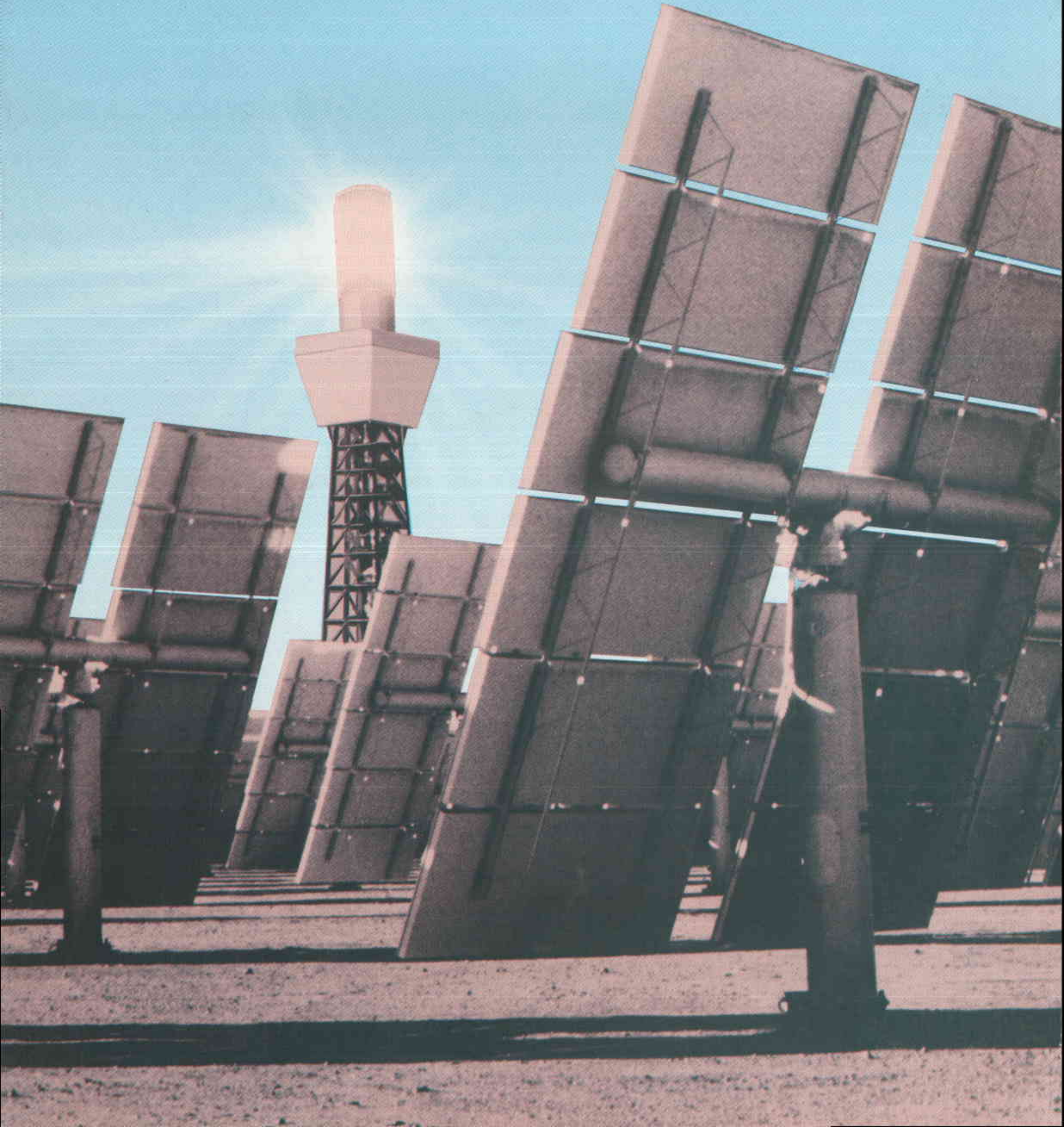
Power From the Sun:

Principles of High Temperature Solar Thermal Technology



Authored by
William B. Stine, Ph.D.
Mechanical Engineering Department
California State Polytechnic University
Pomona, California

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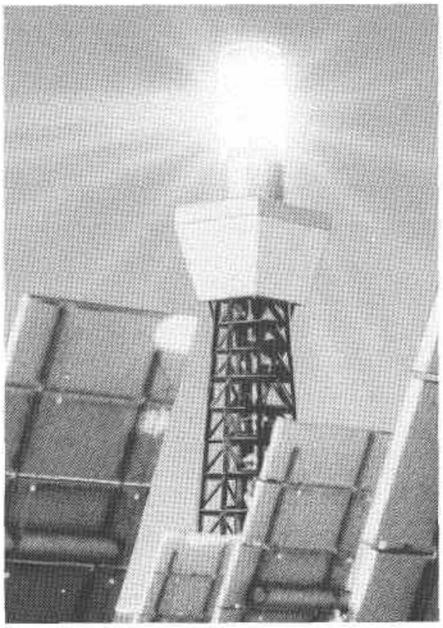

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Preface

The research and development described in this document was conducted within the U.S. Department of Energy's Solar Thermal Technology Program. The goal of this effort 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 systems for introduction into the competitive energy market.

Solar thermal technology uses tracking mirrors or lenses to concentrate solar flux onto a receiver where the solar energy is absorbed as heat and converted into electricity or used directly by industry 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. Distributed receiver technology currently includes parabolic dishes, Fresnel lenses, parabolic troughs, and spherical bowls. Parabolic dishes up to 17 m in diameter track the sun on two axes and use mirrors to focus radiant energy onto a point-focus receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Distributed receiver 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 close to 1500°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 the U.S. Department of Energy and its network of national laboratories that 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.

A Product of the
Solar Technical Information Program

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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. Even before that time, people may be willing to pay a premium for a non-polluting and safe power system that reduces our dependence on fossil fuels.

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 are being 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 enhance 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. Key terms or words are highlighted with **boldface** type. The reader should realize that many concepts here are highly simplified so that only the major points are emphasized. Detailed engineering, mathematics, and physics underlies this simplicity.

Acknowledgments

This document was prepared under the Solar Technical Information Program managed by the Solar Energy Research Institute for the U.S. Department of Energy. Contributors to this document were William B. Stine, California State Polytechnic University; Frank Wilkins, Marty Scheve, and Sig Gronich of the U.S. Department of Energy; Jim Leonard and Al Heckes of Sandia National Laboratory Albuquerque; Al Skinrood and Lee Radosevich of Sandia National Laboratory Livermore; Lorin Vant-Hull of the University of Houston; Richard Holl of H.G.H. Enterprises Inc.; Tom Tracey of Martin Marietta; and Carlo LaPorta of the Solar Energy Industry Association.

Contents

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, gas 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**; a continuous, nonpolluting, abundant source of energy.

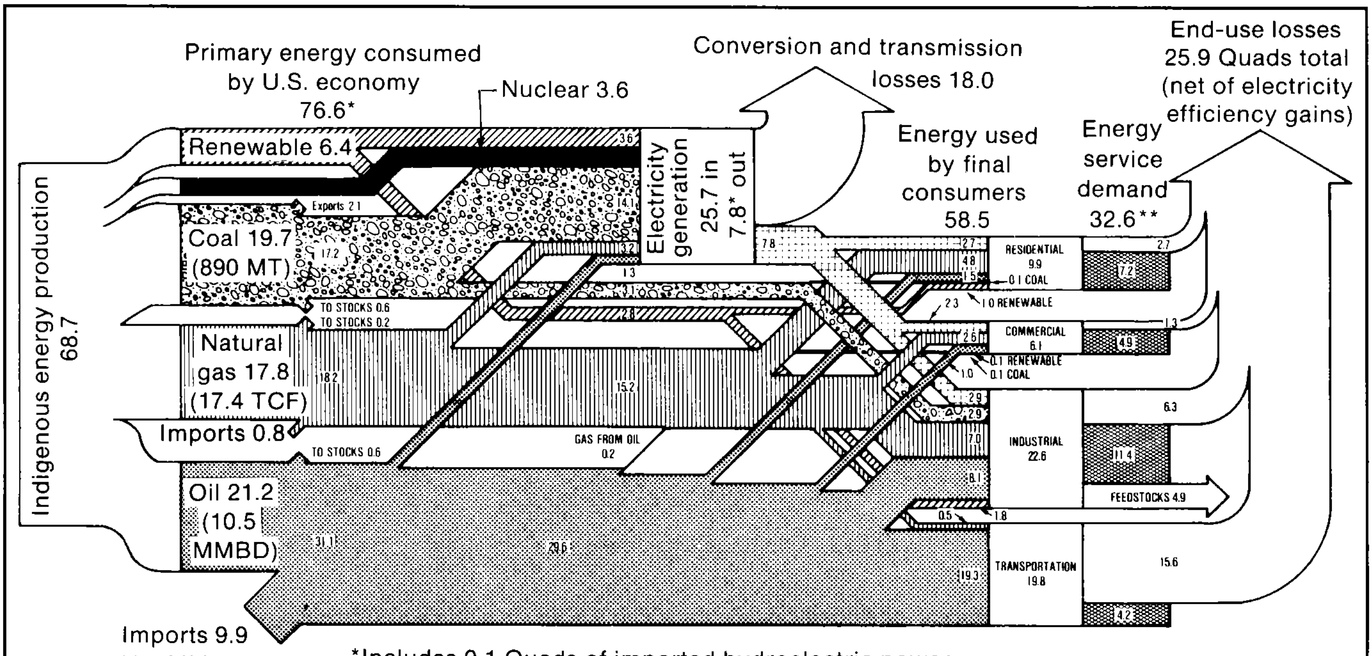
The high standard of living in the United States depends on using large amounts of energy in various forms. With only 6% of the world's population, the United States uses about **half the commercial energy** consumed world wide. In 1984 the U.S. used 76 quads (i.e., 76 x 10^{15} Btu or 80 x 10^{18} J) of energy. This was 4% more than in 1983 and indicates that consumption is rising again after the brief decline resulting from measures taken after the 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 recently, oil and gas were the major contributors in the U.S. but the use of coal has increased because supplies of oil and gas are more limited. Figure 1 depicts the energy sources and where that energy is used in our society. The width of the paths represents the quantity of energy involved.

Our nation's supply of **oil** and **gas** is limited. The current reliance on oil imports extends these resources but leaves us vulnerable to events over which we have no control. During the 1970s, the United States learned the hazards of relying on imported oil. A four hundred percent increase in the cost of oil not only affected everyone's finances, but also significantly contributed to the national inflation rate. Gasoline became a hard to get commodity and long lines at service stations became a sign of the times. The threat of an oil embargo from foreign countries proved that we must plan now for an energy future when less oil and gas will be available.

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

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



*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 Sources and Uses in 1984 (quadrillion Btu)

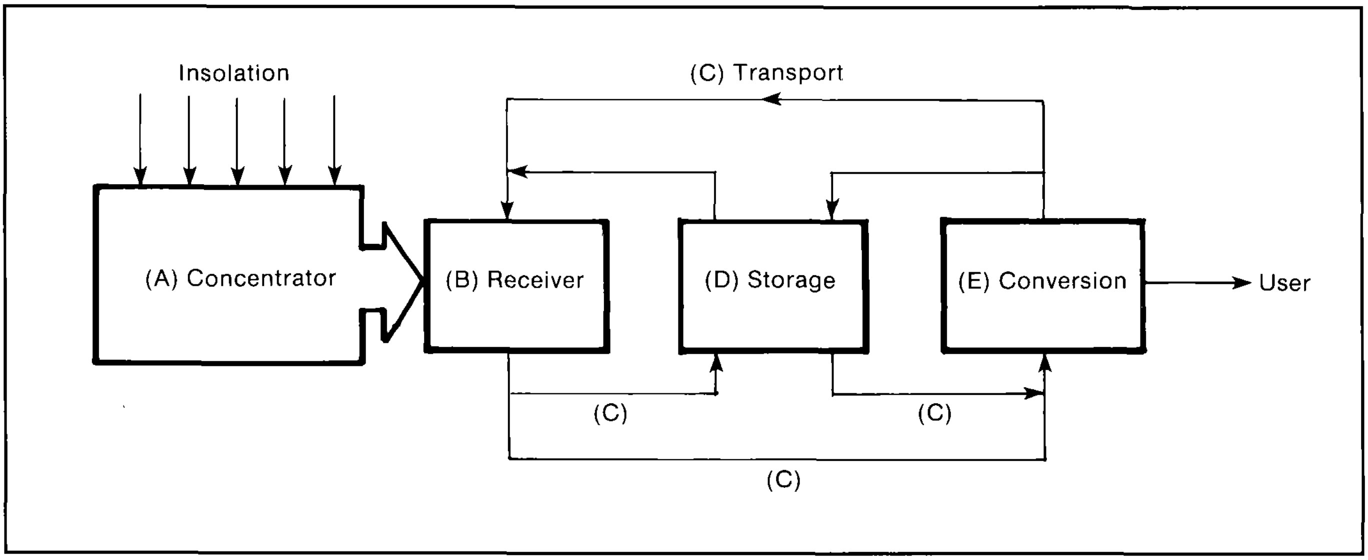


Figure 2. Solar Thermal System. Solar thermal systems convert the sun's radiation to useful products (such as electricity, fuels, or direct heat) by way of a thermal process. The basic elements of any solar thermal design are (A) the tracking optics used to concentrate the sun's energy, (B) the receiver 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.

supplement petroleum used in the other energy-use sectors with coal, gas, nuclear and renewable energy sources, 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. Coal must be mined and, like oil and gas, it emits particulates and sulfur compounds. Also, like oil and gas, when it is burned, coal produces nitrogen oxides (NO_x); a major component of smog. Burning of fuels also increases the carbon dioxide (CO_2) level in the atmosphere, which is thought to be causing an increase in global temperature with consequent changes in climate and sea level. In the long term, we 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 our solar system. Using this solar energy will make a significant contribution to the nation's energy supply.

Solar Thermal Applications

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 using this energy directly for an industrial process or converting it to electricity (Figure 2). In addition, research is now looking at ways of directly using the concentrated solar beam to take better advantage of the highest energy portion of the spectrum. Although equally important, other forms of solar energy conversion such as the direct conversion to electricity by photovoltaic processes, or providing building or 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 1 shows that, of our current energy resources, 34% is used to make **electricity**, with 26% going 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 and commercial installations and its costs have decreased dramatically. Performance has increased steadily in the past decade and projections point to economic competitiveness with fossil fuels and other renewables in the mid to late 1990s.

In the future, solar thermal systems will help 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. In addition, DOE is exploring the possibility of detoxifying hazardous chemicals and altering the properties (e.g., strength and abrasion resistance) of strategic materials using the concentrated solar beam. Recent advances in modifying material properties with lasers point to optimism that a high intensity solar beam may be able to create processes not possible with other technologies.

DOE involvement. In recent years, the U.S. Department of Energy Solar Thermal Technology Program has commissioned **research and development** studies and feasibility experiments for the production of high temperature thermal energy as an option to using fossil fuels. Since 1975 this program has carried out the development of three types of concentrating collector concepts: **parabolic troughs, parabolic dishes**, and **central receivers**. The program emphasizes research and development 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 required temperature range.

To perform research and development 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 of Solar Power

Solar power, as well as space heating and water heating technologies, has been evolving for thousands of years. The Chinese, Greeks, and Romans developed curved mirrors that concentrated 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 building 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 World's Fair in Paris in 1878.

One of the successful leaders of the 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 the 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-powered hydraulic pump. In 1913 he successfully demonstrated the use of a 50-hp solar engine for pumping irrigation water from the Nile River at Meadi, 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, Italy, Russia, Japan, and the United States. Most of the furnaces were developed to simulate the thermal radiation environment produced by a nuclear explosion.

The present DOE Solar Thermal Technology Program was begun in the mid 1970s in response to the energy crisis of that period. Since then, component development and system experiments have proven the technical feasibility of concentrating solar energy and harnessing its power. Although there has been significant progress in increasing efficiency and reducing system costs, the cost of fossil fuels during the intervening period has dropped also. This return to low fuel costs has delayed the time when solar thermal technologies will become economically competitive, except in isolated cases, and necessitated continued improvement in the technology.

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 **collect** and **convert** it, 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. This chapter describes how various solar thermal energy systems work and how the technology developed into its present state.

Comparison of Solar Thermal Technologies

Solar thermal technology has evolved into three distinct types of concentrating collectors: (1) the **parabolic trough**, (2) the **parabolic dish**, and (3) the **central receiver**. Each of these technologies is discussed in 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 1.1). 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 600°F (315°C) are considered optimum because of the line-focusing geometry of the parabolic trough that causes it to have a lower **concentration ratio** (i.e., the ratio of the concentrated solar flux to the incident flux) than most parabolic dishes or a central receiver. As a result, the **operating temperature** (defined by the application) must remain in this range so

Storage- No energy storage is used in this system.

Conversion- Hot oil from the collector field of troughs produces process steam here.

Receiver- A metal tube parallels the focal line, shielded within a larger glass tube. The fluid pumped through the tube is heated to 500° F (260° C) by the solar radiation.

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 the focal line.

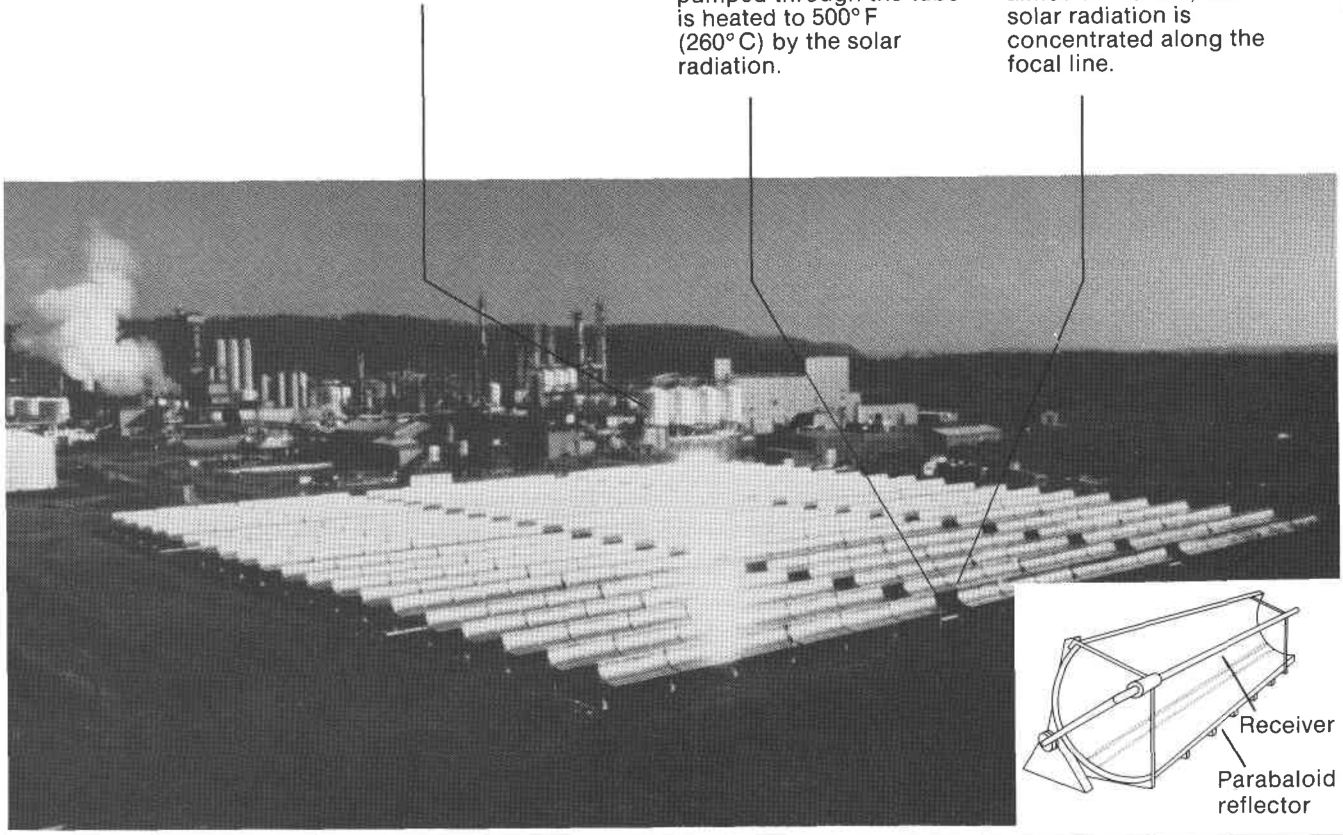
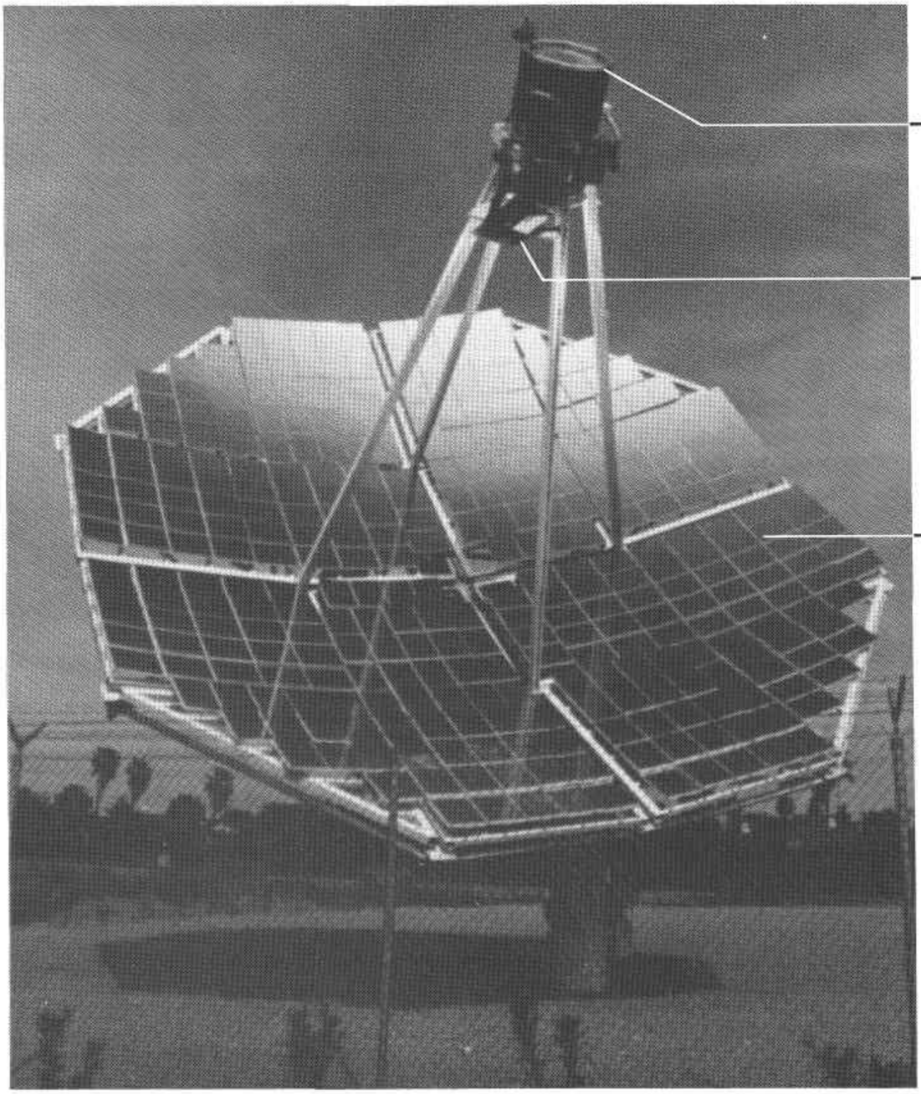


Figure 1.1. A Parabolic Trough System



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

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

Storage- No energy storage is used in this system.

Concentrator- 336 slightly curved silver/glass mirror facets all aimed at a single point.

Figure 1.2. A Parabolic Dish System

that the collector does not lose most of the energy it receives.

The most widespread application for a parabolic trough system will be for providing **process heat** in the form of steam or hot heat-transfer fluids, although it is possible to send the hot fluid through a heat engine to produce electricity. There are industrial demands for heat from 300°F to 500°F (150°C to 260°C), which match the lower operating temperatures of the parabolic trough. Troughs can also be used to generate electricity.

The **parabolic dish** is a concentrating solar collector formed by rotating a parabolic curve about its axis to form a shape called a paraboloid (Figure 1.2). All parallel rays entering the aperture of the paraboloid along its axis will be focused to a **single point**. Therefore, the term **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 is made here between these designs when discussing their operation.

A principal application for a parabolic dish system will be the production of **electrical power** since power conversion efficiency increases with temperature and advantage can be taken of the higher temperature capabilities of these collection systems. Parabolic dish systems have the special capability of providing small, self-contained, high efficiency electrical power generation **modules** of 25-50 kW$_e$.* 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.

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 tower (Figure 1.3). The surface of the receiver is heated as it absorbs the reflected radiation, which in turn heats a fluid. The fluid may be either an intermediate heat-transfer fluid or the power cycle working

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*Subscripts $_e$ or $_t$ used throughout this report indicate electrical or thermal power, respectively.

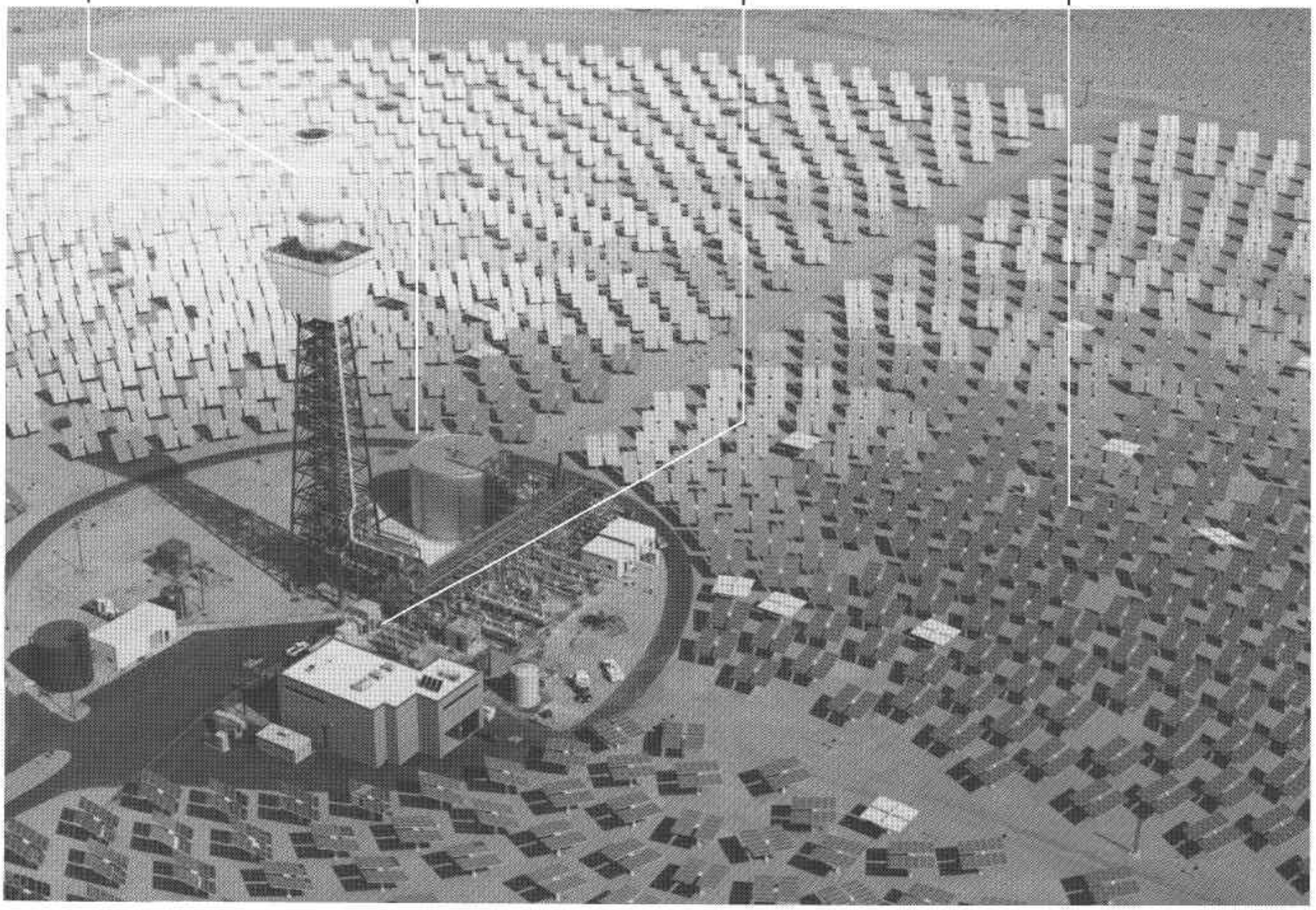
fluid boiled directly in the receiver. In most central receiver systems envisioned today, the heated fluid is pumped down the tower and used to drive a **steam Rankine power cycle** just as fossil fuel or nuclear-generated heat is used in other power plants.

The steam Rankine cycle uses **traditional electrical power generation technology**. Steam normally produced in a steam generator is 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.

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

Because of their high temperature capabilities and modularity, parabolic dishes and 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. The high temperature capability of both dishes and central receivers also makes them suitable for **extremely high temperature applications** (1000°C-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 makes it possible for solar energy systems to supply energy at the required time for industrial users or the electric power industry. Storage of collected thermal



Receiver- Reflected sunlight bathes this 4-story high absorbing surface made of more than 1000 small vertical tubes welded together. Steam is generated here at 960°F (515°C).

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

Conversion- A standard steam-power cycle produces enough electricity to supply 6000 homes.

Concentrator- A field of 1818 silver/glass mirror heliostats track the sun continually and reflect solar radiation onto the receiver

Figure 1.3. A Central Receiver System

energy is **relatively easy** and **inexpensive** for all three solar thermal collection technologies.

The Fundamental Solar Collection Equation

A simple **energy balance** equation governs the performance of any type of solar energy collection system and guides the design of new systems. This document discusses the many aspects of solar energy **system design** and refers to the underlying theory that propels 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 energy system either for direct use or converted into a more valuable form of energy, usually electricity (but possibly fuels or chemicals). It may also be **stored** for later use.

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** from the receiver. 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 from the receiver is separated into **convection** heat loss (the middle term) 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.

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

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} = active area of the **concentrator aperture** (opening) (i.e., not shaded or blocked)

A_{rec} = effective area of the **receiver aperture** or surface

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

σ = the **Steffan-Boltzmann** constant

F = **equivalent radiation 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)

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 convective and conductive 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** means is that the amount of useful energy collected by a collector/receiver system is, at most, equal to the beam normal insolation falling on the collector(s). It can be increased by making the collector or collector field larger, and can be reduced by a number of factors (since ρ, Φ, τ, and α are always less than one).

This document illustrates how the various solar thermal technologies are striving to change and optimize one or more of these parameters to increase the **performance** of a system design or to reduce its **cost**.

The Solar Resource

Before designing a solar thermal energy system, one must understand the energy coming from the sun. Although most of us have experienced the warmth of the sun and its cycles, in order to develop optimum collection systems we must obtain considerable technical information about its energy and the clouds that block or modify its output. Considerable effort is being expended to define just how much solar energy is available at any given site 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 1.1 lists other insolation units that can be used.

Table 1.1. 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. On a clear day, the sun's disc has an apparent size of approximately one-half degree. Beam radiation is the almost parallel rays coming from this disc. 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 solar collector or collector field is directly proportional to the amount of beam normal insolation reaching the collector.

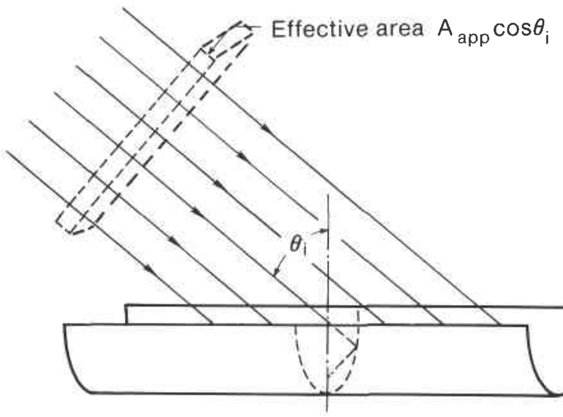
Some of the beam normal insolation reaching the outer atmosphere of the earth is deflected along its path through the atmosphere. This scattered radiation, which reaches the observer from anywhere in the sky other than from the sun's disc, is called **diffuse insolation.**

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 facing up. Because most collectors used in solar thermal systems are highly concentrating, generally only beam normal insolation is of interest. Considerable effort has been expended to obtain and compile data on the beam normal insolation resource.

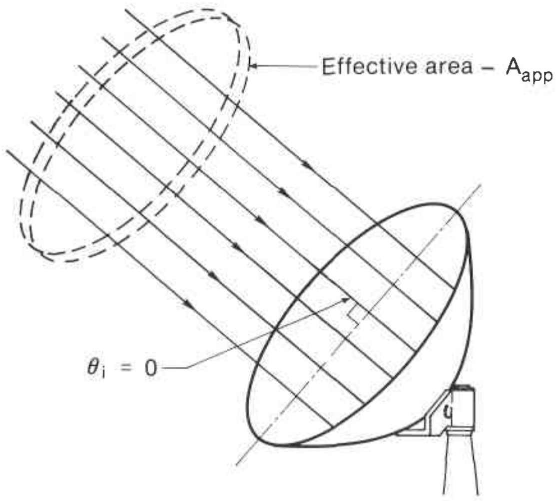
Cosine effect. The maximum amount of insolation passes into a collector or heliostat aperture when it is perpendicular to the rays of the sun. For this case, the **angle of incidence** θ_i, is 0° and the cosine of that angle is one. If the aperture of the collector or heliostat does not point toward the sun, then the angle of incidence is greater than 0°, which **reduces** the amount of energy incident on the collector surface. This reduction is called the **cosine effect** (Figure 1.4).

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

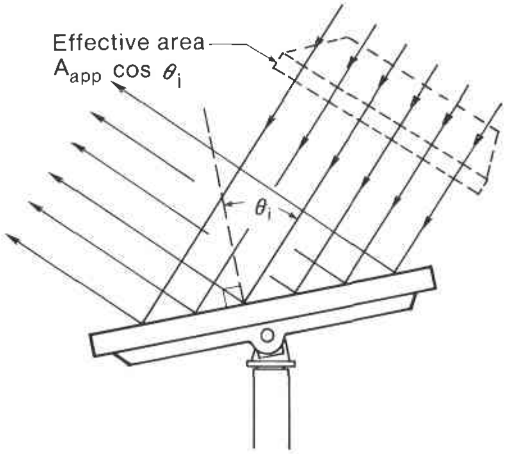
The cosine effect changes as the sun moves across the sky during the day and as these angles change over the seasons. The effect depends on the **orientation** of the collector and its **location**. The cosine effect is greater for designs where the **aperture remains fixed**. For these, the cosine loss is great in the mornings and evenings when beam normal insolation is low. Therefore, the energy loss due to the



Parabolic trough



Parabolic dish



Heliostat

Figure 1.4. The Cosine Effect

cosine effect must be considered in conjunction with the insolation available.

Cosine losses for some of the more common schemes for tracking concentrating collectors are shown in Table 1.2 with their yearly average cosine effects. Central receiver fields are not included. Typical weather data were used to generate these numbers.

Table 1.2. Cosine Effects for Various Concentrator Orientations

(Yearly average for Albuquerque, NM, TMY data)

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

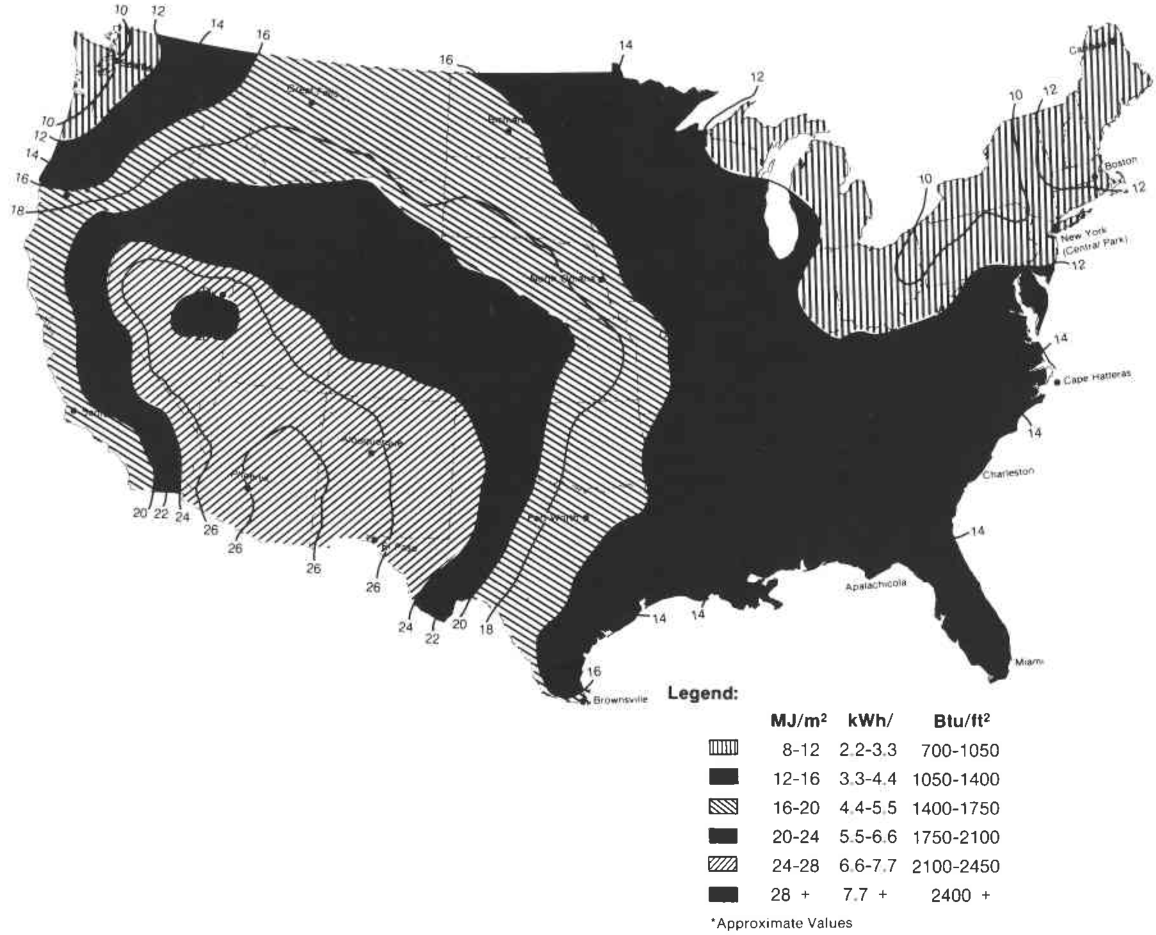
Irradiation. When designing a solar thermal system, it is important to know how much useful energy will be delivered over a period of time such as a day, a month, or a year. The parameter defining the solar energy delivered over a period of time is the **irradiation**. Irradiation is simply the **sum** 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 (Table 1.3).

Table 1.3. Irradiation Units in Common Use

Unit	To convert to MJ/m^2 multiply by
Btu/ft^2	0.011350
Langleys	0.04184
kWh/m^2	3.6

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 from all over the U.S. The accompanying map (Figure 1.5) 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 inadequate and a program is currently underway to improve it. 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.

Sources of data. Without a good definition of our solar energy resource, $I_{b,n}$, the useful energy derived from a solar



Legend:

	MJ/m^2	kWh/	Btu/ft^2
▥	8-12	2.2-3.3	700-1050
■	12-16	3.3-4.4	1050-1400
▧	16-20	4.4-5.5	1400-1750
■	20-24	5.5-6.6	1750-2100
▨	24-28	6.6-7.7	2100-2450
■	28 +	7.7 +	2400 +

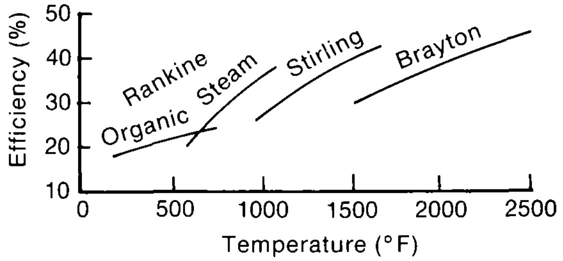
*Approximate Values

Figure 1.5. Annual Average Daily Beam (Direct) Normal Irradiation in the United States (MJ/m^2)

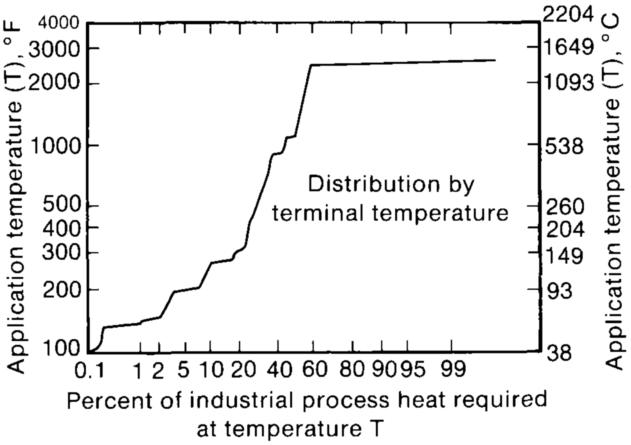
thermal system cannot be accurately predicted or evaluated. The primary solar irradiation data base available to designers today is the **Typical Meteorological Year (TMY)** data base. This is a full year's compilation of hour-by-hour insolation and other weather data for 248 sites in the United States. 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 B.

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 (Figure 1.6). 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 onto a small surface to reduce the heated portion of the receiver and thus minimize heat loss.



Engine Efficiency Temperature Requirements



Process Heat Temperature Requirements

Figure 1.6. Temperatures Required for Electricity Generation and Process Heat Solar Thermal Applications

All collectors used in solar thermal systems are **concentrating collectors**; therefore, the solar energy is collected through a large concentrator **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**:

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

Because solar thermal systems operate at relatively high temperatures, the temperature difference T_{rec} - T_{amb} is **great**. 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 1.7). The concepts described in this report are all designed to provide a receiver area 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 called the **concentrator**. The parameters affected by the design of the concentrator are A_{app}, θ_i, ρ, Φ, A_{rec}. The remaining parameters are functions of the design of the receiver or the weather and will be discussed later.

Parabolic reflectors. The surface of a **parabolic reflector** is shaped so that all rays of light parallel to its axis reflect from the surface through a single point, the **focal point**. Figure 1.8 shows a diagram of the parabola with the primary elements labeled.

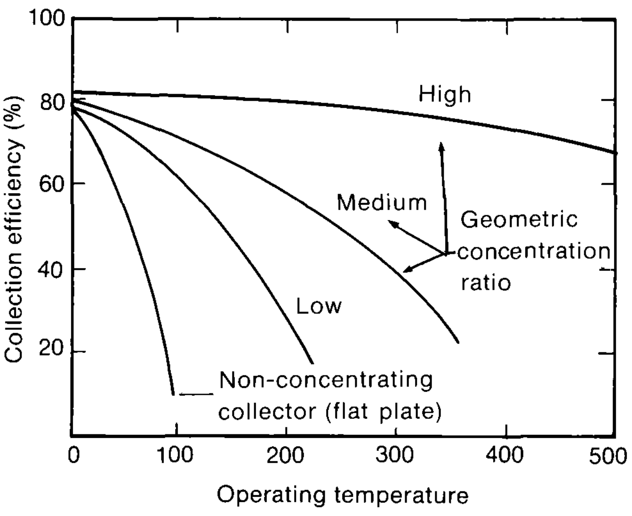


Figure 1.7. Effect of Concentration Ratio on Collection Efficiency (Insolation is the same for each curve)

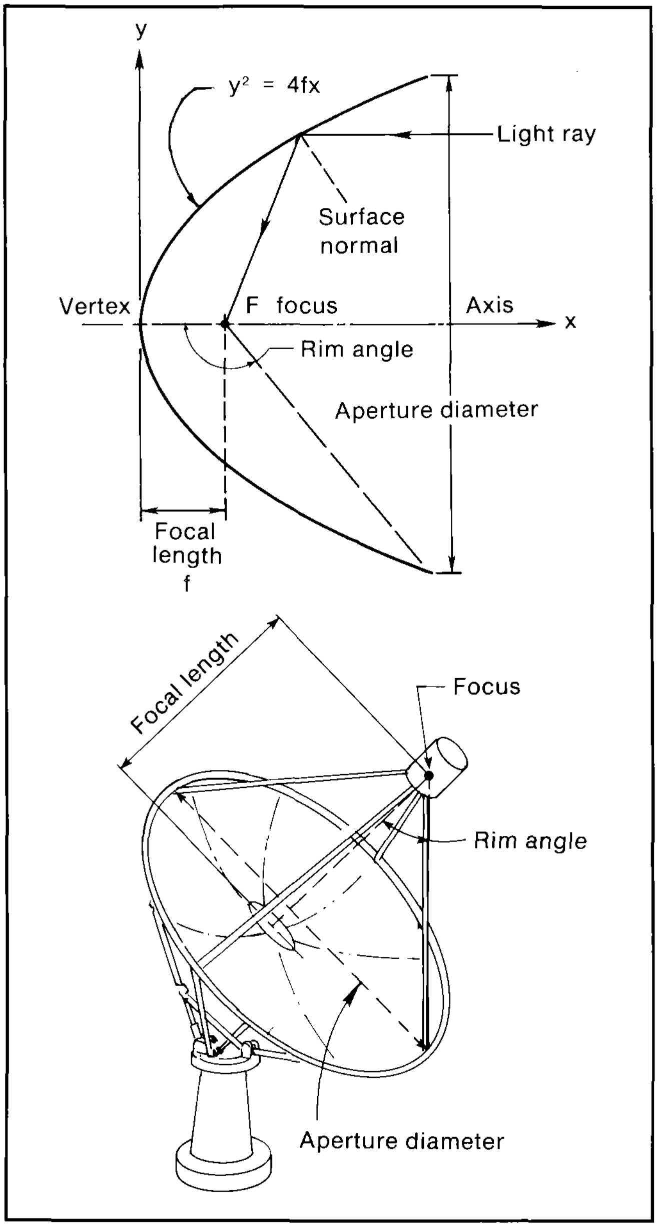


Figure 1.8. The Parabola

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 about 45° when cavity receivers are used, and about 90° with external receivers. Figure 1.9 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.

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 in the section on Receivers.

Very **large rim angles** are not cost-effective since 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 manufactured accurately 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.

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. 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 for support. The movable mirror segments are called **heliostats** (Figure 1.10).

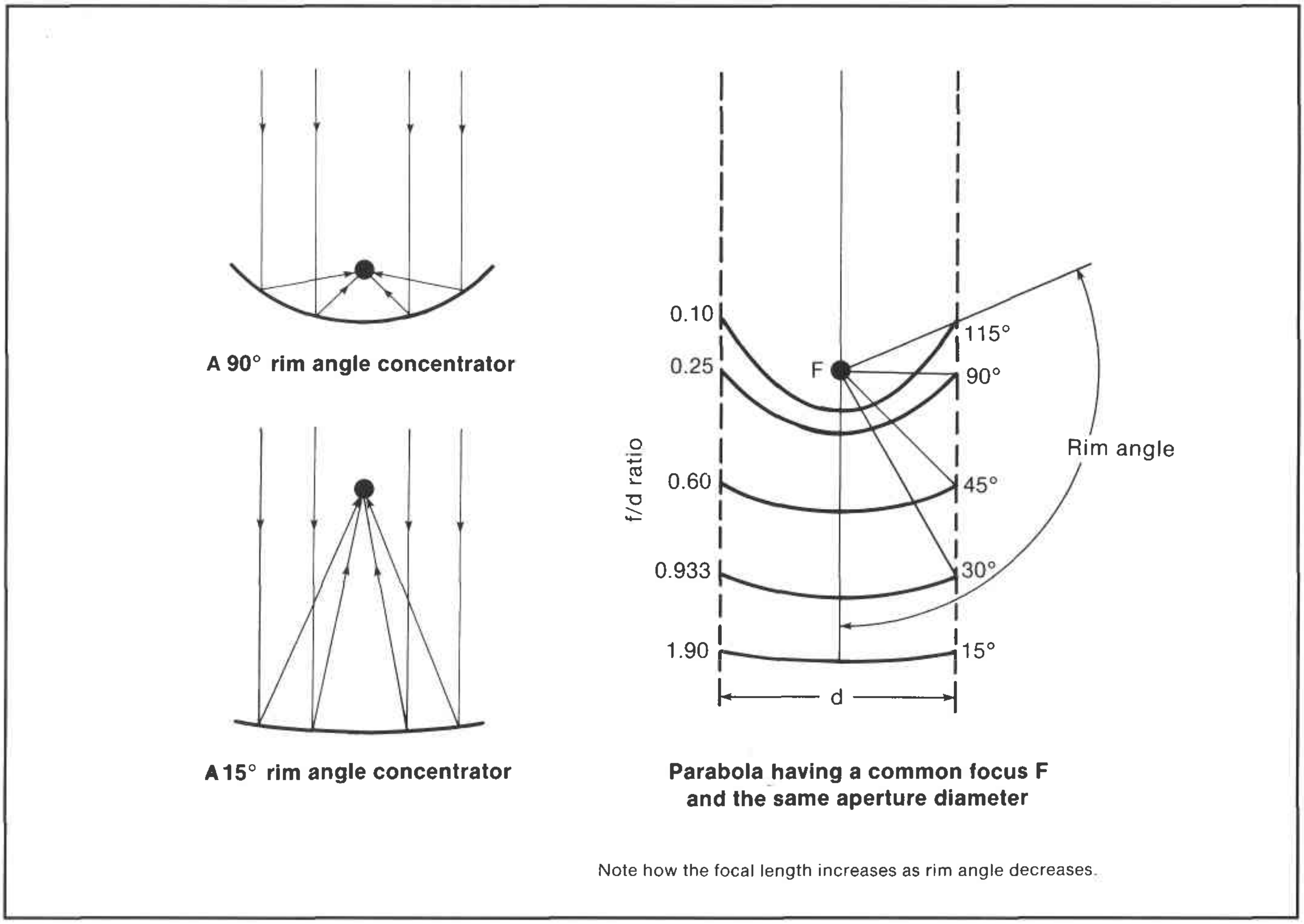
The use of segmented optics to simplify the structure of a concentrating collector adds two optical problems to the design of the collector. First, since the surface must be aimed halfway between the sun and the focus point, there is a varying cosine loss which reduces the amount of energy reflected off of each segment. Secondly, adjacent segments will both **shadow** incident rays and **block** 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 **facets** and these are **canted** (aimed) toward the focus. The facets may also be curved slightly 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 (Figure 1.11) rather than a parabolic one. Spherical concentrators do not focus to a single focal point as parabolic concentrators do. Spherical bowl concentrators, with the concave (inside) surface being reflective, focus the sun's rays along a **radial line** parallel to the incoming rays.

Refractive concentrators. A completely different method to concentrate the sun's rays uses a lens. Here, parallel rays are **bent inward** as they pass through a medium that is different from air (usually glass or plastic) (Figure 1.12). 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.

Optical errors. Several optical errors can result in a deviation from the theoretical collection geometry discussed above. Some of these errors are random and result in spreading of the optical image of the sun at the focus and therefore require the use of **larger receivers** with greater heat loss. Reducing these errors usually means increasing the **cost** of the concentrator. This represents one of the major trade-offs in the design of solar thermal systems.


A 90° rim angle concentrator

A 15° rim angle concentrator

Parabola having a common focus F and the same aperture diameter

Note how the focal length increases as rim angle decreases.

Figure 1.9. Parabola Focal Length and Curvature

Even the best concentrator surfaces deviate from the ideal curve to which they are manufactured. These deviations are called **slope errors** and are measured in milliradians (mrad) of angle that the actual slope deviates from the ideal. In general, the smaller the slope error, the higher the cost of the optical surface. Parabolic concentrator surfaces that are manufactured well 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 meets an optical surface, part of the reflected beam is diffused. This is called **nonspecular reflectance**. Polished aluminum diffuses incident radiation to a greater extent than back-surface, silvered glass mirrors. Thus, it has a higher degree of nonspecular reflectance and makes a poorer solar concentrator.

Two optical alignment errors can displace the focus from the true focus: (1) the **mechanical error** of not positioning the receiver at the true focus, and (2) the **tracking error** of not having the concentrator pointed directly at the sun.

Another ''error'' that cannot be changed with increased concentrator manufacturing quality is the **sun's width**. Because the sun is not a point-source emitting parallel rays, the reflected image spreads in a cone of approximately 0. 53° (9.2 mrad). This acts just like the errors discussed above, and results in additional spread 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 is intercepted by 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 is at the focus, the smaller the fraction that will be captured in a receiver of a 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, and **transfer** 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 Φ, τ, α, A_{rec}, U, and F. The receiver operating temperature T_{rec} is determined in the design of the solar energy utilization system and the remaining parameters are functions of the design of the concentrator or the weather.

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

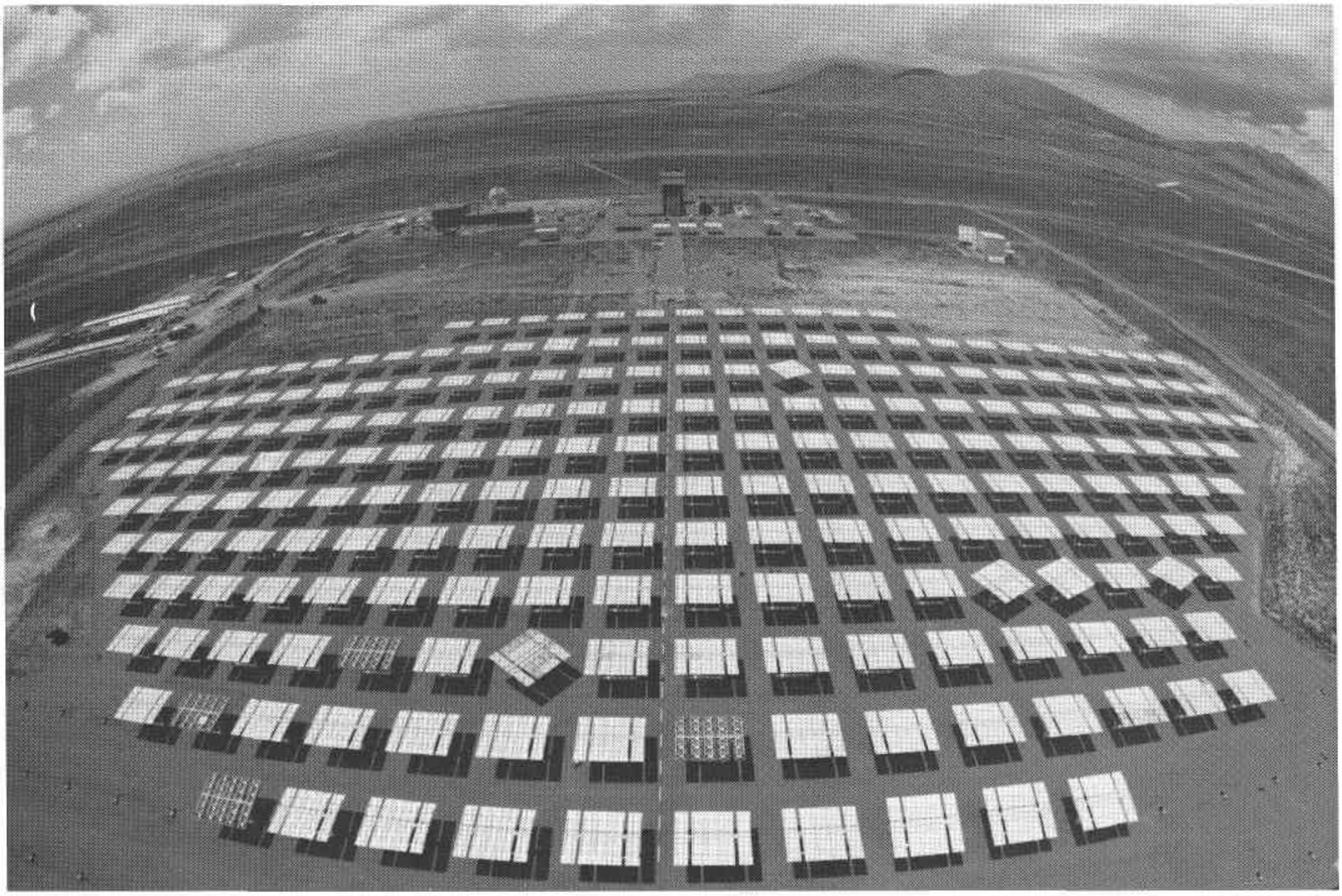


Figure 1.10. A Heliostat Field

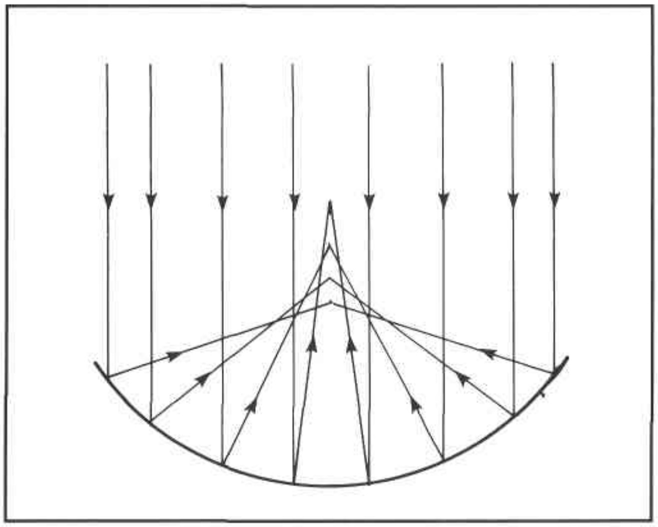


Figure 1.11. A Spherical Reflector

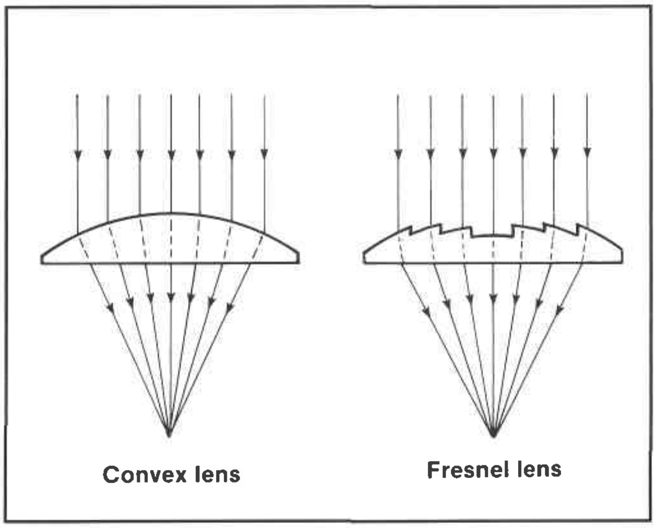


Figure 1.12. Refractive Concentrators

Two receivers are used in solar thermal concentrators: (1) **external** or omni-directional receivers, and (2) **cavity** type receivers (Figure 1.13). 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, then internal reflections ensure that most of it is absorbed onto 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

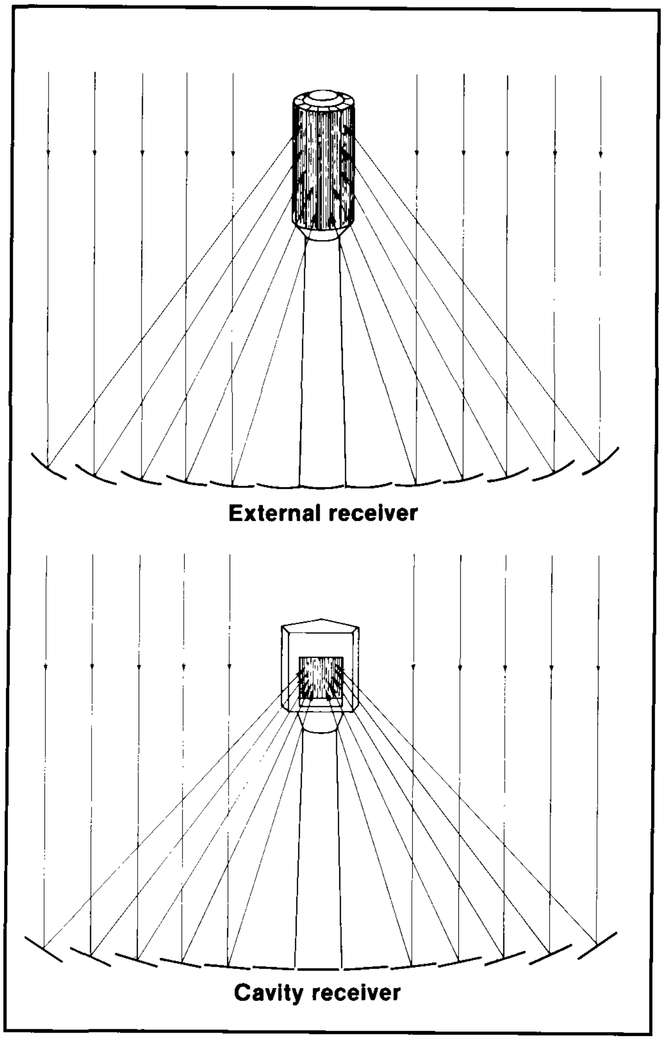


Figure 1.13. External and Cavity Receivers

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.

For many applications, the minimum size of the receiver absorbing surface is limited by **maximum heat flux/thermal stress** conditions. When the absorbing surface is small or its walls thick, a high temperature difference across the absorber wall is required to transfer absorbed heat to the heat-transfer fluid. This temperature difference induces high internal stress in the absorber wall and can lead to cracking, especially over many cycles of heating and cooling. This is an important consideration when high pressure heat-transfer fluids (e.g., water/steam at high temperature) are used because of the thick walls required for the absorber.

To increase the capture factor Φ without increasing the size of the aperture of a cavity receiver, **terminal 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 1.14).

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 reduce the amount of energy being captured by more than the energy loss is reduced.

With quality concentrator optics (as in the case of many central receiver systems), the minimum size of the receiver is no longer limited by the capture factor, Φ, but by the transfer of heat into the working fluid. The absorbing surface will overheat and crack or melt if a high rate of energy is reflected onto too small of an area and the heat-transfer fluid cannot remove the energy rapidly enough.

Convection and conduction heat loss are combined 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** or tube around an 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 that gets through the cover. For clean glass, the value of this term should be greater than 0.9.

Radiation heat loss depends not only on the receiver area, but also on the surface properties and geometry of the receiver and its temperature. The **equivalent radiation conductance F** combines the ability of the receiver to radiate heat with the absorbing capability of the surroundings ''seen'' by the receiver. A receiver can be made to radiate less energy by reducing the ability of the receiver surface to emit radiation (called the **surface emittance**) or, if a cavity-type receiver, by reducing the internal volume of the cavity. Radiation loss increases rapidly as the operating temperature of the receiver increases because of the **fourth power** exponent on this term.

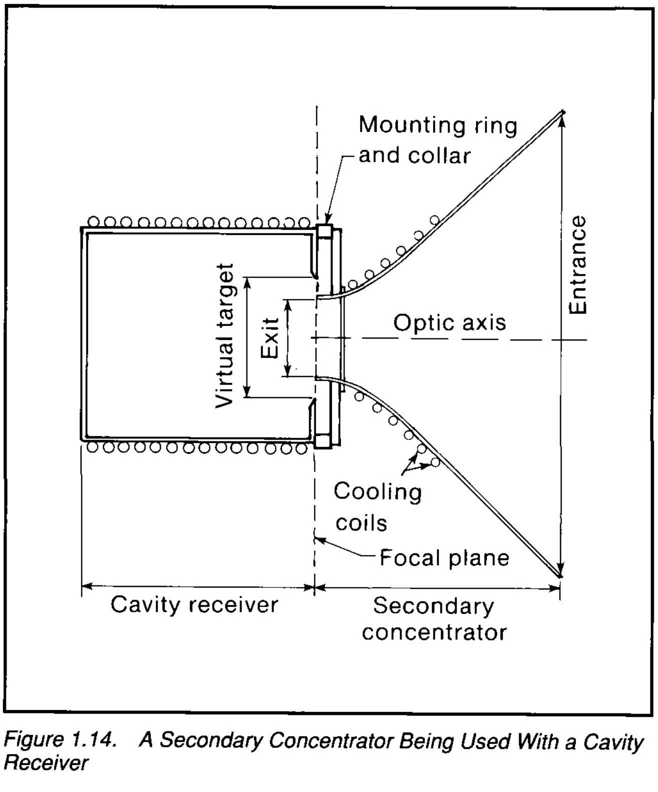


Figure 1.14. A Secondary Concentrator Being Used With a Cavity Receiver

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 (Figure 2.1). Support structure is built to hold the curvature. A black metal tube, usually covered with a larger diameter glass tube to reduce heat loss, 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 **advanced** 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.

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

Concentrator

Because the parabolic trough is parabolic in only two dimensions, it only requires tracking about a **single axis** (the focal line axis) to keep the sun's rays focused. When tracked about only 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 and there is no cosine loss. In the morning and evening, the angle between the sun's rays and the aperture is great and cosine loss is high. North-south oriented troughs usually have their highest cosine loss at noon and the lowest in the mornings and evenings when the sun is due east or due west.

Over the period of a year, a horizontal north-south trough field usually collects slightly more energy than a horizontal east-west field. However, the 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.

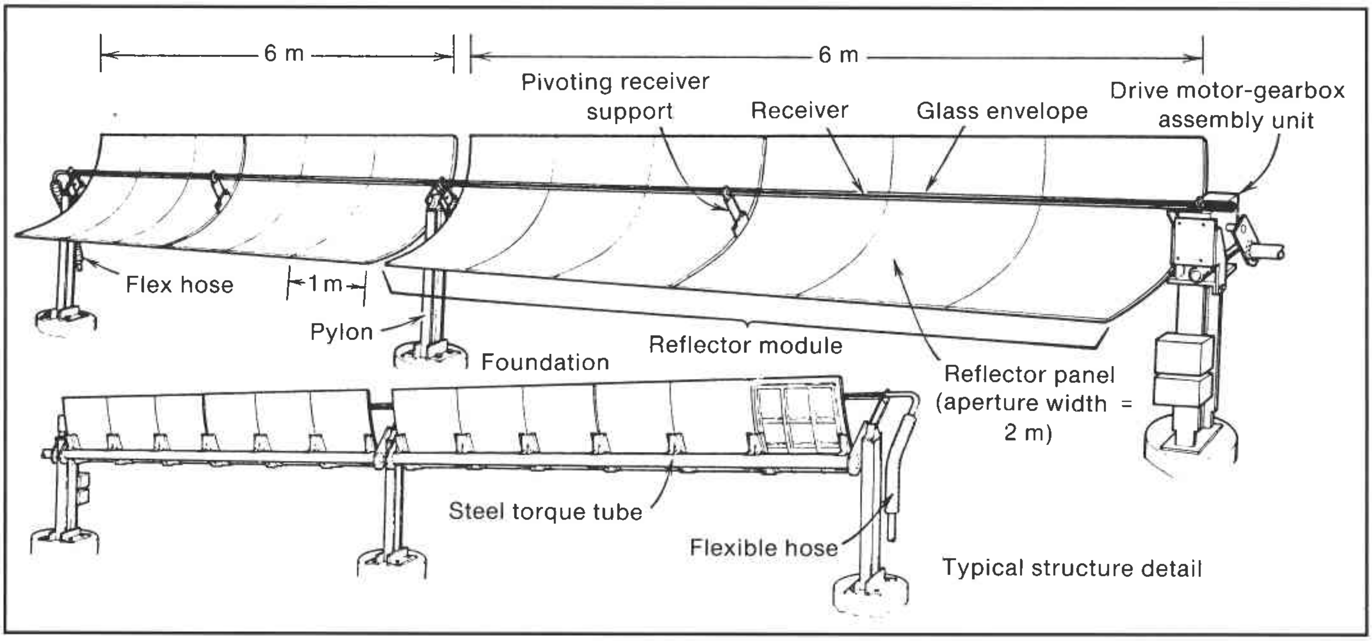


Figure 2.1. Parabolic Trough Subsystem. Half Drive String Shown

This increases the heat loss and the 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 reflective surface is required to increase the aperture area by a given amount since 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 installation cost. Current trough technology produces modules that span 20-ft (6-m) lengths and can be 6 ft to 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 or central receivers. This lower ratio occurs because insolation is reflected to a line focus instead of a smaller point focus or central receiver. 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 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, the optical performance has been found to degrade over long periods. 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 2.2). 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.

A recurring 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 the **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 because of the considerable unbalanced load of the concentrator.

Trough Development

Because the technology of manufacturing parabolic troughs and designing systems incorporating them is more advanced than 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** now range to **600°F** (315°C). However, effort is still being directed toward reducing unit costs and increasing the performance and reliability of the collectors.

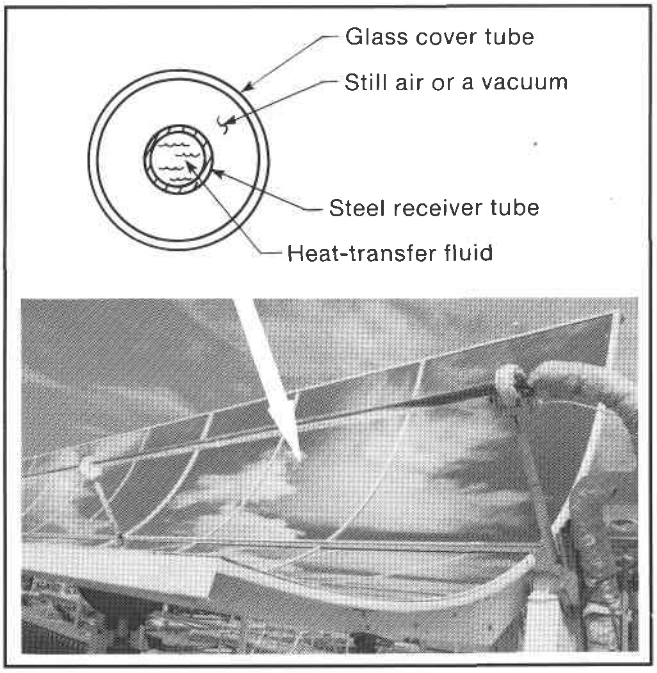


Figure 2.2. Glass-Enclosed Receiver Tube

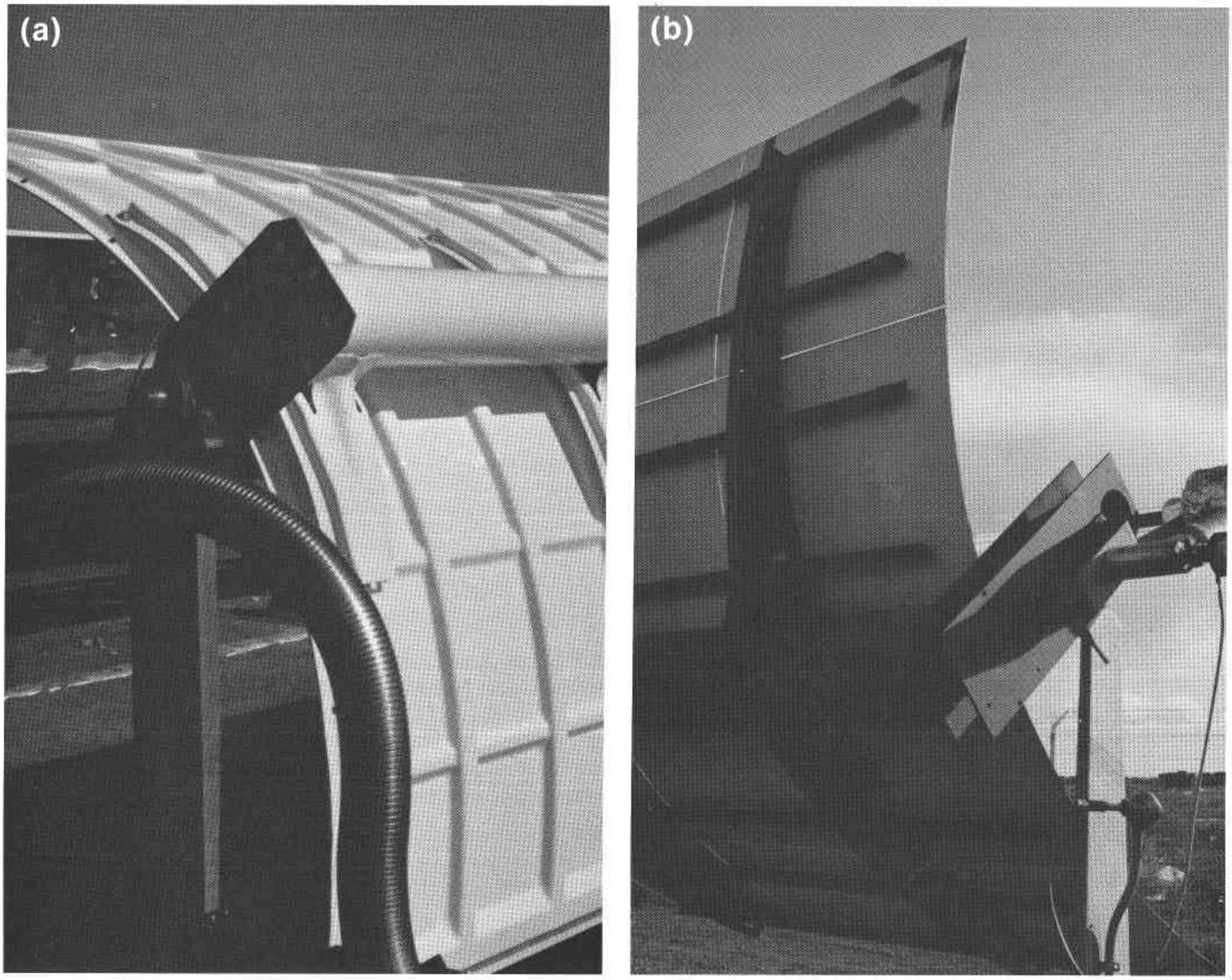


Figure 2.3. A Stamped Ribbed Sheet Metal Parabolic Trough (a) and a Sagged Glass Parabolic Trough (b)

One method of reducing the cost of troughs or any collector being manufactured is to design it so that it can be easily **mass produced**. Generally, 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 mass production of parabolic troughs, a study of mass manufacturing techniques revealed numerous techniques that promise considerable price reduction and production rate increase. One such technique involves using a **stamped ribbed sheet metal** panel to provide a rigid parabolic substructure onto which a glass reflector is bonded (Figure 2.3a). Another mass production approach involves the use of rigid mirrored glass, **sagged** into a parabolic shape and supported by a lightweight structure (Figure 2.3b).

System Experience

Several parabolic trough solar thermal systems have been built and operated throughout the United States (Figure 2.4). Most of these systems provide **process steam** to an industry. They displace fossil fuels such as oil or natural gas as the energy source for producing steam. These systems incorporate fields of parabolic troughs having total **aperture areas** of from **5400 ft^2** to **54,000 ft^2** (500 m^2 to 5000 m^2). Most of these systems supply process steam from **300°F** to **400°F** (150°C to 200°C).

The most current example of power production using parabolic troughs is the **Solar Electric Generating Station (SEGS)** at Daggett, California (Figure 2.5). This is presently the world's largest solar power plant. 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 glass-cover receivers. An oil-based, heat-transfer fluid is used along with a dual-tank thermal storage to extend the operating period. Steam is generated with the heat-transfer fluid and superheated in a natural-gas heater. The superheated steam goes through a turbine, producing electricity for the Southern California Edison grid. 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.

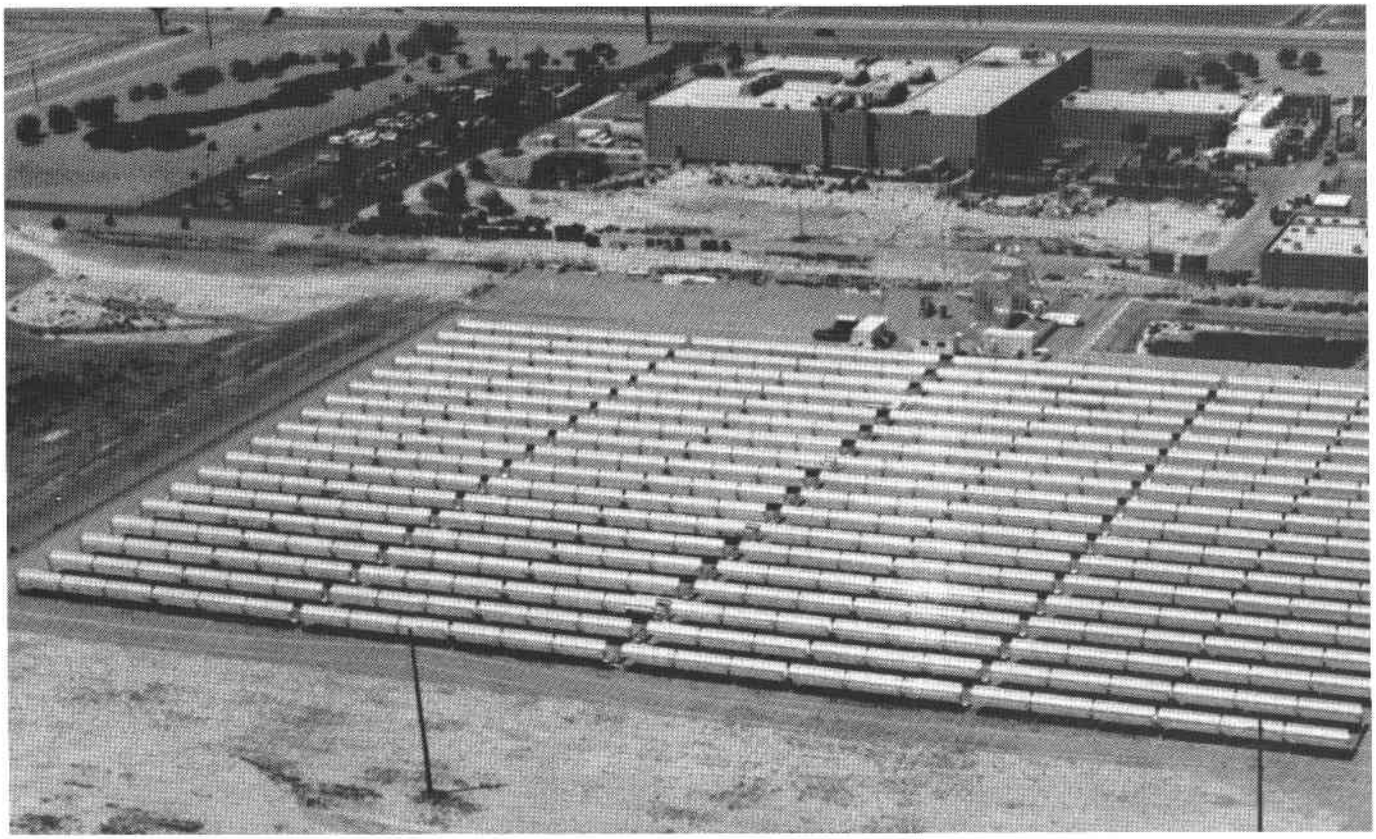


Figure 2.4. Trough Industrial Process Heat Experiment at the USS Chemical Company, Haverhill, Ohio

Figure 2.5. The Solar Electric Generating Station (SEGS) at Daggett, California

Chapter 3
The Parabolic Dish

Concentrators

A parabolic dish (Figure 3.1) must always point directly toward the sun for proper focusing. Therefore, there is no cosine loss ($\cos \theta_i$ in the **fundamental solar collection equation**) to reduce the collector performance since the angle of incidence θ_i is always zero. To maintain a focus, the dish must be tracked about two axes. Most tracking schemes fall into one of two categories: 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 axis 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.

Since parabolic dishes have the potential for small receiver aperture area, A_{rec} at **high solar concentration**, they can be operated at high temperatures without losing too much energy (given by the right-hand terms in the **fundamental solar collection equation**). Therefore, dishes are prime candidates for operating high efficiency **power cycles to make electricity**. Although parabolic dishes are capable of concentration ratios exceeding 10,000, concentration ratios of 1500 or less are needed for power cycle applications.

A special consideration when selecting the reflective material for a dish is that the surface curvature be **compound** (in two dimensions) and that the rim angles are usually around 45°. These require 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 onto supporting surfaces. To overcome this difficulty, early parabolic dish technology used smaller reflective segments called **facets** for many prototypes (Figure 3.2).

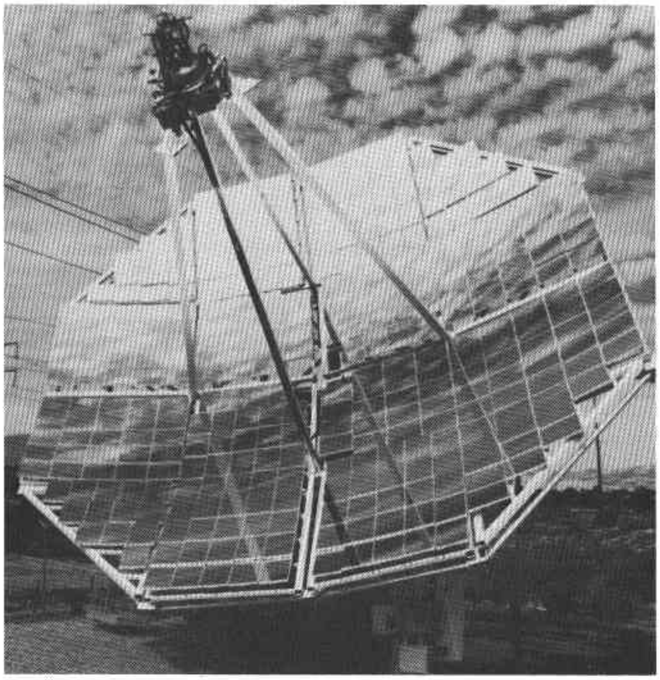


Figure 3.1. Parabolic Dish With a Receiver/Engine Mounted at the Focus

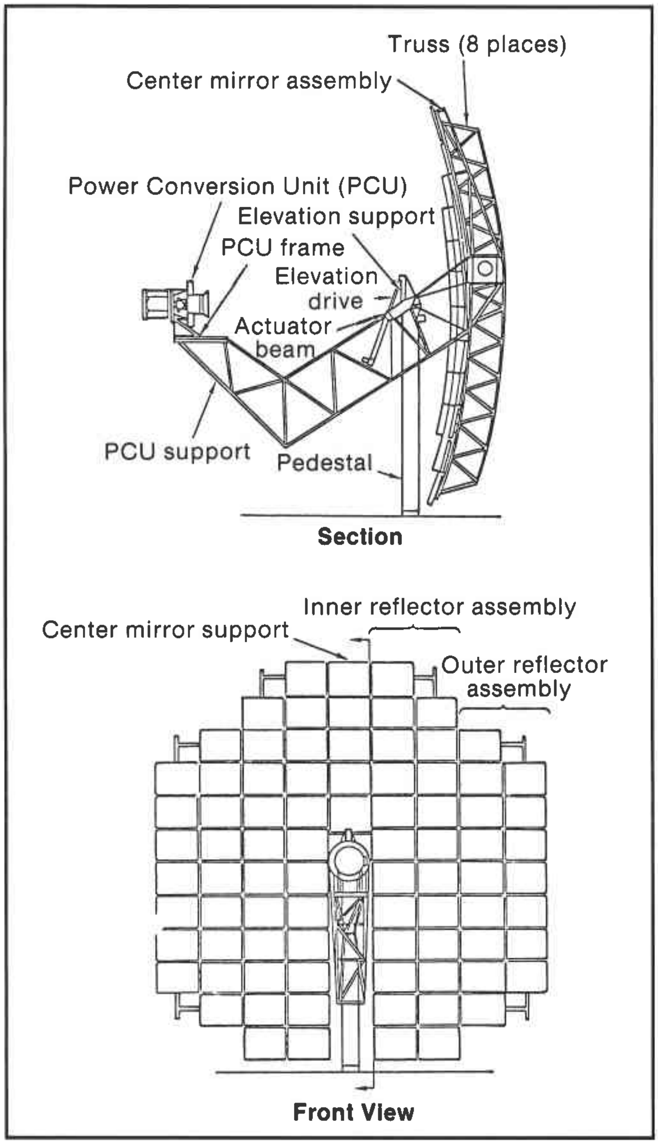


Figure 3.2 Faceted Parabolic Dish Concentrator With Engine at Focus

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

Component evolution. Many variations of concentrator construction have been proposed and tried during the solar thermal development program (Figure 3.3). Early dish concentrators used slightly curved glass mirror facets on a lightweight supporting structure where each **facet** was individually adjusted to focus onto 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 another approach, the paraboloid is divided into several pie-shaped segments called **gores**. These have a long radius of curvature which enhances 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 3.4).

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 3.5). The tracking elements are rotatable slats

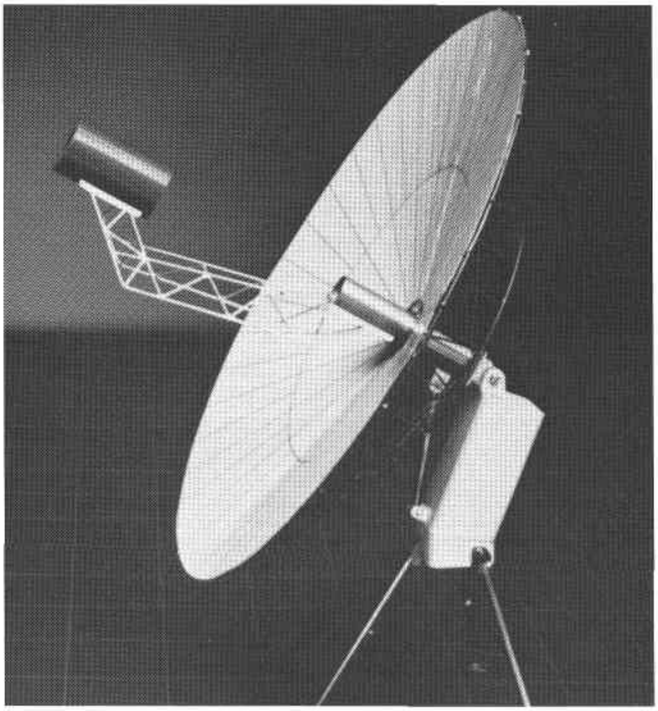


Figure 3.4. Dish Electric System With Stamped Sheet-Metal Gore Construction

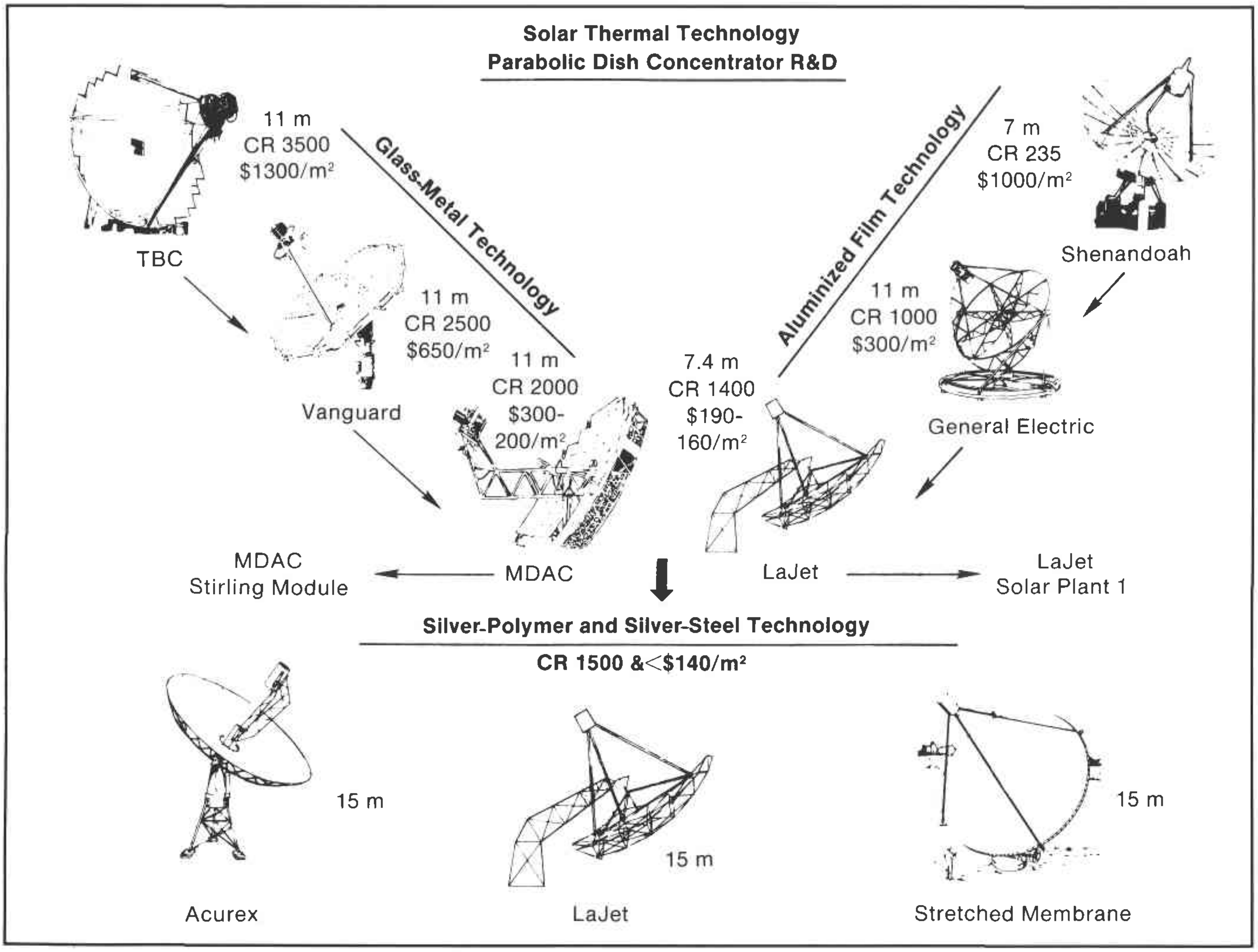


Figure 3.3. Evolution of the Parabolic Dish Solar Concentrator

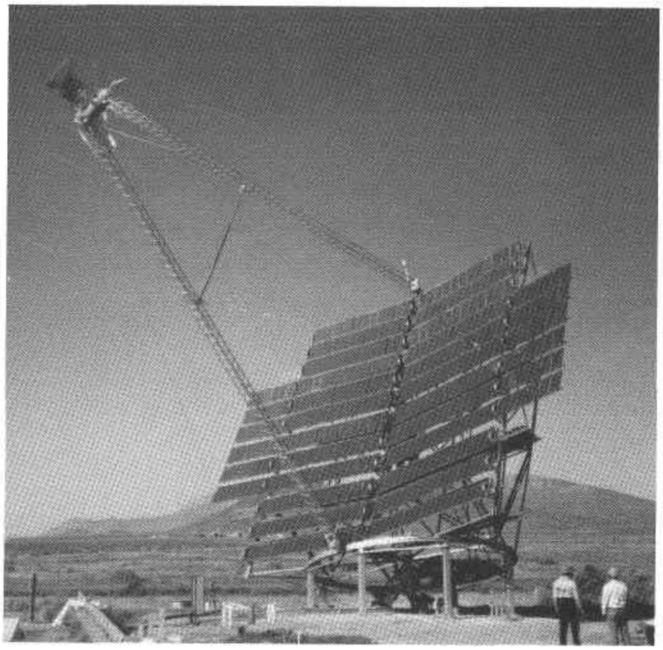


Figure 3.5. Movable Facet Point-Focus Concentrator

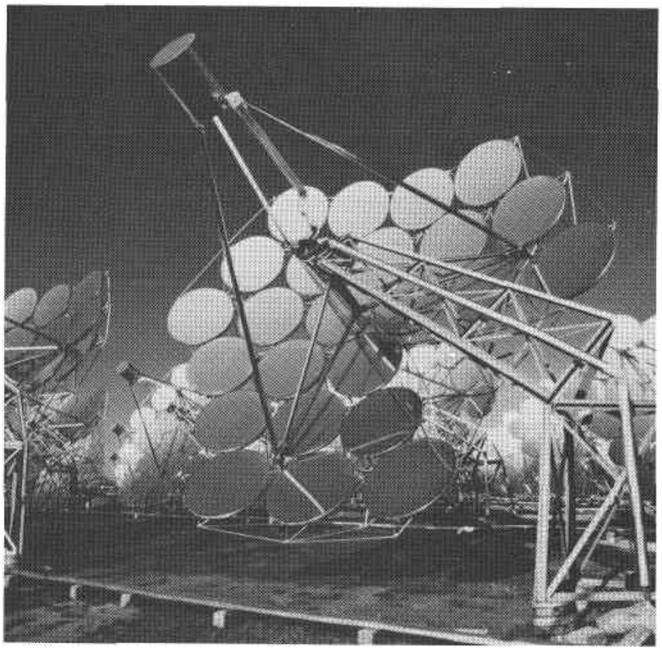


Figure 3.6. Parabolic Dish with Stretched Membrane Facets

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.

Because of the difficulties of fabricating larger dishes to reduce unit and operating costs, numerous concepts use individually focused facets mounted on a tracking lightweight support structure. One such design, known as the **stretched membrane** point-focus concentrator, uses a pair of stretched plastic film (one being reflective) over a hoop (Figure 3.6). The airspace between the membranes is partially **evacuated** so that the reflective membrane assumes a **quasi-spherical shape**. At small curvatures, there is minimal optical difference between a sphere and a parabola; therefore, the sun's radiation meeting the reflector is reflected to a small focal region. These stretched membrane facets are installed on a tracking lightweight supporting structure, and a point-focus concentrator results. A significant advantage of this concept is its simplicity and low cost.

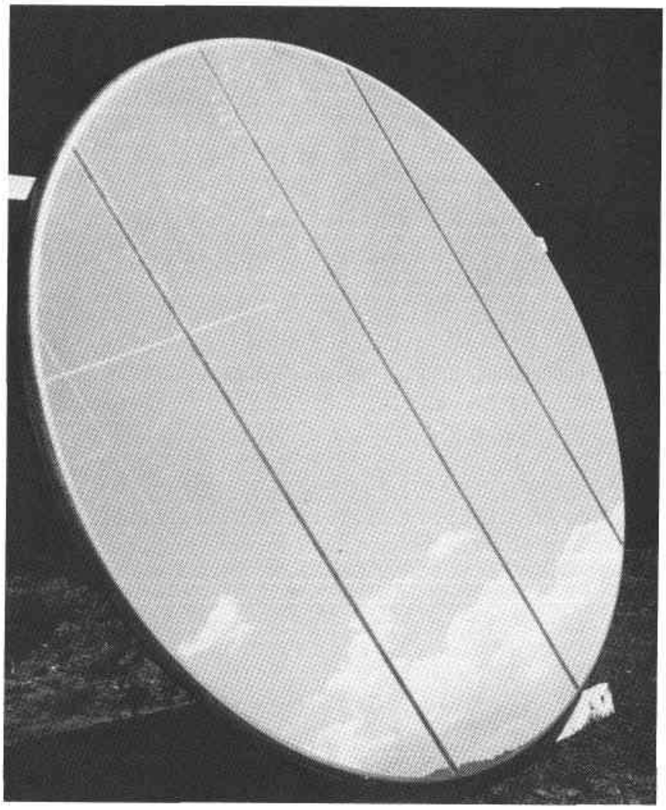


Figure 3.7. A Single Stretched Membrane Concentrator

Since the large, **stretched membrane** approach has demonstrated potential for **weight and cost reduction** of heliostats, work is currently underway to apply these technologies to parabolic dish collectors. The anticipated collector design will be of 100 m^2 to 150 m^2 aperture area, have a rim angle of about 45°, be designed to accommodate a receiver operating at 800°C, and may have from one to five facets. Because of the large rim angle (for a membrane), the manufacturing technique will most likely involve **pre-forming** of a metal, polymer, or composite membrane such that, when it is further deformed under vacuum, it assumes a nearly parabolic shape (Figure 3.7).

Receiver/Engines

The receiver absorbs the reflected sunlight and heats a fluid that passes through it. If the dish is designed to produce electricity, then the power conversion cycle (engine) can be **placed on the ground or 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 following discussion will be on these packages.

Cavity receivers (Figure 3.8) 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

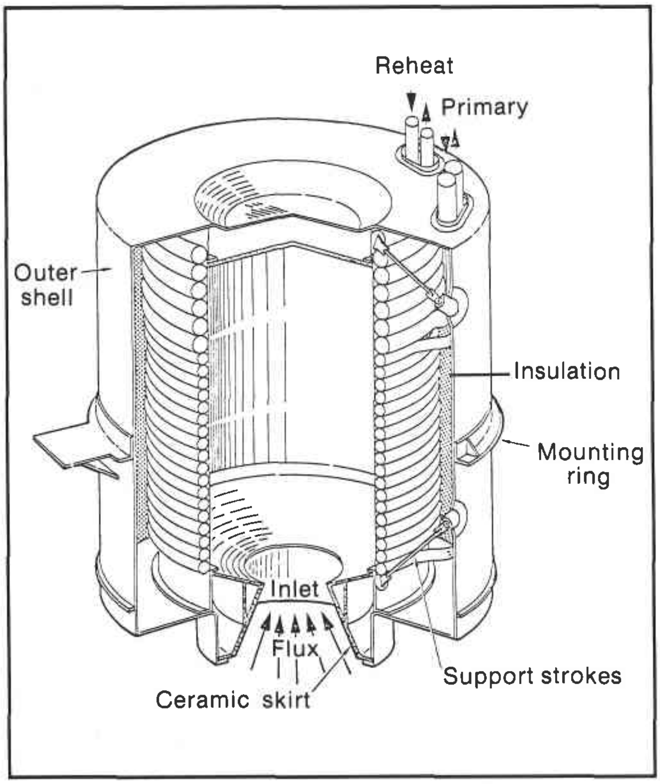


Figure 3.8. A Cavity Receiver for Rankine-Cycle Applications

where heat is transferred to the heat-transfer fluid. Reflected or re-radiated energy is partially re-absorbed 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. Covering the cavity aperture with a window to further reduce losses is required only at high temperatures. The high flux at the aperture makes longevity of aperture windows 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 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 accuracy of the concentrator surface and tracking, there is always an important design/cost trade-off when 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 (Figure 3.9), and the other incorporates a phase-change material in the cavity wall. When heated to operating temperature, either design will retain heat for times when a cloud passes over the collector and insolation is reduced.

Small engines are placed adjacent to the receiver in many applications. These engines are approximately 25-50 kW_e to match the capabilities of the concentrator. Three types of engines have been or are being considered for application to dish concentrators: (1) the **Rankine cycle** (both steam and organic working fluids), (2) the **Stirling cycle** (both kinematic and free-piston), and (3) the **Brayton cycle**. 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 an 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 1830°F or 1000°C) and, therefore, supply heat to high performance engines. A

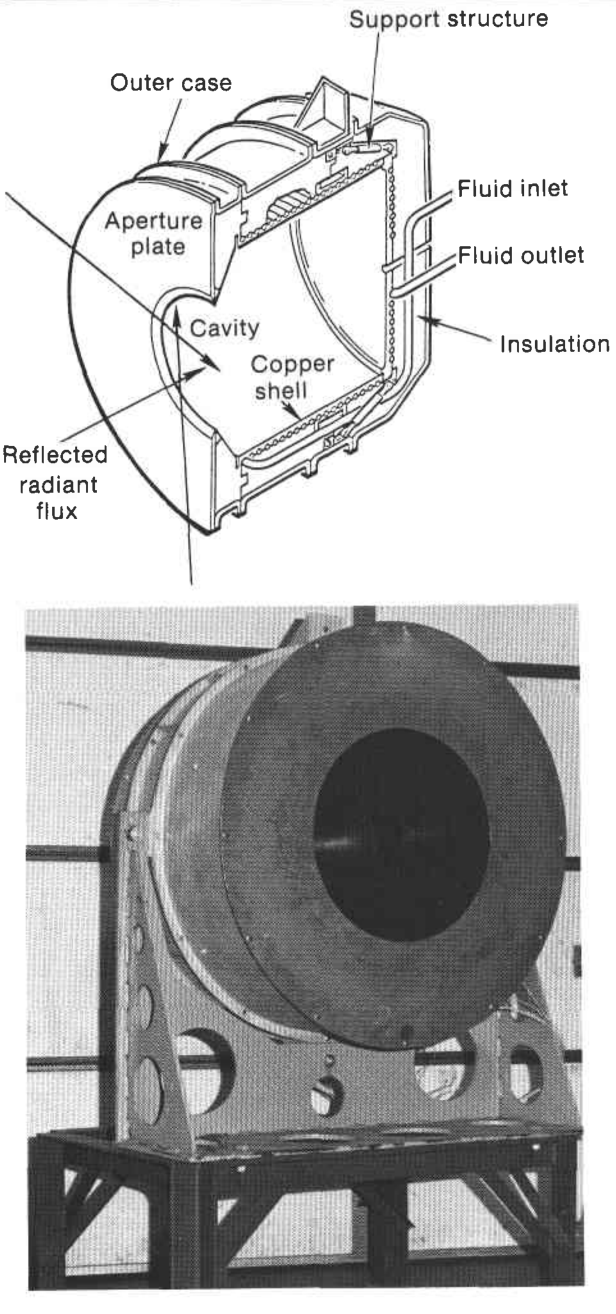


Figure 3.9 Cavity Receiver with Copper Mass Buffer Storage

second major issue is the development of **reliable, low life-cycle cost** 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 loss, attempts are being made to design compact receivers with high heat transfer rates from the absorbing surface 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 3.10). It is then condensed on the tubes containing the engine's working fluid and flows by gravity back to the receiver.

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. Even in a short time the high intensity beam can cause damage to the receiver and its support structure. 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 development. Receiver/heat engine design technology is aimed at using the high temperatures from a dish solar concentrator.

A 25-kW_e **Rankine cycle engine** using an **organic working fluid** and connected directly to a cavity receiver has been developed and tested (Figure 3.11). 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 a Rankine cycle, because its high molecular weight 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 23%.

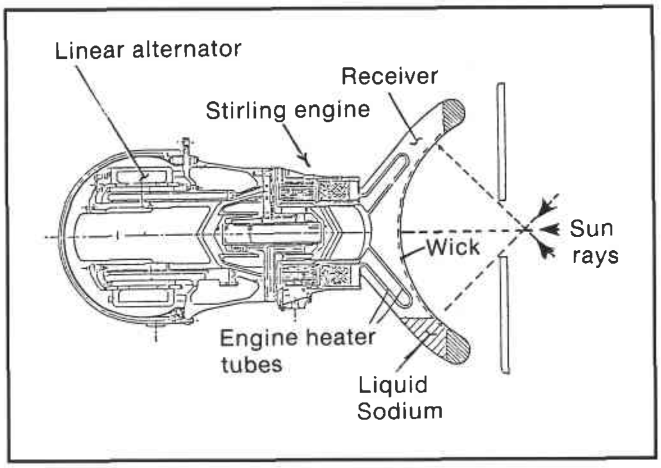


Figure 3.10. Cavity Receiver Using Heat-Pipe Technology Adjacent to a Stirling Engine

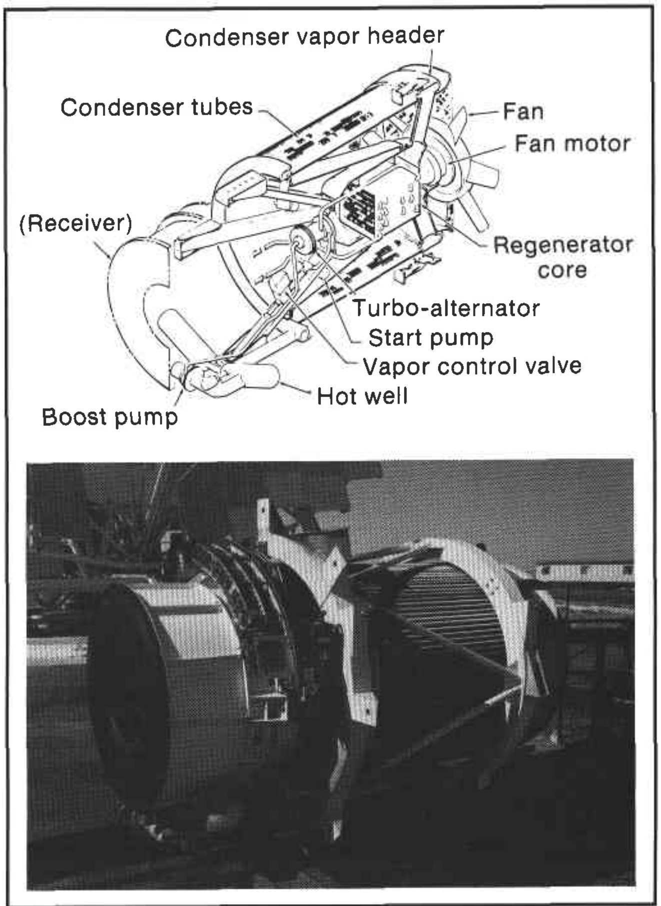


Figure 3.11. A 25-kW$_e$ Organic Rankine Cycle Receiver Module

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 the 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 connected directly 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 called a **free-piston Stirling engine**, which uses a piston that is free to **bounce** back and forth, with no mechanical connections, on "gas springs" located at either end of the cylinder. 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-kW$_e$ **kinematic Stirling engine** mated with a cavity receiver has undergone extensive testing and is being marketed (Figure 3.12). It is a four-cylinder engine using hydrogen as the working fluid. The engine operates 29.4% at a temperature of 1330°F (720°C) at a cycle efficiency of 40%. Having a system of 29.4%, this is the highest solar energy to electricity conversion efficiency ever achieved.

An important issue with the kinematic Stirling engine design 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 and the piston rings. Although not expensive, it requires that the engine be disassembled for their replacement. Extension of seal and ring lifetimes to periods acceptable for remote site daily power generation is proceeding.

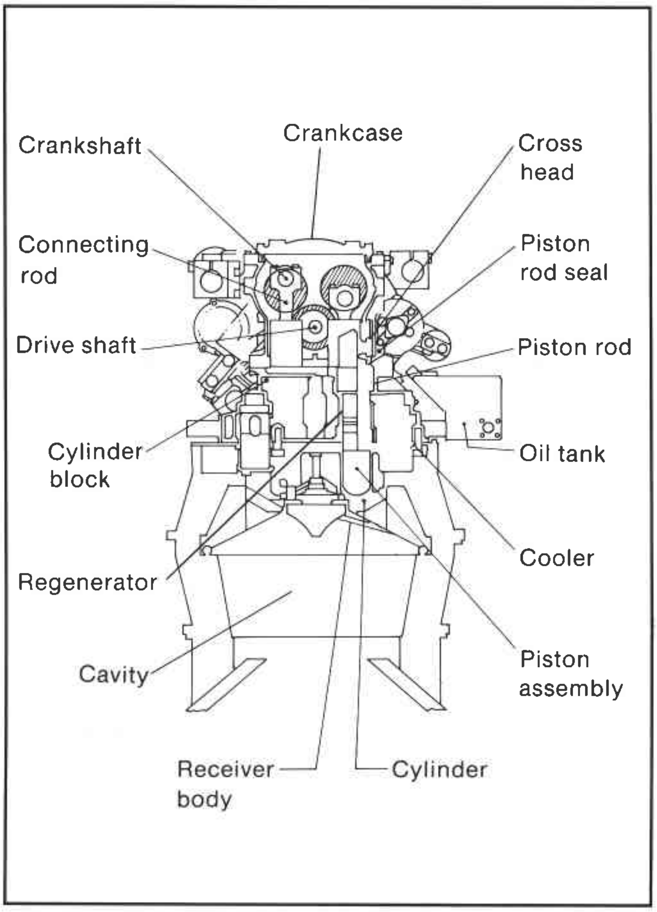


Figure 3.12. A 25-kW$_e$ Kinematic Stirling Engine Receiver Module

Free-piston Stirling engines have only 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 3.13). Since the entire engine contains the working gas and only electrical power leads penetrate the case, gas-sealing problems are minimized. Larger (25 kW$_e$) 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 (1500°F - 2500°F or 800°C - 1400°C) required to operate these engines at high efficiencies. Receivers at these temperatures are less efficient than receivers operating at lower temperatures. Operating at these temperatures exceeds the capability of materials currently used in solar receivers and development of high temperature materials, probably ceramics, will be required.

System experience. Four major dish system experiments are currently being evaluated. 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 preparation of hardware.

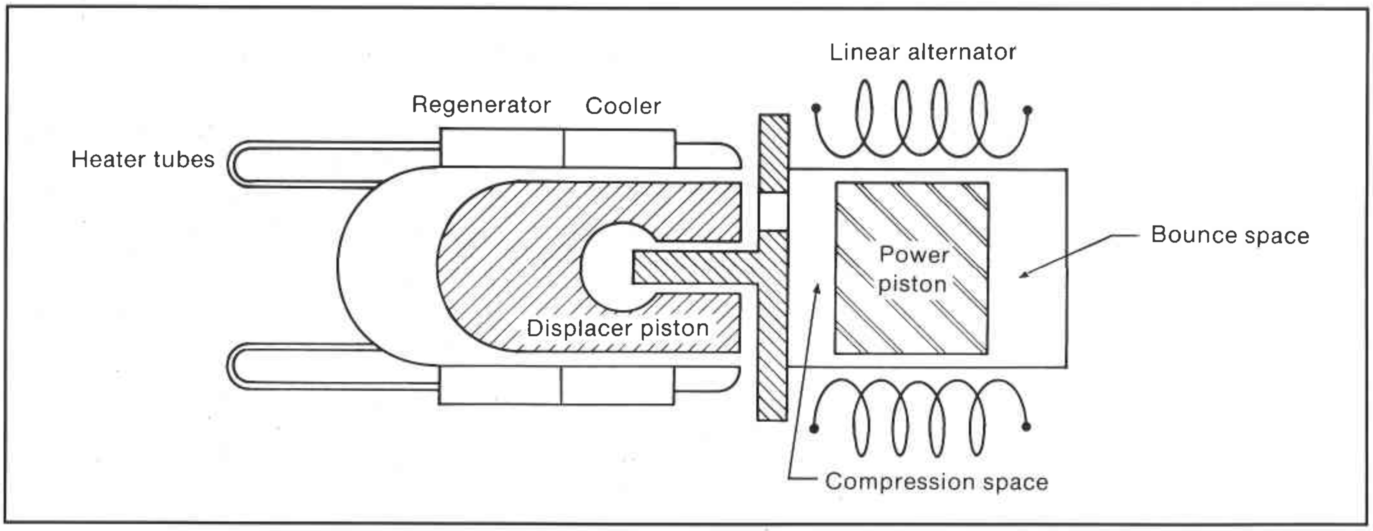


Figure 3.13. Schematic of a Free-Piston Stirling Engine

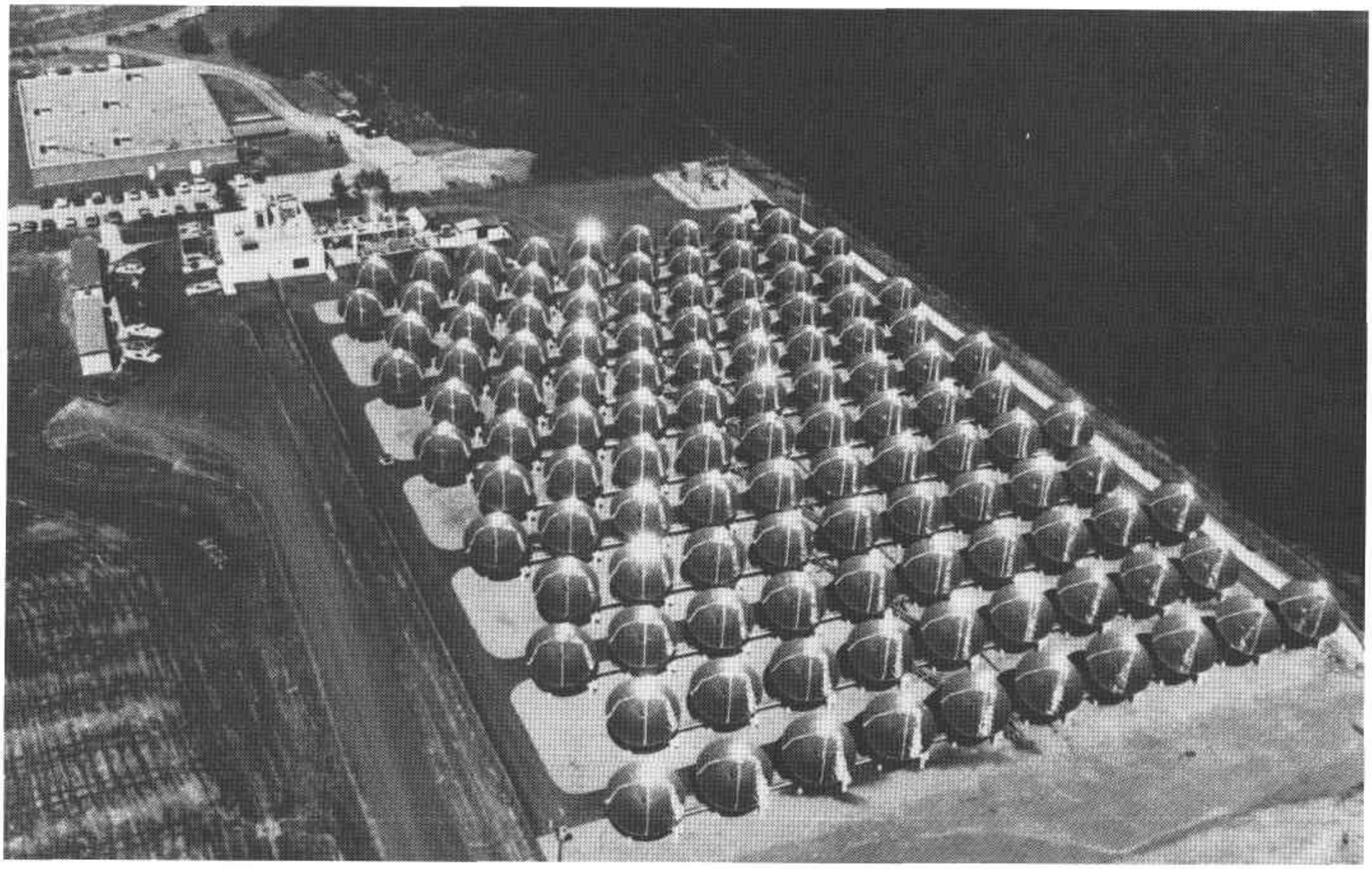


Figure 3.14. Solar Total Energy Project at Shenandoah, Georgia

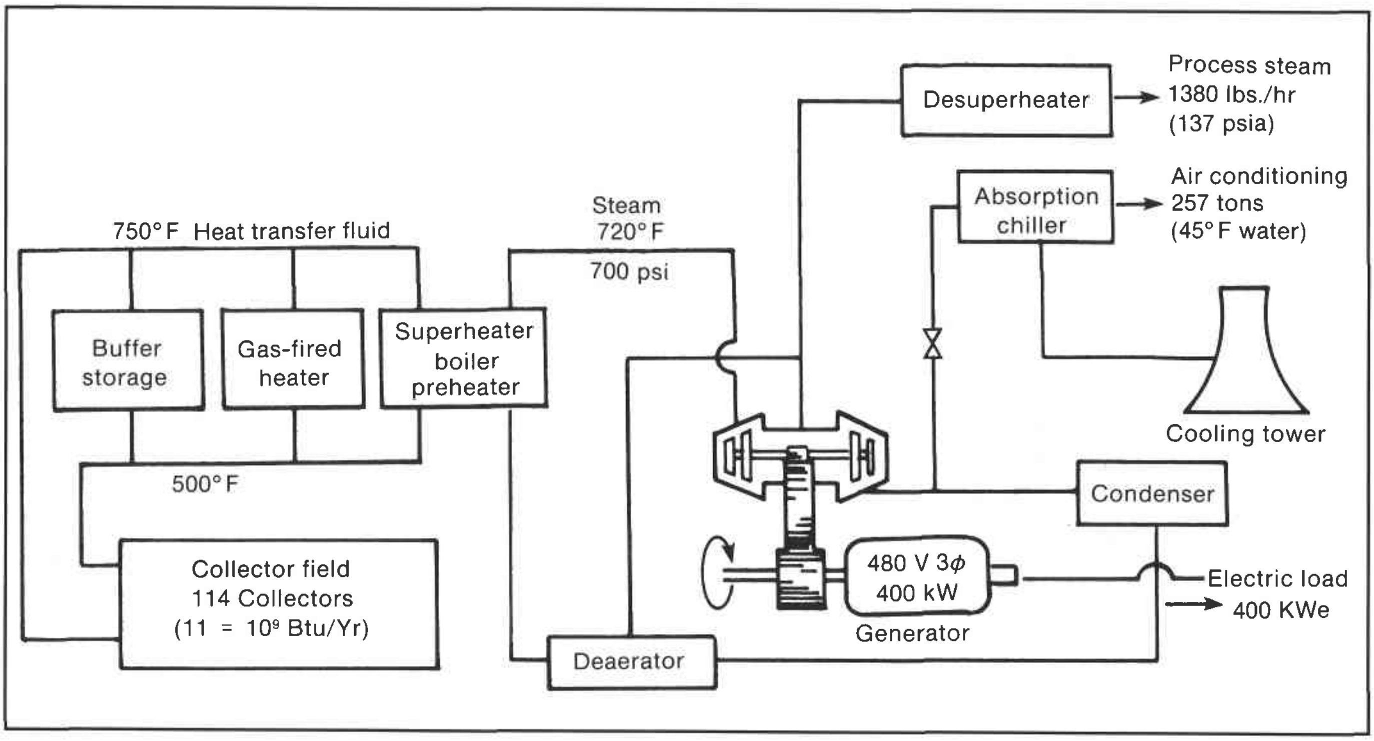


Figure 3.15. Schematic Diagram of the Solar Total Energy Project

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 (4352 m^2) that supplies 750°F (400°C) heat to a central steam Rankine power generation cycle (Figures 3.14 and 3.15). This cycle, operating at 720°F (382°C), produces up to 400 kW$_e$, 1380 lb/hr (626 kg/hr) of 100 psi (700 kPa) process steam and 468 kW$_t$ (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 an absorbing surface as 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 (400°C) and the heated fluid from each collector is pumped through insulated piping to the central total energy cycle.

SOLARPLANT I (Figure 3.16) is a privately financed electric power production facility located in Warner Springs, California. 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 power unit that produces 4.9 MW_e under peak insolation conditions. This represents a peak solar-to-electric efficiency of 17%.

Each collector incorporates twenty-four 5-ft (1.5-m) diameter stretched membrane facets mounted on a lightweight support 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 axes. Cavity receivers are used which have a 10-in. (0.25-m) diameter aperture and incorporate a small amount of phase-change salt to provide buffer storage for the system.

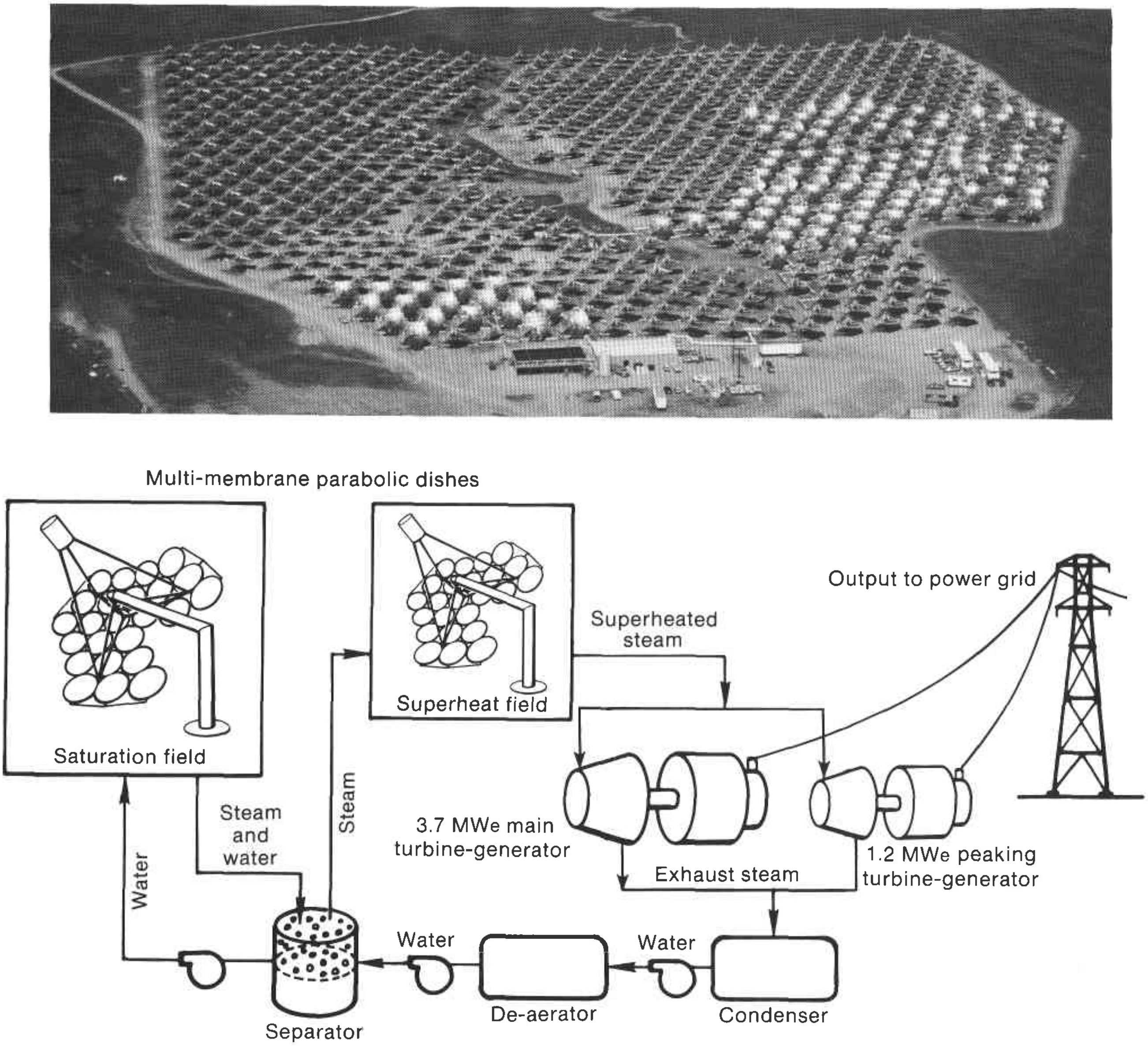


Figure 3.16. SOLARPLANT I at Warner Springs, California

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

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, will provide a maximum of 100 kW$_e$ (Figure 3.17). 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 kW$_e$. Movable-slat point-focus concentrators will be used. Five 3230-ft^2 (300-m^2) concentrators are proposed for this project, with thermal receivers that will supply steam to five 50-kW$_e$ 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.

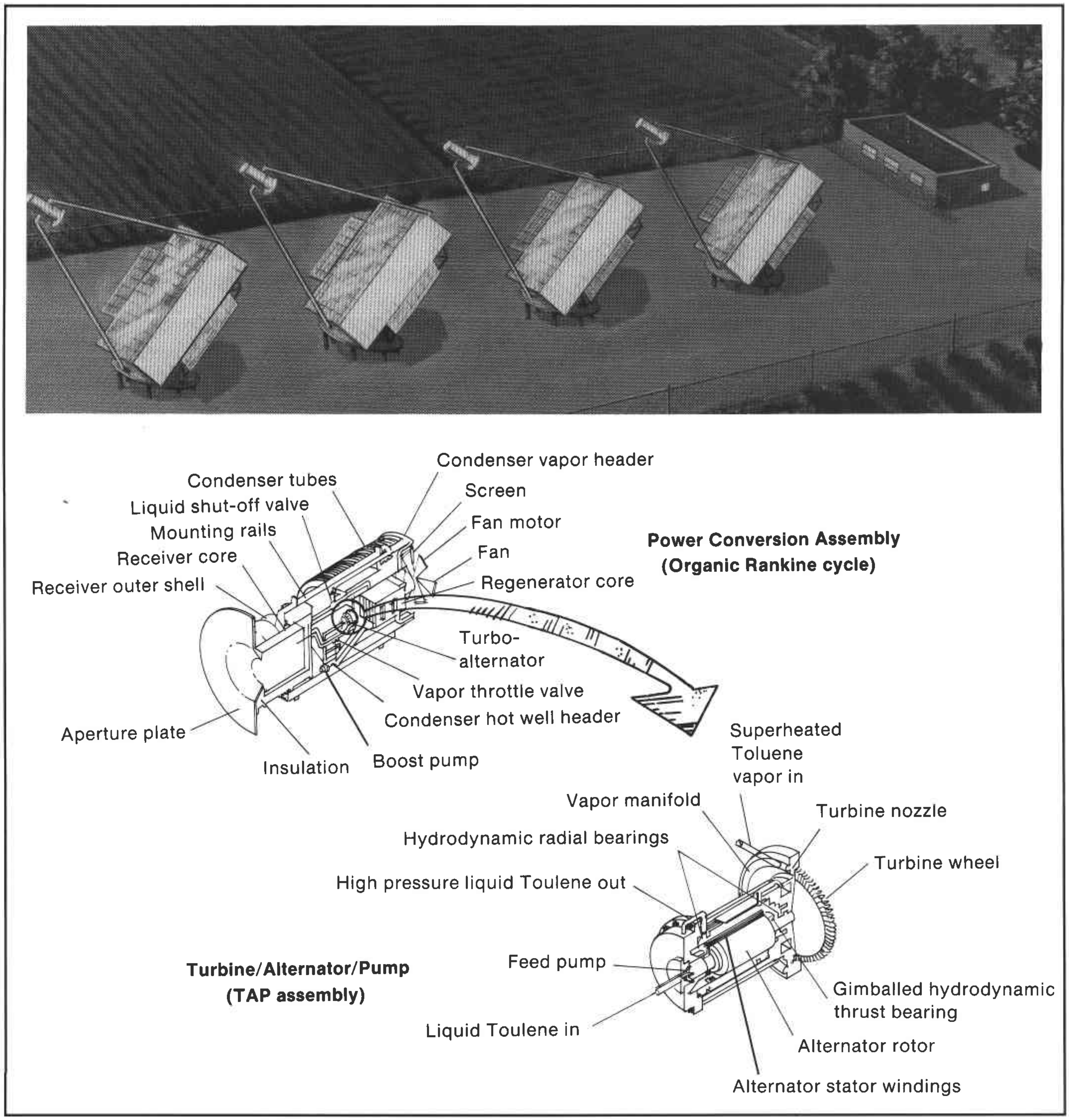


Figure 3.17. Concentrators and Power Conversion Modules for Small Community Solar Experiment at Osage City, Kansas

Chapter 4
The Central Receiver

A typical solar thermal central receiver system is shown schematically in Figure 4.1. The major components include the **heliostat field**, the **receiver**, and the **power conversion system.** A **thermal energy storage** is incorporated in the system shown as it is at the Solar One central receiver system at Barstow, California.

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. A goal 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 it reduces the **cost** of each heliostat per unit area.

A typical heliostat consists of a reflective surface on a frame (Figure 4.2) that is tilted up and down (**elevation**) and rotated around its base (**azimuth**) by small motors. The entire structure is mounted on a pedestal that is set firmly into the ground.

Technical issues. The performance of heliostats encompasses many of the parameters defined in the **fundamental solar collection equation** such as

A_{app} = active (not shaded or blocked) 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 **active** heliostat reflective surface area, multiplied by the number of heliostats in the field. Because incoming sunlight is sometimes **shadowed** by adjacent heliostats, or **blocked** after being reflected (Figure 4.3), the shaded and blocked area of a heliostat is not included as part of this active area. Blocking and shadowing vary with sun angle and heliostat location. The energy output of a central receiver field is proportional to the total active reflective area of heliostats. This area is appreciably less than the land area covered by the heliostat field.

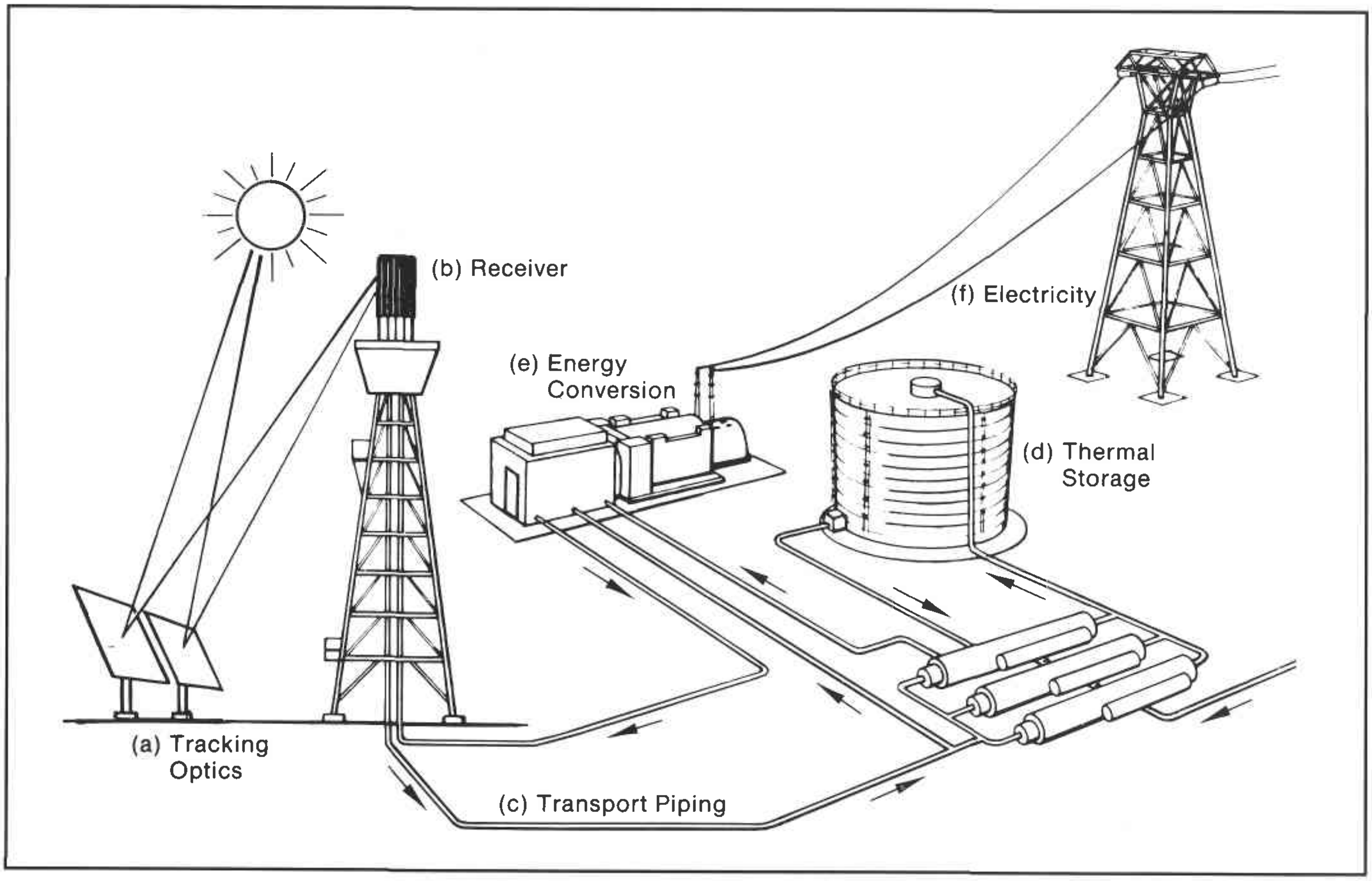


Figure 4.1. Solar Thermal Central Receiver System

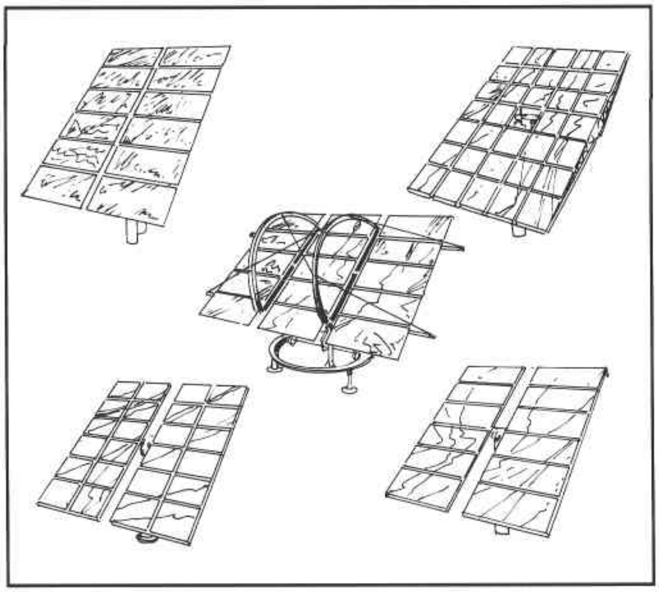


Figure 4.2. Various Heliostat Designs

The effective surface area of a heliostat is also reduced by the **cosine effect** (Figure 4.4). Because heliostats are aimed half-way between the sun and the receiver, the area on which the sunlight falls is reduced by the cosine of the angle between the heliostat's pointing direction and the sun. This angle is different for each heliostat in a field and varies with time. The term cos θ_i in the **fundamental solar collection equation** reflects the average cosine "loss" in system performance.

Heliostat surfaces of high reflectance ρ are used, similar to any concentrating collector. Washing is necessary to remove dirt accumulation so that reflectance 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 location 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 is economically possible, to reduce **spillage** of light from the receiver. For a given receiver size, 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.

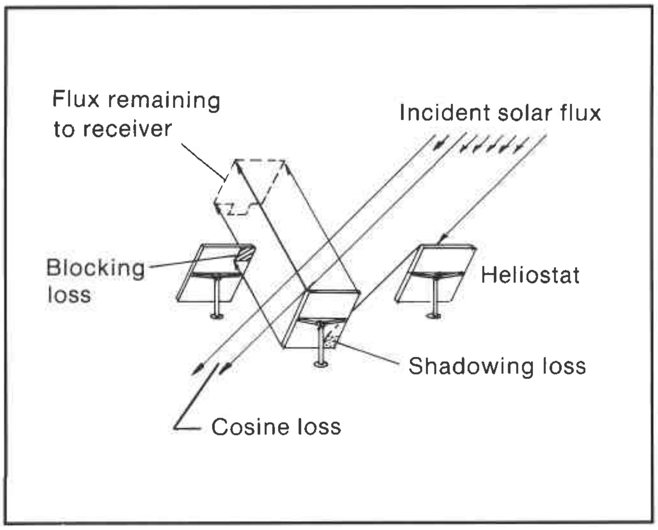


Figure 4.3. Shadowing and Blocking Loss of Solar Flux

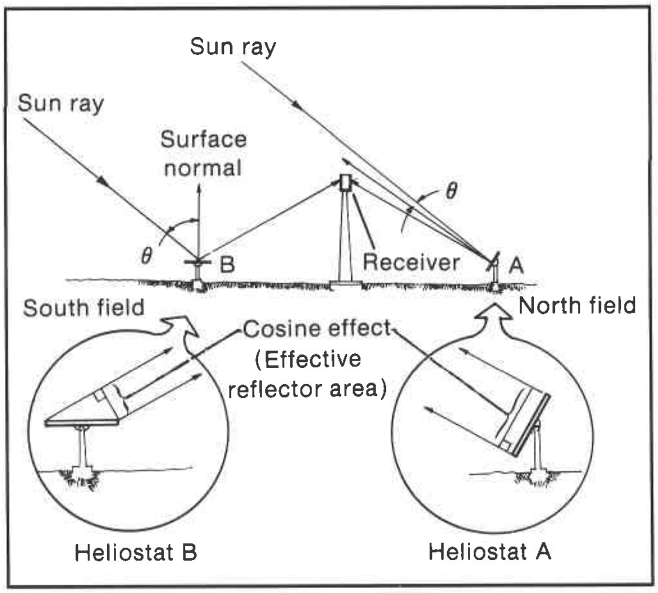


Figure 4.4. The Cosine Effect for Two Heliostats in Opposite Directions From the Tower. For the noontime sun condition shown, heliostat A in the north field has a much greater cosine efficiency than does heliostat B.

A goal in **heliostat development** is to **increase the size** and **reduce the weight** per unit area. Weight, in general, indicates the amount of materials used and, therefore, the cost. If the weight of the mirror panel can be reduced, then 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 heliostats, back-surface glass mirrors are bonded to a substrate backing forming a slightly concave-surface mirror module. These mirrors are then supported on a frame that is attached to a torque tube which attaches to the drive motors (Figure 4.5). Figure 4.6 shows heliostat development from the first design used in Sandia National Laboratories Central Receiver Test Facility (CRTF) to designs that are currently being fabricated and tested.

Stressed membrane heliostats hold promise for providing lightweight units with large reflecting surfaces at a low cost (Figure 4.7). In this concept, a high-strength **structural membrane**, coated with a highly reflective surface, is stretched uniformly on a frame (typically a lightweight hollow structure). The stressed membrane concept is a method of attaining and supporting a large, optically accurate surface, which results in lighter weight and lower cost structures than are currently available. This concept is also especially suitable for the use of polymer reflectors and structural membranes, which may result in further weight and cost reductions and improvements in handling at the factory, in transport, and in the field.

Two scaled-down prototypes of 150-m^2 heliostats are currently under test. For one, the reflector is fabricated of a ring, faced front and rear with a tensioned, 0.010-in. (0.25-mm) thick **aluminum membrane**. In the other

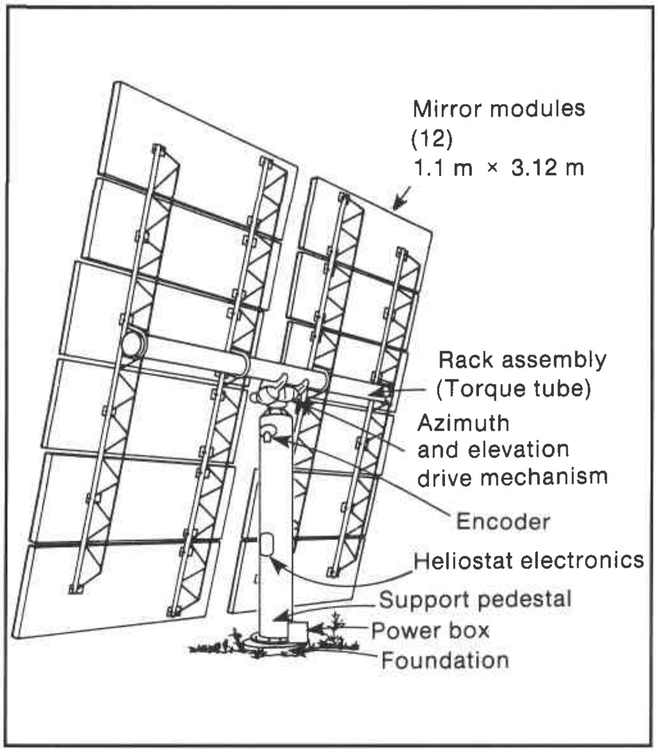


Figure 4.5. Back Side of a Heliostat Used at Solar One

design, a large toroidal ring of 25-cm (10-in.) pipe supports a 0.003-in. (0.0762-mm) **stainless steel membrane**. For both designs, a reflective film is laminated to the outside surface of one membrane. By applying a slight vacuum to the space between, the membranes move to a concave shape that provides focusing. **Defocus** may be achieved rapidly by opening to ambient pressure or even pressurizing the space between the membranes. The strength of the membrane couples with the ring to improve stability and stiffness of the heliostat.

Receivers

Although the heliostat field represents the greatest single 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. Receiver technology development is directed toward optimizing them.

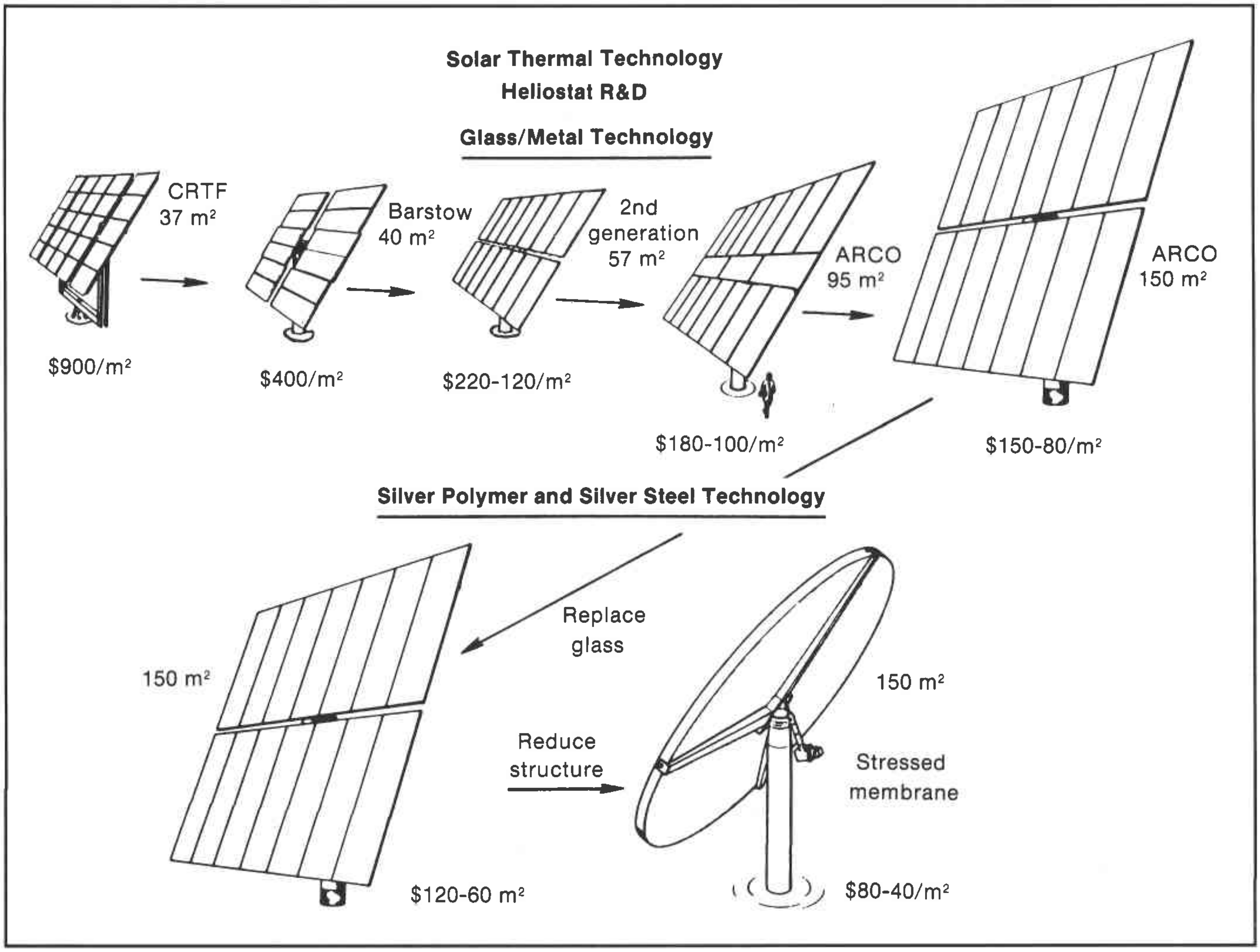


Figure 4.6. Development of Heliostat Technology

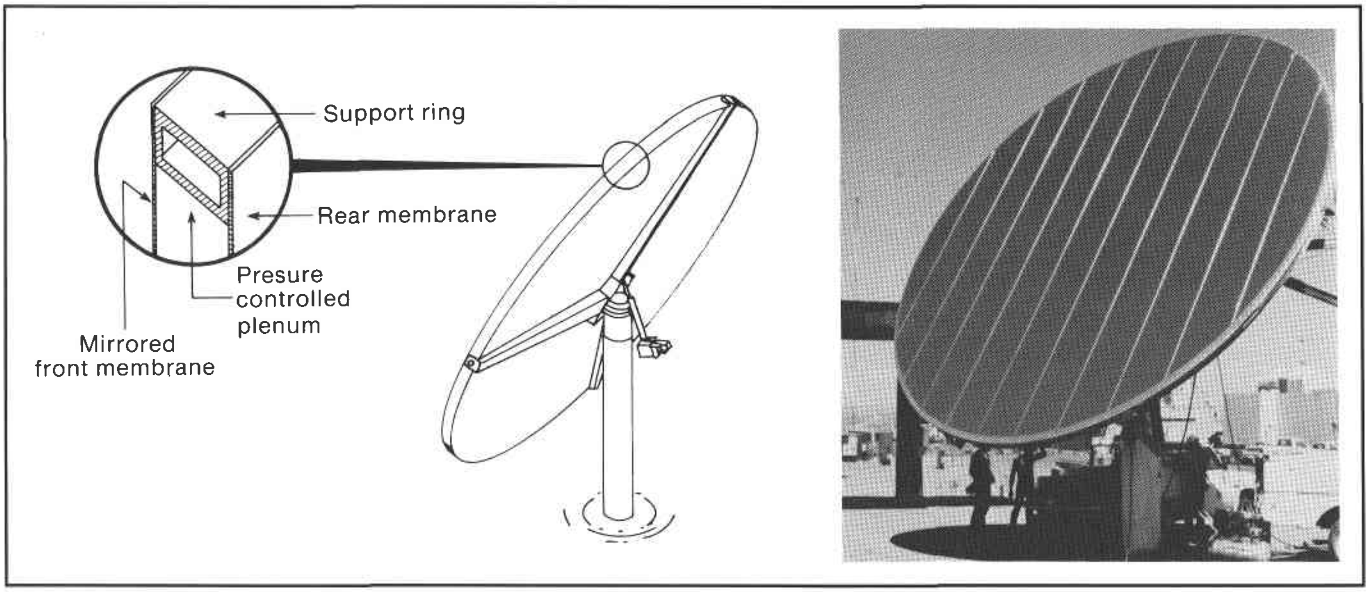


Figure 4.7. A Stressed-Membrane Heliostat

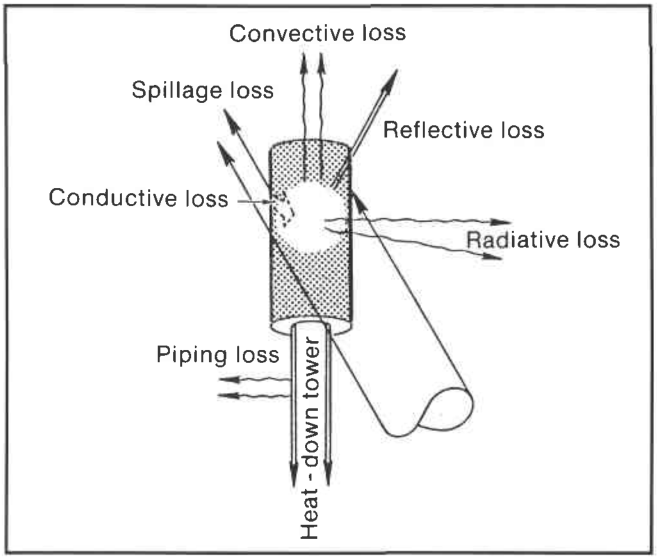


Figure 4.8. Receiver Heat-Loss Modes

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

The power cycle performance is related directly 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.

The great 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 radiation 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 great spillage losses.

The capture factor Φ is affected by both the heliostat field and the receiver. Poor heliostats with large surface errors or tracking tolerances, or when placed far away from the receiver, will produce a **large focal point** 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**, the **maximum allowable flux**, 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 is governed by the interaction between receiver and heliostat field design. One other optical parameter affecting the design of a receiver is the receiver absorptance α. This is typically enhanced by painting the absorbing surface with a flat black, high-temperature paint.

The overall convective and conductive heat loss coefficient U is a measure of how easily a receiver loses heat by convection and conduction (Figure 4.8). Both losses increase with temperature difference.

Under some conditions, the **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 radiating area smaller. However, a cavity receiver has a larger **heated surface area** which increases convective loss. Depending on operating temperature, tradeoffs between **efficiency** and **cost** must be made. It has been determined that external receivers using sodium or molten salt are more effective at temperatures below 1100°F (600°C). Figure 4.9 shows designs of both the external and cavity type receiver.

Conduction loss is a function of how large the heated area is, and the amount of insulation between these surfaces and the outside air. Conduction losses are also minimized by keeping the number of **attach points** from absorber panels

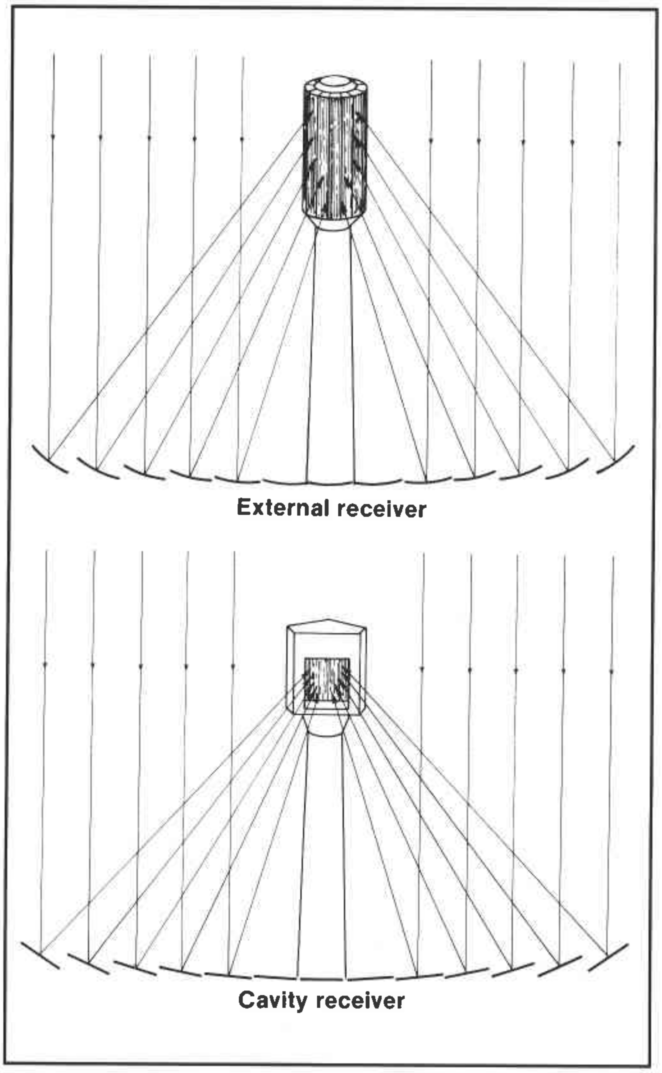


Figure 4.9. Two Types of Central Receivers

to structure at a minimum. The attach points are usually made of stainless steel which has a low thermal conductivity.

Receiver research and development activities have concentrated on finding the best cost/performance receivers for 1100°F (600°C) systems that either produce electricity through coupling with Rankine-cycle steam turbines, or intermediate temperature industrial process heat. **Experimental receivers** have been designed, built, and tested using water/steam, molten salt, liquid sodium, and air as the heat-transfer fluid. 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.

The **Solar One** receiver is an external receiver located at the top of a tower (Figure 4.10). 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 1680 1/2-in. (12.7-mm) diameter heavy-walled Incoloy-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-MW_t **molten salt receiver** was built and tested at the Central Receiver Test Facility in Albuquerque (Figure 4.11). The receiver heats a salt mixture entering at 550°F (288°C) up to 1050°F (566°C). This 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 ft by 18 ft (4 m by 5.5 m). Over 500 hours of testing resulted 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 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 well above ambient.

A 5-MW_t salt receiver has been tested successfully in two separate programs at the Central Receiver Test Facility in Albuquerque. In the second series of tests, it was part of a complete electrical power generating system including storage. Considerable experience has been gained in the use of molten salt as a heat-transfer fluid with this receiver and with others currently on test in Albuquerque and in France.

A **sodium-cooled** experimental receiver also has 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) outside 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 (590°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, thereby reducing heat loss. As with molten salts, sodium is also a 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 was operated at the International Energy Agency project in Almeria, Spain. This receiver had an aperture area of 105 ft^2 (9.7 m^2) and operated at a temperature of 986°F (530°C) and approximately 60 psia (4 bar).

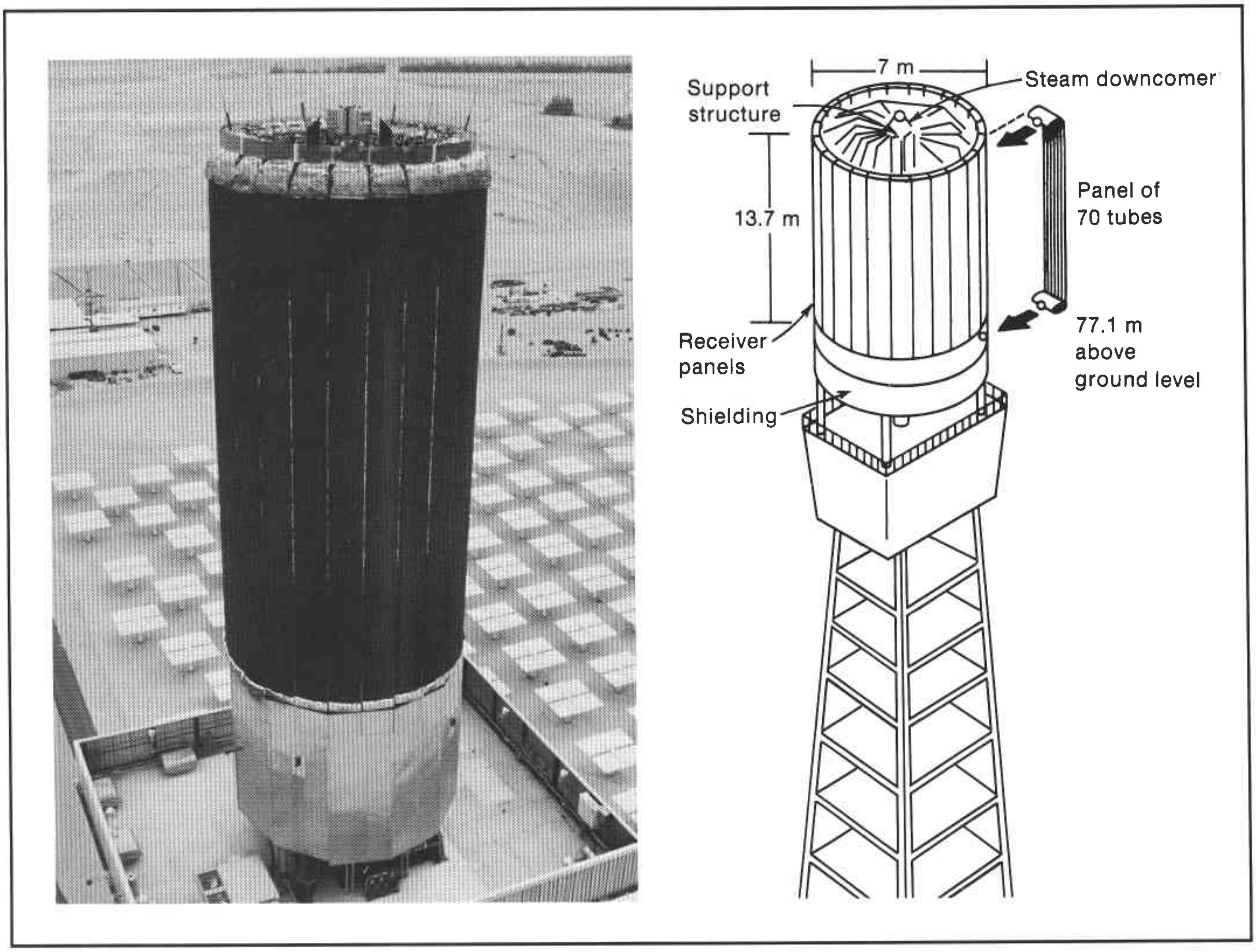


Figure 4.10. The Solar One External Receiver

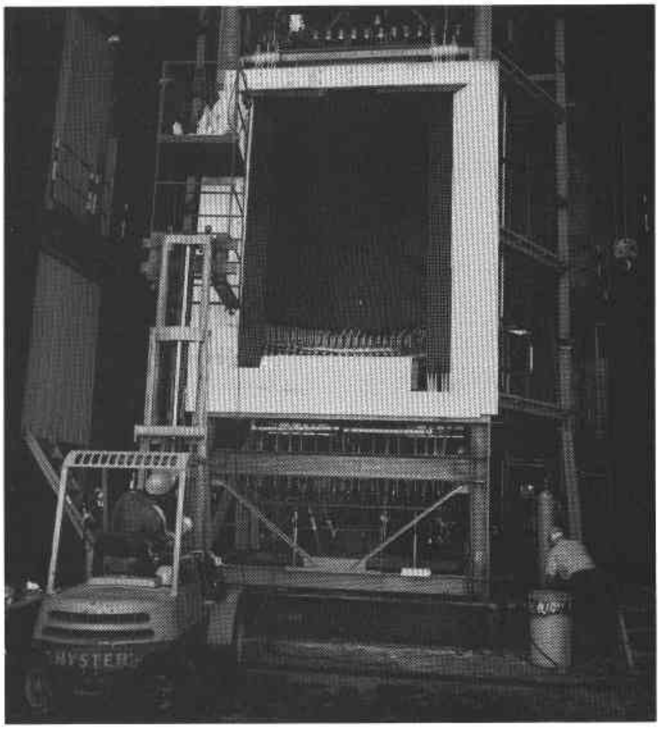


Figure 4.11. The 5-MW$_e$ Molten Salt Cavity Receiver

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 must equal the reflection angle.

Heliostats must not be located too closely together. Just 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 as seen in Figure 4.3.

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 north field heliostats, spacing heliostats farther apart, or **installing more** heliostats

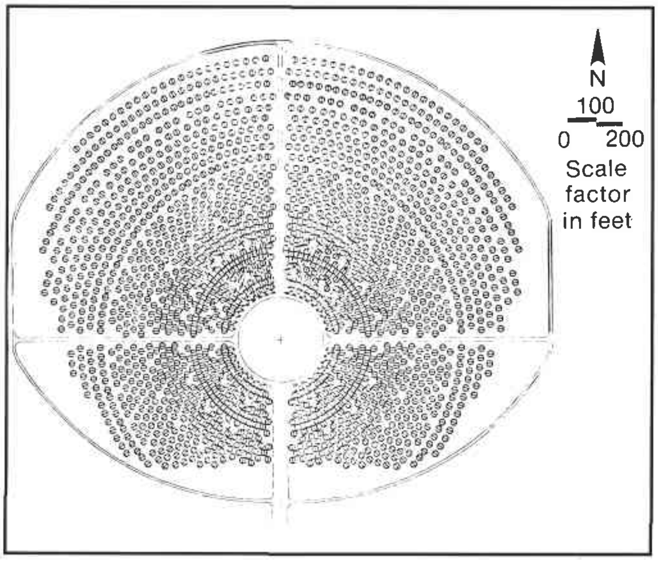


Figure 4.12. A Heliostat Surround Field Lay-Out

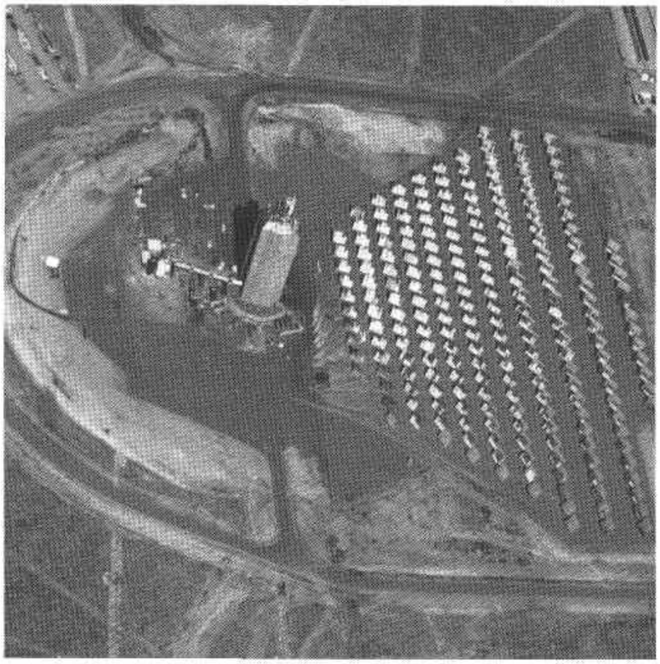


Figure 4.13. A North Pie-Shaped Field of Heliostats

because of their reduced active area. Each alternative increases the cost of the collection system.

As described previously, the two types of central receivers are external and cavity type. **External receivers** can accept reflected sunlight from all directions including heliostats to the south of the receiver (which typically have a high cosine loss). This type of field is called a **surround field** (Figure 4.12). **Cavity receivers** accept reflections only from heliostats located within a narrow included angle to the front of the receiver. A **north pie-shaped field** is used with cavity receivers (Figure 4.13). It has considerably less cosine loss than a surrounding field but will require a substantially taller tower to collect the same energy. Also, a cavity is much **larger** and more **expensive** than an equivalent external receiver. These considerations are the reason for numerous trade-off studies during the design of a central receiver system.

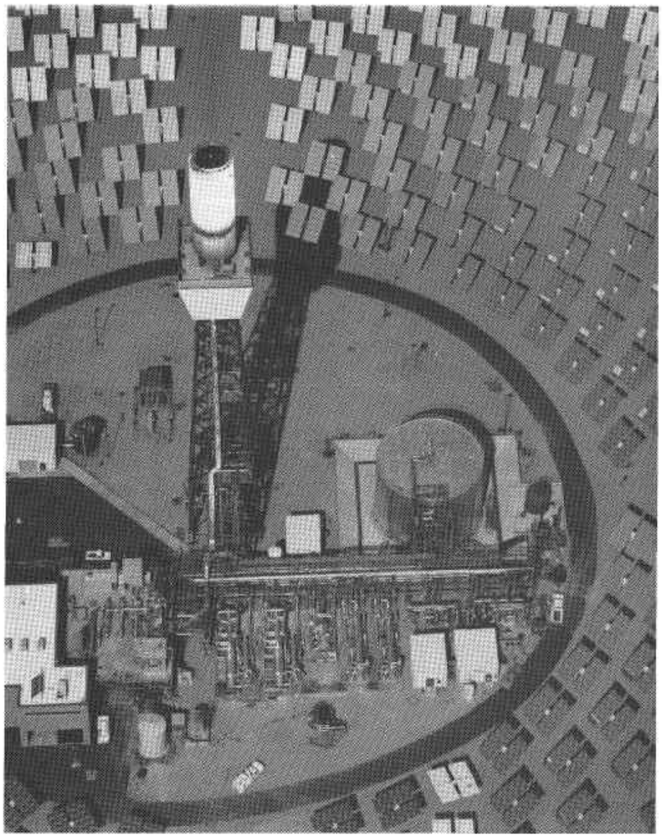


Figure 4.14. The 10-MW_e Central Receiver Pilot Plant (Solar One) in Barstow, California

System Experience

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

The plant has been in operation since 1982, the first two years as a test bed and subsequent years as a commercial Southern California Edison power station (Figure 4.14). As of August 1986, the plant recorded the following milestones:

Maximum instantaneous net power output:
11.7 MW_e

Maximum net energy generated in a day:
88.1 MWh_e

Maximum net energy generated in a week:
456 MWh_e

Maximum net energy generated in a month:
1776 MWh_e

Maximum net energy generated in a year:
8816 MWh_e.

These statistics indicate that Solar One performs 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, where cosine loss is greater.

Each 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 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. The 118,800-ft^3 (3360-m^3) storage tank (Figure 4.15) 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.

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 commercial applicability.

Two central receiver systems are currently being tested in addition to other solar technologies. One system, the **CESA-1** project, uses three hundred 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). Although not an IEA project, it is located at the Almeria site.

Figure 4.15. Solar One's Mixed-media Thermal Storage Unit

The second central receiver system is an experimental **liquid sodium system** that uses ninety-three 423-ft^2 (40-m^2) heliostats to 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 930°F, 1450 psia (500°C, 100 bar) operates a commercial steam motor to produce a maximum net electrical output of 500 kW$_e$.

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: (1) reflective surfaces, (2) heat-transfer fluids, (3) thermal storage, (4) energy transport, and (5) 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.

$$Q_{useful} = I_{b,n}A_{app}\cos\theta_i\ (\rho\Phi\tau\alpha)$$

$$- A_{rec}\ [U(T_{rec} - T_{amb}) + \sigma F(T^4_{rec} - T^4_{amb})]$$

It was also shown that the **capture factor D** is affected by the microscopic quality of the reflective surface finish since **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 a polished metal 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 metal. **Silver** has the highest reflectance of any metal for wavelengths in the solar spectrum. **Aluminum** reflects all wavelengths in 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.

Additional technical issues influencing 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 minimized. If a **lightweight** reflective material is used, then 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 a flat reflective sheet, such as a silvered glass mirror sheet, and **bend** and adhere it 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 stress.** 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 several slightly canted mirror segments, each segment being pulled into a compound curve having a very long radius of curvature; i.e., very nearly flat.

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 severe **weatherability** criteria. Problems with ultraviolet radiation degradation, moisture, sandstorm, and hail damage are important.

The first type of reflective surface to find widespread use in solar thermal concentrators was thin, **polished aluminum** sheets. These sheets are available in large sizes, are relatively inexpensive, and are capable of withstanding some adverse climatic environmental conditions. The major disadvantage is aluminum's 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 content in the glass. The resulting mirror loses the advantage 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 attain the high weatherability characteristics that should be possible with glass back-surface mirrors, and increase their performance in 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 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. Various 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 exposure 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 was 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 at less cost. In addition, it is much lighter and not as brittle as glass. This allows additional cost savings in the concentrator support structure. However, a major drawback of metalized plastic films is that they cannot 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. Another drawback of metalized plastic films is their potential **degradation** in the outside solar environment, possibly requiring replacement in 5-10 years.

Heat-Transfer Fluids

In most 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 over-temperature and melt or crack) and transports it to where the energy is used. Direct absorbtion concepts currently being studied eliminate the absorber/heat-transfer surface with the incoming flux being absorbed **directly** into the heat-transfer fluid.

Technical issues. The **flow** of the heat-transfer fluid through the receiver's absorbing surface passages, and the **heat flux** reflected onto this surface, define the temperature rise of this fluid. High flow rates result in small temperature rises and require high pumping power. At similar heat flux values, lower flow rates transfer the same amount of heat but with a greater temperature rise. Since high receiver outlet temperatures are desired for solar applications, flows are set as low as possible without over-temperaturing the heat-transfer fluid.

Heat-transfer fluids have different **abilities to transfer heat** from the receiver wall into the bulk of the flowing fluid. In general, oils have poor heat-transfer capabilities and boiling water or liquid metals have good capabilities. This heat-transfer capability is increased by increasing the **velocity** of the fluid flow. Because the fluid temperature is highest at the surface of the absorber wall, this is where the fluid temperature limit will be reached. The minimum heat-transfer fluid flow velocity is defined by this consideration.

An important consideration in the selection of the heat-transfer fluid is the **temperature/pressure relationship** required for it to remain a liquid (Figure 5.1). For example, water must be pressurized to at least 1000 psia (6.9 MPa) to remain a liquid at 550°F (288°C) and to 3000 psia (20.7 MPa) to remain a liquid at 700°F (371°C). If the heat-transfer fluid must be maintained at a high pressure, then 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.

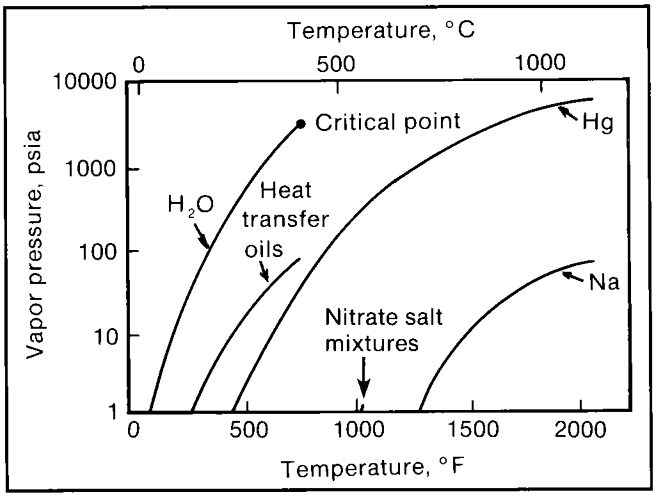


Figure 5.1. Vapor Pressure of Heat-Transfer Fluids (Note logarithmic pressure scale)

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 30 psia (206 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°F** and **750°F** (345°C and 400°C) depending on the particular oil. Above this limit, the oils will **break down** and choke or plug the receiver passages. Another disadvantage of oils is their **low heat transfer coefficient**: it limits the amount of heat that can be transferred per unit area from the solar-absorbing side of the receiver to the fluid side. The result is a large surface area receiver giving high convective losses.

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 1000°F (540°C) can be attained with small, thin-walled receiver absorber surfaces.

Molten salt was tested successfully 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 application at 1050°F (565°C) and above. Even at this high temperature, the pressure of the salt mixture is extremely low (0.15 psia or 1.0 kPa). Because of this low pressure, the heated salt can be readily used as a storage medium since it does not require high pressure tankage.

A disadvantage of molten salt mixtures is that they **freeze** when well above ambient temperature. To compensate for this, piping and components must be highly insulated and

heat traced with steam or electrical heating elements so that the system does not freeze over night or during an extended period of 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. Liquid sodium has the further advantage of having high heat-transfer capabilities. This permits **high peak solar fluxes** on the receiver resulting in smaller, lower loss receiver designs. Freezing of sodium upon shutdown is a problem, as with molten salt.

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

Parabolic dish applications are being developed that use **sodium heat pipes** (Figure 5.2) in conjunction with **Stirling engines**. Liquid sodium is boiled on 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).

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 peak power requirements or 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 a major cost item in the system, then 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

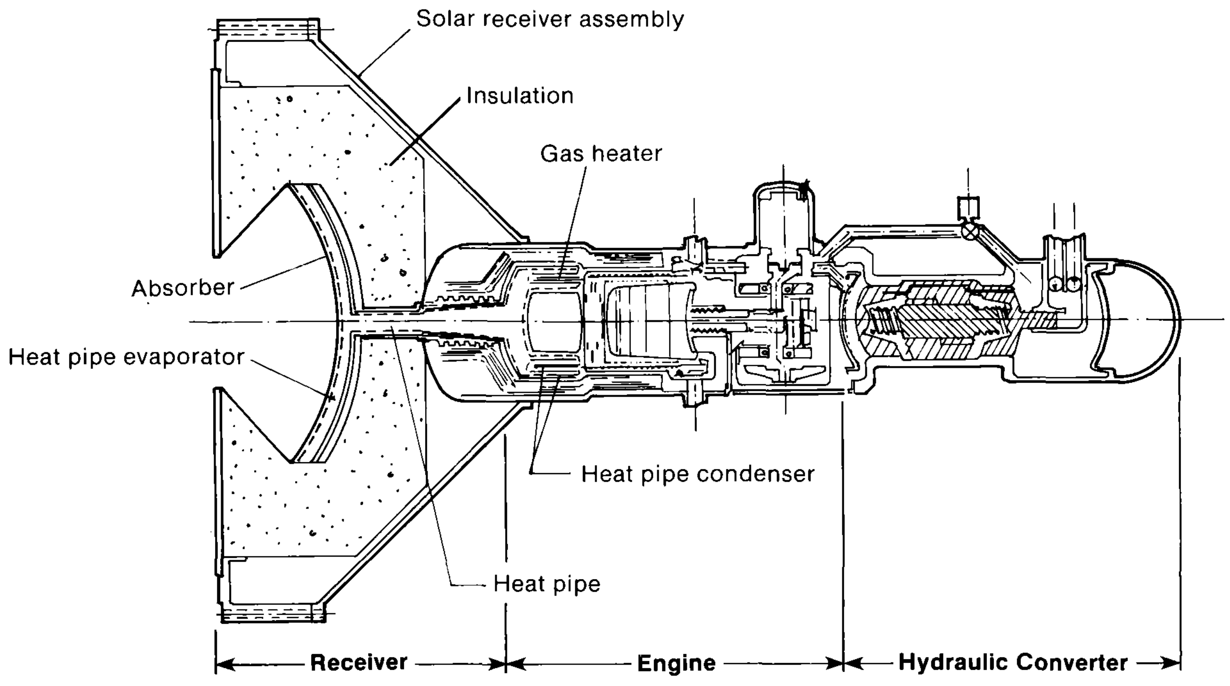


Figure 5.2. A Sodium Heat Pipe Receiver Connected to a Free-Piston Stirling Engine

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 cost of fossil fuel makes 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, then 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 raising the temperature of 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 (as from solid to liquid).

The hot fluid is kept separate from the cold fluid by several methods, the simplest being **two tanks** (Figure 5.3). 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, 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. If the tank is a significant portion of the storage cost, then the cost of this system will be 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 by the end of the day, then only 50% more tankage is required. Breaking down the total tank volume into more segments reduces the excess volume required, at ever-increasing complexity.

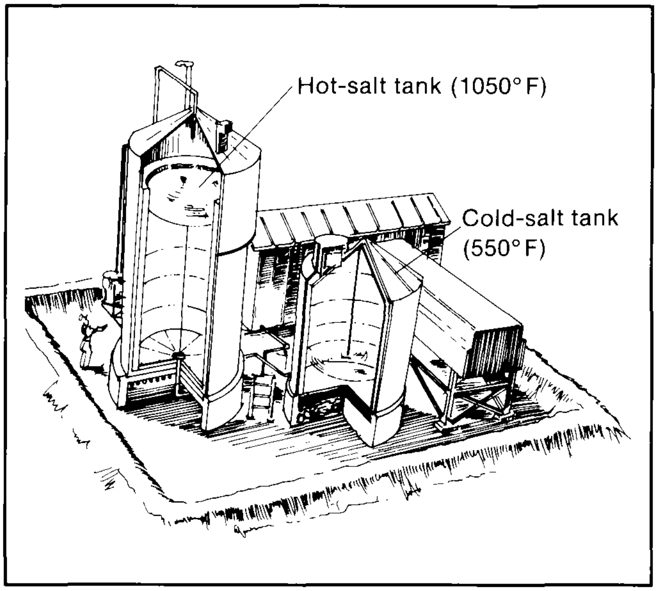


Figure 5.3. Two-Tank Molten Salt Storage

The type of storage used in home 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 for liquid thermoclines have approximately a 5:1 ratio between height and diameter, and flow diffusers are 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 is filled with heat-transfer oil and the oil pumped into or out from the top of the tank to supply or withdraw heat from the bed.

Various 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 for temperatures below 750°F (400°C) since they can be stored at close to ambient pressure. However, they are expensive and hold only 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 large tankage designs possible. Molten salt mixtures are generally preferred because of their lower cost. 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 (Figure 5.4). This is required with storage temperatures above 1110°F (600°C).

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 cannot be located adjacent to the power cycle or heat usage point, then considerable loss of

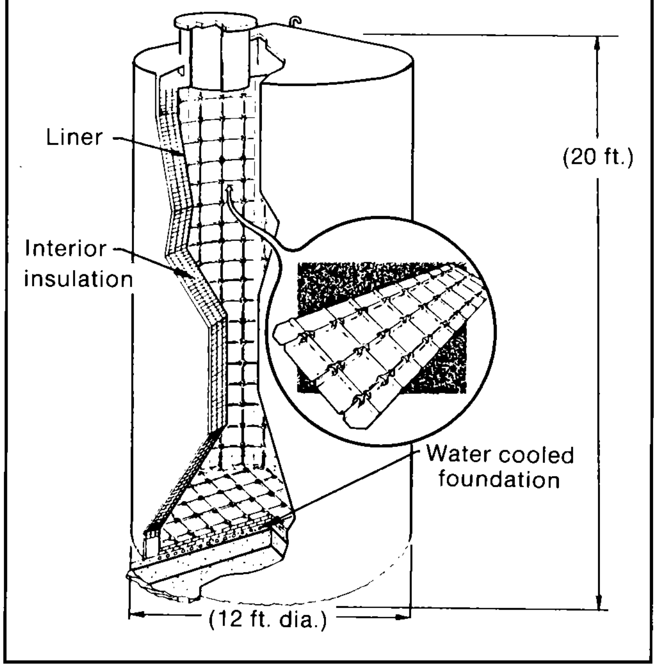


Figure 5.4. Molten Salt Subsystem Research Experiment Hot Tank

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.

A relatively simple endothermic/exothermic reaction is being considered for solar thermal applications. Its high theoretical energy densities and ambient temperature transport make this type of energy transport a possibility.

$$CH_4 + CO_2 \xleftrightarrow{\text{heat}} 2CO + 2H_2$$

With this reaction, 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 closed-loop energy transport cycle is shown in Figure 5.5. A receiver/reactor concept that could be used in this cycle is shown in Figure 5.6.

System Economics

The fundamental issue influencing 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:

$$\text{Cost of energy produced} = \frac{\text{Initial cost of system discounted over its lifetime} + \text{Yearly operating and mainten-ance costs}}{\text{Amount of energy produced in a year}}$$

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 made, 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 using the standard compound

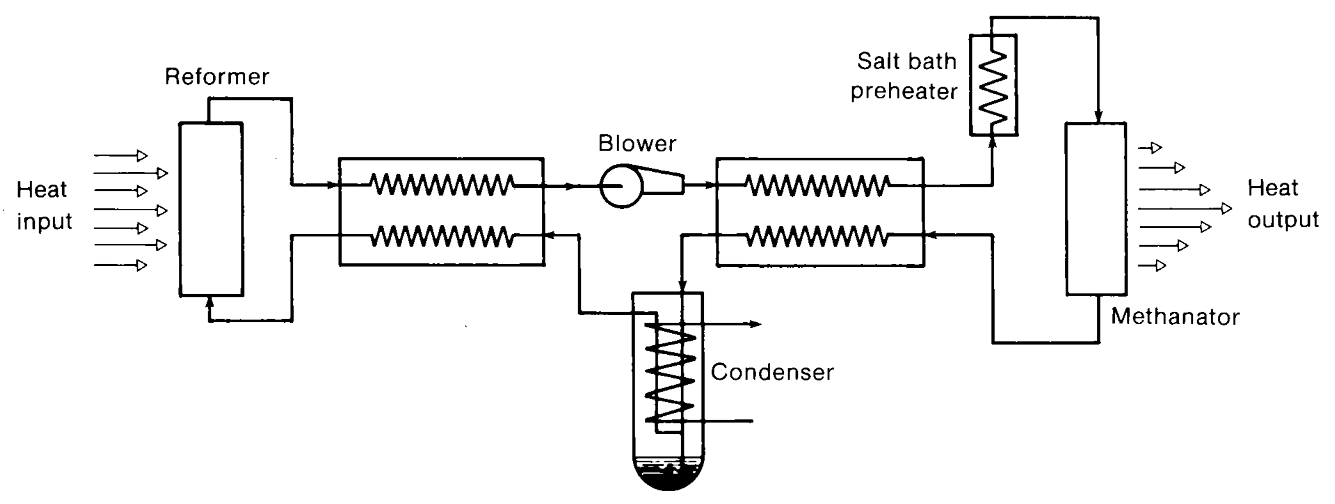


Figure 5.5. Schematic of Closed-Loop CO_2 Reforming and Methanation Transport Scheme

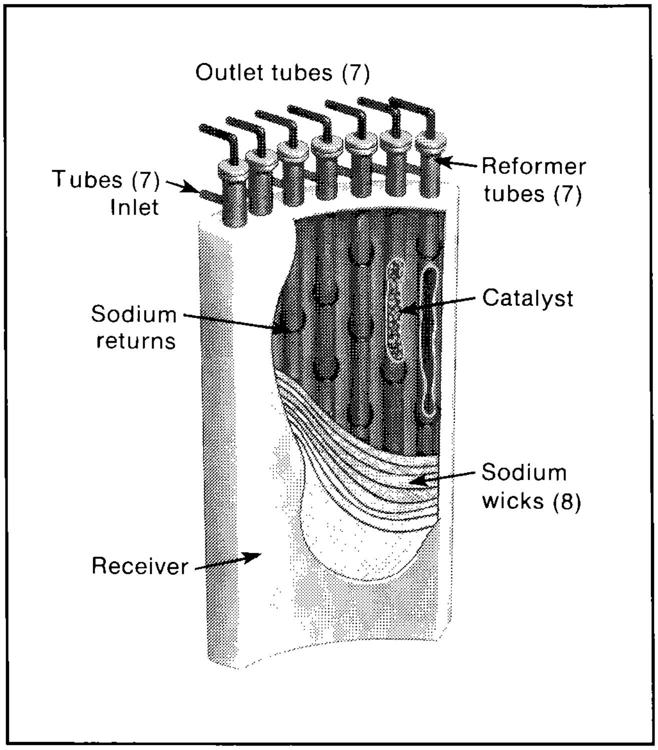


Figure 5.6. Experimental Reformer Receiver Panel Incorporating Sodium Heat Pipe Heat Transfer

interest annuity formula. The cost of energy produced by this solar thermal plant can now be calculated as

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

A full economic analysis is more complex; however, the same techniques are used. The complexity lies in determining the **values used**, 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 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 (6) 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** (no fuel 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 various 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 flow** 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.

Chapter 6
Future Directions and Goals

In ''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) the **cost of energy** that solar thermal systems must achieve to significantly impact the energy market, and (2) how the **components** of a solar thermal plant must be developed so that this cost of energy 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 and the consequent **return on investment**. 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 6.1 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: (1) the cost to build the plant (which is noted here in 1984 dollars per peak output of the plant), and (2) the more important **cost of energy** delivered from the solar plant.

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 Table 6.2.

Table 6.1. System Performance and Cost

	Troughs (heat)	Dishes (electric)	Central Receivers (electric)
Annual Efficiency, %*			
current	32	13	17
5-year	36	17	20
long-term	56	28	22
Capital Cost, $/kW†‡			
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$_e$

*Solar to final product (heat or electricity).

†Troughs are in kW$_t$; dishes and central receivers in kW$_e$.

‡In 1984 dollars.

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 from current to **long-term.** 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.

Component costs are given in Table 6.3 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.

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 should significantly affect the energy market of the 1990s.

Table 6.2. Component Annual Efficiencies

	Troughs (heat)	Dishes (electric)	Central Receivers (electric)
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
Power Conversion or Heat Exchanger, %			
current	99	23	36
long-term	99	41	39

*Short-term storage.

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 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 difficult to produce using conventional techniques. Three unique capabilities of concentrated sunlight as an energy source can be used: (1) **direct absorption** of high energy photons to initiate chemical reaction, (2) **rapid heating** of liquids and solids to produce high value products, and (3) heating materials to very high temperatures in an **atmosphere free of waste products**.

Table 6.3. Component Costs (1984 dollars)

Component*	Troughs (heat)	Dishes (electric)	Central Receivers (electric)
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†			
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

*Area is the concentrator aperture area.

†Troughs are in kW$_t$; dishes and central receivers in kW$_e$.

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 desirable reaction is to **split water** into its constituents: hydrogen and oxygen.

Hydrogen is a 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 can be highly efficient.

No solar thermal plants have been built for the production of fuels and chemicals; however, several 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.

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 34.2°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.

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

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

conduction heat transfer—heat transfer in the absence of medium movement (e.g., through a solid)

convection—heat transfer resulting from fluid motion.

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

dual-axis tracking—a system capable of rotating independently about two axes; e.g., vertical and horizontal.

emittance—a measure of how well a surface can radiate energy.

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.

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 transfer device employing principles of evaporation and condensation.

heat-transfer fluid—a fluid used to exchange heat between different regions.

heliostat—a device for reflecting light from the sun to a desired location. 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 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.

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 which rejects 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 pre-existing structures or facilities.

single-axis tracking—a system capable of rotating about one axis; e.g., north-south or east-west.

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 incorporating both a constant volume and a constant temperature heat addition and rejection process. It is potentially more efficient than a steam engine or gas turbine when regeneration is incorporated because it approximates the Carnot (ideal) cycle.

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 while involving the application or removal 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 concentrator orientation relative to the sun.

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

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
General Sources of Information

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

Textbooks

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

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

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 - An international journal for scientists, engineers and technologists in solar energy and its application. Published monthly by the International Solar Energy Society.

Pergamon Press
Maxwell House, Fairview Park
Elmsford, NY 10523

Journal of Solar Energy Engineering - Transactions of the ASME, Solar Energy Division (published quarterly).

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

Program Reports*

Solar Thermal Power. SERI/SP-273-3047. Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO. 1987. (Available from NTIS.) *Solar Thermal Power.* SERI/SP-273-3047. Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 1987. (Available from NTIS.)

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 Research Program Annual Conference - 1986. To be published in special issue of *Energy, The International Journal,* Pergamon Press, Elmsford, NY.

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.)

Solar Thermal Technology Program Bibliography 1973-1985. SERI/SP-272-3008. Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO. 1986. (Available from NTIS.)

Insolation Data Manuals

Solar Radiation Energy Resource Atlas of the United States. SERI/SP-642-1037. Solar Energy Research Institute, 1617 Cole Blvd., 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, 1617 Cole Blvd., Golden, CO. 1982. (Available from NTIS.)

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

Design Manuals

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

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.)

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, 1617 Cole Blvd., Golden, CO. 1982. (Available from NTIS.)

Appendix C
System Experiment Site 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 a.m. to 5:00 p.m. daily
Tours: Prearranged groups only except public tours 11:00 a.m. and 2:00 p.m. 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 a.m. to 5:00 p.m. Monday through Friday
Travel Directions: From Atlanta airport, take I-85 south for 25 miles. Turn right (west) at Shenandoah off-ramp (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 p.m. to 4:00 p.m. Monday through 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).

Appendix D

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) 586-1623

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 MW_e 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

Martin Scheve
Division of Solar Thermal Technology
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
(202) 586-8110

Research

Frank Wilkins
Division of Solar Thermal Technology
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
(202) 586-1684

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

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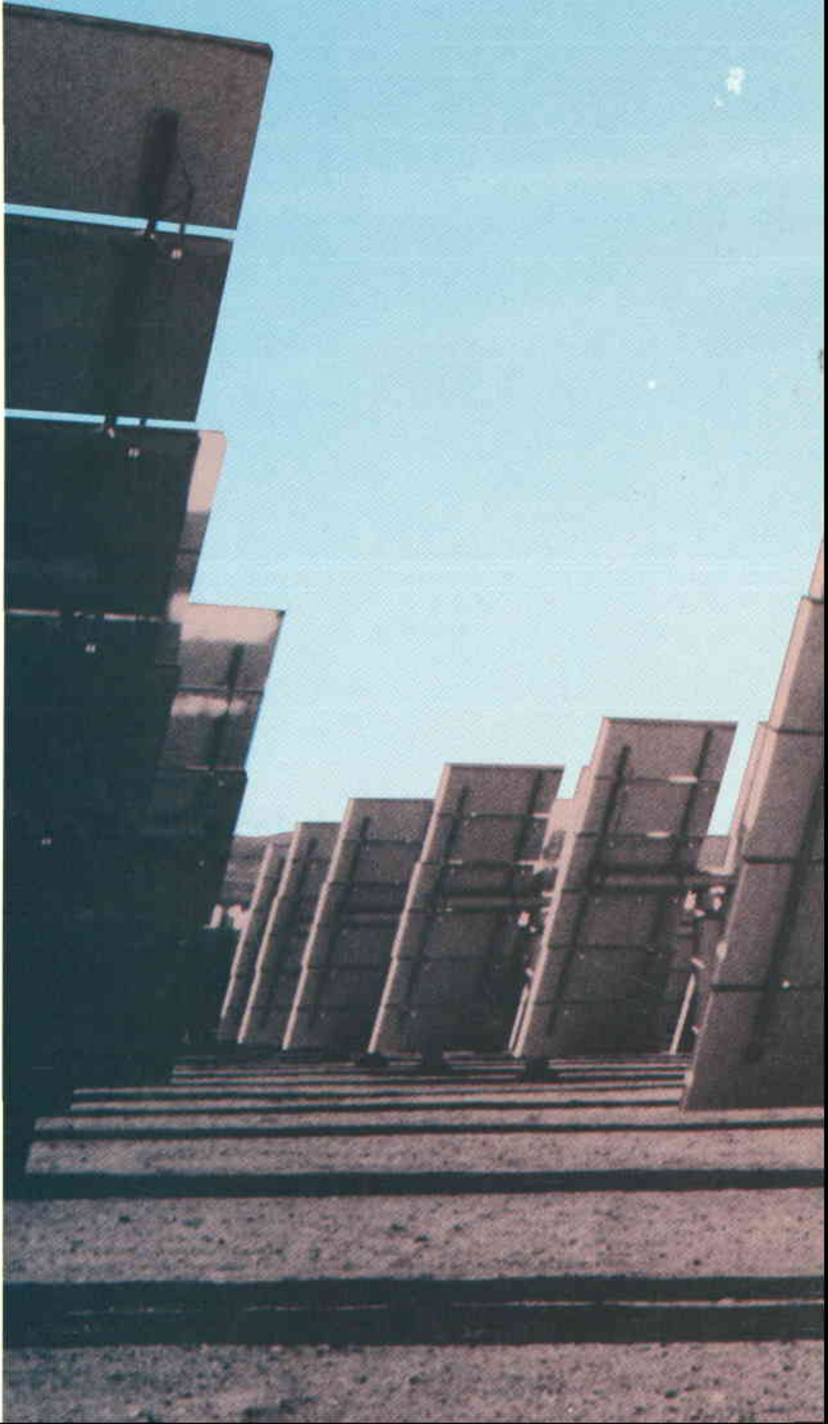

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1617 Cole Boulevard
Golden, Colorado 80401-3393

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