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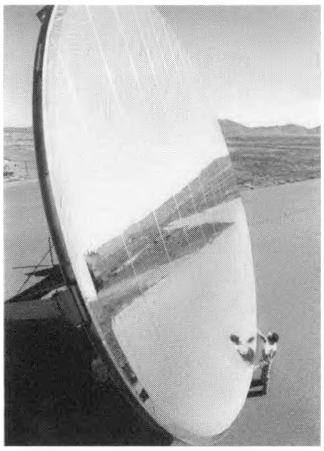

Progress in Parabolic Dish Technology

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Preface

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

Solar thermal technology concentrates the solar flux, using tracking mirrors or lenses, onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies—central receivers and distributed receivers—use 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. Point-focus concentrators as large as 17 meters in diameter track the sun in two axes and use parabolic dish mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multimodule system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve each system concept through solar thermal materials, components, and subsystems R&D and by testing and evaluation. These efforts are carried out with the technical direction of DOE and its network of field 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

Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

Operated for the
U.S. Department of Energy

To successfully contribute to an adequate energy supply at a reasonable cost, solar thermal energy must be economically competitive with a variety of other energy sources. The Solar Thermal Technology Program has developed components and system-level performance targets as quantitative program goals. These targets are used in planning R&D activities, measuring progress, assessing alternative technology options, and developing optimal components. These targets are pursued vigorously to ensure a successful program.

This report describes the current status of parabolic dish technology. Its purpose is to communicate the principal outcomes of DOE's parabolic dish technology R&D efforts carried out at the Solar Energy Research Institute; Sandia National Laboratory, Albuquerque; the Jet Propulsion Laboratory; and other DOE national laboratories. It is written for those in industry, academia, and government who have a special interest in solar thermal systems that use parabolic dishes as collectors.

The evolution of parabolic technology is described, and examples of projects in operation and under construction are included. Solar thermal dish technology can supply either electric or thermal energy to various applications over a broad range of system sizes and temperatures. These solar energy systems will be available by the time this country needs additional electric generation capacity—in the mid to late 1990s—at costs competitive with other energy sources.

Introduction

A Need for New Energy

Energy, like money, is critical in our economy. However, unlike money, which is transferred from place to place, once energy is used, it is gone. In 1986, the United States consumed 74 quads of energy (i.e., 76 x 10^{15} Btu or 80 x 10^{18} J) [1]. This amount is the energy equivalent of every person in the United States consuming 2600 gal of gasoline in a year. Our energy use was split almost evenly among three sectors: industry (35%), buildings (35%), and transportation (30%). We generated and used an amount of electricity equivalent to every woman, man, and child burning twenty 60-watt light bulbs day and night.

In 1988, we depleted an equivalent (or greater) amount of our resources to supply these energy needs. The resources currently used (most of them nonrenewable) are oil (40%), gas (26%), coal (23%), nuclear (6%), and hydroelectric (4%). Most of these resources are burned to produce heat. In 1986, a large portion (36%) was burned in power plants to produce electricity (Figure 1).

Most experts agree that our finite resources of oil and gas are rapidly depleting. As the supply of easily extractable oil and gas decreases, the price for these fuels will rise. The United States has 500 quads of proven crude oil reserves, enough to supply us at our current rate of consumption for 17 years* [2]. The status of our gas reserves is similar.

More oil and gas are available around the world; our proven reserves represent approximately 10% of the world's known supply. Currently, we are importing 38% of our petroleum needs; however, these resources are limited and are being depleted. Also, we must consider that depending on the world's political climate, some of these resources might not be available to us.

Besides the resources we currently use, other energy technologies are available. Many of these technologies are not without drawbacks, however; some can potentially harm people and the environment if not developed properly. For example, large quantities of coal are readily available in the United States but are expensive to mine and burn without being hazardous or degrading our environment. Power from nuclear fission presents other safety, security, and waste management problems.

Comparatively speaking, the sun's energy is a benign resource. Alternative renewable energy technologies such as solar thermal technology are being developed that can provide large amounts of heat, fuel, and electricity. Current studies indicate that additional electric capacity will not be needed until approximately 1995 [3]. By using such technologies, we will be able to meet our future energy

*A proven reserve is the estimated quantities that geologic and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions.

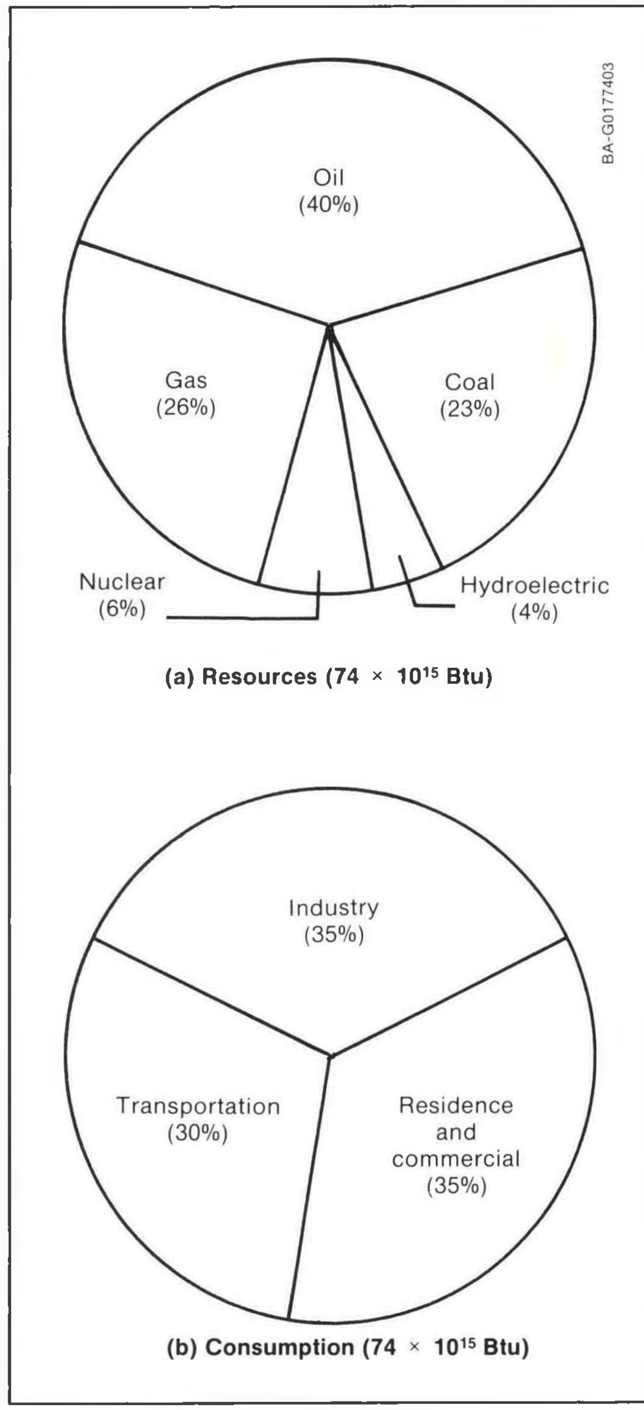


Figure 1. Energy resources and uses

Source: U.S. Department of Energy, Energy Information Agency, *Annual Energy Review 1986.*

demands without depleting our resources or harming ourselves or our natural surroundings.

Systems that derive their energy from the sun will become cost competitive as the price of energy from conventional resources rises (Figure 2). One promising solar thermal technology is parabolic dish solar collectors. These collector systems have several advantages, including their modularity, which allows a small module to be tested for an application before more units are purchased and the addition of more modules as the energy demand increases.

The U.S. Department of Energy (DOE) has been developing this technology for over 11 years. This report traces the knowledge gained since the inception of the parabolic dish development program. It describes the fundamental principles of how the components of dish systems interact to provide heat from the sun's energy. It also describes the factors leading to the current stretched-membrane dish technology that uses free-piston Stirling engines at the focus to generate electricity.

Parabolic Dish Systems

Parabolic dish systems consist of a reflective parabolic dish concentrator that focuses the sun's rays onto a receiver (absorber) mounted above the dish at its focal point. Sunlight is directed onto an opening in the receiver to heat a circulating fluid within coils. The hot fluid can then be transported elsewhere for various thermal uses; it can also be used to generate electricity directly by using the thermal energy to operate a large central power cycle or integrating a small engine and alternator with the receiver at the focal point of each dish.

Each dish can be a complete power-producing unit or module that functions independently or as part of a group of modules (Figure 3). The fluid in a single, large parabolic dish module can reach temperatures as high as 1500°C (2700°F) and can produce approximately 50 kW of electric power or 150 kW of thermal power. Effectively, no limit exists to the size of a central engine generation system.

Applications

Solar-derived heat from a parabolic dish system either can be used directly or can be converted into a different form. System studies suggest two attractive applications: generating electricity and supplying high-temperature heat to industrial processes. Recent studies indicate that the high photon flux at the focus of parabolic dishes can also be directly utilized to drive photon-enhanced chemical processes.

To generate the high temperatures necessary to produce electricity, a small engine is placed adjacent to the focus of a single collector. Another way to achieve these temperatures is to collect concentrated solar energy from many dishes and combine it to power a single central engine.

An alternative to producing electricity is to provide this heat directly to an industrial process that requires high heat. Solar-derived heat at temperatures as high as 1500°C (2700°F) is possible from parabolic dish concentrators. This heat can directly replace heat derived from fossil fuels or electricity.

Because of their high-temperature capabilities, parabolic dish systems are well suited for use in total energy systems where the thermal energy produces electricity and process heat. In such systems, high-temperature, solar-derived energy produces electricity, and heat rejected or extracted from the electric power system after partial expansion is used as process heat for space and water heating and for cooling using an absorption chiller.

Advantages

The parabolic dish system has three advantages over other solar thermal technologies: the high temperatures it can achieve, its modularity, and its versatility. Dishes can produce temperatures well above 1500°C (2700°F), and they are small, approximately 50–150 kW_t. Because of their modularity, parabolic dishes can be located near the point of demand, more dishes can be added to the original system, and the numbers of modules can be modified as

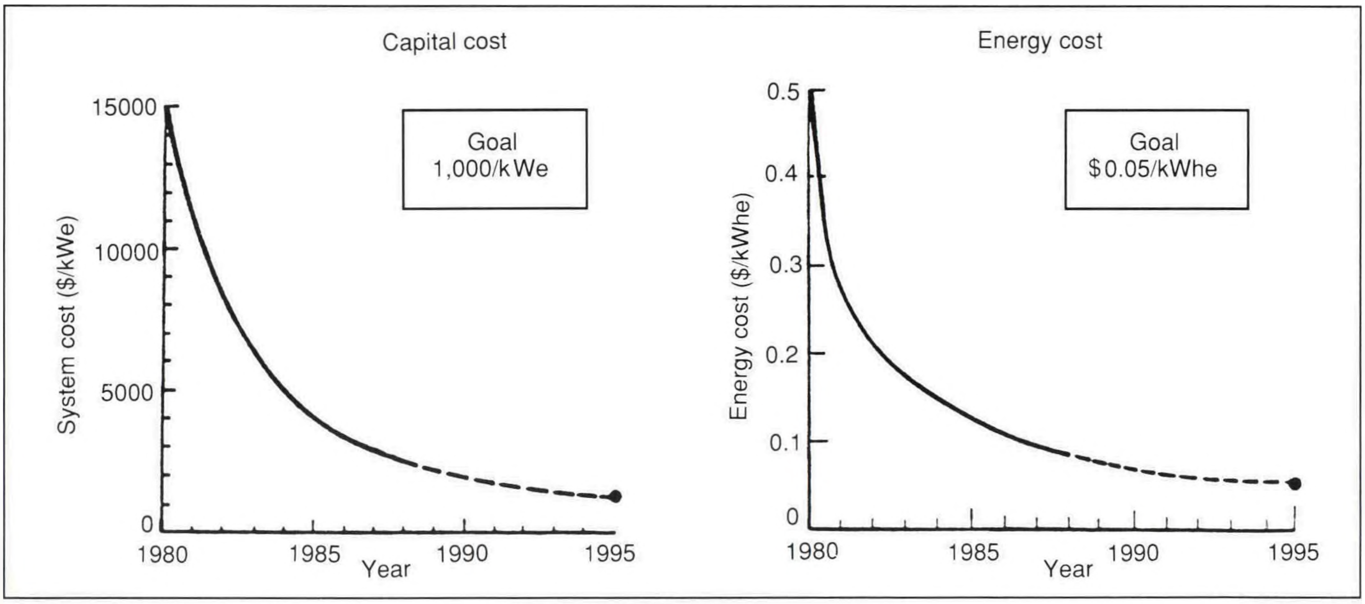


Figure 2. Parabolic dish system and energy cost reduction

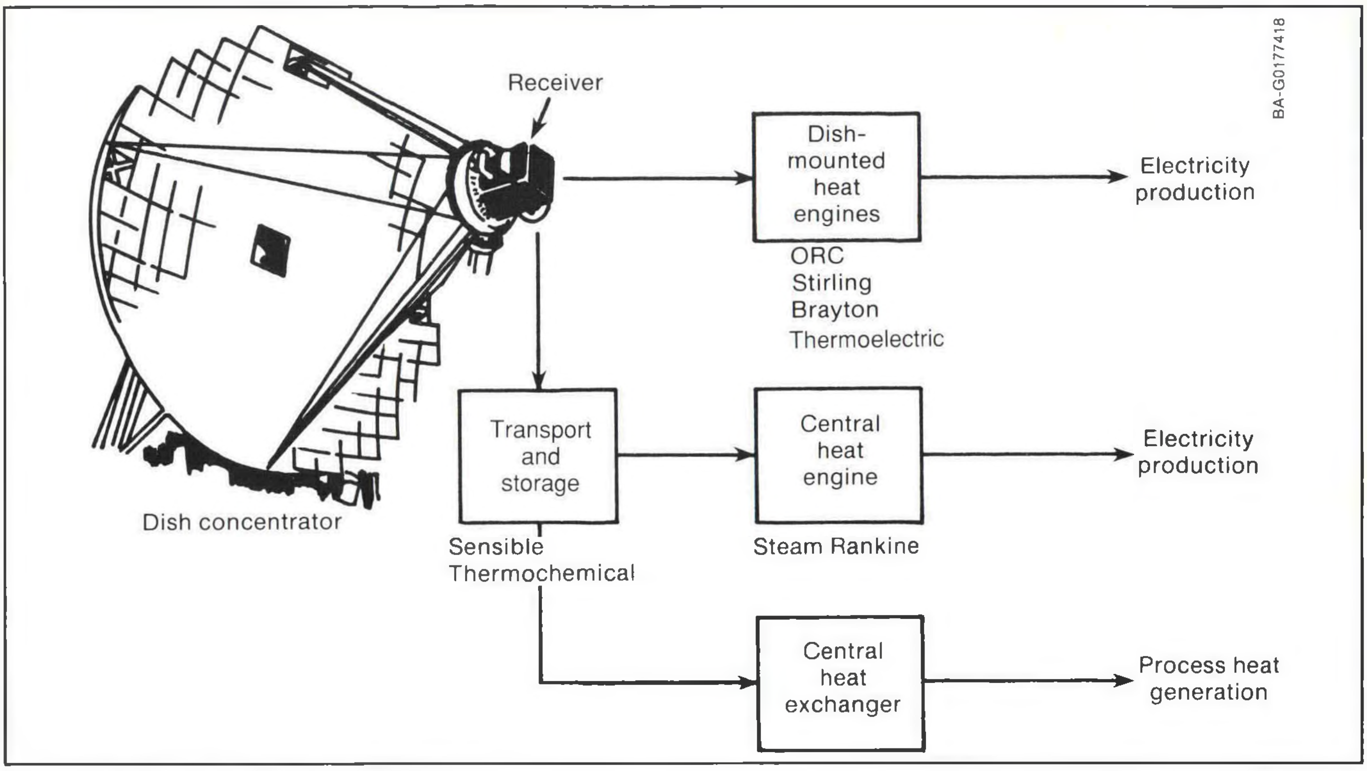


Figure 3. Parabolic dish energy production system

local demand changes. Finally, dishes have applications beyond generating electricity and providing industrial process heat, including producing hydrogen or high-value chemicals and destroying toxic wastes.

Evolution of System Designs

Concentrators

The largest component of a parabolic dish collector is the concentrator, a dish with a reflective surface that tracks the sun to focus sunlight on a receiver. Tracking about two axes ensures maximum solar energy collection throughout the day.

A major thrust in the evolution of parabolic dish concentrators has been toward more efficient structures. Two aspects dominated early concentrator design: heavy structural and nonstructural elements and small concentrator size. A heavy structure is required to support heavy reflective surfaces. Early concentrators used heavy glass mirrors or a polished aluminum sheet. Newer designs use thin plastic reflective films or the structure itself as a reflective surface. As designers decrease the weight of reflective surfaces, they can decrease the weight of the surrounding structure. With fewer materials needed to build the concentrator, the overall cost is reduced.

The size of the concentrator (i.e., aperture diameter) has tended to increase to gain economies of scale. Larger dishes produce more thermal energy for a single support and tracking mechanism, thereby reducing the cost per unit of output. Improving the efficiency of the dish structures has resulted in an increase in the aperture diameter from 5–6 m to 11–12 m.

Small Engines

In the past, three heat engine types have been tried with parabolic dishes: Stirling, Rankine, and Brayton. Because they are usually mounted at the focus of the receiver, heat engines for solar-to-electric dish applications must be adapted for use in random attitudes. Key development issues include achieving high engine efficiency and reliability, low operating and maintenance costs, and effective interfacing of the engine and receiver.

Two major trends have characterized the development of small engines for parabolic dish applications. The first trend is toward increasing the operating temperature of the engine to attain the higher engine efficiencies associated with a higher engine operating temperature. This effort involves not only designing higher-temperature receivers but also developing engines with high-temperature working fluids and internal components capable of operating at the high temperatures attainable with parabolic dishes.

The second trend is toward developing highly reliable engines. Small automobile engines operate for approximately 3000–5000 h before a major overhaul is required; routine maintenance is required every 200–300 h. Solar engines for generating electricity must last at least ten times as long, with considerably less maintenance.

Program Accomplishments

Since 1978, great strides have been made in developing parabolic dishes. Collector performance has improved greatly, and the cost of the concentrator per unit area (a measure of its output) has been reduced from over $1000/m^2 to less than $150/m^2 (Figure 4).

Early parabolic dishes were costly, their structures heavy, and their collector efficiencies poor. Developing lighter-weight reflective materials has led to developing larger, lighter-weight concentrators, thereby reducing their cost by nearly a factor of ten. New stretched-membrane technology promises further cost reductions and increased collector efficiency.

Except for collectors developed for research purposes, collector performance has also increased greatly. The eefficiency with which solar energy is concentrated and collected has increased from about 60% to 90% in 10 years, with a concurrent increase in concentration ratios, indicating the collector can operate at higher temperatures.

Several small engines were tested at the focus of these concentrators. Early, low-efficiency steam engines were replaced with organic Rankine cycles with moderate- and high-performance Stirling engines. Recent advances in free-piston Stirling technology promise to remove the high maintenance requirements of earlier Stirling designs.

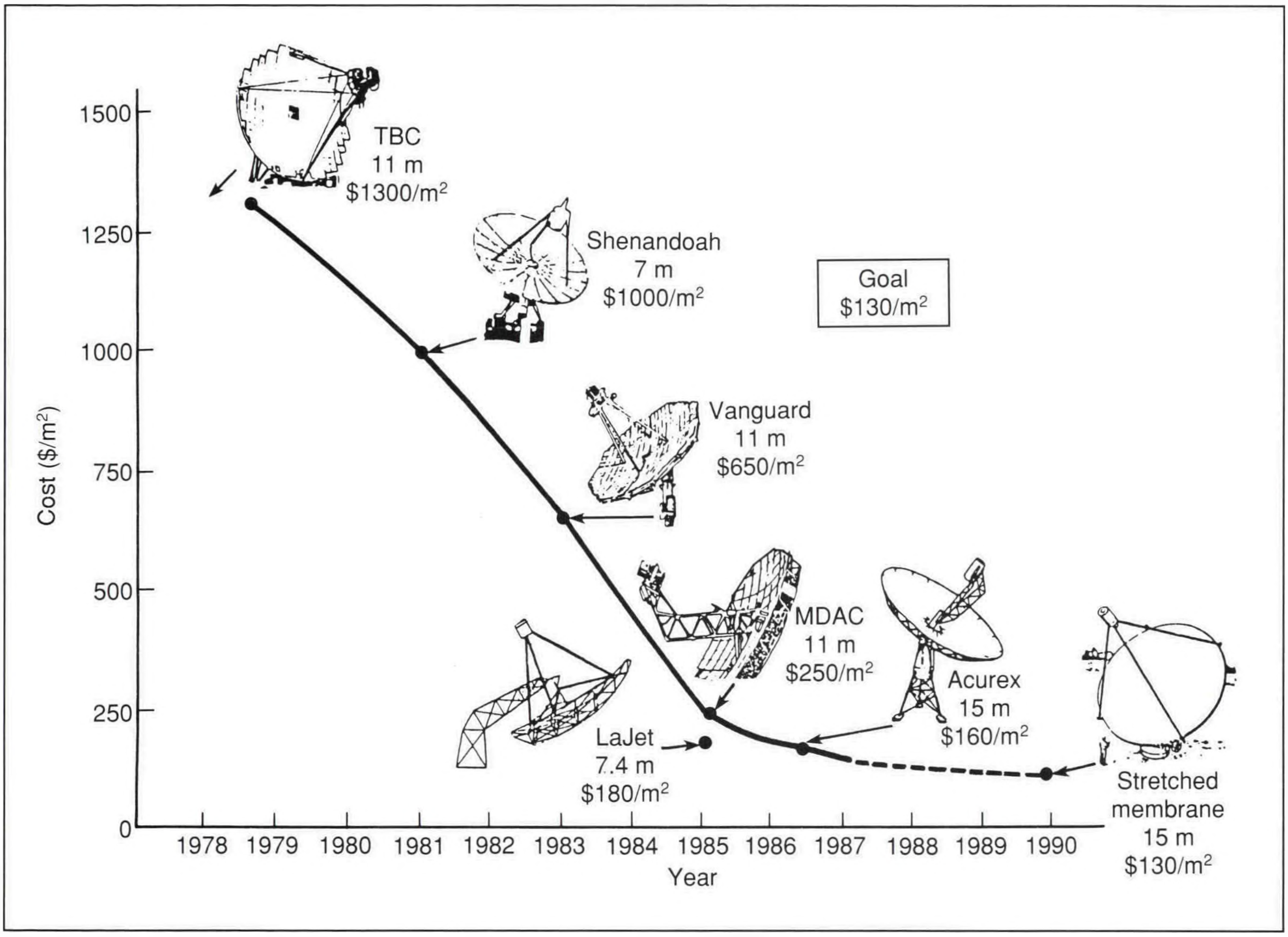


Figure 4. Cost improvements of parabolic dish systems over the past 10 years

Chapter 1
Prototype Parabolic Dish Systems

Development of System Technology

Parabolic dish systems have been designed and tested over the past 15 years. The overriding characteristic of all these systems is their high cost relative to the net amount of electricity produced. System efficiencies have steadily increased, but systems costs have decreased, reducing the overall cost of the energy produced.

Turn-of-the-Century Designs

A number of parabolic dish concentrators were developed before the federal government and industry began parabolic dish projects in the 1970s [4,5]. Concentrating dish mirrors were used in the eighteenth century for melting, calcining, and vitrifying metals and other substances, and in France and Germany, the mirrors were used for setting fires at a distance. In the 1870s, a Frenchman named Pifre built a 4- to 5-m-diameter (13–16 ft) conical and parabolic dish concentrator that powered a steam engine (Figure 1.1).

John Ericsson, the designer of the ironclad ship *Monitor* used during the American Civil War, was the first person to expend a major effort experimenting with solar thermal energy in the United States. He developed the Ericsson cycle heat engine (constant pressure and constant temperature cycle) for solar energy applications. His experiments and an expenditure of $90,000 forced him to conclude that solar-powered engines cost ten times more than conventional engines and that their use could be economically justified only for remote areas of "the sun-burnt regions of our planet."

Early in the twentieth century, Aubry Eneas marketed 11-m-diameter (36-ft) truncated conical dishes that produced steam to drive water pumps (Figure 1.2). Thereafter, as coal and then oil became inexpensive, interest in marketing parabolic dishes subsided. Ideas continued to be developed, however, with patents and experiments on producing power from concentrated solar energy.

Omnium-G Collector System

In the late 1970s, Omnium-G, Inc., designed a parabolic dish collector system with a 6-m-diameter (20-ft) concentrator fabricated from 16 pie-shaped panels of polyurethane foam, forming a paraboloid with a rim angle of 41 deg (f/d = 0.67) (Figure 1.3). A reflecting surface of anodized aluminum sheeting was attached to these panels. Metal trusses supported the panels, which rested on a central elevation bearing on a pedestal. Wheels on a track rotated the pedestal about the azimuth axis. Electric motors receiving rough control signals from a clock and sun sensors helped the system track the sun.

The cavity receiver used a single coil of stainless steel tubing buried in aluminum inside an Inconel™ housing. The aluminum melted during operation to provide uniform heat distribution and thermal storage. The receiver aperture was 200 mm (8 in.), giving the collector a geometric concentration ratio of 900.

This collector was tested using a double-acting reciprocating steam engine with two cylinders. The 34-kW (45-hp)

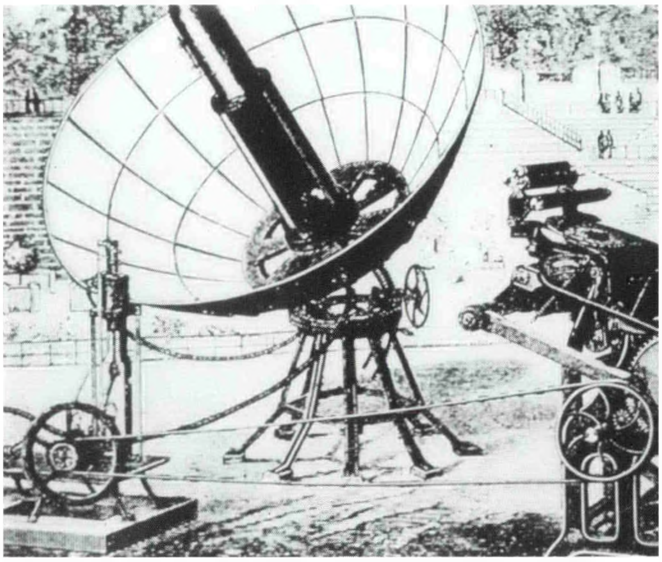


Figure 1.1. Pifre's solar-powered printing press of 1878

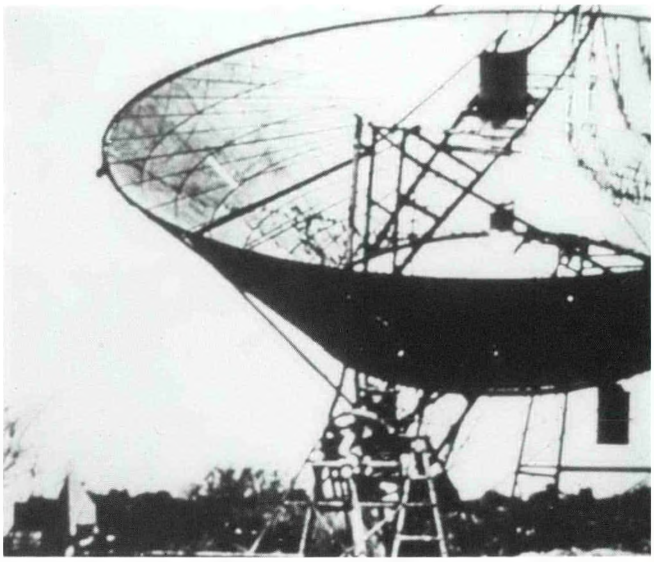


Figure 1.2. Axicon conical concentrator system used at the South Pasadena Ostrich Farm, circa 1901

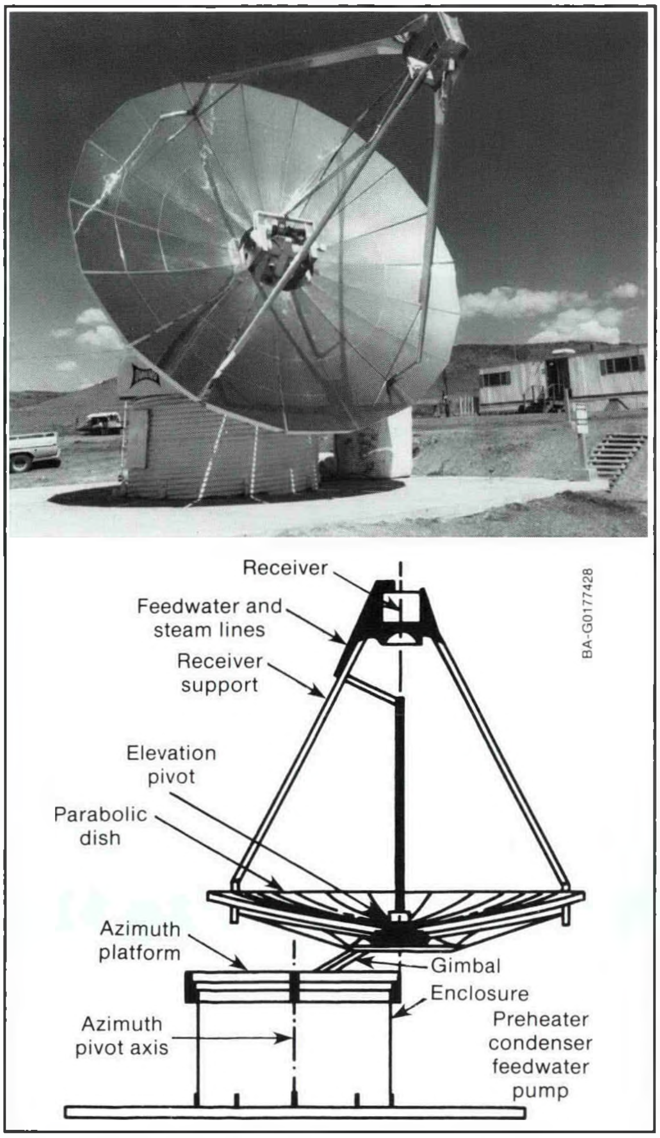


Figure 1.3. Omnium-G tracking concentrator

engine was oversized for the concentrator and operated at 1000 rpm on 315°C (600°F) steam at 2.5 MPa (350 psia). Because its polished aluminum reflector had low reflectance and a large optical error, this collector supplied less energy at the focal point than was needed to adequately power the steam engine.

Jet Propulsion Laboratory Test-Bed Concentrators

E-Systems, Inc., built two 11-m-diameter (36-ft) concentrators for the Jet Propulsion Laboratory (JPL) so it could test parabolic dish receivers and power conversion systems at its Edwards Air Force Base solar test facility in California. These concentrators, patterned on existing dish antenna technology, have good optics; however, they are heavy and expensive and are built only for testing and not for commercial production (Figure 1.4).

The reflecting surface of these concentrators is made of 224 spheric reflector segments of back-surfaced silvered-glass mirrors bonded to contoured blocks of foamed glass. The mirror segments are mounted on a space frame, producing a paraboloid with a focal-length-to-diameter ratio (f/d) of 0.6. Segments with three different spheric radii were placed on the frame at different distances from the axes to minimize the deviation between the spheric and local paraboloid curvature. Tracking is about the azimuth and the elevation axes. Wheels running on a track around the base do the azimuth tracking. The concentrator can be operated at geometric concentration ratios of 1500 to 3000; the measured peak flux concentrations measured above 15,000 suns.

The Vanguard Dish-Electric Generation System

Advanco Corporation developed the Vanguard 11-m-diameter (36-ft) parabolic dish concentrator to power a 25-kW$_e$ Stirling engine-generator module (Figure 1.5). The concentrator has 320 facets, each 46 by 61 cm (1.5 by 2 ft). The foamglass facets have thin-glass, back-surfaced silver mirrors bonded to them. These facets are attached to racks that in turn are attached to a truss structure. The collector tracking uses an exocentric gimbal that reduces the torque requirements of the tracking drives.

This dish concentrator was fitted with the United Stirling Model 4-95 MkII four-cylinder kinematic Stirling engine and was tested at Rancho Mirage, Calif. The collector holds the world's record for converting sunlight to electricity of 31% (gross) and 29% net (i.e., including parasitic losses). This concentrator had good optics and tracking and had a high-efficiency engine. The high cost of the dish, patterned after the JPL test-bed concentrator, and of the engine operation and maintenance, however, resulted in an uneconomic solar collector system.

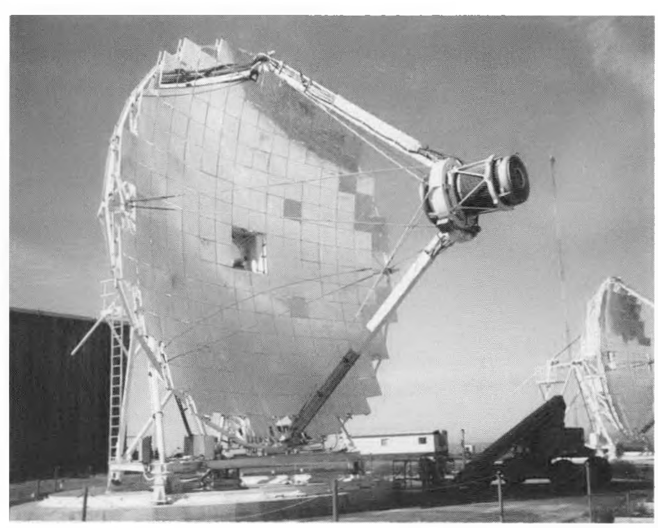


Figure 1.4. Test-bed concentrator designed for Jet Propulsion Laboratory shown testing an organic Rankine cycle engine

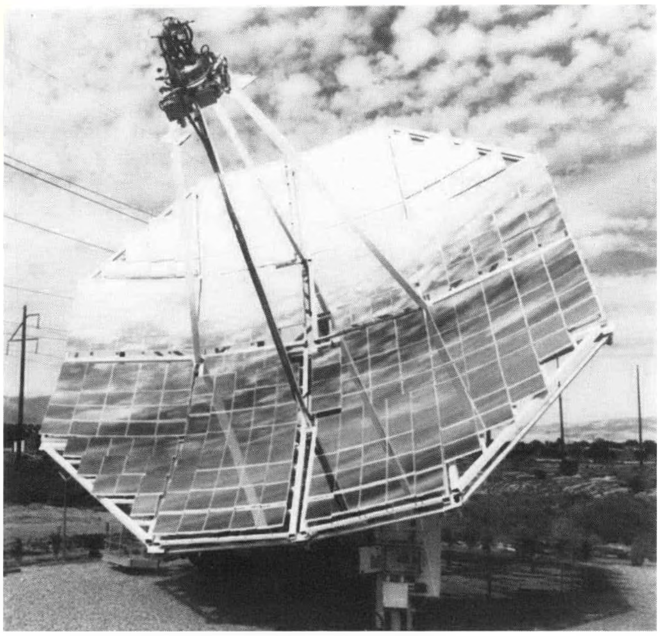


Figure 1.5. The Vanguard parabolic dish collector, with Stirling engine, which holds the world's record for converting solar energy into electricity

Parabolic Dish Concentrator No. 1

General Electric Company fabricated a parabolic dish collector designed specifically to be a low-cost, commercial solar collector (Figure 1.6). This 12-m-diameter (39-ft) parabolic dish concentrator was tested at Edwards Air Force Base, but it did not meet the low-cost goal of the design.

Known as the Parabolic Dish Concentrator No. 1, this collector has 12 radial gores, each comprising an inner, center, and outer panel. The 36 panels are attached along their radial edges to 12 radial steel ribs located in front of the reflective panels. The reflective surface is an aluminized plastic film (Llumar™) laminated to a plastic sheet that is bonded to a molded fiberglass and balsa wood sandwich panel. The concentrator has a f/d ratio of 0.5 and was designed for geometric concentration ratios of 1500.

Azimuth tracking is accomplished by rotating the entire frame, which is on wheels, on a circular track. Elevation movement is about a horizontal trunnion axis. The movement is controlled using a computer-based ephemeris for the rough pointing and sun sensors for the fine tracking. The sensors maintain the alignment of the solar image within the receiver aperture.

Power Kinetics, Inc., Capitol Concrete Collector

An 80-m^2 (864-ft^2) slat point-focus concentrator manufactured by Power Kinetics, Inc. (PKI), was the first slat dish concept built for industrial process heat applications. It was tested as a process steam production unit at Capitol Concrete Products in Topeka, Kans. (Figure 1.7).

The concentrator comprises 108 identical movable curved slats, each supporting eight 31-cm by 31-cm (1-ft by 1-ft) square back-silvered glass mirrors mounted on polyurethane foam. The slats are mounted on a space frame that is set on a steel track. Rotating the concentrator about the track on casters provides azimuth tracking, and rotating each slat around its center of gravity provides elevation tracking.

This unit has an approximate f/d ratio of 0.9, with an estimated geometric concentration ratio of 250. These ratios were considered adequate for the specific process heat application, which required energy at only 149°C (300°F). For this application, concentrated sunlight is focused into a vertical tube cavity receiver where process steam is generated.

A larger version of this concentrator was fabricated and tested to power a 25-kW$_e$ engine at its focus. This concentrator has a total reflective area of 133 m^2 (1400 ft^2). A cavity receiver incorporating a 25-kW$_e$ organic Rankine cycle engine-generator is placed at the focus of this concentrator (Figure 1.8). Numerous design problems caused PKI to stop testing this concentrator. An even larger version was designed for use in the proposed Small Community Solar Experiment at Molokai, Hawaii.

Shenandoah Total Energy System

The Solar Total Energy Project at Shenandoah, Ga., operated by the Georgia Power Co., uses a field of 114 parabolic dish collectors with a total aperture area of 4352 m^2 (46,845 ft^2) to supply 400°C (750°F) heat to a central steam Rankine power generation cycle (Figure 1.9). This cycle, operating at 382°C (720°F), produces as much as 400 kW$_e$ of electric power, 626 kg/h (1380 lb/h) of 940 kPa (137 psi) process steam, and 1065 kW$_t$ (257 tons) of air conditioning for the adjacent Bleyle Knitwear factory.

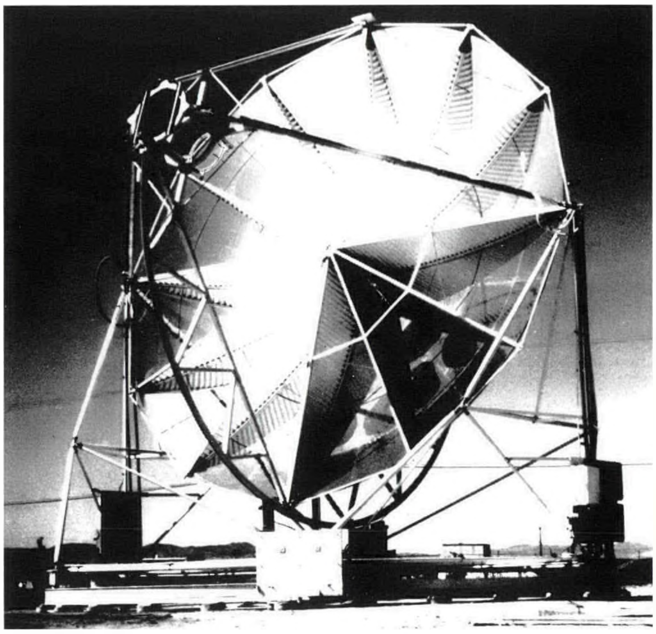


Figure 1.6. General Electric parabolic dish concentrator no. 1

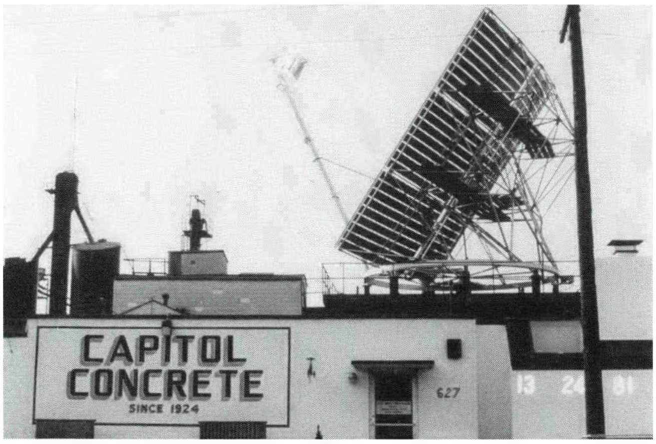


Figure 1.7. Power Kinetics, Inc., point-focus concentrator producing process heat at Capitol Concrete Co. in Topeka, Kans.

The 7-m-diameter (23-ft) 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. Solar heat is concentrated to a cavity receiver and transferred to a silicone-based heat-transfer fluid at temperatures as high as 399°C (750°F). The heated fluid from each collector is then pumped through insulated piping to the central total energy cycle, producing electricity, process steam, and chilled water. The geometric concentration ratio of this 0.5 f/d collector is 234.

This system has been consistently producing energy since 1983. With good insolation and operating only on solar energy, the system has produced 100 kW of electricity (gross) and met the demand for 273 kg/h (600 lb/h) of process steam and 211 kW_t (60 tons) of refrigeration. With the aid of a fossil fuel heater, the system produced a peak (gross) power output of 330 kW_e and met similar demands for process steam and cooling. The system has a peak solar-to-total energy conversion efficiency of about 14%. Currently, the system is being upgraded to include a second auxiliary heater.

McDonnell Douglas Stirling System

McDonnell Douglas Astronautics Corp. developed a parabolic dish incorporating a kinematic Stirling engine and tested it at several sites. The 90-m^2 (968-ft^2) dish concentrator consists of eighty-two 91-cm by 122-cm (3-ft by 4-ft) spherically curved glass mirrored facets (Figure 1.10). These facets are attached to a factory-aligned space frame to minimize field installation costs. The dish surface is slotted at the bottom, so the power conversion unit can be lowered for servicing.

The engine, manufactured by United Stirling AB of Sweden, is the Model 4-95 engine described previously. Mounted adjacent to the receiver, this four-cylinder regenerative engine used hydrogen as the working gas to achieve a design output of 25 kW_e. This unit operated with engine efficiencies over 40% and a net solar-to-electric efficiency of 29%.

Solarplant One

Solarplant One is a privately financed electric power production facility located in Warner Springs, Calif., that is designed to produce a maximum power of 4.9 MW_e (Figure 1.11). It uses a field of 700 Model LEC 460 multifaceted, stretched-membrane dish collectors manufactured by the LaJet Energy Company. The field has a total aperture area of 28,940 m^2 (311,500 ft^2) and is divided into two sections, one to produce 232°C (450°F) saturated steam and the other to superheat this steam to 400°C at 3.2 MPa (750°F at 465 psi) directly in the collector receivers. The superheated steam is piped to a central Rankine cycle engine that produces 4.9 MW_e under peak insolation conditions. This process has a peak solar-to-electric efficiency of 17%. The average yearly electric output is designed at 12,000,000 kWh.

Each 41-m^2 (441-ft^2) concentrator uses twenty-four 1.5-m-diameter (5-ft) stretched-membrane facets mounted on a lightweight supporting structure. A thin, aluminized plastic film is stretched on either side of a rigid ring, with a slight vacuum drawn between the membranes to provide focusing. The entire structure tracks about the polar and declination axes. The system uses cavity receivers that have a 25-cm-diameter (10-in.) aperture and a small amount of phase-change salt to provide buffer storage.

Solarplant One is currently being modified to a solar-diesel combined cycle. Two 1-MW diesel generator sets were installed that have exhaust heat recovery exchangers. In this configuration, the turbines can be powered either with solar-generated steam or steam generated from the heat remaining in the diesel engines' exhaust.

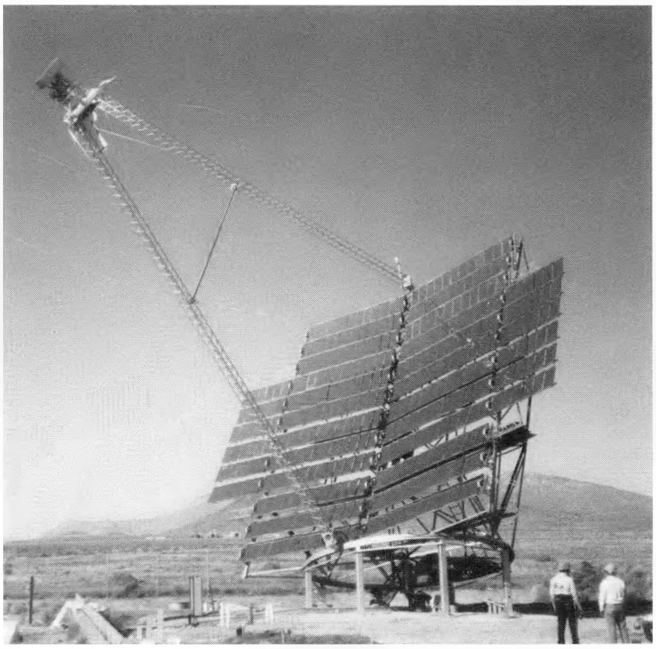
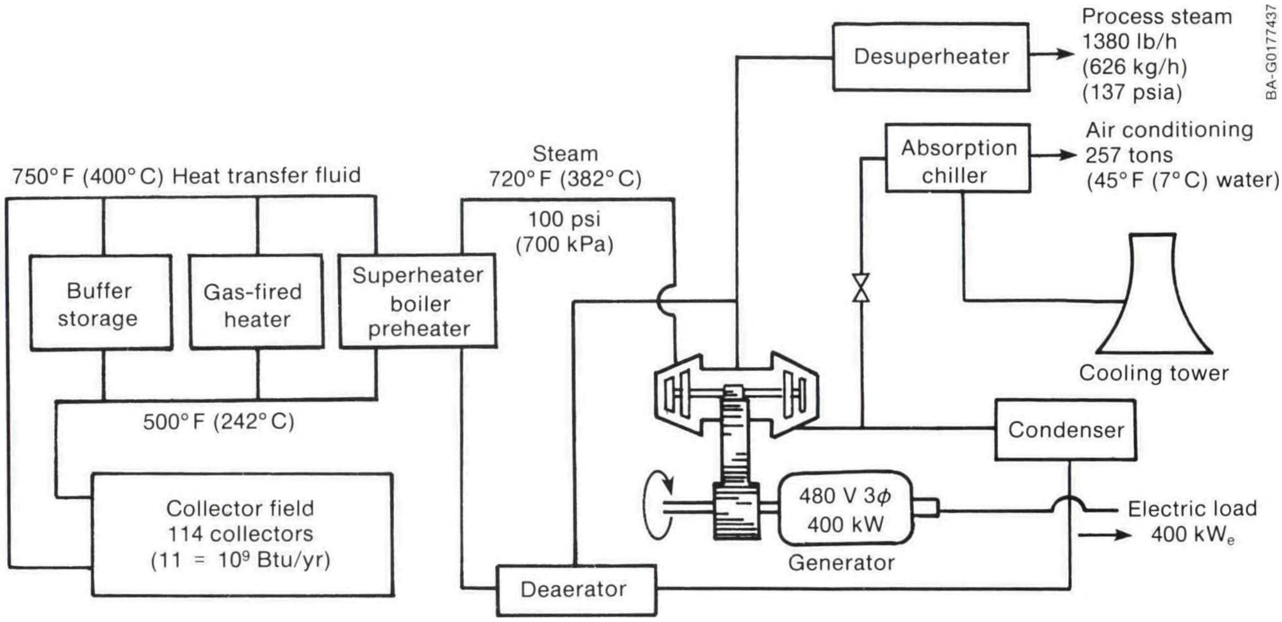


Figure 1.8. Power Kinetics, Inc., development concentrator powering the Barber-Nichols organic Rankine cycle engine



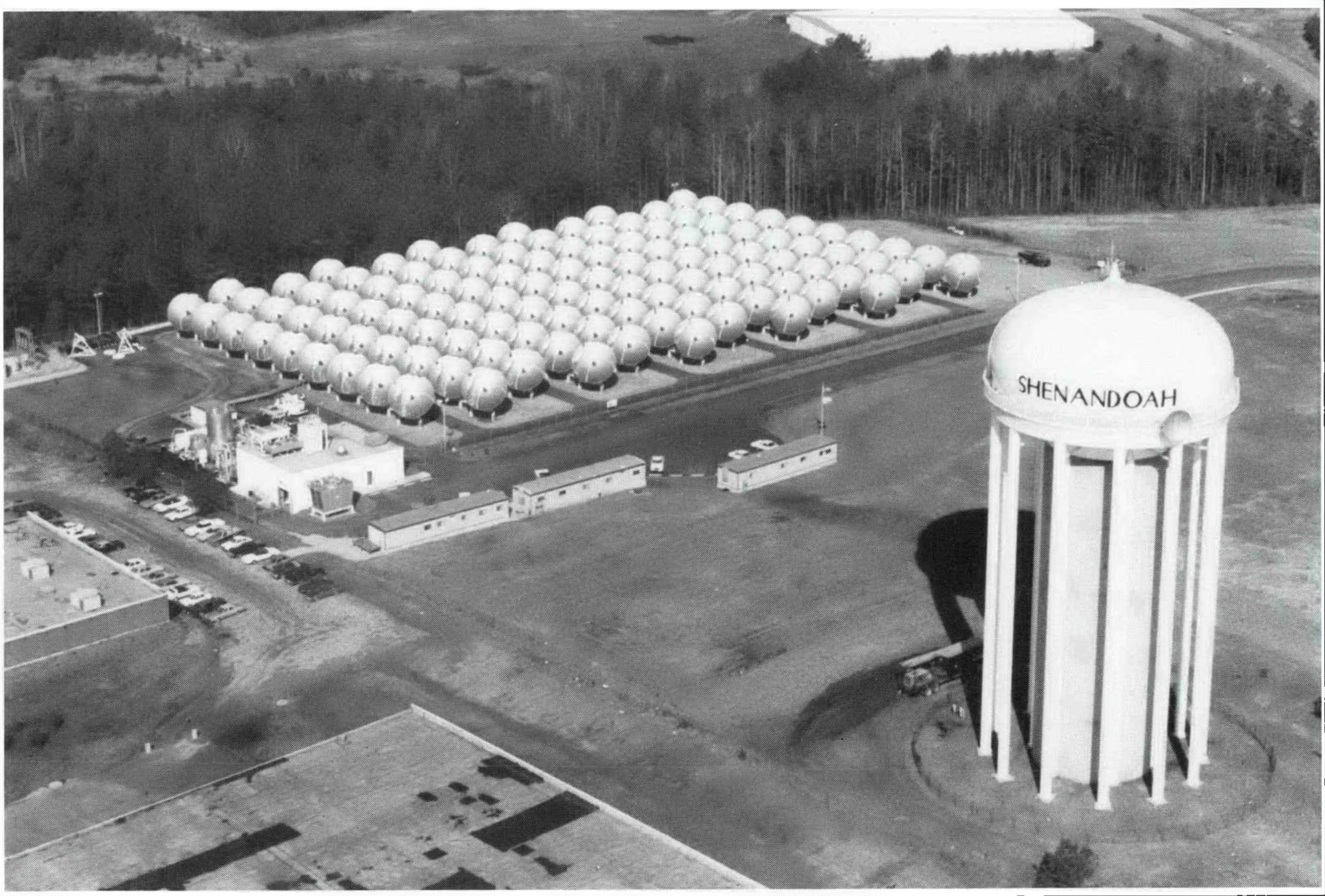


Figure 1.9. Georgia Power Solar Total Energy System at Shenandoah, Ga.

Program Directions

As a result of these engine prototype programs, the importance of providing engines and concentrator hardware with a long mean time before failure has become obvious. Low maintenance considerations might lead the designer away from some concepts with theoretically high engine efficiencies. Specifically, designs with sliding mechanical seals and bearing surfaces must be avoided if power generation systems with numerous engines are to be operated economically.

The same consideration must be used when evaluating concentrator concepts. A few failures and adjustments during prototype testing might appear minor, but when these same designs become operational in large quantities, the maintenance expense can be high. These lessons, along with developments in reflective-film technology and the free-piston Stirling engine, lead to the conclusion that parabolic dish systems that produce electricity at a cost of 5¢/kWh$_e$ will be available by the 1990s.

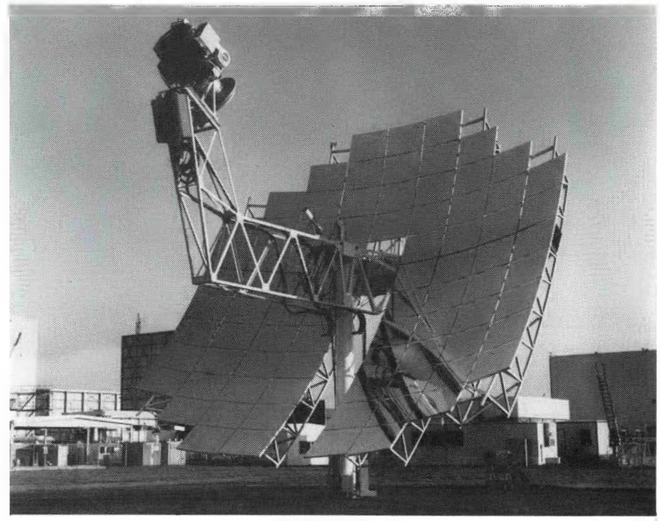


Figure 1.10. McDonnell Douglas dish concentrator using a United Stirling Model 4-95 engine at the focus

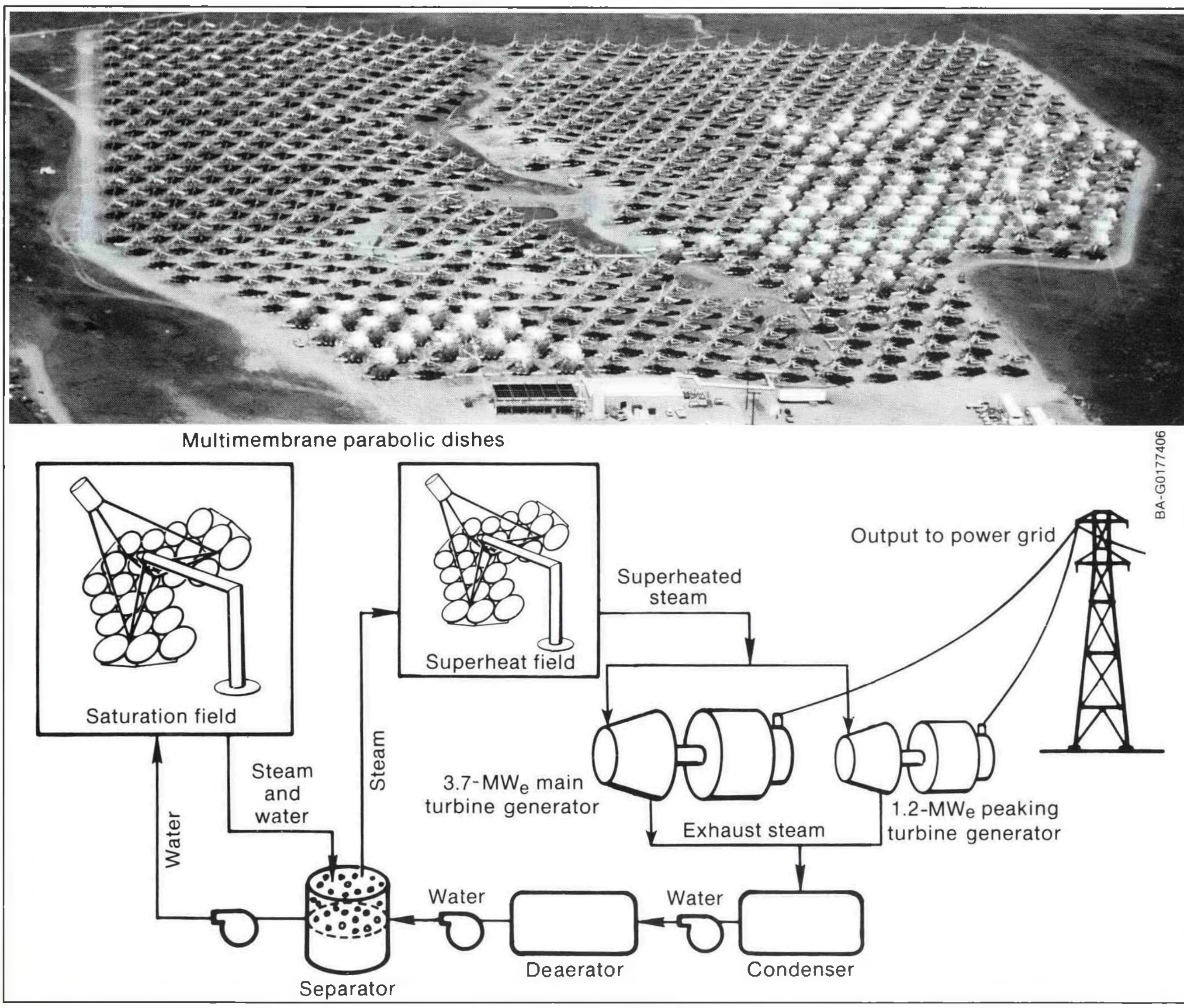


Figure 1.11. Solarplant One at Warner Springs, Calif.

Chapter 2
Dish Concentrators

In terms of performance and cost, the most important element of a parabolic dish collector is the concentrator, which intercepts the sun's radiation over a large area and concentrates it into a small region. In the 1970s, concentrators proposed for commercial applications were heavy, expensive, and inefficient. Developments in lightweight reflective materials and new structural concepts have progressed so that the current concentrator is about 90% efficient and costs less than $160/m²$.

Dish performance and cost can be improved, as evidenced by current research on lightweight reflective surfaces and the development of prototypes in which the reflective surface is part of the dish structure. This research indicates that concentrators with efficiencies of 78% and a cost of $130/m²$ will be available in the next decade.

Several different concentrator designs—with varying reflecting surfaces, structural techniques, and tracking—were tried. This chapter describes what was learned during the development of each of these designs and the future direction of research and development (R&D).

Fundamentals of Collector Performance

A simple energy balance equation governs the performance of any solar energy collection system and guides the design of new systems. This equation describes the underlying theory that drives many aspects of parabolic dish system design.

In most solar thermal collection systems, the sun's radiant energy is first concentrated and then converted into high-temperature thermal energy or heat that comes from absorbing the concentrated radiant flux on a surface. Most new technology centers around optimizing this conversion. Once this thermal energy is obtained, it is transferred from the solar energy system either for direct use or conversion into a more valuable form of energy, usually electricity but possibly fuels or chemicals.

The fundamental solar collection equation defines the instantaneous performance of the system. Although it is important to design a system with high instantaneous collector efficiency at a peak design condition, it is more important to know how the system will perform over time as the insolation, the angle of incidence, and the ambient temperature change. All these variables averaged over a year are called the *annualized collector efficiency*, which is a function of the location and typical year analyzed. As a general rule, a system with high instantaneous collector efficiency also has a high annualized collector efficiency.

The rate of useful energy collected by a solar thermal collection system is the difference between the amount of solar radiation reaching the receiver minus the heat lost from the receiver (Eq. 2.1). The amount of solar radiation reaching the receiver depends on the amount available, the size of the concentrator, and several parameters describing the loss of this radiation on its way to being absorbed. Heat loss from the receiver is separated into convection-conduction heat loss and radiation heat loss. The rate of heat loss increases as the area of the receiver or its temperature increases.

$$Q_{useful} = I_{b,n} A_{app} E \cos\theta_i (\rho \Phi \gamma \alpha) - A_{rec} [U(T_{rec} - T_{amb}) + \sigma F (T_{rec}^4 - T_{amb}^4)] , \qquad (2.1)$$

where

$I_{b,n}$ = beam normal solar radiation (rate of solar energy per unit area coming from the sun's disk and surrounding bright region at the collector location, usually measured within a 5-deg cone)

A_{app} = area of the concentrator aperture

E = effective aperture area fraction (fraction of peripheral aperture area not blocked by structure or receiver or intermediate spaces between reflective surfaces)

θ_i = the angle of incidence (the angle between the sun's rays and a line perpendicular to the concentrator aperture)

ρ = concentrator surface reflectance (the fraction of incident energy reflected by the reflective surface, which is always less than one)

Φ = capture fraction (the fraction of energy leaving the reflector that falls on or into the receiver, which is always less than one)

γ = transmittance of anything between the reflector and receiver (such as air or a receiver aperture cover sheet, which is always less than one)

α = receiver absorptance (the fraction of energy absorbed, which is always less than one)

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

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

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)

σ = the Stefan-Boltzmann constant

F = equivalent radiative conductance (combines the ability of a surface to lose energy by radiation [i.e., its emittance] with the ability of the surroundings to absorb this energy).

According to this equation, the amount of useful energy collected is, at most, equal to the beam normal insolation falling on the concentrator; it can be increased by enlarging the individual concentrator or the collector field area; and it is reduced by several factors because ρ, Φ, γ, α, and E are always less than one (Figure 2.1).

Although visualizing solar collection in an equation such as Eq. 2.1 might be easier, solar collector efficiency more often describes the overall performance of a solar energy system and is directly related to Eq. 2.1 as

$$\eta_{col} = \frac{Q_{useful}}{I_{b,n}\, A_{app}} \;. \tag{2.2}$$

Substituting Eq. 2.1 for Eq. 2.2, we have an expression for solar collector efficiency in terms of the fundamental engineering variables previously described:

$$\eta_{col} = E \cos\theta_i\, (\rho\Phi\gamma\alpha) - (1/CR_g\, I_{b,n}) \times [U\,(T_{rec} - T_{amb} + \sigma F\,(T_{rec}^4 - T_{amb}^4)] \;, \tag{2.3}$$

where the geometric concentration ratio, defined as

$$CR_g \equiv (A_{app}/A_{rec}) \;, \tag{2.4}$$

was substituted for the ratio of aperture to receiver area.

This document describes the progress being made in parabolic dish technology research to change and optimize one or more of the parameters of Eq. 2.1 to decrease the cost and increase the performance of a system design.

Advantages of Concentration

Parabolic dishes are concentrating collectors; solar energy is collected through a large aperture area and reflected onto a smaller receiver area to be absorbed and converted to heat. The efficiency of electric generation cycles increases with temperature, and most industrial applications for heat are well above the boiling point of water (Figure 2.2). As operating temperature increases, however, heat loss from the receiver also increases, resulting in less useful energy coming from the collector (lower collection efficiency). When high temperatures are required from a solar collector, the sunlight must be concentrated. This concentration reduces the heated area of the receiver, thereby reducing heat loss.

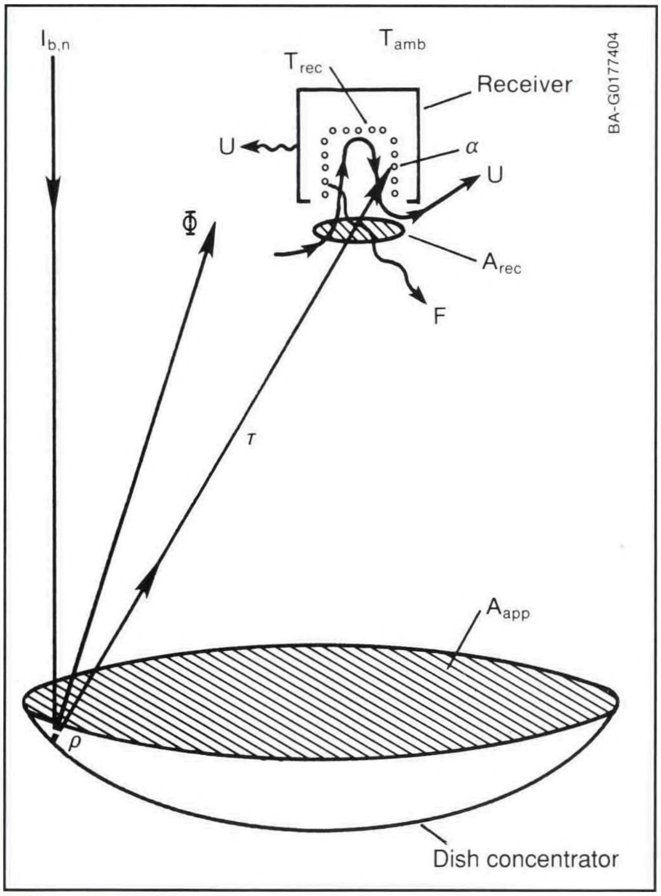


Figure 2.1. Symbols used in Eq. 2.1

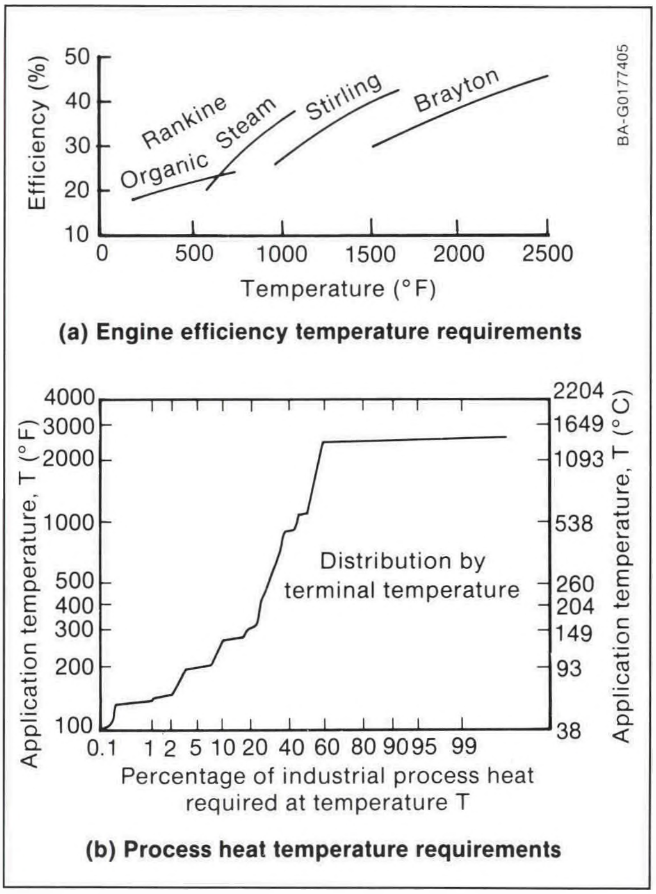


Figure 2.2. Temperature requirements for electricity generation and process-heat solar thermal applications

The advantage of concentration is evident from Eq. 2.1. Because solar thermal systems operate at relatively high temperatures, the difference between the receiver temperature and the ambient temperature is large. This difference results in high heat losses, which reduce the useful energy collected. To compensate for this loss, concentrating the incident sunlight allows the aperture area of the receiver to be reduced without reducing that of the concentrator.

The extent to which the aperture area of the receiver is reduced relative to that of the concentrator is called the *geometric concentration ratio*, previously defined in Eq. 2.4. Parabolic dish collector concepts described here are all designed with receiver aperture areas considerably smaller than those of the concentrator to reduce receiver heat loss at high temperatures.

A fundamental trade-off exists, however, between increasing the geometric concentration ratio and reducing the cost of the collector because collectors with high concentration ratios must be manufactured precisely. Generally, a direct correlation exists between the accuracy of the concentrator and its cost.

Concentrator Optics

The concentrator intercepts sunlight with a large opening and reflects it to a smaller area. The parameters in Eq. 2.1 affected by the design of the concentrator are the following:

- Concentrator aperture area A_{app}
- Receiver area A_{rec}
- Effective aperture area fraction E
- Angle of incidence θ_i
- Surface reflectance ρ
- Capture fraction Φ.

The remaining parameters are functions of the receiver design or the weather (see Chapter 3).

Paraboloid Concentrators. The *paraboloid* is a surface generated by rotating a parabola about its axis. The resulting surface is shaped so that all rays of light parallel to its axis reflect from the surface through a single point, the *focal point*. The parabolic dish is a truncated portion of a paraboloid and is described by the equation

$$x^2 + y^2 = 4fz \, , \qquad (2.5)$$

where z is the distance from the vertex parallel to the paraboloid's axis of symmetry, and f is the focal length. Figure 2.3 shows the paraboloid with the primary elements labeled.

The focal-length-to-diameter ratio f/d defines the parabola's shape and the relative location of its focus. This shape can also be described by the rim angle or the angle measured at the focus from the axis to the rim or a point where the paraboloid was truncated. Parabolas for solar applications have rim angles from less than 10 deg to more than 90 deg. Figure 2.4 shows a family of parabolas with the same aperture diameter but different f/d and rim angles. At small rim angles, a parabola differs little from a sphere. Sometimes spheric surfaces are used to

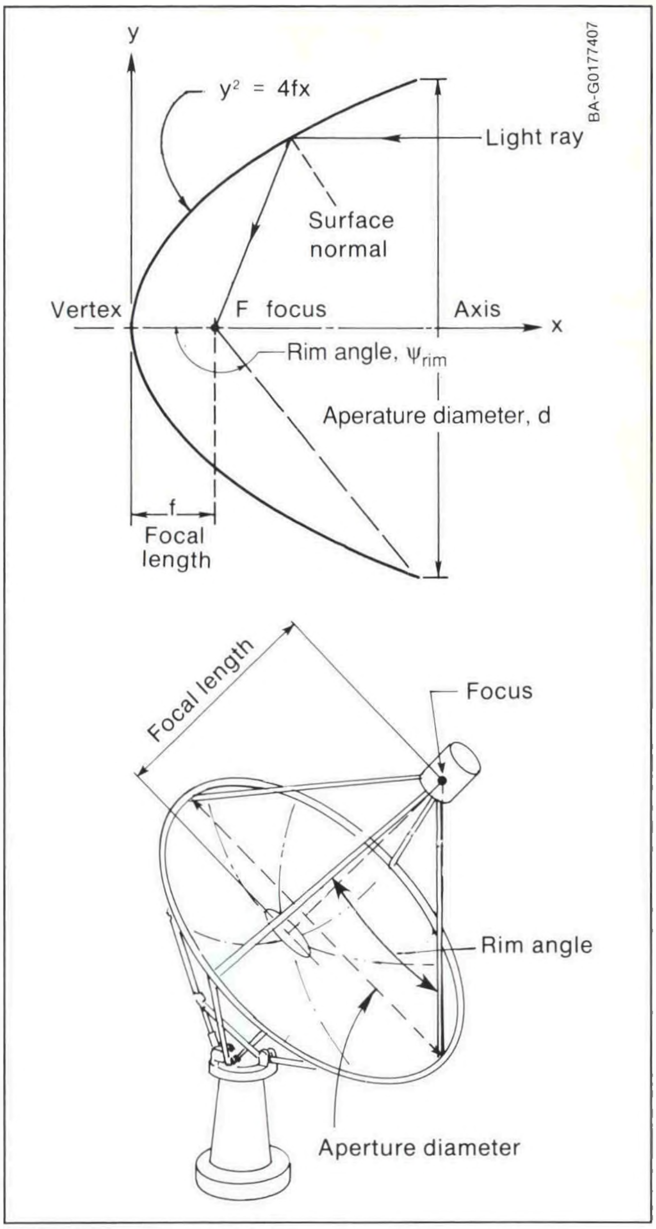


Figure 2.3. The paraboloid

approximate parabolic surfaces because they are easier to produce, especially with stretched membranes.

The relationship between f/d and the rim angle is

$$f/d = \frac{1}{4 \tan (\psi_{rim} / 2)} \, . \qquad (2.6)$$

For example, a parabola with a rim angle of 45 deg has an f/d of 0.6. The smaller the rim angle is the larger the ratio. A parabola with a very small rim angle is an almost flat surface, and the focal point and the receiver must be placed far from the concentrator surface.

Parabolas with rim angles less than 50 deg are used when the reflected radiation passes into a cavity receiver, whereas parabolas with larger rim angles are best when the reflected radiation bathes an external surface receiver. These two receiver types are discussed further in Chapter 3. Parabolas with rim angles exceeding about

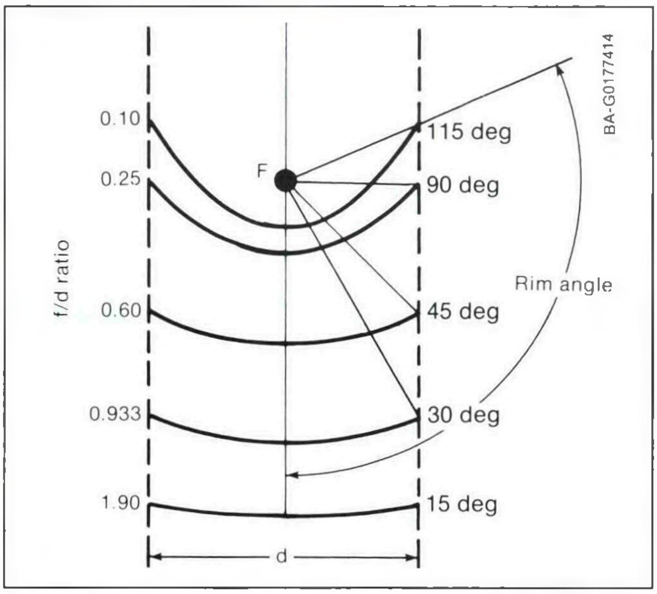


Figure 2.4. A family of parabolas with the same aperture area but different focal lengths

90 deg are not cost effective because they require a large reflector surface and structure to provide small incremental increases in aperture area near the edge of the concentrator.

Very small rim angles (less than 10 deg) result in the focus being far from the reflective surface. This surface must be accurately formed to minimize the spread of the reflected beam over this long distance, so the collector does not need a large receiver surface area with its resulting high heat loss.

Optical Errors. Operating concentrators typically have several optical errors that cause them to deviate from the theoretical parabolic optics previously discussed (Figure 2.5). Some errors are random and cause the optical image of the sun to spread at the focus. Reducing these errors usually means increasing the cost of the concentrator, creating one of the major trade-offs in designing parabolic dish systems.

Even the best concentrator surfaces deviate from the ideal curve to which they were manufactured. This deviation, called *slope error*, is the average angle by which the actual surface slope deviates from a true parabola. Because the slope error varies over the surface, it is typically specified statistically as one standard deviation from the mean expressed in milliradians. In general, the smaller the error in the optical surface, the more the collector costs.

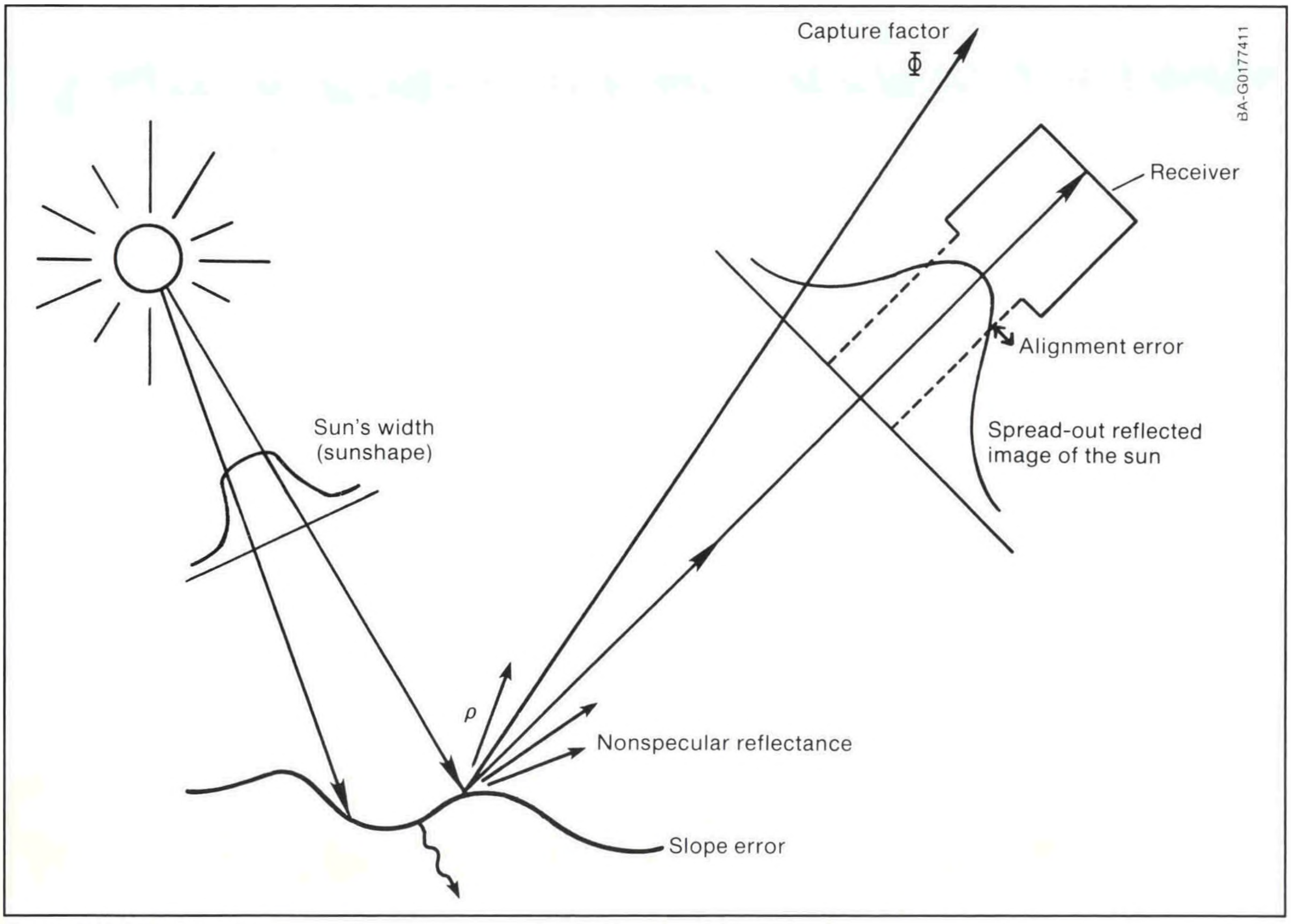


Figure 2.5. Optical errors

Well-manufactured parabolic concentrator surfaces can have an average slope error of 2.5 mrad (about 0.15 deg).

A second source of optical error is the reflective surface itself. When a beam of parallel rays hits an optical surface, the reflected beam can be diffused. The extent to which this diffusion happens is called *nonspecular reflectance*. For example, commercially polished aluminum diffuses incident radiation to a greater extent than back-surfaced glass mirrors. Likewise, current commercial silvered polymers produce a greater nonspecular reflectance than back-surfaced glass mirrors. Coatings are being developed, however, that give polymer films a specular reflectance equivalent to glass.

Two optical alignment errors dislocate the actual focus: the error in mechanically aligning the receiver relative to the concentrator and the tracking error where the concentrator axis is not pointed directly at the sun. Although not completely random, tracking errors are treated as such for simplicity.

One last factor that cannot be corrected with increased concentrator manufacturing quality is the sun's width. Because the sun is not a point source giving parallel rays, the reflected image spreads in a cone of approximately 8.7 mrad (0.5 deg). The effect is similar to the other errors and spreads the reflected radiation at the focus.

The total optical error of a concentrator is approximated by summing these errors:

$$\sigma_{tot}^2 = \sigma_{surf}^2 + \sigma_{track}^2 + \sigma_{sun}^2 , \tag{2.7}$$

where the surface error combines surface slope error and specularity:

$$\sigma_{surf}^2 = (2\sigma_n)^2 + \sigma_m^2 .$$

Table 2.1 shows a representative error budget. Summed as in Eq. 2.7, these values result in a total concentrator optical error of 5.5 mrad.

Table 2.1. A Representative Error Budget for Parabolic Dish Concentrators

Error Type	Values (mrad)
Tracking Error σ_{track}	1.5
Sun Shape σ_{sun}	2.73
Surface Slope Error σ_n	2
Surface Specularity σ_m	2

The effect of optical errors on collector performance is represented by the capture fraction in Eq. 2.1, which is the fraction of the reflected beam that enters the receiver. This parameter is a function of 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 larger the receiver surface area must be and, therefore, the smaller the concentration ratio. Any radiation not entering the receiver falls outside and is called *spillage*.

Concentrator Designs

Some of the more prominent concentrators representing parabolic dish technology are discussed in the following subsections.

True-Paraboloid Dish

The paraboloid dish is the only true point-focus concentrator; even a perfect paraboloid cannot focus the sun's energy to a point because the sun's rays diverge (Figure 2.6). The surface of a paraboloid must follow Eq. 2.5.

An advantage of this dish is that no area is lost within the aperture because of element spacing or shadowing and tilting facets. A disadvantage is that once fabricated, the optical shape is difficult to adjust, requiring an accurate manufacturing process. A second disadvantage is that mechanically or thermally induced distortions in one region of the parabola tend to affect the entire paraboloid shape.

Stretched-Membrane Concentrators

A design that promises to provide a lightweight, inexpensive concentrator is the stretched-membrane collector (Figure 2.7). This design uses a thin reflective membrane that is stretched around a hoop and usually has a second membrane on the back of the hoop. To form the optical shape and provide rigidity, a slight vacuum is drawn on the space between the membranes. If the membrane is thin and flexible, the resulting optical shape will be spheric.

Because spheric and parabolic reflectors are similar in their ability to concentrate for long focal lengths, a spheric stretched-membrane concentrator must have a long focal

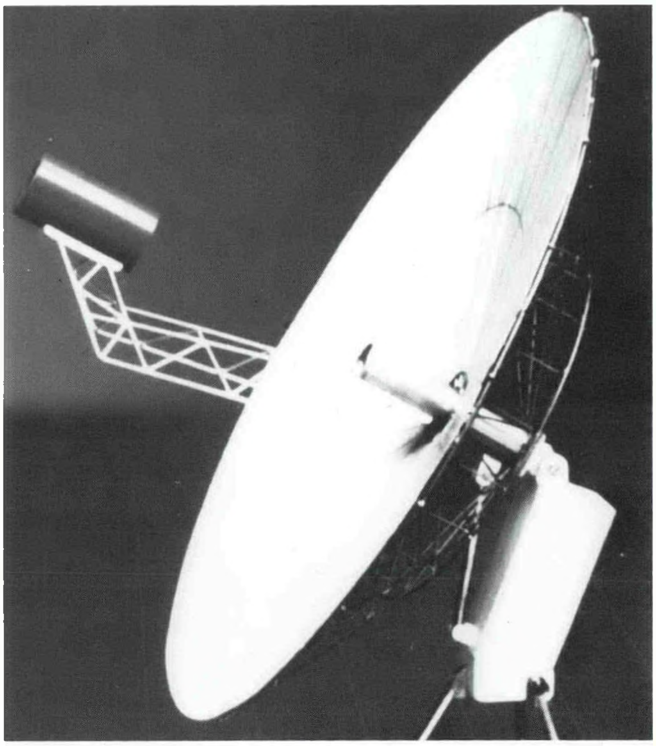


Figure 2.6. A true-paraboloid dish design

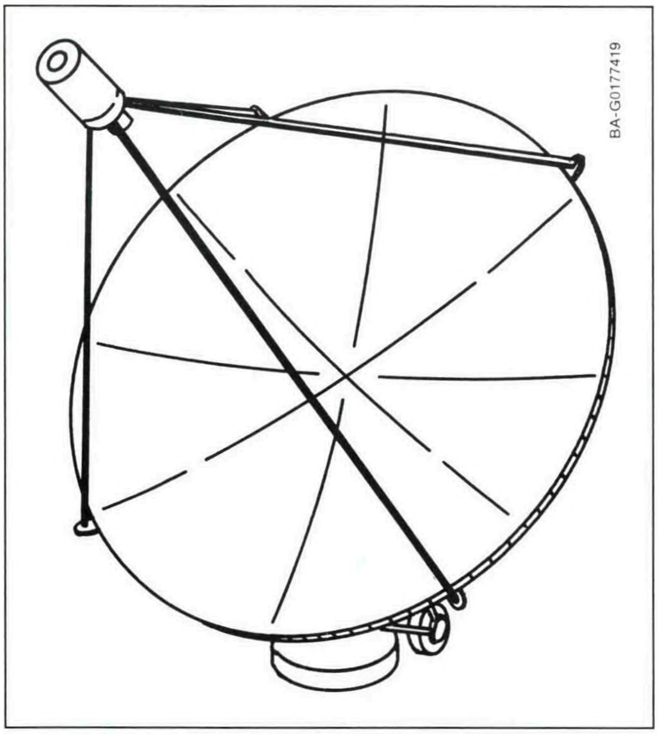


Figure 2.7. A single stretched-membrane dish

length. This design problem is a major one when heavy receiver and engine units must be supported far from the reflector and tracked. One proposed method for reducing the focal length and maintaining optical accuracy is to pre-stretch the membrane beyond its elastic limit into some shape that becomes parabolic once a vacuum is drawn.

To use the stretched-membrane design without shortening the membrane's focal length or placing the receiver far from the concentrator, researchers developed and tested a concentrator with multiple stretched-membrane facets (Figure 2.8). Here, facets with long focal lengths but small diameters are mounted on a tracking frame and canted toward the receiver. The resulting overall focal length of the multiple-membrane concentrator is small relative to the total diameter of the support frame. This design results in a more rigid structural support for the receiver.

Focused Facet Concentrators

Instead of fabricating a single, large paraboloid, designers can divide the surface into several small facets, with each facet fabricated and attached to a frame that holds them in place in the paraboloid (Figure 2.9). Typically, this design allows individual facets to be adjusted, approximating a parabolic curve.

Often, however, the facet's curvature is not parabolic for two reasons: flat or spheric surfaces are easier to fabricate than segments, and square segments are easier to fabricate than radial segments. If square segments with a parabolic curvature are used, the advantage of simple manufacture is lost because the curvature of any segment is repeated only eight times. The alternative is to use flat or spherically curved facets with a few different curvatures to compensate for different radial positions on the paraboloid support structure. Spheric optics approach parabolic optics at long focal lengths, which is possible if the aperture is broken into many facets.

In addition to the difficulties of fabricating and keeping track of multiple-shaped facets, this optical design requires considerable fastening hardware and installation labor as well as labor to align the facets after installation.

Slat Concentrators

Instead of using a rigid paraboloid shape to concentrate the sun's rays, small, movable reflectors can be placed on a large surface with each one aimed so a ray coming from the sun is reflected to the receiver. This concept underlies the Power Kinetics, Inc., movable-slat, point-focus concentrator (Figure 2.10). This concentrator uses flat, reflective facets bent in two directions attached to a curved, horizontal slat. The slat pivots horizontally so it can track in elevation. Many rows of slats are aligned on a tilted frame that tracks the sun in the azimuth direction. The receiver stays fixed relative to this frame.

Optically, this arrangement has several disadvantages relative to the true paraboloid. First, the concentrator aperture only tracks about a single axis and, therefore, suffers from cosine losses (i.e., cos θ_i does not equal 1.0). Because the reflecting surface of each segment must face halfway between the sun and the focus, the sun's angle of incidence on the surface varies with time of day and season. When the sun is in the extremely high altitude position (around noon during the summer) or in low altitude positions (in the winter or mornings and afternoons), the sunlight is not concentrated from the full reflective surface area.

Another disadvantage of this arrangement is that if spaced closely to reduce the structure, adjacent slats can block incident rays and shadow-reflected rays. This situation reduces the effective aperture area. The greatest blocking and shadowing occurs when large angle differences exist between the sun and the support frame. The end result reduces the optical efficiency over a year's operation.

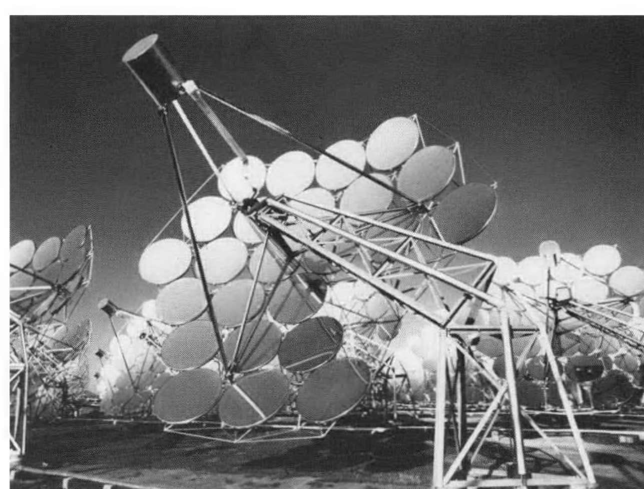


Figure 2.8. La Jet LEC460 multifaceted stretched-membrane concentrator

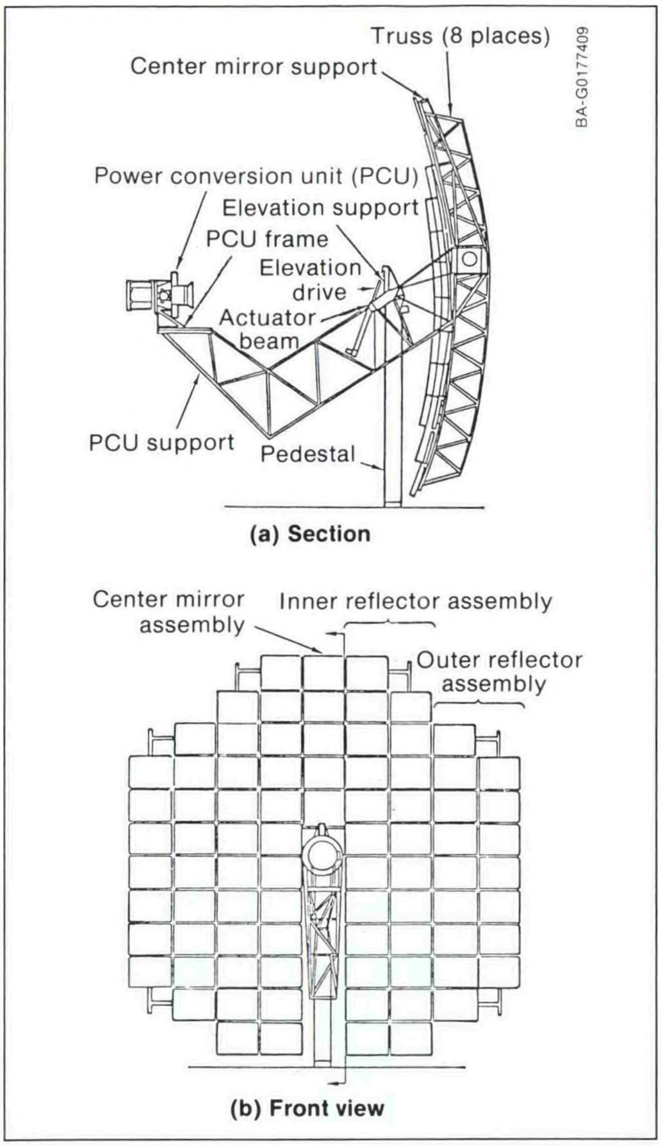


Figure 2.9. McDonnell Douglas focused-facet concentrator

Refractive Concentrators

An alternate method to concentrate the sun's rays is to use a lens (usually glass or plastic) to refract parallel rays inward toward a focus. Glass lenses, however, are usually too massive for solar thermal applications. Because concentration depends only on the angle at which light enters and leaves a lens and not on the thickness of the lens, thin lenses can be made by reducing the material between the top and bottom surfaces. This procedure gives a saw-toothed cross-section, called a *Fresnel lens*, that can be molded into the surface of a thin sheet of plastic (Figure 2.11).

A Fresnel lens can tolerate a much greater slope error than the parabolic reflector, but it requires precise, high-quality facets. Even with high-quality facets, each saw-toothed edge forms a local area where the light rays are not properly refracted. Because each facet acts like a prism, the result is an overall chromatic aberration at the focus.

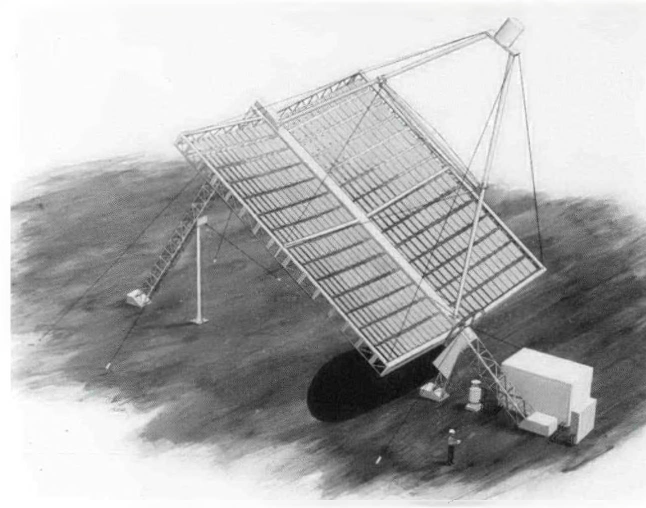


Figure 2.10. Power Kinetics, Inc., slat concentrator

Refractive concentrators have other disadvantages. Light passing through the plastic material reduces the amount of light transmitted. Making the material thin reduces but does not eliminate this loss. Thin lense material is not structurally strong, so a substructure is necessary to support it. This substructure blocks incoming light, further reducing the amount of energy reaching the receiver.

A possible advantage of the refractive concentrator is that the focus is close to the ground, making it easier to maintain a focus-mounted engine. However, a cavity receiver loses more heat, making the overall effect of this advantage questionable.

Although Fresnel refractive lenses are used for parabolic troughs and concentrating photovoltaics, they have not

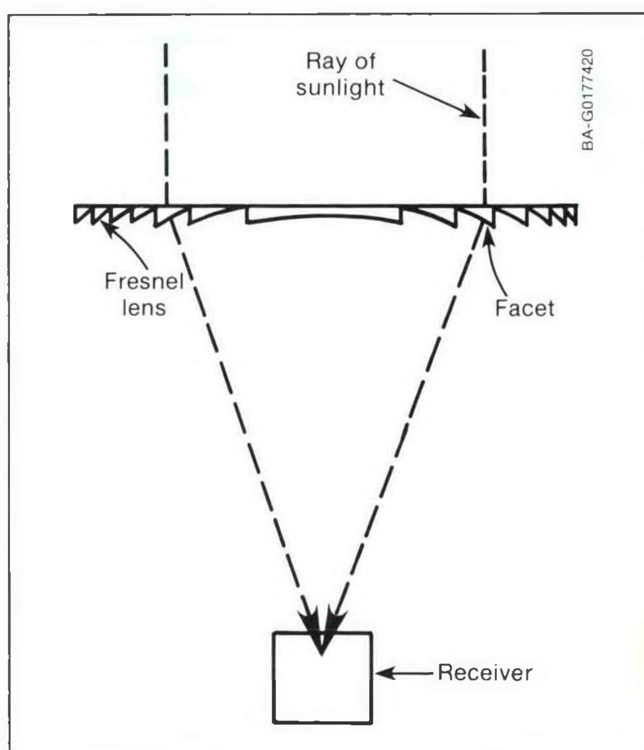


Figure 2.11. Fresnel lens optics

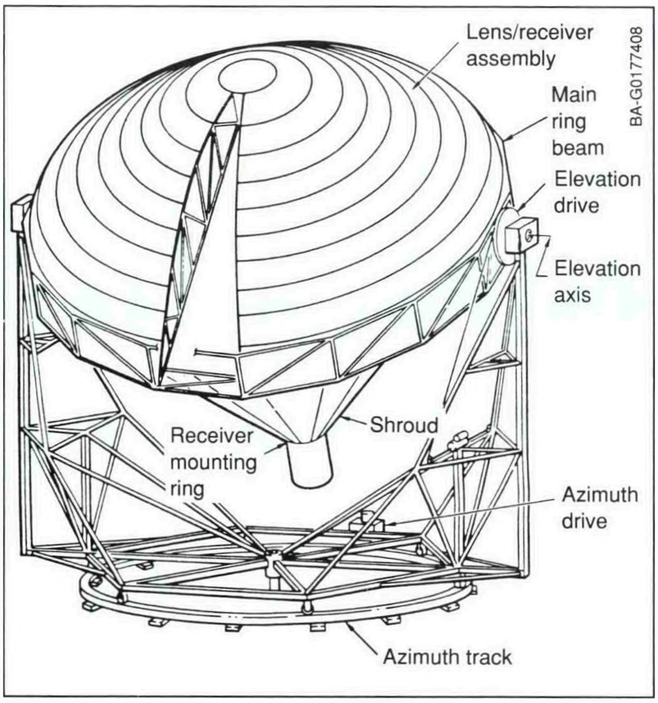


Figure 2.12. Point-focus domed Fresnel lens concentrator

been used for point-focus concentrators. A 14-m-diameter (46-ft) acrylic-domed point-focus Fresnel concentrator was proposed (Figure 2.12). A single sector—termed a *gore*—of a full lense was built and tested. It had an average optical efficiency of 79% at a concentration ratio of 1500. It was found that the refractive concentrator's predicted optics were much less efficient than the reflective counterpart (≈80% as compared to 90%) with no real cost savings. Therefore, full-scale Fresnel concentrators have not been built.

Reflective Surfaces

Most concentrators depend on a reflective surface to concentrate the sun's rays to a smaller area. The surfaces are either polished metal or metals deposited on the back surface of a protective, transparent material (called *back-surfaced* or *second-surface mirrors*). The quality of a reflective surface is measured by its reflectance and specularity. *Reflectance* is the percentage of incident light that is reflected from the surface. *Specularity* is a measure of the ability of a surface to reflect light without dispersing it at angles other than the incident angle. An ideal surface reflects all incident light rays at an angle equal to the angle of incidence.

In addition to high reflectance, the material must have a low weight per unit area. A lightweight reflective material keeps the weight and cost of the supporting structure down. Also, because the reflective material covers a large area, it must have a low cost to keep the total concentrator cost down.

Reflectance

Reflectance is the percentage of incident light reflected by a surface. As shown in Eq. 2.1, the concentrating collector's performance is directly proportional to the reflectance of the mirrored surface.

Also, the microscopic quality of the reflective surface's finish affects the capture fraction because surface specularity can cause the reflection of spreading beams from a concentrator. Evaluating the microscopic quality of the surface requires measuring specular and hemispheric reflectances. *Hemispheric reflectance* is a measure of the total reflected energy in any direction, whereas specular reflectance is a measure of the percentage of incident energy reflected into different solid cone angles (i.e., 0.5 deg, 0.25 deg, etc.).

Reflective Materials

Most reflective surfaces are constructed of metal. Under laboratory conditions, polished silver has the highest reflectance for the solar energy spectrum of any metal surface. Aluminum reflects most of the solar spectrum but does not have silver's high level of reflectance. Although commonly used in the automotive industry, chromium plating has a relatively low reflectance and is not applicable to solar concentrators.

Silvered Steel or Aluminum. A recent concept under development in reflective coatings is to apply a surface-protected silver reflective coating to a stainless steel or aluminum surface. This process uses a material known as sol-gel that can be applied like paint and, when cured, forms a thin glass-like coating.

A durable, highly reflective surface can be made by first applying a thin coat of sol-gel to stainless steel to provide a smooth subsurface, then plating or depositing the silver reflective coating (Figure 2.13). The next step is to deposit a layer of silicon oxide and then another sol-gel coating. When cured at high temperatures, the resulting reflector has the strength and flexibility of stainless steel and the high reflectance and weatherability of a thin-glass mirror.

Reflective Plastic Films. Aluminized plastic films are available for solar applications. A variety of plastic films with aluminum sputtered onto the back surface were used for many years for solar concentrator reflective surfaces. Although the optical properties of most plastics degrade after long exposure to ultraviolet rays, adding stabilizers effectively slows this degradation.

Silvered plastic film with a high reflectance (96% with high specularity) is now available and promises to be the reflective surface of choice for many new designs (Figure 2.14). The film has a low cost and is highly reflective, flexible, and lightweight.

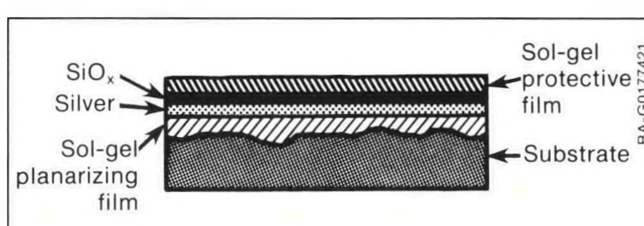


Figure 2.13. Cross-section of sol-gel reflective surface

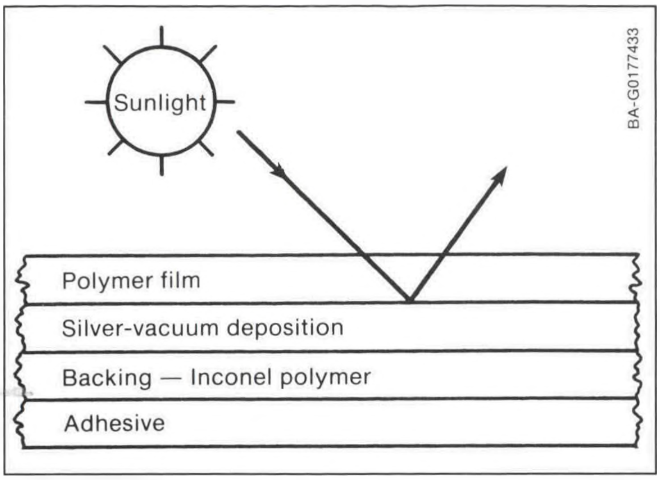


Figure 2.14. Cross-section of a silver-polymer reflective film

A major drawback of metalized plastic films is that they can not be mechanically washed like glass. Less abrasive washing techniques are currently being studied. High-pressure sprays are one possible solution, as is the application of surface-hardening coatings.

Back-Surfaced Glass Mirrors. Back-surfaced silvered-glass mirrors are made by silverplating the surface of a glass sheet and applying protective copper plating and protective paint to the silver coating. This technique has been used for numerous common applications, such as bathroom mirrors, for many years. For traditional mirrors, the glass is thick, making it heavy and difficult to bend. These mirrors typically have a low transmittance because the glass contains iron. Although a polished silver surface has a reflectance of almost 98%, the resulting mirror does not have this high reflectance because incident light must pass twice through the thick, low-transmittance glass. Further, thick glass can not be bent into the compound curves required for most parabolic dish applications.

To maintain the high weatherability of the glass back-surfaced mirror and increase solar applications, thin-glass mirrors were developed. The glasses used are usually iron-free and do not absorb strongly in the solar spectrum. These mirrors can have a reflectance close to 98%.

Polished Metal. The first reflective surface widely used in parabolic dish concentrators was thin, polished aluminum sheets. These sheets are available in large sizes and are relatively inexpensive. Their major disadvantage is they only have a moderate specular (nonscattering) reflectance of about 85% when new.

Another disadvantage of polished metal reflectors is their poor weatherability. Athough they were designed to withstand adverse climatic conditions, after a few years of exposure, the surface reflectance deteriorates, and no washing procedure can return it to its original value. Researchers conclude that the surface reflectance degrades more rapidly in industrial applications where products of combustion and other components make the surrounding air corrosive.

Weatherability and Cleaning

Because solar collectors are placed outside for decades and are expected to perform without significant degradation, reflective surfaces must meet stringent weatherability criteria. It is important to consider degradation caused by ultraviolet radiation, moisture, sandstorms, and hail. In addition, the process of cleaning reflective surfaces, either naturally by rain and snow or mechanically, can abrade the surface.

Various surface materials respond differently to these processes. Typically, glass-faced surfaces have excellent weatherability characteristics and can be washed using techniques that might abrade softer surfaces. Plastic surfaces generally are more difficult to wash because the particles being removed are abrasive. Hard surface coatings are currently under development that can be applied to polymer surfaces to minimize soiling and make cleaning easier. These high-technology coatings render plastic surfaces almost as hard as glass.

Polymers used in parabolic dish collectors do degrade over time because they are exposed to the sun's ultraviolet light. Studies indicate, however, that if they can be made inexpensively, the collectors could simply be replaced after three to six years.

Surface Curvature Considerations

In selecting the reflective material for a dish, a designer must consider that the surface curvature is compound (in two axes) and that with dish rim angles as high as 45 deg, significant bending is required. High residual mechanical stress and bonding problems arise when large, flat glass mirrors are bent into shape and bonded on supporting surfaces. To overcome these problems, designers of early parabolic dishes leaned toward using smaller reflective segments, called *facets*, for many applications.

The concentrator designer has two choices when making the curved reflective surfaces. One is to use flat reflective sheets, such as silvered glass mirrors, and bend and adhere them onto a curved subsurface 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.

Cost and Performance

In the early 1970s, reflective surfaces were either heavy, silvered glass or polished metal with initial reflectances (85%) that decreased rapidly when exposed to the environment. R&D over the last 10 years has led to current concentrators that use thin, high-quality glass mirrors and aluminized plastic films with a reflectance of 88% and a cost of $15/m^2$ to $20/m^2$.

Research indicates that reflective surfaces with a reflectance of 92% and a cost of $10/m^2$ are attainable in the near future. Two surfaces are being pursued: silvered polymer films and silver directly plated onto structural materials. In addition, researchers are examining the weatherability of these surfaces and how to wash them.

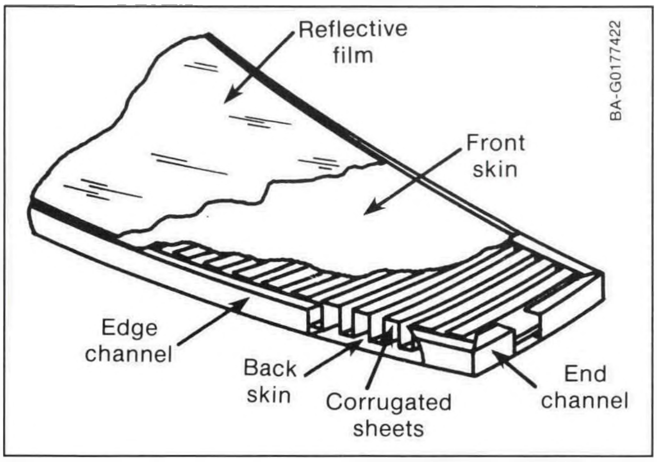


Figure 2.15. Optical surface with corrugated structural support

Structure

Many choices face the designer in deciding the best way to accurately maintain the concentrator's shape. As more efficient structural techniques are developed, the cost of a concentrator can be reduced.

Structural Optical Surface

One design option used in many dishes is to combine the optical elements with the structural elements using stamped metal gores (pie-shaped elements) bolted together along their edges (Figure 2.15). Alternative designs use laminated gore panels with honeycomb, foamglass, balsa wood, or corrugated sheet metal as the spacer between an outer face sheet and an inner face sheet, which is the optical surface. These designs often suffer from heavy, inefficient structural members and result in large-scale warpage if not adequately strengthened. A recent design using thin metal corrugation between the face sheets appears to minimize these faults.

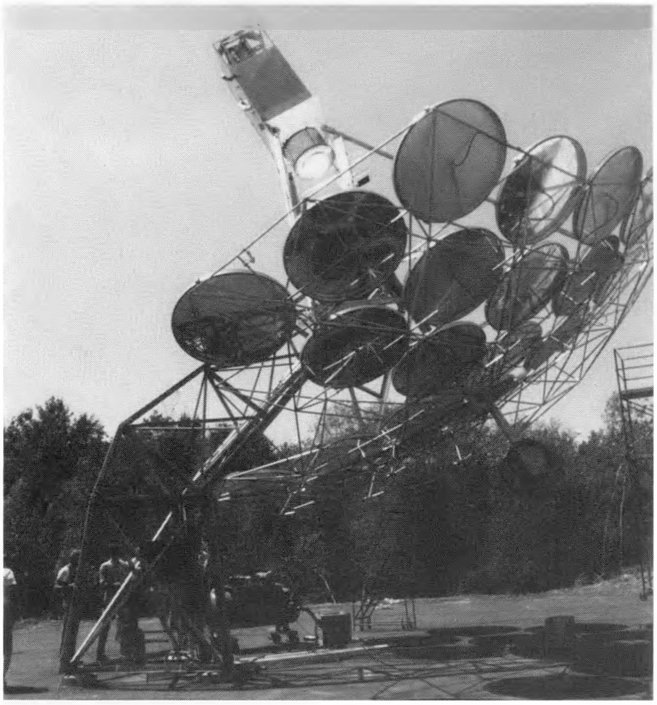


Figure 2.16. Space frame support of mirror facets

Space Frame

A second design option separates the optical elements from the structure. Here, efficient tubular structural elements in triangular truss segments carry the load throughout the reflector structure. Reflective mirror facets are then attached to this frame (Figure 2.16). Although lightweight and structurally efficient, this design requires considerably more fabrication than the structural gore.

Stretched Skin

Atmospheric pressure can be used to form the curvature of the reflective surface. Stretching a thin, reflective skin like a drumhead on a hoop and slightly evacuating the region behind it reduces the size of the structure required to support the optical surface. Because a hoop in uniform compression is a highly efficient structural element, an extremely lightweight supporting structure is possible.

The major disadvantage of this design is that the membrane becomes spheric when the back side is evacuated. To optically compensate for this shape, long focal lengths must be used where the spheric reflector approaches a parabolic reflector. This adjustment can be done either by mounting many small membrane facets on a space frame and aiming each at a single focal point or by placing the receiver far from a single membrane reflector.

A concept is currently being considered that reduces the number of facets and eliminates a space frame. The design involves preforming the membrane beyond its elastic limit so that when the space behind it is evacuated, the membrane forms a paraboloid rather than a sphere. With this concept, a single stretched-membrane concentrator could be used with f/d ratios that would not require an excessively long receiver support structure (Figure 2.17).

The advantages of the stretched-membrane concentrator are that it uses a lightweight reflective surface and that the overall structure is efficient, thus reducing design and fabrication costs.

Tracking

Methods

Parabolic dish concentrators must track about two independent axes so the sun's rays remain parallel to the concentrator's axis. These two axes are azimuth-elevation (az-el) and polar (equatorial) (Figure 2.18). *Azimuth-elevation tracking* allows the concentrator to move about one axis perpendicular to the earth's surface (the azimuth axis) and another axis parallel to it (the elevation axis). *Polar tracking* uses one tracking axis aligned with the earth's axis of rotation (the polar axis) and another axis perpendicular to it (the declination axis). For either tracking method, the angle of incidence, θ_i in Eq. 2.1, remains zero throughout the day. The tracking axis selected is important to the overall design of the concentrator.

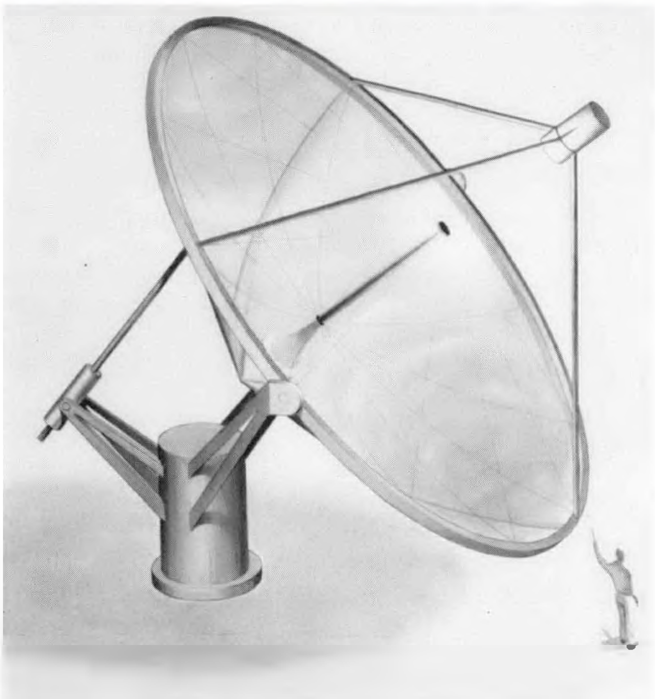


Figure 2.17. Stretched-membrane dish concentrator concept

Movable-slat concentrators typically have a frame that tracks about one axis (azimuth or polar) with the slats holding the mirror tracking about a second axis. Because the mirrors on these slats form portions of different parabolas, only an approximate focus can be maintained. Likewise, the angle of incidence for the mirrors is not zero but varies throughout the day.

Azimuth-Elevation Tracking. The tracking movement rate for azimuth-elevation tracking about either axis is not uniform and must be determined instantaneously using either an ephemeris table or equations from a computer or a sun sensor such as a shadow band.

The tracking rate depends on the latitude, date, and time of day, with azimuth and elevation tracking at about 10 deg/h. As solar noon approaches, the azimuth tracking rate increases rapidly near the summer solstice, with rates 10 times the average occurring at 32 deg latitude. At latitudes between the tropics, an infinite rate anomaly occurs when the sun is directly overhead that must be accounted for in designing a tracking system.

Using this tracking mode distributes the weight of the dish to many support points around the base. Azimuth tracking can be done by supporting the weight of the full collector on a ring track about the base with three or more wheels carrying the load to the track. Elevation tracking about the horizontal axis can be done using two trunnions at the concentrator periphery with a pure vertical load on the bearings and no thrust loading.

Polar Tracking. This tracking mode is used for most astronomical telescopes. Polar tracking has the advantage of a constant tracking rate at the earth's rotational speed (15 deg/h) and a slow movement about the declination axis (a maximum of 0.0163 deg/h at the equinoxes). These constant and extremely slow tracking rates give rise to the possibility of using a simple clock drive to track about the

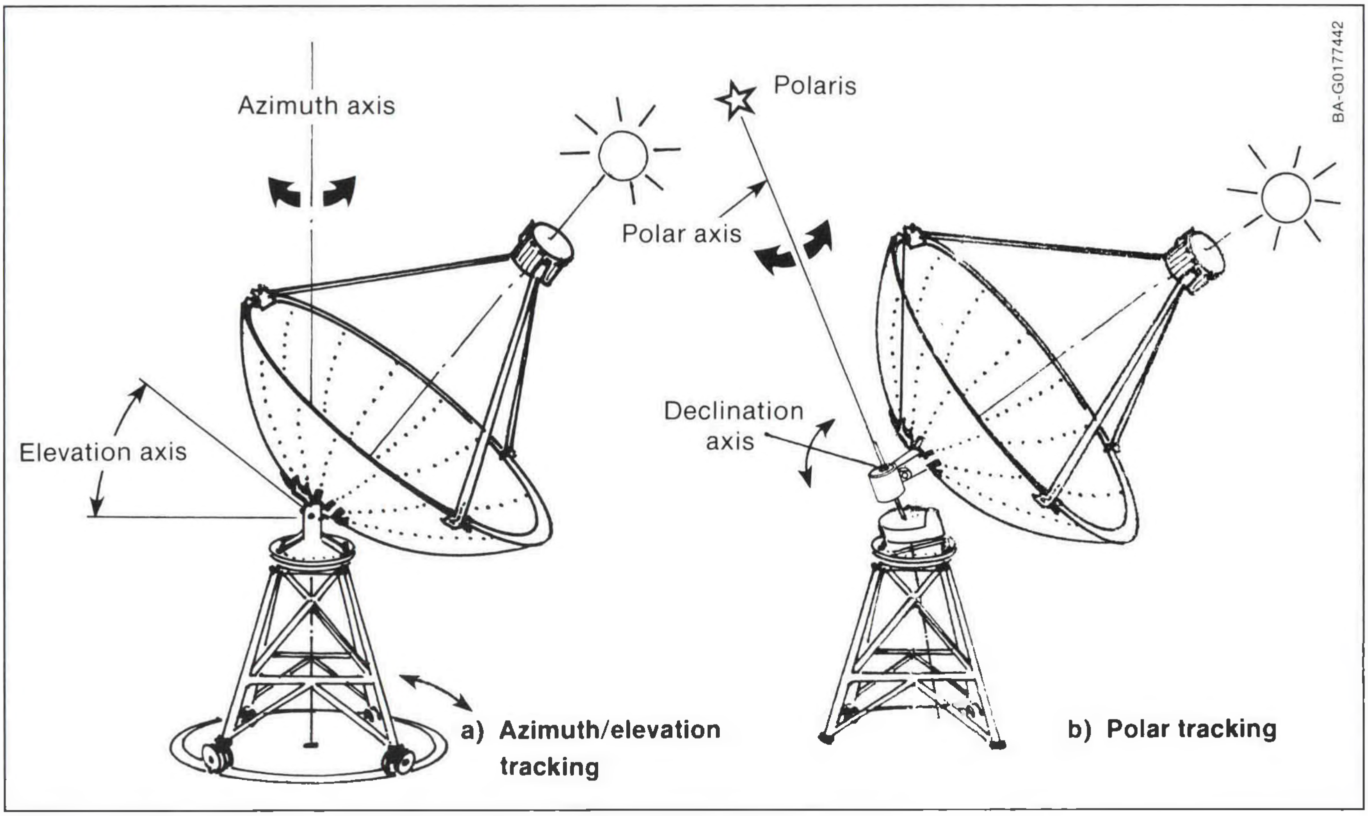


Figure 2.18. Basic parabolic dish tracking modes

polar axis and making incremental adjustments about the declination axis daily or less often.

The simplicity of the tracking rates is offset by several disadvantages. One is that the mass of the collector is supported on a tilted axis giving high thrust loading and moments. Another is that the collector tilting to the east or west causes an imbalance of moment. Further, it is difficult to design the tracking mechanism so the receiver can be lowered enough to do the maintenance on it and the associated hardware. The advantages of slow, fixed-rate tracking are offset because some means must be provided to rapidly detrack the collector in emergencies, requiring higher tracking motor power and some way to control the speed of movement.

Walk-off Protection

A problem with cavity receivers is that if a power failure occurs or if the tracking system fails while the collector is in focus, the high-flux focal point passes across the front of the receiver at a slow rate. This movement can cause the surfaces and, possibly, the receiver support structure to overheat. This failure mode is called *walk-off* because the focus moves across the receiver at the rate of 1 deg every four minutes. Most systems can defocus the concentrator in emergencies. For some, a battery system or other uninterruptable power supply is required in case of a power failure. An alternative is to use refractory materials to passively protect the receiver or provide active water cooling.

Stow Considerations

Tracking systems provide for storing the concentrator overnight and during inclement weather as well as positioning the concentrator for maintenance operations. Concentrators should be stowed in the facedown position at night in most climates to prevent dew and dust from accumulating on the reflector surface. If this facedown position is not possible, the vertical position is preferable to the faceup position. For many tracking system designs, especially polar mounts, even vertical stow is not possible, and the collectors must remain pointed at some elevation angle above the horizon. If they are in the faceup position, however, the reflective surfaces can be washed when it rains. Tracking (and control) systems can be designed that respond to rain by rapidly turning the concentrator faceup to take advantage of this natural washing.

When designing a tracking system, a designer must consider the ease of maintenance for the components placed at the focus of a parabolic dish concentrator. This consideration is especially important when small engines are usedin the receiver design. Tracking systems can be designed so the receiver can be lowered for servicing, such as the McDonnell Douglas parabolic dish that uses a Stirling engine at the focus (Figure 2.9).

The wind also affects tracking system design. When wind speed increases beyond a specified maximum for safe operation, the tracking system must stow the concentrator in a position that minimizes the effect of high winds. A good high-wind stow position for a parabolic dish is horizontal. The tracking system must be designed to stow the concentrator in this position rapidly. This rapid positioning demands much more powerful drive motors than required for normal solar tracking. If the tracking system does not allow for a horizontal stow position, the dish and support structure need to be reinforced to withstand the extra wind loads.

Program Directions

The cost of a parabolic dish concentrator includes the structure, reflective surface, tracking system, and ground support. If the weight per unit area of concentrator surface is reduced, the concentrator size can be increased without significantly increasing the costs of the other collector components. The result is a collector with higher output for the same or a lower cost. Therefore, a major thrust of the parabolic dish program is to reduce the cost and weight (per unit area) of the concentrator surface. The single-facet stretched-membrane dish will meet the cost and performance goals defined to make parabolic dish solar collectors economically viable.

Typical design and cost (per unit aperture area) goals for this collector are given in Table 2.2.

Table 2.2. Design Goals for Parabolic Dish Concentrators

Aperture Area	150 m^2 (1615 ft^2)
Receiver Operating Temperature	800°C (1475°F)
Optical Efficiency	91%
Weight	30 kg/m^2 (6.14 lb/ft^2)
Cost	\$130/m^2 (\$12/ft^2)

Source: Ref. 6.

Chapter 3
Receivers

The function of the receiver is to intercept and absorb the concentrated radiation reflected from the concentrator. Once absorbed, this energy is transferred as heat to either a heat-transfer fluid (to carry the collected energy elsewhere) or directly to the working fluid of a power conversion cycle adjacent to the receiver. Early parabolic dish receivers were simple coils of tubing painted black and encased in an insulated housing. These receivers would lose over 20% of the heat reflected to them and degrade rapidly. Current receiver technology has raised receiver efficiency to a nominal 87% at a cost of $40/m^2 of concentrator aperture area.

Current receiver research is directed toward increasing the receiver's operating temperature so that high-temperature engines can be mounted adjacent to the receiver. With liquid metal heat pipe technology, new receiver designs can take advantage of the extremely high heat-transfer rates of liquid metals and operate efficiently at the high temperatures required for efficient engine operation.

Receiver efficiencies of over 90% are projected for engine-receivers operating at 700°–1000°C (1250°–1800°F) and at a cost of $40/m^2. For process heat applications, expected to be in the range of 300°–500°C (550°–950°F), receiver efficiency appears to be attainable at a cost of less than $40/m^2.

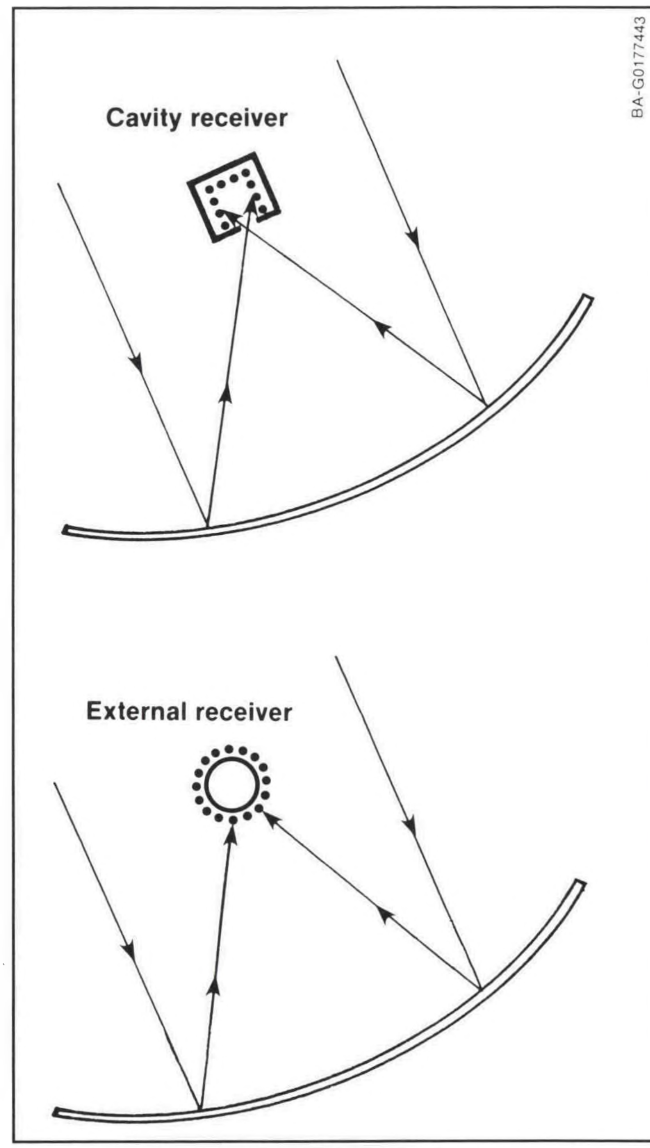


Figure 3.1. Two types of receivers used with parabolic dish concentrators

Receiver Design

Two types of receivers are used with parabolic dish concentrators: external (omnidirectional) and cavity (Figure 3.1). *External receivers* have absorbing surfaces in direct view of the concentrator and depend on direct radiation absorption. *Cavity receivers* have an aperture (opening) through which reflected radiation passes. Once inside the cavity, internal reflections ensure that most of the entering radiation is absorbed on the internal absorbing surface.

Cavity receivers are typically used with parabolic dish concentrators because they have a lower heat-loss rate at high operating temperatures. Concentrated radiation entering the aperture spreads inside the cavity and is absorbed on the internal walls where heat is transferred to a fluid. Energy reflected or reradiated from the walls is reabsorbed internally on the cavity walls. Rim angles of approximately 45 deg are considered optimum for cavity receivers because reflected radiation coming from the concentrator edges is reflected into a smaller cavity opening as a result of the flat view angle. To date, most major parabolic dish collector programs use the cavity receiver concept.

External receivers are usually spheric and absorb radiation coming from all directions. The apparent size of the receiver target does not significantly decrease for reflected radiation from the concentrator edges as it does with cavity receivers. Concentrators matched to the receiver target, therefore, will have wide rim angles as high as about 90 deg. The parabolic dish developed by Solar Steam, Inc., uses an external receiver (Figure 3.2).

A major advantage of the cavity receiver is that the maximum concentration of solar flux does not impinge directly on the heat-transfer surface as with an external receiver having the same capture area. With a cavity receiver, the concentrator's focal spot is placed at or just outside the cavity aperture and spreads inside the cavity before

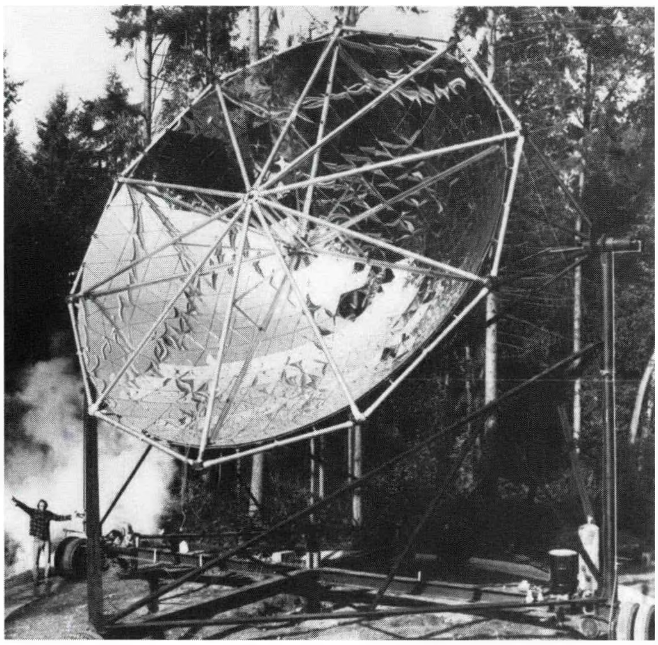


Figure 3.2. Parabolic dish with an external receiver constructed by Solar Steam, Inc. (the white receiver is visible at the center of the dish)

encountering the larger absorbing surface area. This spreading process reduces the incident flux (rate of energy deposited per unit surface area) that must go to the heat-transfer fluid. When incident flux is high, it is difficult to transfer the heat from the opposite side of the receiver surface rapidly enough to prevent thermal cracking or melting.

A second advantage of cavity receivers is reduced convection heat loss. The cavity enclosure not only provides protection from the wind but also might reduce natural convection. Because the internally heated surface area of a cavity is usually large, and the aperture typically is tilted at a 45-deg angle, strong buoyancy forces do cause some natural convection currents that draw cool ambient air into the cavity. Despite these currents, however, the cavity receiver is preferable to the external receiver for high-temperature applications because of the cavity's relative heat loss.

Another advantage of cavity receivers is that incoming or reemitted radiation is reflected internally and absorbed. This internal reflection increases the cavity's effective absorptance to a value greater than that of the surface within the cavity. Because radiation losses are important at high temperatures, this advantage becomes more important for higher-temperature applications.

Receiver Performance

Equation 2.1 gives the parameters affected by the receiver design:

- Capture fraction Φ
- Transmittance τ
- Absorptance a
- Receiver area A_{rec}
- Convective-conductive heat-loss coefficient U
- Equivalent radiation conductance F
- Receiver operating temperature T_{rec}.

Capture fraction, transmittance, and absorptance are optical terms and should be as close as possible to their maximum value of 1.0. The remaining parameters are found in the subtractive terms on the right-hand side of the equation, which represents the heat lost from the receiver. These parameters should be at minimum values.

Operating Temperature

The receiver operating temperature is normally defined by the application for which the parabolic dish collector is designed. For electricity generation, a higher operating temperature means higher solar-to-electric conversion efficiency.

A fundamental trade-off exists between the advantages of higher receiver operating temperatures and the disadvantage of lower receiver efficiency with higher temperatures. Equation 2.1 demonstrates that increasing the operating temperature increases heat loss, thereby reducing the useful energy supplied by the collector. The parameters that multiply the receiver temperature are functions of the receiver design and can be reduced to lower heat loss.

Receiver Aperture Area

The effect of reducing the receiver area relative to the concentrator aperture area is best seen in Eq. 2.3, where the geometric concentration ratio CR_g replaces the area terms of Eq. 2.1. Increasing the concentration ratio (i.e., reducing the receiver aperture area for a given concentrator area) directly reduces heat loss because the surface area from which heat is lost is reduced. This effect is true for both cavity and external receivers because with external receivers, A_{rec} is the receiver's surface area rather than the aperture through which the heat passes.

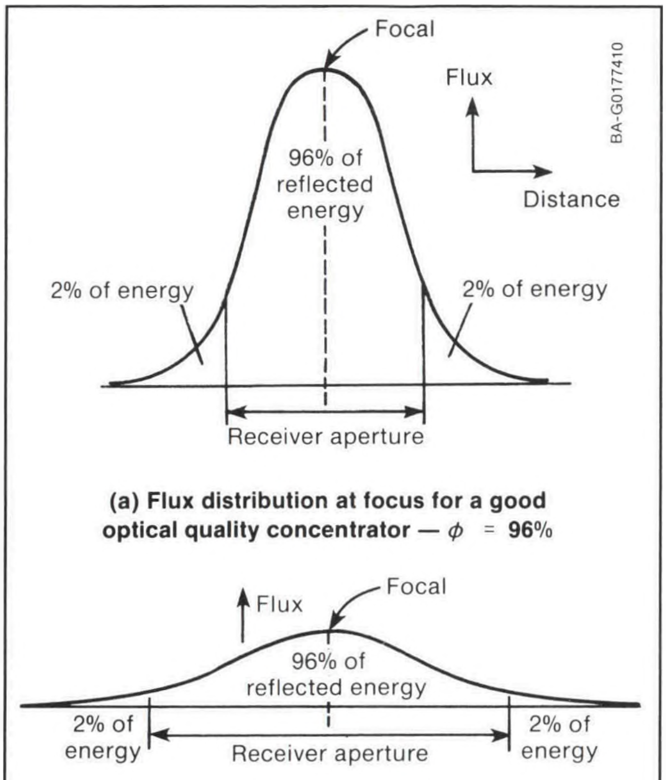
However, decreasing the receiver area reduces the amount of reflected energy going into the receiver, thereby reducing the useful energy collected. An optimum aperture area exists for any specific concentrator, as discussed in the next subsection.

Capture Fraction

The most important factor in matching a concentrator to a receiver is the *capture fraction* Φ in Eq. 2.1, which is the fraction of energy reflected from the concentrator that enters the receiver. The capture fraction is determined by the total optical quality of the concentrator and the size of the receiver aperture (Figure 3.3).

The optical quality of the concentrator, described in Chapter 2 as a sum of optical errors from different sources, causes the reflected radiation to spread out in a shape similar to a Gaussian distribution. To capture all the reflected energy, the receiver would need a large aperture area.

Reducing the aperture area decreases the capture fraction because less reflected energy is intercepted. Because the spread of reflected radiation at the focus is a function of



(a) Flux distribution at focus for a good optical quality concentrator — ϕ = 96%

(b) Flux distribution of focus for a poor optical quality concentrator — ϕ = 96%

Figure 3.3. Reflected flux distribution at the focal point and aperture size for a good- and poor-quality concentrator with some capture factor

the optical quality of the concentrator surface and its tracking accuracy, an important design cost trade-off always exists in balancing these two factors.

An optimum receiver aperture area exists for a given concentrator optical error, insolation, receiver design, and operating temperature. By making the receiver larger than optimum, the benefit of the additional energy that enters is offset by the increased losses. By making the receiver smaller than optimum, losses are reduced, but energy is blocked from entering.

To increase the capture fraction without increasing the aperture size requires using secondary concentrators at the receiver aperture. These highly reflective trumpet-shaped surfaces capture reflected radiation from a wide area and reflect it down through the cavity receiver aperture (Figure 3.4). The net result is an increase in the capture fraction without an increase in the receiver aperture area (or a decrease in the area without a decrease in the capture fraction).

Secondary concentrators generally improve the performance of parabolic dishes that have large optical errors. The addition of secondary concentrators can reduce the negative effects of any or all of the components of optical error discussed in Chapter 2, including surface slope error and specularity, tracking error, and sun shape. However, a secondary concentrator adds to the collector cost, and because the concentrator is located in a high flux density region, it must have high reflectance and well-designed cooling.

Optical Parameters

The convection loss from inside a cavity receiver could essentially be eliminated by covering the aperture with a transparent window. A window, however, reduces the incoming energy by the transmittance term τ in Eq. 2.1. *Transmittance* is simply the fraction of energy that gets through the cover. For clean fused quartz, the value of this term should be greater than 0.9 at incident angles close to normal.

Most current cavity receiver designs do not use a cover window. Covering the cavity aperture is required only at high temperatures or when the cavity is to be pressurized, as in some gas receiver designs.

Coating the absorbing surface with a material with a high absorptance value for radiation in the solar (visible) spectrum enhances receiver performance. These coatings are, typically, dull black. Coatings are available that have an absorptance of over 0.90 and that can withstand temperatures as high as 1375°C (2500°F). The effective absorptance of the cavity receiver at the aperture is always greater than that of the interior surface coating but is never greater than 1.0.

Figure 3.4. A secondary concentrator

Heat-Loss Parameters

Decreasing the convective-conductive heat-loss coefficient U in Eq. 2.1 can also improve receiver performance. Convective heat loss is usually less for a cavity receiver than an external receiver. The wind velocity and receiver attitude also affect the convective heat-loss coefficient. This loss can be reduced by putting a window at the aperture of a cavity receiver or a glass cover sheet around an external receiver. Reducing the value of this heat-loss coefficient also lowers the transmittance.

Reducing the conduction-loss paths lowers the conduction-loss portion of this coefficient. Two such paths are the heat loss from a cavity through the surrounding insulation to the receiver's exterior skin and from conduction through the supports that attach the absorber to the receiver structure. Using adequate cavity insulation and minimizing the required supports and low-conductance materials (such as stainless steel) help reduce these losses.

The equivalent radiative conductance combines the ability of a surface to lose radiation energy with the ability of the surroundings to absorb this energy. This parameter is mostly affected by the emittance of the receiver's absorbing surface; high emittance values give high equivalent radiative conductance values. Emittance is a property of the absorbing surface and is increased when this surface is within a cavity. Surface coatings have been designed that have low emittance values for long wavelength radiation. Many of these coatings degrade rapidly in the high flux environment of a parabolic dish receiver.

Design Considerations

A factor important to receiver design is thermal fatigue, which is caused by the receiver temperature cycling daily (or more often during cloudy weather) from ambient to operating. This cycling causes early receiver tubing failures. Receiver designs that incorporate thin-wall tubing and operate at uniform temperatures typically have fewer problems with thermal fatigue.

Concentrated solar flux at the focus of a dish concentrator is high. Placing the absorbing surface directly at the focus, as with external receivers, requires extremely high heat-transfer rates from the receiver's absorbing surface to the heat-transfer fluid.

The absorbing surfaces of cavity receivers are located where the flux has diffused to a larger area and is less intense than at the focus. Because placing the absorbing surface away from the focus increases the size of the absorbing surface and, therefore, its heat loss, researchers are designing compact receivers with high heat-transfer rates. One concept is to use reflux boilers or heat pipe technology to obtain high heat-transfer rates.

Current Technology

Organic Rankine Cycle Receivers

The cavity receiver used for the organic Rankine cycle developed by Barber Nichols uses a copper cylindrical cavity absorber with an insulated aperture plate (Figure 3.5). The outside surface of the cylindrical copper core is grooved, and tubing is wound around its full length and brazed to the core. The toluene working fluid (a petroleum-based fluid much like paint thinner) is pumped through this tube

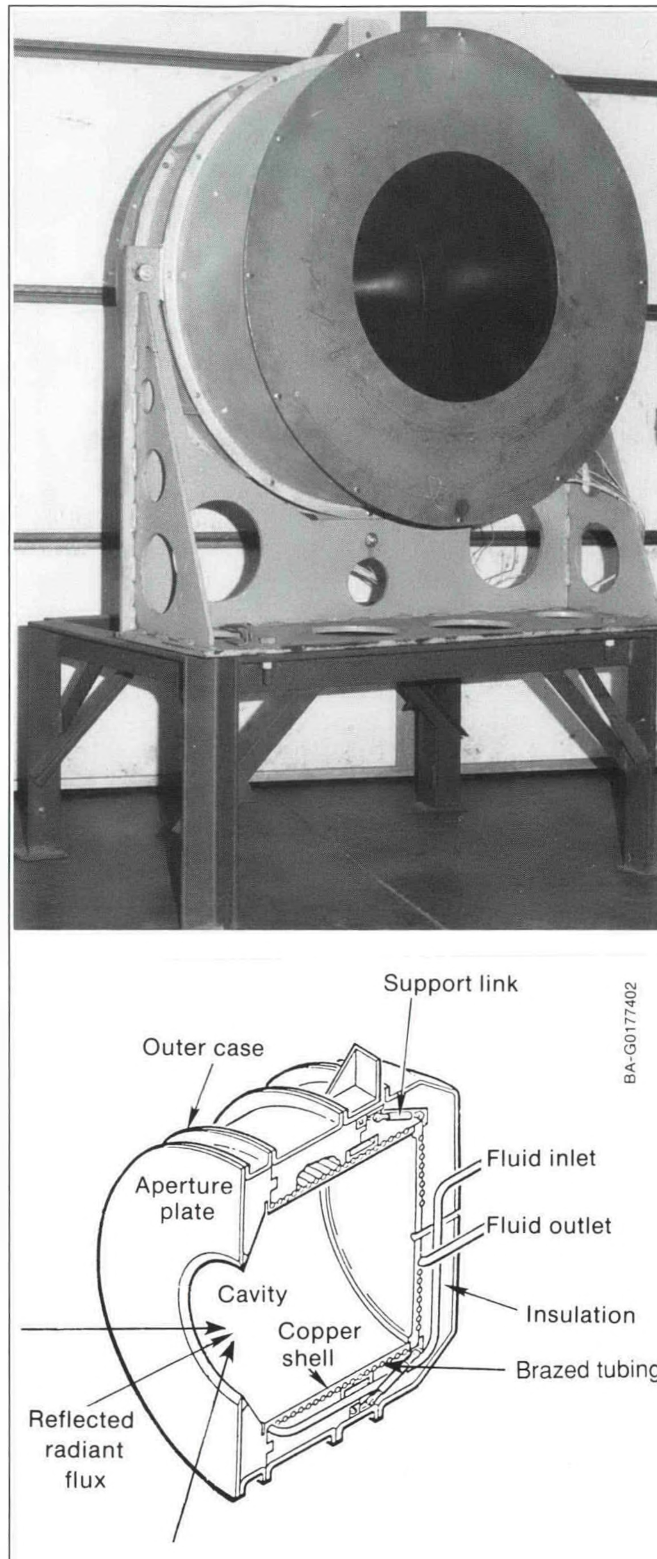


Figure 3.5. Receiver for the Barber-Nichols toluene organic Rankine cycle

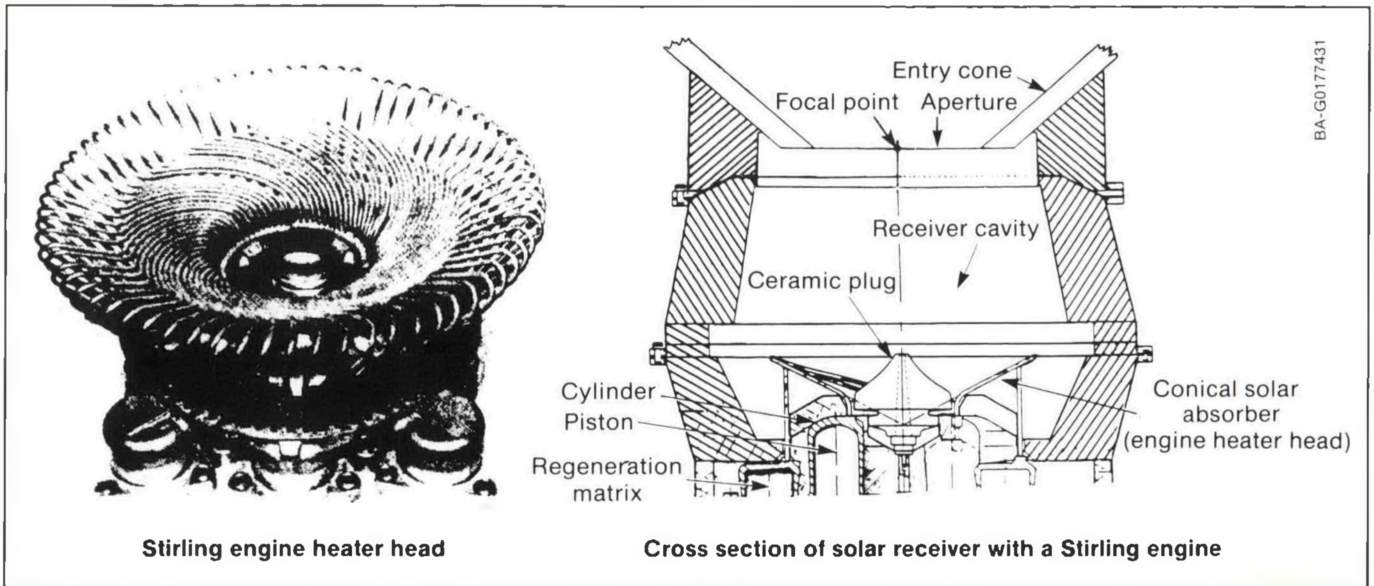


Figure 3.6. Cavity receiver incorporating the United Stirling Model 4-95 engine heater head

and then vaporized. The mass of the copper core provides some heat storage to smooth transients in insolation.

Stirling Engine Receivers

Kinematic Stirling engines are currently used with cavity receivers. The receiver has a conical aperture and an insulated housing that forms the receiver cavity. At the back of the housing is a circular bundle of small-diameter tubes that are the heater tubes for the engine (Figure 3.6). The engine working gas is passed through these tubes and heated.

Brayton Engine Receivers

In cavity receivers that use Brayton cycles, pressurized air is heated from the compressor. Here, instead of heating the air across a metal tube or other heat-transfer surface, the entire receiver cavity is pressurized, and the air working fluid is passed through porous silicon carbide panels that form the back wall of the cavity. Heated air then passes through mullite (an aluminum silicate ceramic) panels that provide a small amount of sensible heat storage. Because the receiver must operate at high pressure, a fused silica window is affixed to the receiver aperture to prevent the compressed air from leaking out (Figure 3.7).

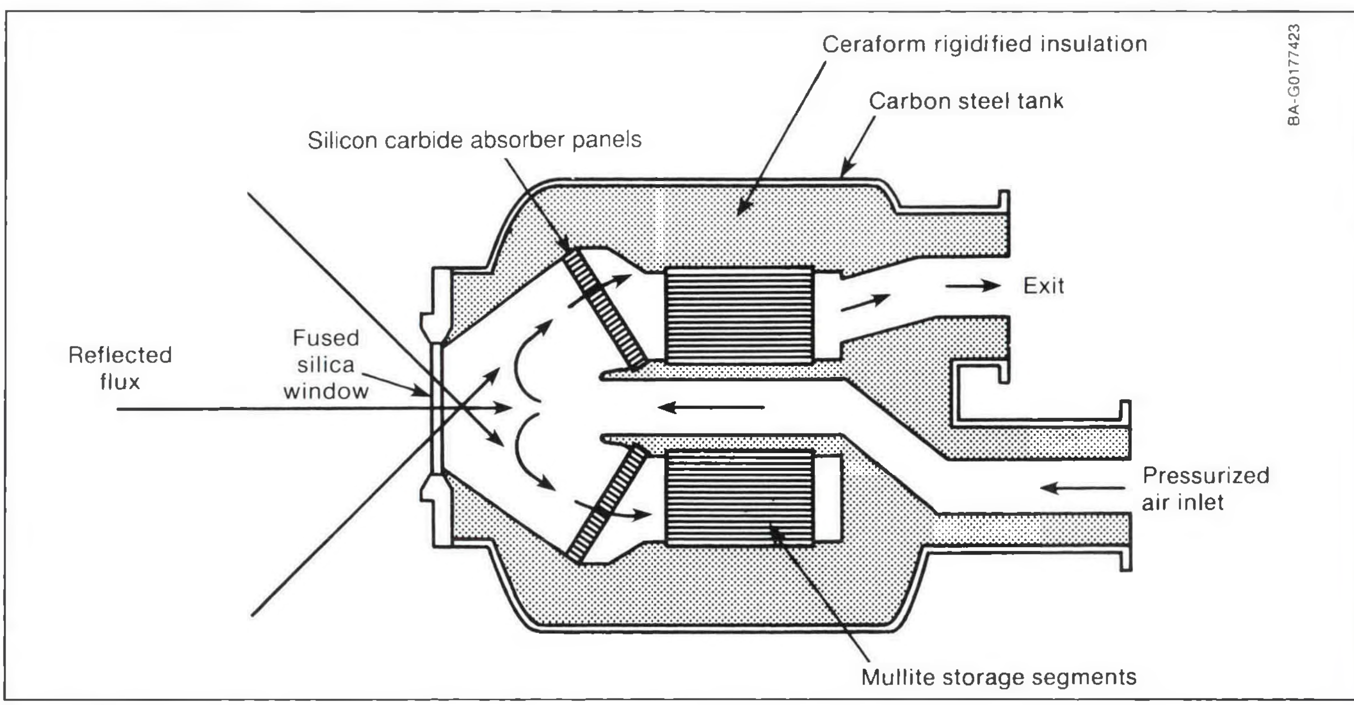


Figure 3.7. Brayton cycle ceramic receiver using pressurized air

This receiver was tested at temperatures as high as 1375°C (2500°F). Initial problems with the aperture window breaking were solved, and the receiver operated at an efficiency of 60%.

With another Brayton cycle concept, the air working fluid is heated in the receiver at atmospheric pressure, and the compressor inlet and turbine exhaust are operated at subatmospheric pressure.

Hybrid Receivers

A cavity receiver was designed and tested that incorporates a natural gas burner to provide supplementary heat when solar energy is not available. This concept was incorporated into a receiver with a Stirling engine attached (Figure 3.8). Hot combustion products from the burners pass into the receiver cavity where they heat engine heater tubes located in the end of the cavity.

Liquid Metal Reflux and Heat Pipe Receivers

Recent receiver designs use the extremely high heat-transfer rates and constant temperature associated with liquid metal vaporization and condensation. To keep the interior heated surfaces of cavity receivers small, receivers must allow large amounts of heat to transfer across small surfaces. This transfer is possible using reflux boiler or heat pipe technology (Figure 3.9).

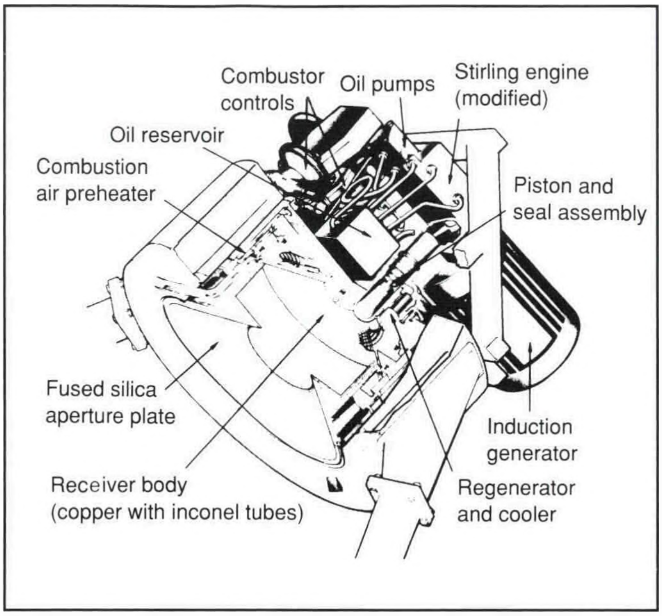


Figure 3.8. Hybrid receiver using a gas-fired burner with a United Stirling Model 4-95 Stirling engine

With the heat pipe receiver, a wick on the surface leading up from a puddle of liquid metal—such as sodium or potassium—wets the back side of the receiver absorbing surface. Heat from the incident solar flux causes the liquid to evaporate into the chamber behind the absorber. Also in

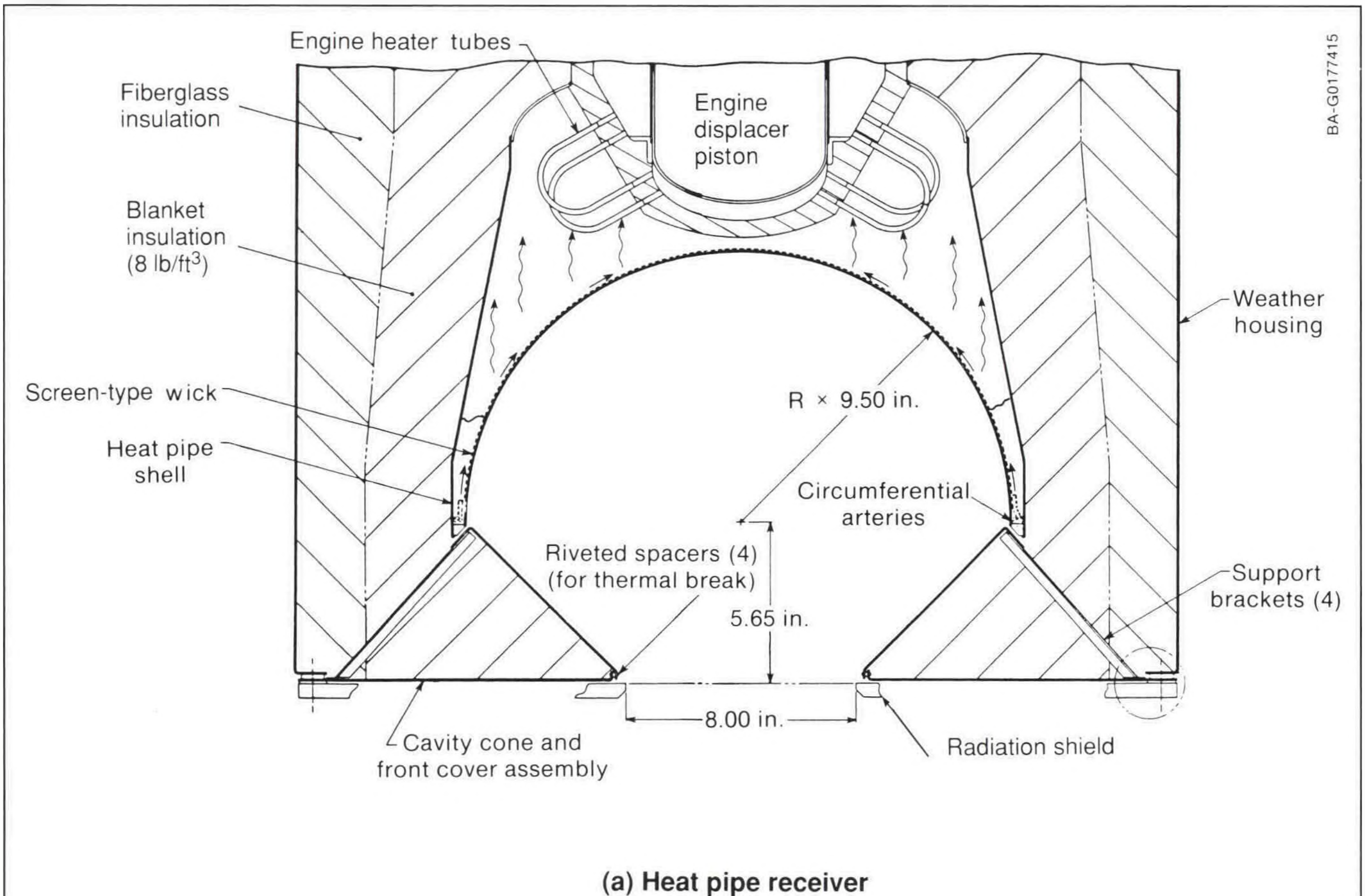


Figure 3.9. Receivers using liquid sodium as the heat-transfer agent (Continued)

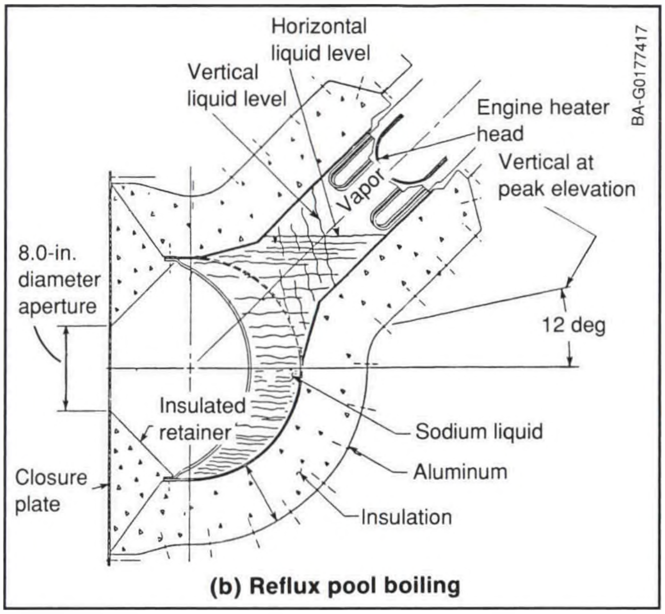


Figure 3.9. Receivers using liquid sodium as the heat-transfer agent (Concluded)

this chamber are tubes containing the engine working fluid, which is slightly cooler than the boiling point of the liquid metal. The metal vapor condenses on these tubes, transferring its heat of vaporization. The condensed liquid then falls to the bottom of the receiver where the wick draws the liquid up the back side of the absorbing surface.

Reflux boilers work similarly, except that the liquid metal boils on the back side of the absorber surface rather than being drawn up by a wick.

An advantage of both heat pipes and reflux boilers is that they act as thermal diodes, only permitting heat transfer in one direction. In other words, when the solar flux decreases because of clouds, little heat flows from the fluid being heated back out the receiver.

Program Directions

The overriding issue for designing parabolic dish receivers is to raise the operating temperature, which economically increases engine efficiency. Because parabolic dish concentrators can operate high-efficiency engines at high temperatures (above 1000°C [1830°F]), they can successfully compete with the high-temperature capabilities of fossil fuels.

A major thrust in parabolic dish receiver development is incorporating liquid metal reflux boiler or heat pipe technology into receiver design. By using these technologies, heat can be transferred at high flux levels and constant temperature. The result is a compact, high-temperature receiver that has the low heat loss needed to operate with high engine efficiency.

Chapter 4
Heat Engines

Small engines with electric generators are placed adjacent to the receiver in many parabolic dish applications. These 25- to 50-kW$_e$ engines match the thermal input capabilities of the concentrator. Three types were considered for use with dish concentrators: the Rankine cycle (steam and organic working fluids), the Stirling cycle (kinematic and free-piston), and the Brayton cycle.

Mounting small engines close to the focus of a parabolic dish has two advantages: It reduces energy loss during transport, and it eliminates the expense of a field matrix of high-temperature, heavily insulated piping and associated fittings. However, these advantages are partially offset by the added structure needed to support the engine's weight and an increased maintenance requirement.

The alternative to having a small engine for each concentrator is to collect the high-temperature heat from many collectors and transport it by insulated pipe to a large central engine. The advantages could be economies of scale and increased reliability. Currently, however, the focal-point engine concept is favored because it promises to provide energy at a lower cost.

Small focal-point engines have been part of the parabolic dish program since its inception. Early dish applications used oversized, low-temperature engine-generators with low engine efficiency. These engine-generators had many mechanical problems, were expensive, and often did not generate much net electric power. Currently, kinematic Stirling engines and Rankine cycles with either steam or organic working fluids appear to have the potential for high performance and low maintenance. Under development, these systems have engine efficiencies that are considerably higher than their predecessors.

Research on a free-piston Stirling engine shows it has the potential for high performance and low maintenance. Researchers hope this engine can be built at the capital cost goal of \$300/kW$_e$ and maintain an engine efficiency of 41%. Yearly operations and maintenance might cost less than \$10/m^2 [6].

Heat Engine Performance

The solar-to-electric conversion efficiency is one of the most important design parameters of a parabolic dish system. Chapter 2 discusses the decrease in solar collector efficiency and the increase in engine efficiency that occur with temperature. An optimum operating temperature, therefore, exists for any engine-collector combination.

Engine Efficiency

Heat engine efficiency is the percentage of thermal work that can be converted into mechanical work. The efficiency of any thermal conversion cycle (engine) is limited by the Carnot cycle (ideal engine) efficiency derived from the second law of thermodynamics. Carnot cycle efficiency is only a function of the temperatures at which heat is transferred to, and rejected from, the engine.

The actual engine efficiency of any real engine can be written in terms of Carnot cycle efficiency as

$$\eta_{cyc} = \beta_{Carnot} \left(1 - \frac{T_L}{T_H} \right) , \qquad (4.1)$$

where the term in parentheses is the Carnot cycle efficiency. The terms T_H and T_L are absolute-scale temperatures (°R or K) of heat input and rejection, respectively, and β_{Carnot} is the ratio of actual engine efficiency to Carnot cycle efficiency.

This equation shows how raising the operating temperature affects engine performance. Regardless of the size of the collector or how much energy is being converted for a fixed heat rejection temperature (usually close to ambient temperature), the higher the temperature of thermal energy input, the higher the engine efficiency. Because no other theoretical limitation exists on converting mechanical work to electricity, raising the temperature of heat input to the engine likewise raises the engine efficiency.

The ratio of real to ideal efficiency is a function of the cycle type and the many engine design variables. For many current power cycles, the ratio has values of about 50%.

Parabolic dish technology is being driven to higher and higher temperatures to attain the higher efficiencies associated with these temperatures. What limits the temperature in many applications are the receiver heat loss and the materials used in the receiver and the hot portions of the power conversion cycle.

Solar-to-Electric Conversion Efficiency

Equation 2.3 shows that solar collector efficiency decreases with operating temperature; however, Eq. 4.1 shows that the engine efficiency of a power conversion cycle increases with its operating temperature. Because parabolic dish technology frequently involves combining solar collectors and power conversion cycles, it is important to consider the behavior of the combined collector and engine efficiencies; their product represents the solar-to-electric conversion efficiency.

When Eqs. 2.3 and 4.1 are multiplied together (i.e., when the engine and concentrator efficiencies are combined), the product shows that solar-to-electric efficiency increases with temperature, reaches a maximum, and then decreases at very high temperatures. Every solar collector and engine combination has a unique operating temperature at which maximum solar-to-electric conversion efficiency is attained (Figure 4.1). This optimum efficiency is rather broad; therefore, a range of operating temperatures is available. The goal is to match the performance of collectors with that of engines to attain optimum solar-to-electric efficiency.

Small Engine Development

The development of engines for parabolic dishes has been driven by four major factors: reliability, low operations and maintenance cost, high engine efficiency, and low capital cost. The engine size currently being considered (25–50 kW_e) is defined by current estimates of the size limitations of parabolic dish concentrators, considering the collection and engine efficiencies.

A fundamental trade-off exists among engine cost, efficiency, and operation and maintenance costs to produce electricity at a competitive cost. For solar applications, engines with low efficiency must be inexpensive and require little operations and maintenance expense. High-efficiency engines can cost more, have higher operations and maintenance expenses, or both. This trade-off is evident in Figure 4.2 where these three parameters are approximated for different engine types.

Many of the engines discussed in the following subsections are or were under development for automotive or space power. The strategy of the parabolic dish program was to use these engines rather than embark on a solar-specific engine design effort. As a result, many different types of engines not optimized for solar applications were tried on parabolic dish concentrators.

Design and size requirements for parabolic dish applications are similar to those for the automobile industry. A major difference is that for automotive engines, a short service life of approximately 3000 h is acceptable

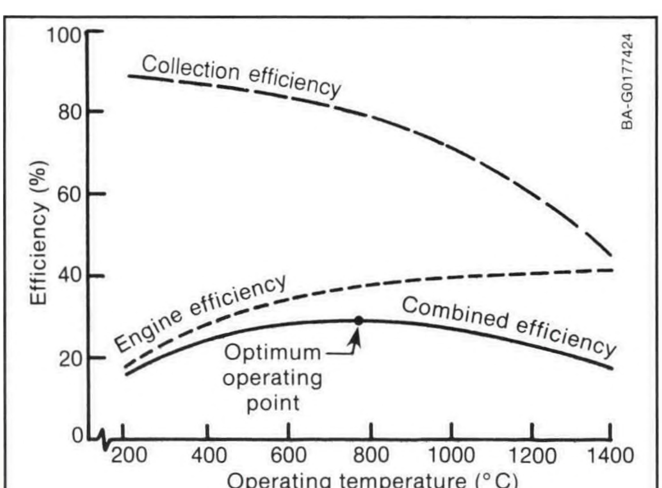


Figure 4.1. Combined solar collection and engine efficiency variation with operating temperature

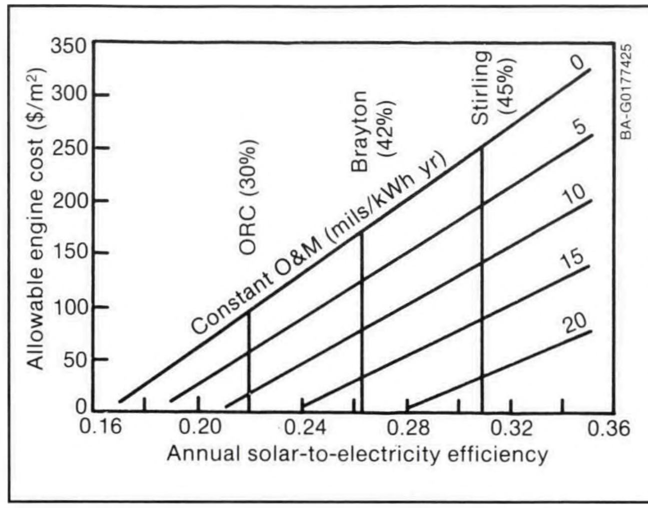


Figure 4.2. Allowable engine capital and operations and maintenance costs for different engines (engine efficiency in parentheses). These costs are for a levelized energy cost of 5¢/kWh$_e$.

compared with approximately 50,000 h for solar applications. However, no engine for automotive applications is currently under consideration.

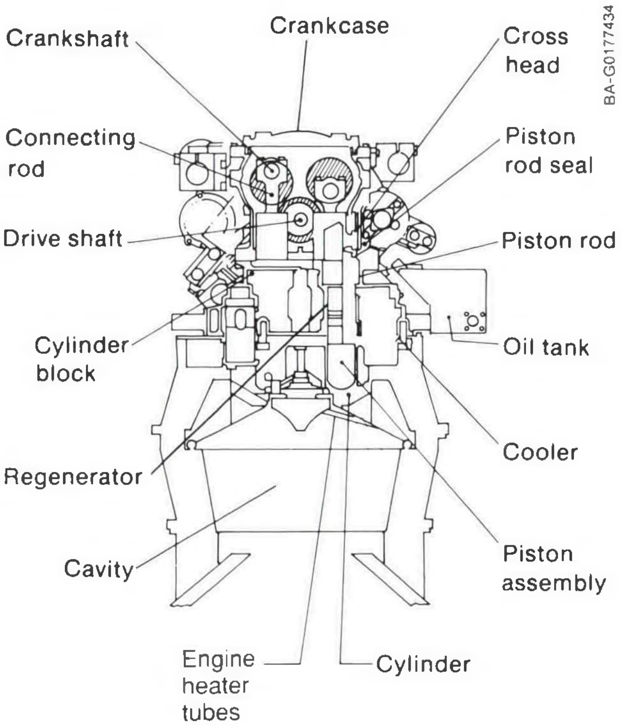
Stirling Engines

Because of its potentially high solar-to-electric efficiency in small (25–50 kW_e) units, the Stirling engine is the major candidate for parabolic dish applications. Two different engine designs using the Stirling cycle are being developed and tested as receiver-engine modules. One type, known as a kinematic Stirling engine, uses pistons directly connected to a crankshaft or swashplate that provides mechanical power to a rotating shaft that drives a rotating alternator.

The other type, a free-piston Stirling engine, uses pistons that are free to bounce back and forth on "gas springs" located at either end of the cylinder with no mechanical connection. This design eliminates most of the mechanical bearings and seals of the kinematic design and allows for a hermetically sealed unit. A linear alternator or hydraulic or pneumatic pump can be built into the power unit to produce electricity or hydraulic power from the back-and-forth motion of the pistons. If a hydraulic or pneumatic pump is used, the output can drive an external motor connected to an electric generator with little loss of power.

Applications. The United Stirling AB of Sweden's Model 4-95 kinematic engine, originally developed for automobiles, was modified and tested for several different solar applications, including use in conjunction with a hybrid receiver incorporating a combustion heater (Figure 4.3). This receiver is a kinematic, double-acting, reciprocating engine with four 95-cm^3 (5.8-$in.^3$) cylinders in a square pattern connected by a cooler, a regenerator, and the heater tubes.

Either hydrogen or helium can be used as the working gas; hydrogen is preferable. Heater tubes inside a cavity solar receiver operate at a maximum temperature of 750°C (1380°F) and a maximum hydrogen pressure of 15 MPa (2200 psi). Connected to an electric generator, the unit has a maximum output rating of 30 kW_e.



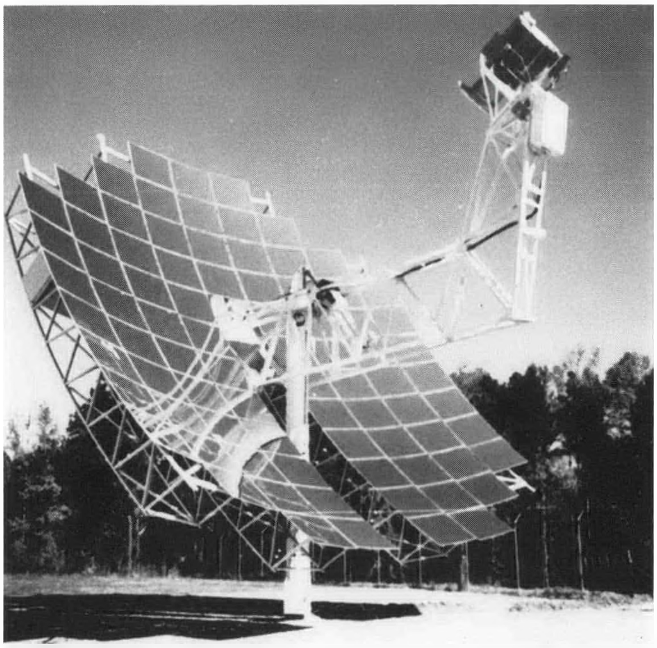


Figure 4.3. United Stirling Model 4-95 Stirling engine

The heater temperature is kept constant under varying solar input conditions by varying the pressure of the hydrogen working gas. Power output is controlled by varying the pressure of the hydrogen working gas. The high-pressure working gas is sealed from the crankcase through linear seals on the piston-connecting rods where a cross-head mechanism changes the eccentric motion from the crankshaft to linear translation.

This engine, in combination with a cavity receiver, was operated in solar applications at power levels exceeding the 24-kW$_e$ design with engine efficiencies of over 40% (gross). When mounted to the Vanguard concentrator, this engine produced a world record for solar-to-electric conversion of 29%. Testing revealed problems with lubrication, heater tube failure, and excessive linear seal wear.

Developments. An important issue with the kinematic Stirling engine designs is the longevity of the linear or rotary gas and oil seals; these seals are located where the shaft motion is transferred from the piston portion of the engine to the crankcase. Although the seals are inexpensive, replacing them involves disassembling the engine.

A different design currently being developed by Stirling Thermal Motors uses helium and a swashplate rather than a crankshaft to convert the linear piston motion to shaft rotation (Figure 4.4). This engine has four 120-cm^3 (7.32-in.^{3}) cylinders and can develop a maximum output of 25 kW. Changing the angle of the swashplate varies the stroke of the pistons and, therefore, the power output. This action eliminates the gas pressure control for varying the power, which is prone to leakage because of the multiple check and solenoid valves. The engine uses a pressurized crankcase, eliminating the pressure difference across the piston rod seals and providing potentially long lifetimes.

Free-piston Stirling engines have two basic moving parts—the displacer and power pistons—and show promise for long, low-maintenance lifetimes. Some small (as large as 12.5 kW), free-piston Stirling engines with linear alternators have been in operation; however, they are still in the design and development phase. Because the entire engine contains the working gas, and only electric power leads penetrate the case, gas sealing problems are minimized.

Larger free-piston Stirling engines with outputs of 25 kW$_e$ are being developed and also show promise for high engine efficiency and long life. One of these designs, by Mechanical Technology, Inc., uses a linear alternator to directly convert the solar energy to electricity inside the engine casing (Figure 4.5). The other design being developed, by Stirling Technology Company, generates a hydraulic power output that connects to a hydraulic pump coupled to an induction generator (Figure 4.6).

Organic Rankine Cycles

Organic working fluids, such as toluene, or fluorinated hydrocarbons, such as freons, replace the traditional steam Rankine cycle for some distributed engine parabolic dish applications. The major advantage of these fluids is their high molecular weight, permitting high engine efficiency and the use of low-power turbine expanders that are not too small and do not run at excessive rotational speeds. A second advantage of some organic fluids is that saturated vapor directly from the boiler can be expanded without liquid droplets forming in the turbine, resulting in a more efficient Rankine cycle.

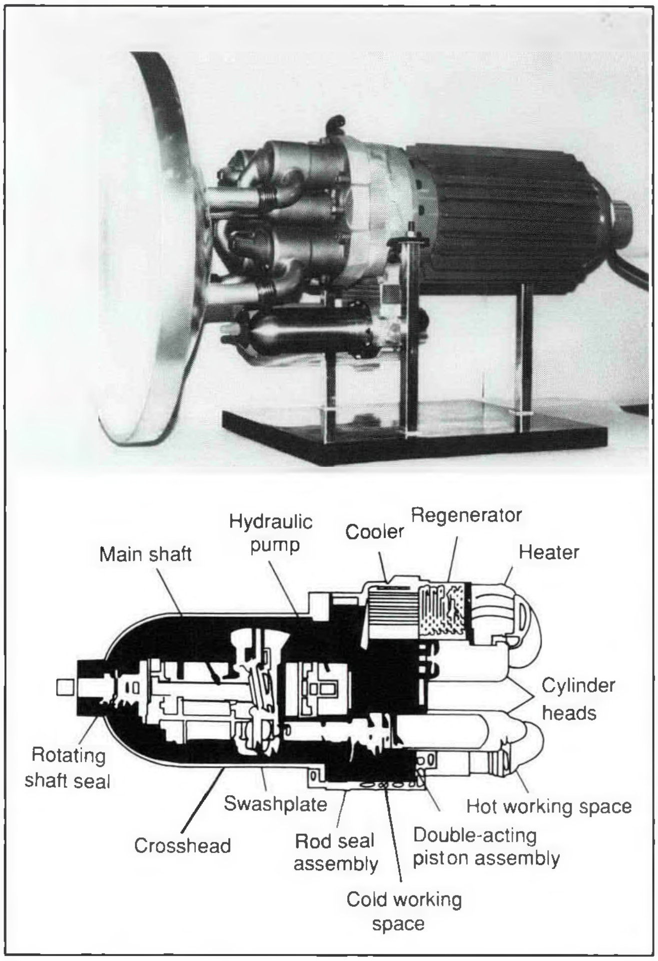


Figure 4.4. Stirling Thermal Motors Model 4-120 Stirling engine with swash-plate drive

Applications of many organic Rankine cycles, however, are limited to relatively low temperatures of approximately 400°C (750°F) because the working fluids attain high pressures and degrade at high temperatures.

Applications. Considerable solar testing and development were performed on a 27-kW_e organic working fluid Rankine cycle developed by Barber-Nichols, Inc. (Figure 4.7). This cycle uses toluene as its working fluid. Toluene was chosen because of its high molecular weight (92 versus 18 for steam) and its expansion characteristics.

Toluene, heated in the solar receiver to 400°C at 4.1 MPa (750°F at 600 psia), expands in the turbine and then passes through a regenerator before entering a fan-driven condenser. A tube carrying the toluene is wrapped around the outside of the receiver absorbing surface where the toluene vaporizes. Heat is rejected from the cycle through a fan-cooled condenser adjacent to the engine.

The engine design uses a high-speed permanent magnet alternator built on the same shaft as the turbine and the pump. A single-stage, 5-in.-diameter impulse turbine is used that turns at 60,000 rpm with a maximum output of 41 hp. The engine efficiency is 23%.

The major problems encountered with early designs of this engine-generator combination were excessive bearing wear caused by rotor dynamic and electrodynamic effects and electric arcing from the rotor to the alternator housing. Solutions to both problems have been found and tested.

Developments. No major development program currently exists for organic Rankine cycle engines because of the low-temperature limitations of most organic fluids and their lower theoretical solar-to-electric conversion efficiencies.

Steam Rankine Cycles

Steam is an excellent, well-understood working fluid for Rankine cycle engines. In a Rankine cycle, water is pumped to a high pressure where it is heated until it boils, forming steam. This steam can then be superheated beyond the temperature where boiling began. The high-temperature, high-pressure steam is then expanded through a turbine or reciprocating engine. The exhaust steam is then condensed before it reenters the pump.

Deciding what expansion device to use is important in designing a solar steam system. Most commercial power plants use turbines to expand the steam. For central engine parabolic dish systems at Shenandoah, Ga., and Warner Springs, Calif., small steam turbines are used. To date, however, individual receiver parabolic dish applications using steam use only reciprocating engine expanders because a concentrator module engine puts out little power (25–50 kW_e), and a properly designed steam turbine of this size will have small blades rotating at extremely high speeds. Because these turbine blades will have high stresses, small high-speed steam turbines are not feasible.

Although this technology has been maturing for almost 200 years, reciprocating engines are less efficient than

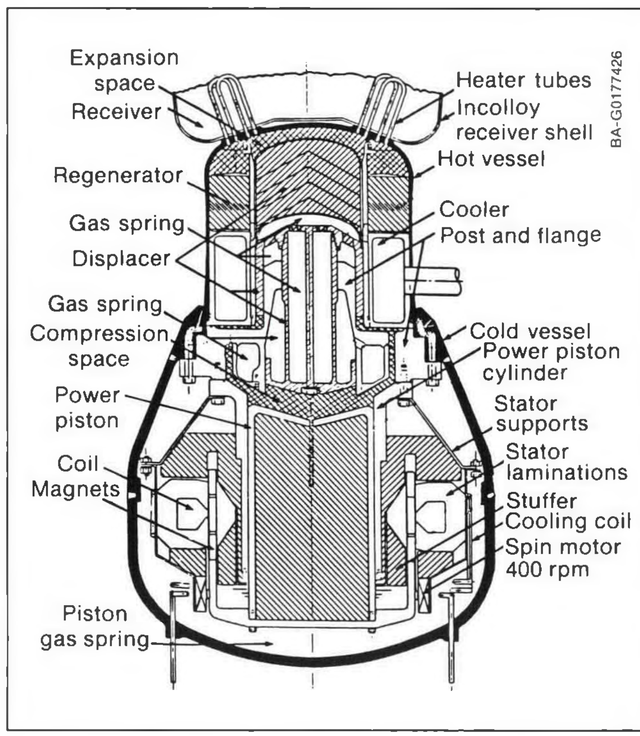


Figure 4.5. Free-piston Stirling engine with linear alternator developed by Mechanical Technology, Inc.

large turbines and suffer from large frictional loads, particularly the small engines. In addition, reciprocating expanders traditionally have lubrication problems. As a result, they have not produced good results; the major problem is low engine efficiency.

Applications. Reciprocating engines using steam as the working fluid were tested early in the parabolic dish program. One engine, designed by Roy F. Ferrier Co., was built by Omnium-G and tested on Ferrier's concentrator. This two-cylinder, double-acting engine was designed to operate as high as about 1000 rpm, with a rated output of 45 shaft hp from 315°C steam at 2.4 MPa (600°F at 350 psia). The engine was oversized for the collector, causing low engine efficiencies. It was not developed any further.

The Jet Propulsion Laboratory (JPL) tested two reciprocating steam engines built by Jay Carter Enterprises for solar applications. One was a single-cylinder, single-acting expander with a nominal speed of 1800 rpm and a rated output of 8 hp. In tests, the engine operated using solar energy–derived steam and attained its maximum engine efficiency with 390°C (730°F) steam and an electric power output of 1.45 kW_e at an overall solar-to-electric efficiency of 11% net. Testing revealed many mechanical wear problems.

The second Carter engine was a two-cylinder, single-acting expander with a rated shaft power of 23 hp at 3600 rpm. JPL measured a maximum solar-to-electric efficiency of 20% using 540°C (1000°F) steam and an expansion ratio of 10:1, resulting in a gross electric output of 16 kW_e. As a result of these tests, researchers felt that correcting leakage problems and using a larger system inlet valve would increase the efficiency; however, this engine was not developed further.

Developments. A slightly different concept is being evaluated in which superheated steam at 450°C/6.89 MPa (810°F/800 psi) powers a 50-kW_e, four-cylinder reciprocating steam expander—a converted diesel engine. This

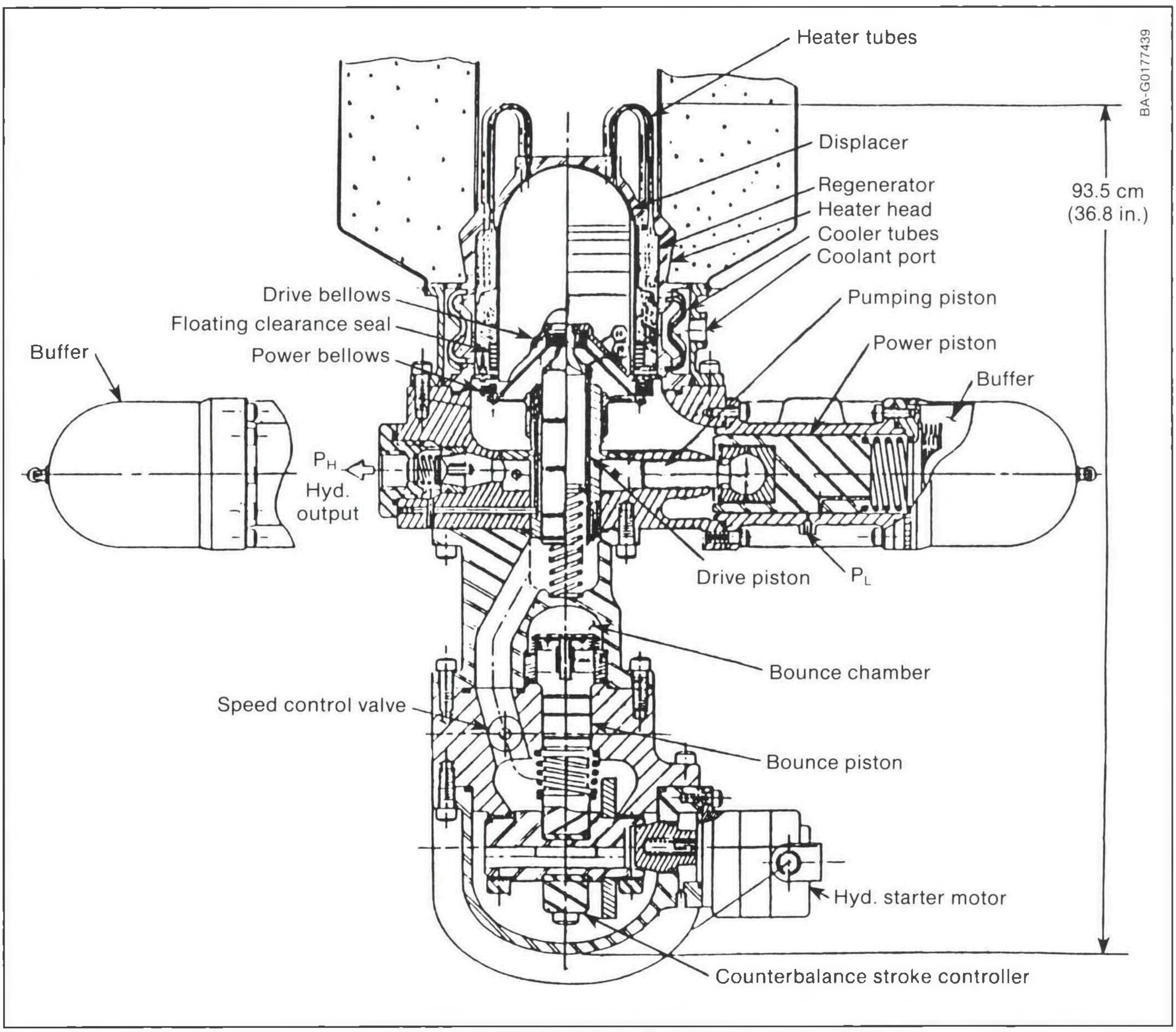


Figure 4.6. Free-piston Stirling engine with hydraulic power output developed by Stirling Technology Company

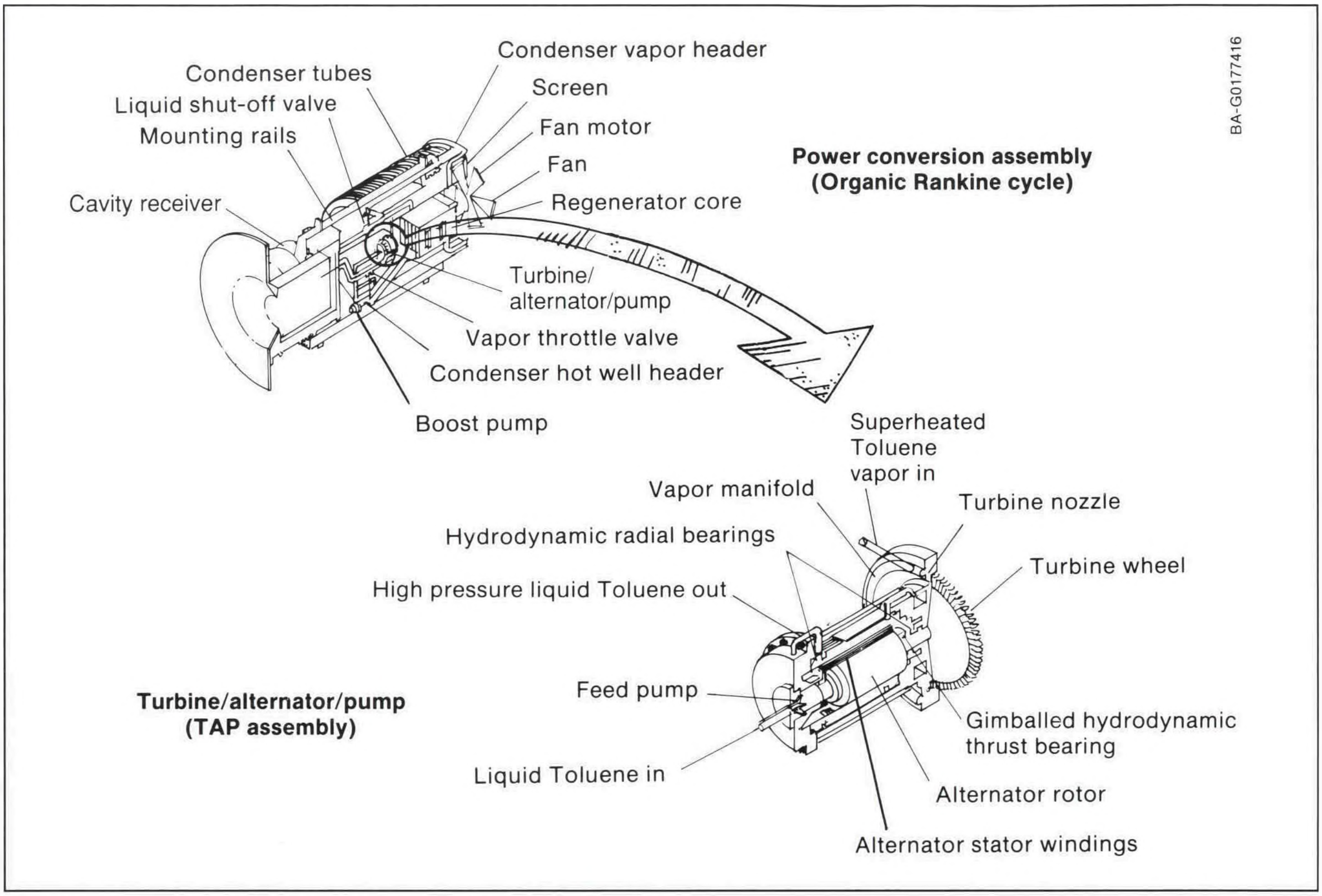


Figure 4.7. Barber-Nichols organic (toluene) Rankine cycle

engine, located at the collector base, is shown in Figure 4.8. This engine was developed by the Australian National University. A similar three-cylinder version, also developed by the Australian National University, was proven in its White Cliffs, Australia, solar project. This modified Lister diesel engine has three "bash valves" incorporated into the cylinder head to let high-pressure steam into the cylinder when the piston nears top dead center. Although this engine operates with a moderate engine efficiency (19%), the university chose it for this application because of its low price and low maintenance requirements.

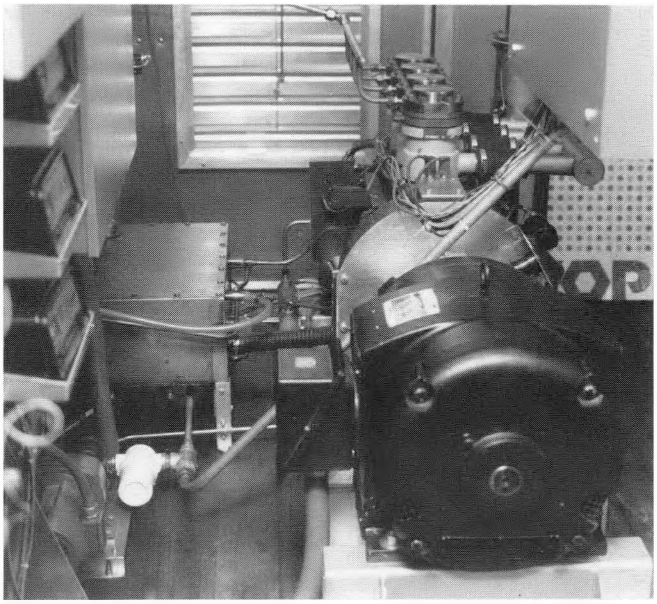


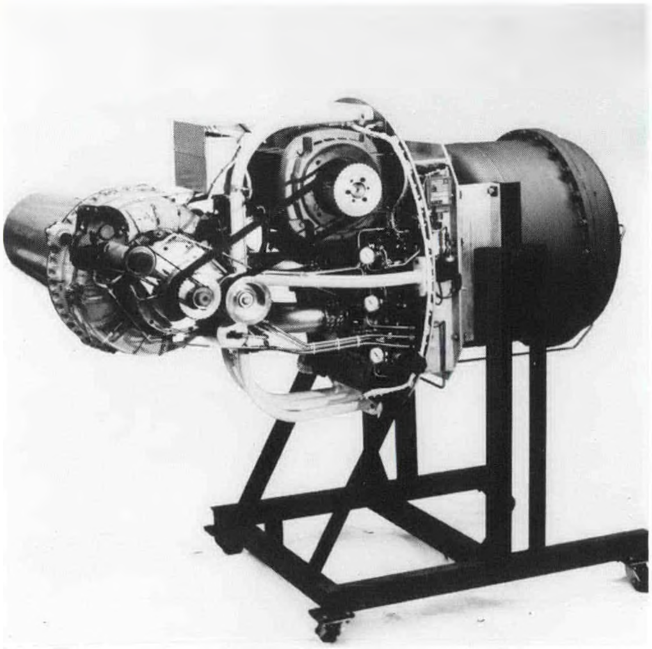
Figure 4.8. The 50-kW reciprocating steam engine for the Small Communities Solar Experiment at Molokai, Hawaii

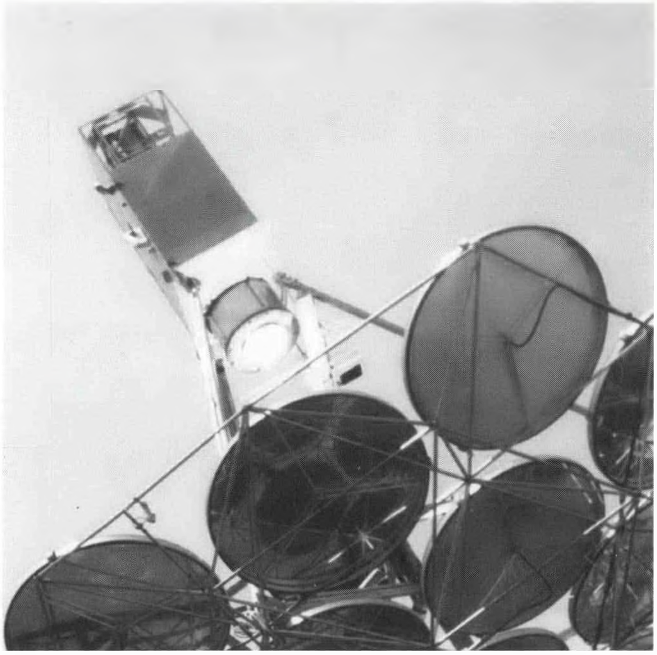
Brayton Engines

Brayton cycle engines were first considered for solar thermal energy conversion systems because of their low maintenance and long life. These engines, similar to small jet aircraft engines, use concentrated solar energy to heat the compressed gas before it expands through a turbine. Currently, no Brayton cycle engines are under development for terrestrial solar applications.

Applications. Two air-cycle Brayton engines were originally developed for other applications (Figure 4.9) and were modified to use with parabolic dish concentrators. One requires a pressurized-air solar receiver, and the other calls for an atmospheric-air solar receiver.

Garrett Turbine Engine Corporation has developed a Brayton cycle engine based on its automotive gas turbine engine. This 25-kW_e hybrid engine uses a single-stage radial turbine and a single-stage centrifugal compressor with variable inlet guide vanes. A porous rotating ceramic disk regenerator is incorporated into the design of this engine.





(a) (b)

Figure 4.9. Two Brayton cycle engines considered for solar applications: (a) The Garrett Turbine Engine Company's pressurized receiver concept and (b) the subatmospheric engine concept

A bench test of this engine using fuel and a turbine inlet temperature of 930°C (1700°F) resulted in an engine efficiency of 29.8% and an estimated overall solar-to-electric conversion efficiency of 20.4%. Problems encountered with this engine include internal air leakage (particularly at the regenerator), bearing wear, mechanical interferences, and dynamic instabilities.

A second engine is called the subatmospheric Brayton cycle because the compressor inlet and turbine outlets are below atmospheric pressure, but heat is added at atmospheric pressure. This engine was originally developed by Garrett AiResearch for heat pump applications. This engine design has the turbine, compressor, and permanent magnet alternator on a common shaft. The shaft is driven by 870°C (1600°F) air entering the radial turbine, which has a nominal output of 5 kW_e. The turbine exhaust goes through a recuperator and an air-cooled radiator and back into the compressor inlet at a pressure below ambient. A combustor between the receiver and the turbine permits this engine to be operated on either solar energy, fuel, or both.

The engine was tested with a solar receiver and found to have a solar-to-electric conversion efficiency of 17%, which decreased to 13.4% in subsequent testing. Researchers surmised that this drop was the result of increased internal leakage. Bench tests of a later version gave a conversion efficiency of 20%. Major problems were with bearing lubrication and air leakage.

Developments. Brayton cycle engines are not currently being developed for solar applications because of the high temperatures (800°–1400°C [1500°–2500°F]) required to operate them at high engine efficiencies. Solar collector efficiencies are low at these high temperatures, which limits overall solar-to-electric conversion efficiencies to approximately 26% with the current technology. To operate at these temperatures, materials currently used in solar receivers and engines are unsuitable, requiring the development of high-temperature materials, probably ceramics. In addition, no small, high-efficiency Brayton engines are currently available to modify for solar applications.

Central Engines

If thermal energy is collected from a field of parabolic dish collectors and piped to a central engine, this engine must be larger than those considered for individual focal-point engine applications. Because the efficiency of most turbines and compressors increases with size, central Rankine and Brayton cycles are generally more efficient than their 25- to 50-kW_e focal-point counterparts. Energy loss during transport and other system considerations, however, can negate the advantage of small efficiency gains.

Applications

Steam Rankine cycles using turbines are possible for engines with outputs above 500 kW_e. Two currently operating systems, the Shenandoah Solar Total Energy Project (Figure 4.10) and Solarplant One, use steam Rankine cycle central engines. A major advantage of these systems is their use of existing power plant technology. Off-the-shelf components can be successfully used without additional development.

Turbine steam expanders are used at both the Shenandoah and Solarplant One facilities. At Shenandoah, a single, four-stage steam turbine rated at 400-kW_e output is used. Superheated steam at 380°C/4.8 MPa (720°F/700 psia) drives this turbine at 42,500 rpm. At Solarplant One, a 3.6-MW_e main turbine and a 1.24-MW_e peaking turbine are operated in parallel. The inlet steam for both turbines is superheated to 400°C/4.7 MPa (750°F, 675 psi).

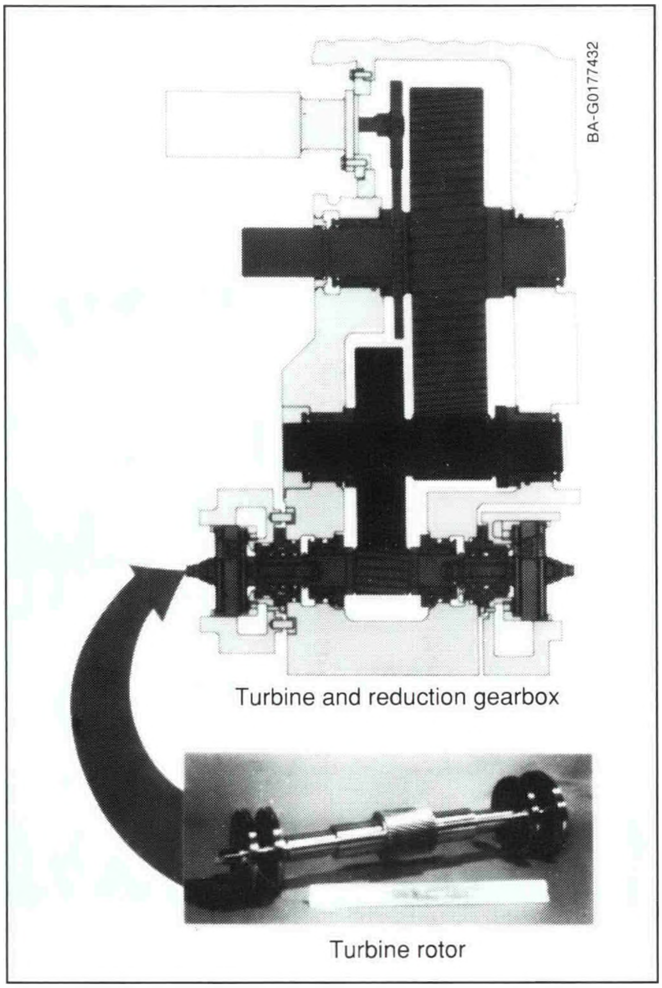


Figure 4.10. Central 400-kW$_e$ steam turbine and reduction gearbox used at the Solar Total Energy Project at Shenandoah, Ga.

Developments

The advantage of the central engine is its higher efficiency, although with the added cost of piping and heat loss. Whether this advantage overrides the system reliability and flexibility of the focal-point small engine because of its modularity (Figure 4.11) will determine the future of central engine applications.

A recent study shows that conventional steam Rankine cycles are currently available for central engine systems in the 500-kW$_e$ to 50-MW$_e$ output range (for collector fields incorporating 15 to 1500 twelve-meter-diameter [39-ft] concentrators). Organic Rankine or Brayton cycles combined with steam Rankine bottoming cycles could be designed using available equipment with higher efficiencies than the pure steam Rankine cycle.

Another potential engine for a central engine dish system is the steam-injected Brayton cycle used either by itself or with a Rankine cycle as a bottoming cycle. Efficiencies of about 40% are considered possible in the 50-MW$_e$ power range using several concepts that currently require further engineering development.

Advanced Concepts

Liquid Metal Thermal Electric Converters

The liquid metal thermal electric converter (LMTEC) can potentially operate for a long time and has a high solar-to-electric conversion efficiency (Figure 4.12). This engine is attractive for solar applications because it has no moving parts. Further, the potential maximum engine efficiency approaches Carnot (ideal) cycle efficiency.

Liquid sodium (or other liquid metal) is pumped to a high pressure by an electromagnetic pump (passing a moving magnetic flux through the liquid metal) and then heated. The liquid sodium is then ionized in a β"alumina solid electrolyte through which only positively charged ions pass. The electrons are conducted through an external electric load and back to a porous electrode in contact with the other side of the β"alumina electrolyte, producing electric power. These electrons then recombine with the sodium ions leaving the electrolyte, producing sodium vapor. Heat is removed from the sodium vapor to condense it before it reenters the electromagnetic pump.

Bench-test modules operating at 600°–1000°C (1150°–1900°F) were tested using sodium. The solid electrolyte degraded early, creating a major problem.

Current LMTEC testing is with sodium, and theoretical performance predictions indicate that the engine can reach efficiencies of slightly over 30% when operating at 1000°C (1850°F). At this temperature, solar collector efficiency would be low, resulting in a low solar-to-electric conversion efficiency. Potassium and mercury working fluids with a high vapor pressure, however, could theoretically give higher engine efficiencies at lower temperatures. If a mercury β"electrolyte could be developed, the engine might reach efficiencies as high as 40% at 700°C (1300°F). Further development of this engine for solar applications is not continuing because of electrolyte development problems.

Regenerative Thermoelectrochemical Converter

The regenerative thermoelectrochemical converter (RTEC) could provide high engine efficiency (40% is the goal), a long life at the relatively low temperature of 540°C (1000°F), and low-temperature storage (Figure 4.13).

The fundamental concept being developed uses two reversible chemical reactions (currently undergoing patent proceedings) that occur in an electrochemical cell and produce electricity. One reaction is reversed in a solar-heated boiler and the other in a condenser. The products are then recycled back to the electrochemical cell, providing a closed, continuous process. Because of the low temperature of the intermediate chemical products, only the boiler and recuperator need to be placed at the concentrator focus. The other components can be installed on the ground. All fluids in the ground portion of the system are at 150°C (300°F) or less, making it possible to transport energy to distributed or central electrochemical cells. The electrochemical cell and the condenser can be decoupled by storing the intermediate products. The advantage of this

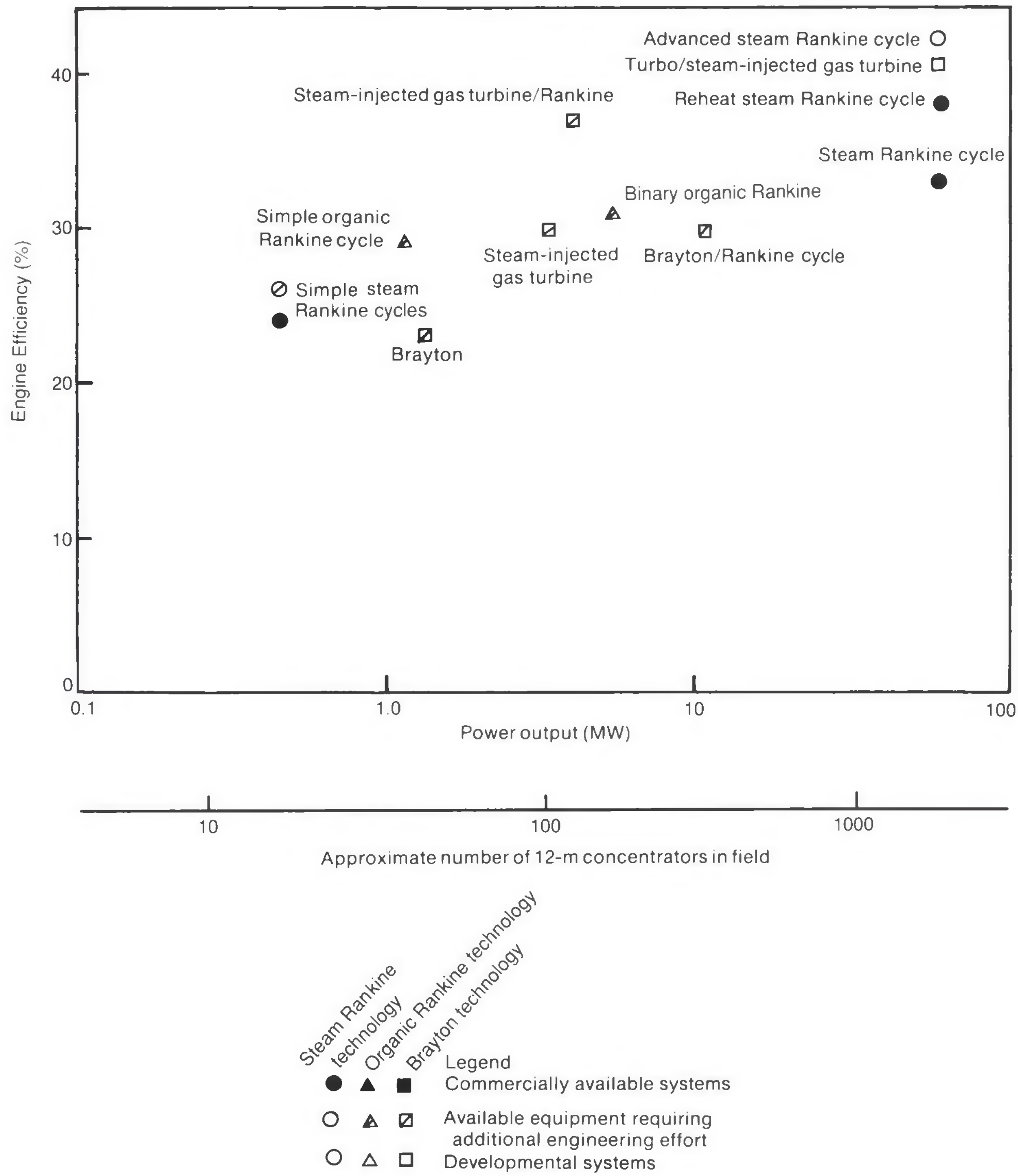


Figure 4.11. Central heat engines for use with parabolic dish fields

system is that electricity can be continuously generated while the solar portion operates intermittently.

Program Directions

Table 4.1 summarizes the advantages and disadvantages of each major cycle. The information is based on limited solar experience with each cycle because none has operated for any length of time in a solar application.

The first two criteria in Table 4.1 are measures of the amount of electric energy that a particular engine can derive from a dish of a given size. The best engine operates at high engine efficiency at a low temperature, thereby minimizing receiver heat loss. As discussed earlier, even though theoretically engine efficiency increases with temperature, the solar-to-electric conversion efficiency reaches a maximum at some temperature.

Table 4.1. Advantages and Disadvantages of Different Power Cycles for Application to Parabolic Dish Systems

	Organic Rankine	Kinematic Crankshaft Stirling	Kinematic Swashplate Stirling	Free-piston Stirling	Brayton
System Efficiency	med	high	high	high	med
Operating Temperature	low	med	med	med	high
Capital Cost	med	med	med	med	med
Maintenance	med	high	med	low	low
Experience	med	med	low	low	low

The next criterion, engine cost, can only be projected now because economies of mass production must evolve for any design. Factors that could affect the final mass production cost are using exotic or energy-intensive materials, requiring precision fitting of numerous parts, or developing new production techniques for parts such as ceramic turbines.

Maintenance (and operation) costs should be based on experience. Engines with few systems and moving parts generally do not have high maintenance costs. Rotating bearing surfaces usually require less maintenance than sliding bearing surfaces. Pressure seals that move have inherent problems and a high potential for failure. Engines that can be hermetically sealed, such as household refrigerator compressors, typically last longer than those open to air, moisture, and dust.

Table 4.1 shows that the current crankshaft-type kinematic Stirling engine can have a high engine efficiency. Its efficiency is at the expense of having to frequently replace some sliding and rotating seals. The swashplate Stirling engine should have considerably lower maintenance costs.

The Brayton cycle is expected to have low maintenance requirements but only moderate engine efficiencies; it also requires high operating temperatures, resulting in low collector performance. Therefore, no Brayton cycle engines are currently being developed for solar applications.

Much test experience was gained on the organic Rankine cycle, but its operating temperature is limited by the working fluid and, therefore, has a low engine efficiency. This engine also does not have a high potential for future parabolic dish applications.

Currently, the kinematic swashplate Stirling and the free-piston Stirling engine concepts are being developed further for parabolic dish applications. The promise of a low-maintenance engine with high engine efficiency at moderate operating temperatures makes this development highly important in decreasing the cost of electricity delivered by dish systems.

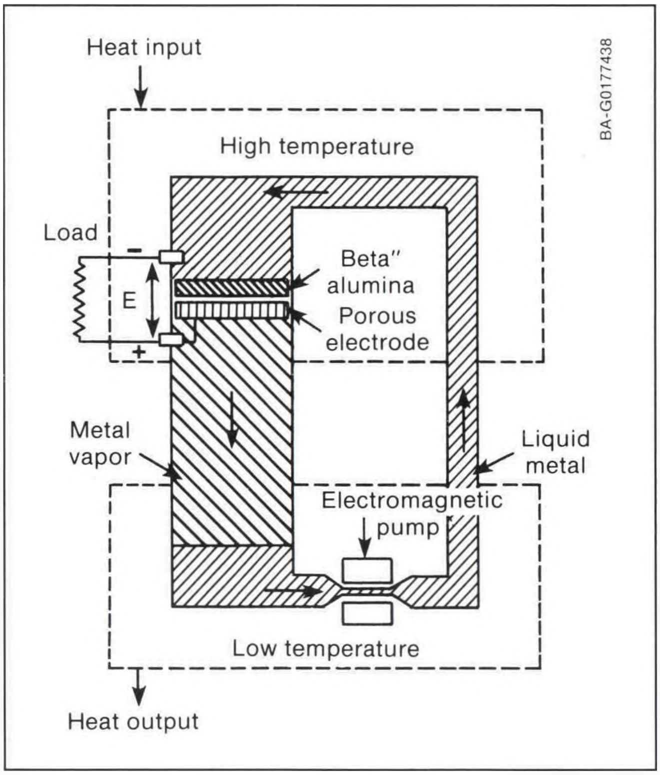


Figure 4.12. Liquid metal thermal electric converter (LMTEC) engine

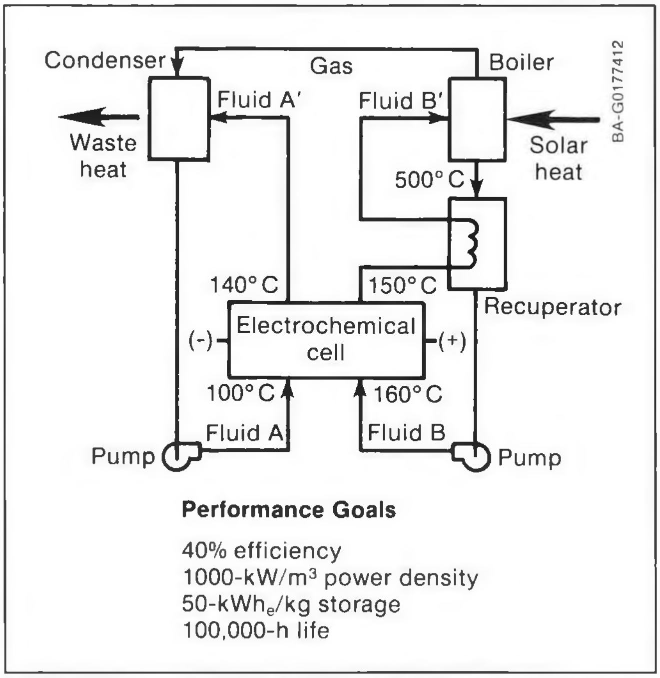


Figure 4.13. Regenerative thermoelectrochemical (RTEC) engine

Chapter 5
Energy Transport and Storage

Energy Transport

Because incident solar energy is dispersed over a large area, to be useful it must be concentrated, converted into thermal energy, and transported to the point of use. In many solar thermal systems today, the thermal energy is transported through insulated pipes.

With parabolic dish technology, a major issue is finding the best method to transport collected energy. Because parabolic dishes are two-axis, tracking, point-focus collectors, a two-dimensional energy transport grid, comprising either electric wires or insulated piping depending on the system design, is required to transport the collected energy from each receiver to the point of use.

When the system is designed to generate electricity, the alternatives are to transport high-temperature thermal energy from each dish through insulated pipes to a centrally located power generation system or to generate electricity at each collector and transport the electricity through wires to the point of use. Two variations of the latter scheme are in use: placing the power generation cycle at the focus of each concentrator and running power wires down to the ground and piping heat-transfer fluid from the receiver to a small engine on the ground at each collector's base.

Considerable thermal energy is lost when the heated fluid is transported. This loss not only occurs because of the steady-state heat transfer through the insulation but also because the entire piping mass must be heated to operating temperature during the morning start-up after cooling overnight.

Central power generation systems (>50 MW_e) are usually more efficient because of the larger size. Additionally, fewer components fail in a large single unit than in many smaller units. Likewise, large units usually require fewer operating personnel per unit of output. With parabolic dish systems, the major drawback of a central power conversion system is the cost of, and heat loss from, the connecting piping.

Distributed small engines eliminate the matrix of insulated piping, which is replaced with a matrix of power wires. Another important advantage is that because each engine forms an individual power generation module, the engines can be installed in small groups and the number increased or decreased as electricity demand changes. An operational advantage is that losing one unit does not mean losing the whole field. However, because many small engines are used, they must have high efficiency and reliability and be mass produced, so their advantages are not overshadowed by low energy production and high initial and operating costs.

Heat-Transfer Fluids

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

The heat flux into the receiver and the flow rate at which this fluid is pumped through the receiver's passages define the temperature at which the heat-transfer fluid leaves the receiver. For a given heat flux, a high flow rate reduces the fluid outlet temperature, and a low flow rate increases this temperature.

An important consideration in selecting the heat-transfer fluid is the temperature-pressure relationship required for the fluid to remain a liquid (Figure 5.1). For example, water must be pressurized to at least 7 MPa (1000 psia) to remain a liquid at 290°C (550°F) and to 21 MPa (3000 psi) to remain a liquid at 370°C (700°F). If the heat-transfer fluid must be maintained at a high pressure, the receiver and all connecting piping must have thick walls. A drawback to this design is that heat transfer across thick walls is poor, and more energy is needed to restart the system in the morning because of the excessive heat capacity of the entire system. In addition, thick walls increase the cost of the receiver.

Petroleum- and silicone-based heat-transfer oils are used in some parabolic dish systems. The major incentive to using these oils is their low vapor pressure at high temperatures. Many do not reach 100 kPa (15 psi) until their temperature

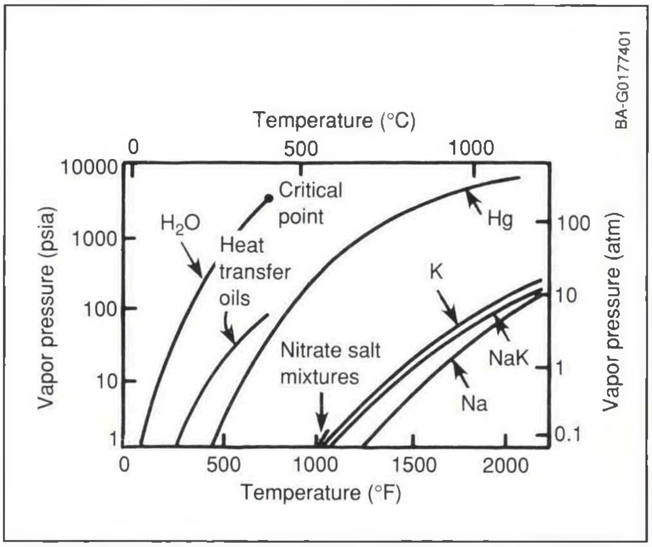


Figure 5.1. Vapor pressure of heat-transfer fluids
(note logarithmic pressure scale)

is 315°C (600°F) or higher, thereby simplifying system designs. The maximum temperature at which these oils can be operated ranges between 345° and 400°C (650°–750°F), depending on the particular oil. Above this limit, most oils break down and coke or plug the receiver tubing.

New heat-transfer fluid technology is being evaluated for high-temperature parabolic dish applications. Two candidate heat-transfer fluids are molten salts and liquid metals. With these fluids, parabolic dish systems can attain operating temperatures well above 400°C (750°F) with small, thin-walled receiver absorber surfaces.

Molten salt mixtures by weight of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3) are being considered for applications at 565°C (1050°F), below the temperature where decomposition begins. Even at this high temperature, the vapor pressure of the salt mixture is low. This low vapor pressure allows the heated salt to be used as a storage medium.

A disadvantage of molten salts is that they freeze at temperatures well above ambient. To compensate for this condition, piping and components must be highly insulated or electrically heated to prevent the system from freezing overnight or when shut down for long periods.

Liquid metals with low melting points also have low vapor pressures at high temperatures. Currently, liquid sodium and a eutectic mixture of sodium and potassium called NaK are being evaluated as heat-transfer fluids for parabolic dish applications. The advantage of these fluids is that they provide extremely high heat-transfer rates away from the absorber surface. As with the molten salts, the liquid sodium freezes when the system shuts down, creating a problem. The eutectic mixture NaK, however, does not freeze at room temperature. Also, both liquid metals are extremely hazardous to handle; they react vigorously with moisture in the air and burn spontaneously in air when heated.

Using liquid metals as heat-transfer agents includes putting them into pumped heat-transfer systems and reflux boilers or heat pipes. A major advantage of using them in pumped systems is that the pump can be an electromagnetic one, where a moving flux field, rather than an impeller, causes the fluid to flow. This pump does not physically penetrate the fluid piping.

Gases can be heated directly in the receiver to attain the extremely high temperatures required by Stirling and Brayton power cycles. Gases such as hydrogen and helium are preferable to liquids because they do not decompose at high temperatures. Also, the pressure is not fixed by the temperature alone but can be varied by changing the amount of gas. Hydrogen and helium also provide high, uniform heat-transfer rates from the absorbing surface and are not affected by the receiver tilt. In addition, they generally are noncorrosive.

Thermochemical Energy Transport

Thermochemical energy transport uses reversible endothermic-exothermic chemical reactions to store and then release heat. The intermediate chemicals move at near ambient temperature, eliminating most heat losses. A relatively simple endothermic-exothermic reaction, with its high theoretical energy density, is being considered for parabolic dish applications:

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

With this reaction, the concentrated solar energy provides heat to produce carbon monoxide and hydrogen. These products are transported at ambient temperature to the point of use, where the reverse exothermic reaction takes place on a catalytic reactor. This type of energy transport cycle can be either open or closed loop, depending on the chemical system (Figure 5.2).

Electricity Transport

With an engine-generator placed at the focus of the dish, only two or three electric wires transport the energy from the receiver to the ground. A matrix of wires transports electricity within the solar collector field to a single point where the total field output is connected to the point of use or to a power grid for distribution.

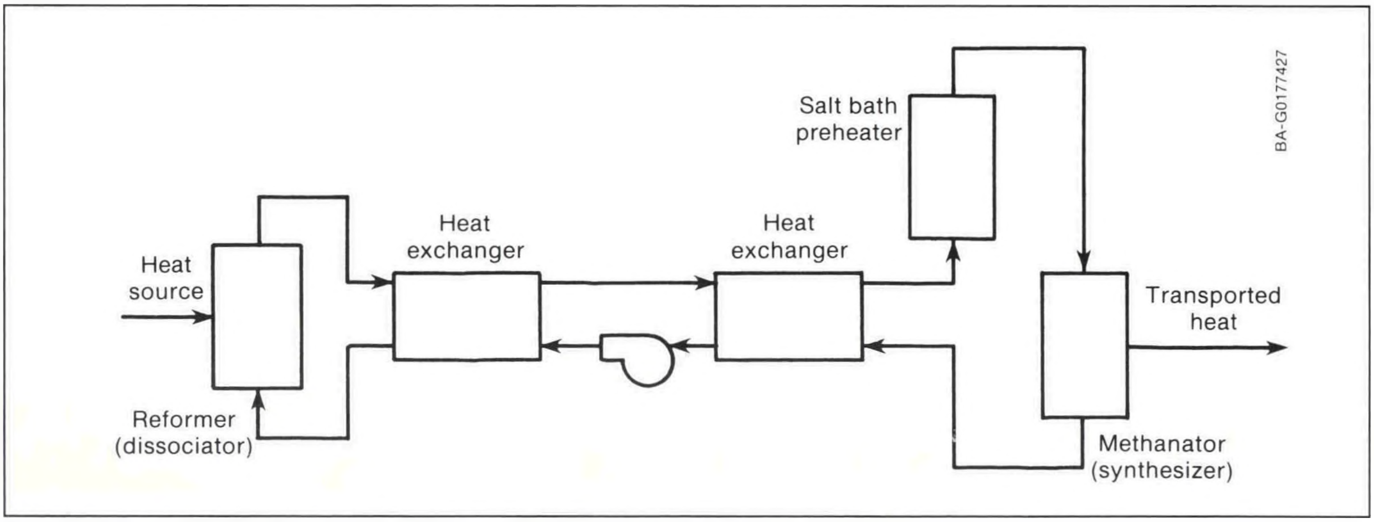


Figure 5.2. Closed-loop carbon dioxide–methane thermochemical transport

Energy Storage

A major advantage of solar thermal systems is that the thermal energy collected when the sun is shining can be stored for later use. Storage is best accomplished where thermal energy is brought to a central point. Most of the schemes discussed here are most suitable for central engine or industrial process heat systems. The development of storage technology for parabolic dishes has not been emphasized because parabolic dish systems that produce inexpensive energy must first be developed, before the addition of storage makes sense.

Using distributed engine-generators for each concentrator requires storing electric energy rather than thermal energy. Current systems do not use storage; however, batteries, superconducting magnets, and fuels that can later be used in a fuel cell are all being considered.

Fundamentals of Thermal Energy Storage

Solar thermal technologies are better able to meet industry demands and electric power production than other alternative energy technologies because the energy is easy to store. The amount of thermal energy stored is a function of the type and amount of storage material and its temperature.

Heat can be stored in a material in two modes: sensible heat and latent heat. *Sensible heat storage* depends on raising the temperature of the storage medium. The amount of heat stored can be written as

$$Q_{sto} = \rho V c_p (T_1 - T_2) \,, \qquad (5.1)$$

where

ρ = density of the storage medium (kg/m^3)

V = volume of the storage container (m^3)

c_p = specific heat of the storage medium (kJ/kg °C)

T_1, T_2 = initial and final temperature of the storage medium (°C).

Materials with a high density and specific heat allow more sensible heat storage in a given volume for a given temperature change. These materials must also be inexpensive to make thermal energy storage economically feasible.

Latent heat storage uses the heat of fusion or vaporization of a material. This process ideally occurs at a constant temperature, usually determined by the pressure. The amount of heat stored can be written as

$$Q_{sto} = \rho V h_{pc} \,, \qquad (5.2)$$

where h_{pc} is the latent heat of phase change (vaporization or fusion) (kJ/kg).

Materials with phase changes at temperatures equal to, or slightly above, the application temperature and at pressures close to ambient are chosen for latent storage media. Inexpensive materials that have a high density and high latent heat of phase change, depending on whether it was the liquid-vapor phase change or the solid-liquid phase change, provide the most economic latent storage.

The Role of Storage

The size of the storage defines the role thermal storage plays in parabolic dish system design. Small amounts of storage to smooth out system control, called *buffer storage*, keep the system operating for tens of minutes when clouds temporarily obscure the sun. Somewhat larger day-extension storage prolongs system operation to meet the end of a demand schedule that extends beyond sunset. Larger diurnal storage provides overnight storage, which can be used for early morning start-up or on cloudy days.

Several alternatives were tried to provide buffer storage in parabolic dish systems. In one, the cavity receiver had thick copper walls on which the concentrated solar energy was absorbed. Once heated, the copper walls transferred the heat to the working fluid. In a variation of this design, a high-temperature phase-change material surrounded the cavity receiver absorbing walls. Heat was then transferred to the working fluid through this material. In either design, the heat retained in the material was extracted when insolation decreased. A third alternative was to store a small quantity of the heated working fluid in a tank for later use.

Just as cost savings are realized when the same fluid is used for heat transfer and the power cycle, similar savings are possible 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 for holding heat.

The Hybrid Alternative

An alternative to storage that meets both the need to smooth out the energy supply rate and the need to extend the operating period is to operate the system in the hybrid mode, where solar heat is replaced by fossil fuel heat when solar energy is unavailable. In most solar energy system designs used today, only a small storage or minimal hybrid operation is required because existing sources of electric power or process heat can continue to supply energy during reduced solar output. A solar energy system is typically shut down when the sun is not shining. In the future, however, as solar energy systems meet greater demands, thermal energy storage or hybrid operation to extend or continue operation will become an important design requirement.

Program Directions

In current parabolic dish systems that use a piping matrix to transport energy, approximately 15% of the collected energy is lost. This loss can be reduced to less than 1% by using distributed engines connected directly at each concentrator's receiver. Current work on engine-receiver combinations is directed toward this goal.

Chapter 6
Economic Goals and Market Potential

Research by industry, universities, and federal laboratories suggests that parabolic dish solar thermal systems built using current state-of-the-art technology are likely to produce electric power below 12¢/kWh$_e$ (1984 dollars). Likewise, it is probable that process heat can be produced by parabolic dish systems at 6¢/kWh$_t$ ($1.70/therm). For some applications, these systems are already competitive with conventional energy sources.

The development program for these systems is working toward improving performance and reducing system costs to lower the cost of electric power production to about 5¢/kWh$_e$ [7]. The cost of high-temperature thermal energy will likewise be reduced to 3¢/kWh$_t$ ($0.90/therm).

For these systems to have widespread acceptance, purchasers must be assured that they will operate over the 15- to 20-year lifetime necessary to realize these energy costs. As a result, reliability, availability, and system operational considerations are receiving increased attention. Industry and end users need to develop confidence in this technology for a self-sustaining market to evolve in the near future.

The performance and cost goals given in this document (Table 6.1) represent goals attainable through future research and development efforts [8]. If these goals are met, parabolic dish solar thermal systems will have a significant impact on the energy marketplace of the 1990s.

Table 6.1. Summary of System Cost Goals

Type of Energy	Goal	Current
Electric Systems	5¢/kWh$_e$	13¢/kWh$_e$
Thermal Energy Systems	3¢/kWh$_t$	6¢/kWh$_t$

Solar Energy System Economics

Solar energy technologies are being developed to provide alternatives to fossil fuels and other energy production technologies. The benefits of developing solar technologies will be realized when the cost of delivering conventional resources to the customer and society exceeds that for solar-derived electricity or thermal energy.

Cost Factors

The cost of energy varies with type, time and rate of demand, and the location of use. Electric energy is typically the most valuable type of energy; fuels easily used for transportation, such as petroleum, are priced higher per unit energy than stationary fuels, such as coal and uranium.

Although the amount of energy used is fundamental to its cost, the rate at which it is used is also important. For example, electric power suppliers must build and pay for large power plants just to supply the peak energy demand rates (usually occurring on summer afternoons or winter evenings), making the cost of this peak demand power more expensive than the 24-h constant base load. Parabolic dish solar systems produce their maximum energy on clear, hot summer days; these systems then are a good way to meet peak energy demands for air conditioning in summer.

Finally, the location of the demand for energy affects the cost of energy because of the transmission cost. For example, in many remote sites throughout the world that are far from major electric power grids, the cost of electricity is higher than in urban centers. This cost is higher because the alternatives are local electric generators powered by diesel engines or by expensive transmission lines from distant power grids. Small modular parabolic dish systems offer the potential for sizing local electric power generation facilities of the exact size required, from 25 kW to multimegawatts.

Levelized Energy Cost

The ultimate measure of the performance and cost of a parabolic dish energy system is the cost of the energy produced. Several methods can evaluate the economics of solar energy systems, including those predicting the system payback period, internal rate of return, and the cost of energy averaged over the life cycle of the system (levelized energy cost [LEC]). To examine solar system economics, a highly simplified approach to the latter method is developed here.

The fundamental parameter defining the cost of energy from a parabolic dish (or any other) system is the levelized cost of producing energy. In the method described here, the yearly cost of producing electricity is the cost to operate the system for a year plus the yearly payment required to pay back the initial cost of building the system (capital cost) divided into equal installments at a specified interest rate. The total energy produced for a year is the net power output of the system (gross output minus parasitic losses) integrated (summed) over the year. The LEC is

$$\mathrm{LEC} = \frac{\mathrm{OC} + \mathrm{CC}\left[\dfrac{i(1+i)^n}{(1+i)^n - 1}\right]}{\int_{\text{year}} \eta_{col}\, \eta_{cyc}\, A_{tot,app}\, I_{b,n}\, dt} \tag{6.1}$$

where

η_{col} = solar collector efficiency

η_{cyc} = engine efficiency (if applicable)

$A_{tot,app}$ = total effective concentrator aperture area in the collector field (m^2)

CC = total capital cost of system ($)

OC = yearly operating cost ($)

$I_{b,n}$ = beam normal insolation (kW/m^2)

i = yearly interest rate or internal rate of return

n = lifetime of system (yr)

t = time (h).

To reduce the cost of solar-derived energy from a parabolic dish system, the system must be in an area of high insolation, incorporate efficient collectors and power conversion systems, have a low capital and operating cost per unit aperture area, and have a long lifetime (Eq. 6.1).

Cost and Performance Goals

DOE has developed a set of reasonably expected goals for both annual efficiency and capital and operating cost for every component of a parabolic dish system [9]. When combined, these goals provide a system that will produce thermal energy at a levelized energy cost of 3¢/kWh and electricity at 5¢/kWh. At this LEC, parabolic dish systems will be competitive in the broadest markets for electricity and high-temperature thermal energy.

Table 6-2. Parabolic Dish Component Annual Efficiencies

Component	Goal (%)	Current (%)
Industrial Process Heat		
Optical Materials	92	88
Concentrators	78	70
Receivers	95	87
Transport	94	93
Storage	98	—
Heat Exchange	99	99
Electricity		
Optical Materials	92	88
Concentrators	78	70
Receivers	90	87
Transport	99	93
Power Conversion	41	23

Performance Goals

The annual average parabolic dish system efficiency goal for producing process heat for industry is to attain a peak collection efficiency of approximately 68%. When incorporating engine efficiency for electricity generation, the goal is a 28% solar-to-electric efficiency. To attain these performance goals, a set of reasonably expected component performance goals was established. These goals, along with current levels, are shown in Table 6.2.

Cost Goals

To go along with these performance goals, component cost goals must result in systems that will deliver energy at a competitive cost. Most of the performance goals noted here can be met with current technology, however not at a cost that results in the desired LEC of 3¢ or 5¢/kWh of energy delivered.

The cost goals can be stated in terms of the overall capital cost to build a parabolic dish system for the production of process heat or electricity. For process heat systems, the capital cost goal is $430/kW$_t$. Achieving this goal requires a 45% reduction in the cost of current systems, which is $780/kW$_t$. For parabolic dish systems to produce electricity at a competitive rate, the systems must cost less than $1200/kW$_e$. Because current technology can produce these systems at a cost of $3400/kW$_e$, a 65% reduction in system cost is required to attain this goal. In both cases, these reductions appear attainable while system performance is still maintained at the required levels.

These system cost goals, broken down into goals for the major components, are presented in Table 6.3.

To date, the efforts of industry and the federal government have led to steadily decreasing energy costs for solar thermal systems. Continuing evolution of system components and design will further decrease costs, increasing the number of potential applications. As volume production for solar components increases, economies of scale will be realized, resulting in further decreases in the cost of solar thermal energy.

Market Potential

Electricity and process heat are the applications of major interest for parabolic dish technology. Within both the electricity and heat markets, potential applications exist for these energies in a broad range of delivered energy costs. The parabolic dish program cost and performance goals are a compromise between maximizing the probability of attaining the goals and maximizing potential market penetration in competition with fossil fuels. Although the goals are highly ambitious, achieving them would yield large returns in the form of an inexpensive and widely applicable source of renewable energy. Parabolic dish technology will have significant applications and early market penetration well before achieving the long-term goals.

Table 6.3. Parabolic Dish Component Costs

Component	Goal ($\$/m^2$)	Current ($\$/m^2$)
Industrial Process Heat		
Optical Materials	10	20
Concentrators[a]	130	160
Receivers	30	40
Transport	65	70
Storage	20	—
Heat Exchange	40	50
Balance of Plant	20	35
Yearly Operations and Maintenance Cost	6	8
Electricity		
Optical Materials	10	20
Concentrators[a]	130	160
Receivers	40	40
Transport	35	70
Power Conversion	300	380
Balance of Plant	20	35
Yearly Operations and Maintenance Cost	5	8

[a] Includes optical material cost.

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