is significant. It may be possible to produce a transportable fuel such as hydrogen using only the sun and water as the feedstocks.

Another promising approach is to use the capability of direct concentrated sunlight to provide heating rates that are difficult and expensive to achieve with fossil fuel heating. For chemical reaction systems with multiple pathways, the rate of reaction along each pathway is a function of time and temperature. By controlling the rate of heating of the reaction mass, one pathway may be favored over another. Rapid solar heating may be used in this way to enhance the production of higher value chemicals over lower value alternative products.

Another possible use is for enhancing catalytic endothermic processes by direct absorption of solar energy on a catalyst. This can be used where direct solar heating positively affects the rate of a process on a solid catalyst. Here, most of the solar spectrum will be used and the conversion be highly efficient..

No solar thermal plants have been built for the production of fuels and chemicals; however, several exciting possibilities are being researched. In general, the production of fuels and chemicals represents a longer-range and potentially more valuable application of solar energy than the simple absorption of solar energy to produce heat.

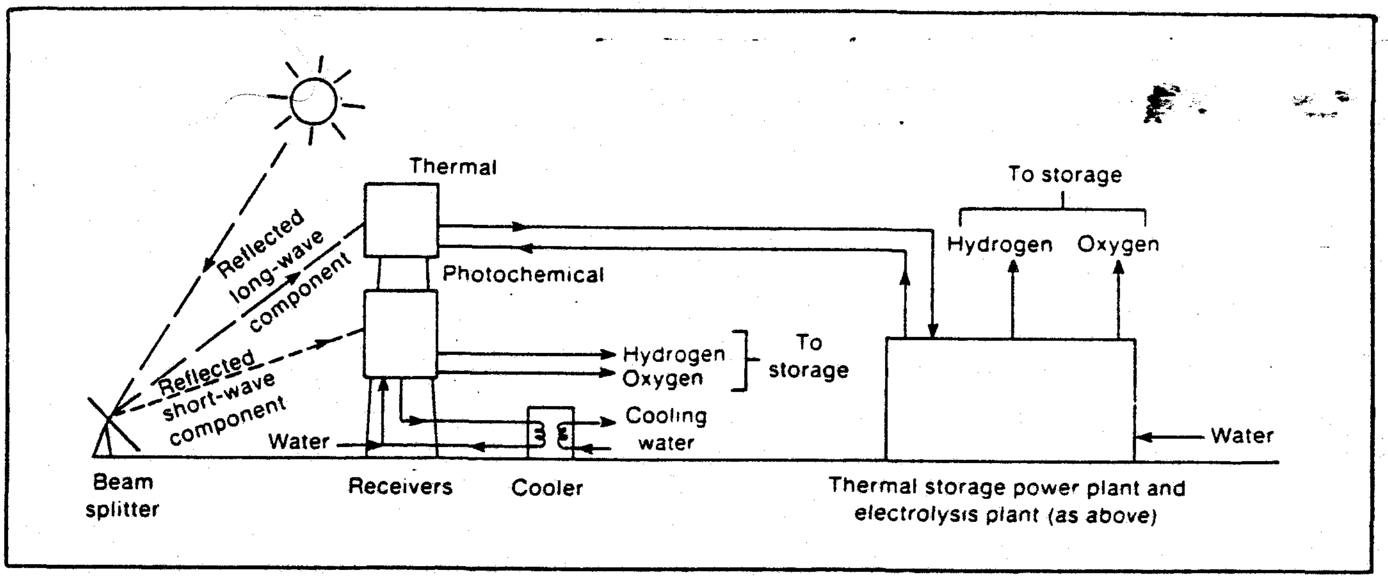


Figure 58. Schematic of a quantum/thermal system that utilizes a spectrally selective beam splitter

CHAPTER 6 - FUTURE GOALS

In a recent document (National Solar Thermal Technology Program - Five Year Research and Development Plan - 1986-1990), the state of the Solar Thermal Technology Program was evaluated and goals set for future developments. These goals were formulated to address two fundamental issues: 1) what energy cost must solar thermal systems achieve to significantly impact the energy market, and (2) how must the components of a solar thermal plant be developed so that this energy cost is technically attainable?

These issues were approached by developing system and component level goals. System goals are energy prices that should be met for solar thermal systems to have a significant economic effect in the utility electric or process heat marketplace. They were determined based on competition with fossil fuel energy sources. Component goals were set, based on projected cost and performance improvements that, when combined into a system, would meet the system goals.

The ultimate performance goal of any energy system is the cost of energy produced. As discussed, the cost of energy produced is a function of how inexpensive the system is (capital cost) and how well it performs (annual efficiency). Table 3 gives goals for the three basic types of solar thermal systems. As discussed previously, trough systems are best suited for the production of process heat for industry whereas the higher temperature capabilities of dish and central receiver systems are more applicable to electricity generation. Cost and performance figures are given only for these applications. Note that the costs of trough systems are based on thermal energy output rather than electrical energy output.

Three sets of performance numbers are given for each system: (1) the current technology status, (2) what is reasonably expected in 5 years at the current rate of development, and (3) the long-term goals to make the systems competitive. Annual efficiency defines how much of the sun's radiation over the year is converted into either process heat or electricity. Cost is broken into two categories: the cost to build the plant (which is noted here in 1984 dollars per peak output of the plant) and the more important cost of energy delivered from the solar plant.

Table 3. System Performance and Cost

	Troughs (heat)	Dishes (elect.)	Central Receivers (elect.)
Annual Efficiency, %			
current	32	13	17
5-year	36	17	20
long-term	56	28	22
Capital Cost, \$/kW[a]			
current	760	3400	2900
5-year	590	2100	1800
long-term	370	1300	1000
Energy Cost			
current	30/MBtu	13¢/kWh$_e$	13¢/kWh$_e$
5-year	23/MBtu	7¢/kWh$_e$	8¢/kWh$_e$
long-term	9/MBtu	5¢/kWh$_e$	4¢/kWh$_e$

[a] Troughs are in kW$_t$, dishes and central receivers in kW$_e$

Each component within a system has a 'component' efficiency that, when multiplied by the other component efficiencies, gives the overall system efficiency. These component efficiencies are given in the Table 4.

Note that there is one exception: optical materials. Their efficiency and cost is included in the concentrator cost for each type of system and should not be multiplied or added to obtain total system values. Optical materials performance is included here to indicate its relation to overall concentrator performance.

A discontinuity will be noted when examining the change in performance and cost of the dish-electric system receiver and power conversion system. This discontinuity exists because the current technology is based on a large field of dishes collecting heat and transporting it to a central power conversion cycle. The long-term dish system figures assume that receiver/engine module technology has been developed.

Table 4. Component Annual Efficiencies

	Troughs (heat)	Dishes (elect.)	Central Receivers (elect.)
Optical Materials, %			
current	88	88	88
long-term	92	92	92
Concentrators, %			
current	44	70	55
long-term	65	78	64
Receivers, %			
current	75	87	90
long-term	90	90	90
Transport, %			
current	98	93	99
long-term	98	99	99
Storage, %			
current	-	-	98
long-term	98	98	98
Power Conversion or Heat Exchange, %			
current	99	23	36
long-term	99	41	39

Component costs are given in Table 5 in 1984 dollars per unit of size. Most are given in terms of the total collector field aperture area. This is a measure of size of these components and a fairly accurate scaling factor for slight changes in system size. Economies of scale are not represented. The storage cost is given in terms of the amount of thermal energy it can store (kWh_t) which defines its size, and the power conversion cycle or heat exchanger cost is given in terms of the peak output of the unit.

Table 5. Component Costs

	Troughs (heat)	Dishes (elect.)	Central Receivers (elect.)
Optical Materials, $\$/m^2$			
current	20	20	20
long-term	10	10	10
Concentrators, $\$/m^2$			
current	200	160	150
long-term	110	130	40
Receivers, $\$/m^2$			
current	40	40	80
long-term	30	70	30
Transport, $\$/m^2$			
current	40	70	45
long-term	30	7	25
Storage, $\$/kWh_t$			
current	-	-	25
long-term	20	-	20
Power Conversion or Heat Exchange, \$/kW[a]			
current	50	380	600
long-term	40	300	350
Balance of Plant, $\$/m^2$			
current	35	35	65
long-term	20	20	30
Yearly Operations and Maintenance, $\$/m^2$			
current	15	8	12
long-term	6	10	9

[a] Troughs are in kW_t, dishes and central receivers in kW_e

As in the previous table, there is a separate category for reflective materials. The cost of the reflective material is included in the cost of the reflector.

Again, note the discontinuity between the dish-electric current costs and long-term costs. As described above, this is the result of a transition from central engine technology to modular engine technology. The transition decreases the cost of transport but increases the cost of the receiver and operations and maintenance. The overall result gives a significant reduction in the cost of electricity generated.

DOE has developed these performance and cost goals to direct future research and development efforts. If these goals are met, solar thermal systems will significantly affect the energy market of the 1990s.

APPENDIX A

Glossary of Terms

alternator—an electric generator that produces alternating current.

absorber—that part of a receiver where concentrated radiation is absorbed and transferred as heat to the working fluid.

absorptance—the ratio of absorbed to incident solar radiation. Absorptivity is the property of a material to absorb radiation.

baseline—reference against which a comparison is made.

baseload electric plant—an electrical generating facility that is designed primarily to satisfy a continuous demand.

Brayton-cycle engine—a heat engine that uses the thermodynamic cycle used in jet (combustion turbine) engines.

Btu—British thermal unit; the amount of heat required to raise the temperature of one pound of water (at 342°F) one degree Fahrenheit.

buffer storage—energy storage that is designed to allow a solar energy system to operate smoothly under transient solar conditions.

busbar energy cost—the cost of producing electricity, including plant capital and operating and maintenance expenses. Does not include cost of transmission or distribution.

cavity receiver—a receiver in the form of a cavity where the solar radiation enters through one or more openings (apertures) and is absorbed on the internal heat-absorbing surfaces.

central receiver system—a solar-powered system that uses an array of computer-controlled sun-tracking mirrors (heliostats) to concentrate the available solar radiation and focus it onto a nearby tower-mounted receiver. The energy absorbed by the receiver is removed as thermal energy.

closed-loop system—a system in which no part is vented to the atmosphere.

cogeneration—production of two or more types of energy by the same system; e.g., electricity and process heat.

collector efficiency—the ratio of the energy collection rate of a solar collector to the radiant power intercepted by it under steady-state conditions.

concentrator—a device that concentrates the sun's radiation onto a given area, thereby increasing the intensity of the collected energy.

concentration ratio—ratio of reflected radiant power impinging on a surface divided by the radiant power incident upon the reflecting surface.

convection—heat transfer resulting from fluid motion caused by a temperature difference.

distributed receiver system—a solar-powered system in which each concentrator has its own attached receiver.

dual-axis tracking—capable of rotating independently about two axes; e.g., north-south and east-west.

endothermic reaction—a chemical reaction that absorbs heat.

evaporator—a heat exchanger in which a fluid undergoes a liquid-to-vapor phase change.

external receiver—an exposed heat receiver, typically cylindrical in shape. In this type of receiver, tubes containing the heat-transfer fluid form the outer surface of the receiver and directly absorb the radiant energy.

field experiment—the construction and testing of a solar energy system in an actual operating situation.

flat-plate collector—a nonconcentrating device that collects solar radiation, both diffuse and direct.

flux (radiant)—the time rate of flow of radiant energy.

flux density—the radiant flux incident per unit of area.

generator—a machine that converts mechanical energy into electrical energy.

heat exchanger—a device that transfers heat from one fluid to another.

heat pipe—a passive heat exchanger employing principles of evaporation and condensation to transfer heat effectively.

heat-transfer fluid—the fluid circulating through a receiver that absorbs the sun's heat.

heliostat—a device for reflecting light from the sun in a desired direction. A typical heliostat may consist of a number of flat (or slightly concave) mirror facets mounted to a drive mechanism capable of pointing the mirror array in any desired direction, usually onto a fixed receiver.

hemispherical bowl collector—a stationary, bowl-shaped, solar thermal collector that concentrates radiant energy onto a movable linear receiver.

hybrid system—an energy conversion system that can be operated from solar energy or fossil fuel either interchangeably or simultaneously.

insolation—the solar radiation flux density available at the earth's surface. The maximum energy rate is about 1000 W/m^2 (317 $Btu/hr\ ft^2$)

line-focus collector—a solar collector that absorbs concentrated radiant energy along a line of focus.

irradiation—the cumulative amount of insolation falling over a specified period of time.

module—(1) unit consisting of a concentrator with support structure, receiver, and power conversion equipment. It can stand alone or be clustered with others to provide greater power capacity; (2) a self-contained unit that performs a specific task or class of tasks in support of the major function of the system.

molten salt solar thermal system—a solar thermal system that uses a molten salt or salt mixture as the heat-transfer fluid and possibly to store thermal energy.

organic Rankine cycle engine—a Rankine-cycle engine that uses an organic fluid instead of water/steam as the working fluid.

parabolic dish collector—paraboloidal dish, dual-axis-tracking, solar thermal concentrator that focuses radiant energy onto an attached point-focus receiver or engine/receiver unit.

parabolic trough collector—a paraboloidal trough, usually single-axis-tracking solar thermal concentrator that focuses radiant energy onto an attached linear-focus receiver.

peak Watt—unit used for the performance rating of solar-electric power systems. A system rated at one peak Watt delivers one Watt at a specified level of insolation.

point-focus collector—a solar collector that absorbs concentrated radiant energy at a point of focus.

Rankine-cycle engine—a closed-loop heat-engine cycle with a working fluid pumped under pressure to a boiler where heat is added, a turbine where work is generated, and a condenser used to reject low-temperature heat to the environment. The thermodynamic cycle upon which water/steam turbines are based.

receiver—the component of a concentrating collector that accepts concentrated radiation and transfers it as heat to the heat-transfer fluid.

repowering—the retrofitting of existing fossil-fueled utility or process-heat power plants with solar energy collection systems to displace a portion or all of the fossil fuel normally used.

retrofit—the installation of solar energy systems in already existing structures or facilities.

single-axis tracking—capable of rotating about one axis.

solar energy—energy in the form of radiation emitted from the sun and generated by means of a fusion reaction within the sun.

solar furnace—a solar device used to obtain extremely high temperatures (over 2760°C; 5000°F) by focusing the sun's rays.

solar thermal electric conversion—the conversion of solar energy to thermal energy, and then to electricity by an engine or power cycle.

solar thermal energy system—a system that uses heat produced from the sun's rays to produce mechanical power, electrical power, or process heat.

Stirling-cycle engine—an externally heated engine using pistons driven by an alternately heated and cooled gas. It is potentially more efficient than a steam engine or gas turbine.

storage-coupled—using an energy storage system to permit an end-use system to operate during periods when solar power from the receiver is inadequate (or not present) to satisfy the load.

sunfuels—transportable fluids produced, from either nonrenewable or renewable resources, by using energy from the sun in the synthesis process.

thermal energy storage system—any rechargeable unit capable of storing thermal energy for later use. Examples are storage as sensible heat in nitrate salt, oil, sodium, rock, water, or soil.

thermochemical conversion process—any process that transforms a set of chemical reagents into a different product set of chemicals involving the application or deletion of heat energy.

thermocline storage—the storage of thermal energy where the hot and cold media are in the same container (tank) with the lower density hot fluid floating atop a higher density cooler fluid of the same type, or with the hot solid material being separated from cooler solid material by a thermal gradient as in air/rock, air/ceramic brick applications.

total energy system—an energy system that uses heat rejected from the generation of electricity to satisfy additional energy needs; e.g., process steam, heating, and cooling requirements.

tracking system—the motors, gears, actuators, and controls necessary to maintain a proper concentrator orientation with regard to the sun.

turbine—a bladed engine or machine driven by the pressure of steam, water, air, etc.

working fluid—a fluid which is heated, cooled, pressurized, and expanded to do work; e.g., drive a turbine, in a power cycle. The pressurized working fluid in some systems is heated by passing through a heat exchanger from which it absorbs heat from a heat-transfer fluid. In other systems it is heated directly in the receiver.

APPENDIX B

Units of Measure

To Convert from:	To:	Multiply by:
acre	m^2	4046.9
angstrom	m	10^{-10}
AU (astronomical unit)	m	1.4960×10^{11}
bar	Pa	10^5
barrel (petroleum, 42 gal)	m^3	0.1590
Btu (thermochemical)	J	1054.35
Btu/ft^3	J/m^3	3.723×10^4
Btu/h	W	0.29288
Btu/h ft °F	W/m K	1.7296
Btu/h ft^2	W/m^2	3.152
Btu/h ft^2 °F	W/m^2 K	5.675
Btu in./hr ft^2 °F	W/m K	0.14413
Btu/lb$_m$	J/kg	2324.0
Btu/lb$_m$ °F	J/kg K	4184.0
cal/cm^2 min	W/m^2	697.3
cfm	m^3/s	4.7195×10^{-4}
degree (angle)	rad	17.45×10^{-3}
ft	m	0.3048
ft (H_2O) (29.2°F)	Pa	2989.0
ft lb$_f$	J	1.356
ft lb$_f$/lb$_m$ °F	J/kg K	5.377
gallon (gal) (U.S. liquid)	m^3	3.785×10^{-3}
hectare	m^3	10^4
horsepower (hp)	W	745.7
horsepower (boiler)	W	9809.5
in. Hg (60° F)	Pa	3377.0
J/s	W	1.0000
kJ/h m^2	W/m^2	0.2778
kWh	J	3.6×10^6
langleys/min (Ly/min)	W/m^2	697.3
lb$_m$/ft^3	kg/m^3	16.018
lb$_m$/s	kg/s	0.45359
light year	m	9.461×10^{15}
micrometer (micron)	m	10^{-6}
mile	m	1609.3
Nm	J	1.0000
N/m^2	Pa	1.000
ounce (fluid)	m^3	2.957×10^{-5}
psi	Pa	6895.
second (angle)	rad	4.848×10^{-6}
therm (10^5 Btu)	J	105.4×10^6
ton (short, 2000 lb)	kg	907.2
ton (refrigeration)	W	3516.8
ton of TNT	J	4.2×10^9
tonne	kg	10^3

APPENDIX C

General Sources of Information

Included below is a partial list of sources of information on solar energy that include significant material on solar thermal systems.

Textbooks:

Kreith, F., and J.F. Kreider, *Principles of Solar Engineering*. New York: McGraw-Hill, 1978.

Kreider, J.F., *Medium and High Temperature Solar Processes*. New York: Academic Press, 1979.

Stine, W.B., and R.W. Harrigan, *Solar Energy Fundamentals and Design*. New York: John Wiley & Sons, 1985.

Handbooks

Dickinson, W.C., and P.N. Cheremisinoff, eds. *Solar Energy Technology Handbook*. New York: Marcel Dekker Co., 1980.

Kreider, J.F., and F. Kreith, eds. *Solar Energy Handbook*. New York: McGraw-Hill Book Co., 1981.

Technical Journals

Solar Energy
Pergamon Press
Maxwell House, Fairview Park
Elmsford, NY 10523

Journal of Solar Energy Engineering
The American Society of Mechanical Engineers
United Engineering Center
345 East 47th Street
New York, NY 10017

Program Reports*

Solar Thermal Technical Information Guide. SERI/SP-271-2511, Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO, 1985. (Available from NTIS.)

National Solar Thermal Technology Program - Five Year Research and Development Plan - 1986-1990. U.S. Department of Energy-Solar Thermal Technology Division, Washington, D.C. 20585, 1986.

Proceedings of the Solar Thermal Technology Conference (Albuquerque, New Mexico, June 17-19, 1986). SAND86-0536, Sandia National Laboratories, Albuquerque, NM 87185, June 1986. (Available from NTIS.)

Solar Thermal Research Program Annual Conference (Lakewood, Colorado, Feb. 20-22, 1985). SERI/CP-251-2680, Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO, 1985. (Available from NTIS.)

Solar Thermal Technology - Annual Evaluation Report, Fiscal Year 1985. U.S. Department of Energy-Solar Thermal Technology Division, Washington, DC 20585, 1986. (Available from NTIS.)

*NOTE: Those documents noted as available from NTIS may be obtained by writing: National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

Insolation Data Manuals

Solar Radiation Energy Resource Atlas of the United States. SERI/SP-642-1037, Solar Energy Research Institute, Golden, CO, 1981. (Available from NTIS.)

Knapp, C.L., and T.L. Stoffel, *Direct Normal Solar Radiation Data Manual.* SERI SP-281-1658, Solar Energy Research Institute, Golden, CO, 1982. (Available from NTIS.)

Design Manuals

Harrigan, R.W., *Handbook for the Conceptual Design of Parabolic Trough Solar Energy Systems. Process Heat Applications.* SAND81-0763, Sandia National Laboratories, Albuquerque, NM, 1981. (Available from NTIS.)

Falcone, P.K., *A Handbook for Solar Central Receiver Design.* SAND 86-8009, Sandia National Laboratories, Livermore, CA, 1986. (Available from NTIS.)

Kutscher, C.F., R.L. Davenport, D.A. Dougherety, R.C. Gee, P.M. Masterson and E.K. May, *Design Approaches for Solar Industrial Process Heat Systems: Non-tracking and Line Focus Collector Technologies.* SERI/TR-253-1356, Solar Energy Research Institute, Golden, CO, 1982. (Available from NTIS.)

System Experiment Tour Information

Experiment:	Solar One Central Receiver Powerplant
Contact:	Southern California Edison Public Information Center
Address:	P.O. Box 325 Daggett, CA 92327
Telephone:	(619) 254-2810
Hours/Days:	Visitor Center: open 9:00 to 5:00 daily
Tours:	prearranged groups only except public tours 11:00 and 2:00 Sundays
Travel Directions:	about 12 miles east of Barstow, CA, on I-40; take the Daggett off-ramp and follow signs to Solar One (2 1/2 mi. east on National Trails Hwy.).

Experiment: Solar Electrical Generating Station (SEGS parabolic trough power plant)
Contact: same as Solar One
Address: same as Solar One
Telephone: same as Solar One
Hours/Days: same as Solar One
Travel Directions: site is adjacent to Solar One

Experiment: Solar Total Energy Project
Contact: Public Information Contact
Address: 7 Solar Circle
Shenandoah, GA 30264
Telephone: (404) 253-0218
Hours/Days: 9:00 to 5:00 / Monday-Friday
Travel Directions: from Atlanta airport, take I-85 south for 25 miles. Turn right (west) at Shenandoah offramp (Georgia Hwy. 34) for 1/4 mile, turn right (north) on Amlajack Blvd. for 1/4 mile, then left at Solar Circle.

Experiment: Central Receiver Test Facility (CRTF)
Contact: Public Tour Guide
Address: Sandia National Laboratories
CRTF - Organization 6222
P.O. Box 5800
Albuquerque, NM 87185
Telephone: (505) 844-4414
Hours/Days: 1:00 to 4:00 Monday thru Friday
Travel Directions: enter Lackland Air Force Base at Gibson Ave. gate (identify yourself as CRTF visitor). Turn right (south) at Wyoming St., turn left (east) at "Solar Power Tower" sign and follow (small) signs to CRTF (about 8 miles from gate).

Principal Contacts and Sources of Additional Information

Central Receiver Technology

Sigmund Gronich
Division of Solar Thermal Technology
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
(202) 252-1623

John Holmes, Manager
Central Receiver Technology Div. 6227
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185
(505) 844-6871

Central Receiver Test Facility

Nyles Lackey
U.S. Department of Energy
Albuquerque Operations Office
P.O. Box 5400
Albuquerque, NM 87115
(505) 846-3220

John V. Otts
Central Receiver Program Manager, 6222
Sandia National Laboratories
Albuquerque, NM 87185
(505) 844-2280

10 MWe Pilot Plant (Solar One)

Michael Lopez
U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, CA 94612
(415) 273-4264

Distributed Receiver Technology (Parabolic Dish and Trough)

Dean Graves
U.S. Department of Energy
Albuquerque Operations Office
P.O. Box 5400
Albuquerque, NM 87115
(505) 846-5202

James Leonard, Manager
Distributed Receiver Technology Division, 6227
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185
(505) 844-8508

Research

Frank Wilkins
Division of Solar Thermal Technology
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
(202) 252-1684

L. J. Shannon, Director
Solar Heat Research Division
Solar Energy Research Institute
1617 Cole Boulevard, 15/3
Golden, CO 80401
(303) 231-1104

Bimleshwar P. Gupta, Manager
Solar Thermal Research Program
Solar Energy Research Institute
1617 Cole Boulevard, 15/3
Golden, CO 80401
(303) 231-1760

BILLBOARD PHOTO INSERTS

Parabolic Trough System (photo of USS Chemicals)

RECEIVER - A metal tube runs down the focal line, shielded by a larger glass tube. The fluid pumped through the tube is heated to 260°C (500°F) by the concentrated sunlight.

CONCENTRATOR - A trough in the shape of a parabola is covered with reflective material. When aimed at the sun, the solar radiation is concentrated along line.

STORAGE - No energy storage is used in this system.

CONVERSION - Hot oil from the collector field produces process steam here.

Parabolic Dish System (show MDAC dish/Stirling)

CONCENTRATOR - Eighty-two slightly curved silver-glass mirror facets all aimed at a single point.

RECEIVER - A cavity receiver where hydrogen passing through very small tubes is heated to 720°C (1328°F).

STORAGE - No energy storage is used in this system.

CONVERSION - A Stirling engine mounted just behind the receiver, produces a maximum of 23 kW of electricity.

Central Receiver System (photo of Solar One)

CONCENTRATOR - A field of 1,818 glass mirror heliostats, continuously track the sun reflect the sun's rays to the receiver.

RECEIVER - Reflected sunlight bathes this four story high absorbing surface made of over one-thousand small vertical tubes welded together. Steam is generated here at 515°C (960°F).

STORAGE - Excess heat is stored in this tank which contains a mixture of rocks, sand and oil.

CONVERSION - A standard steam power cycle produces enough electricity to supply 2,500 homes.