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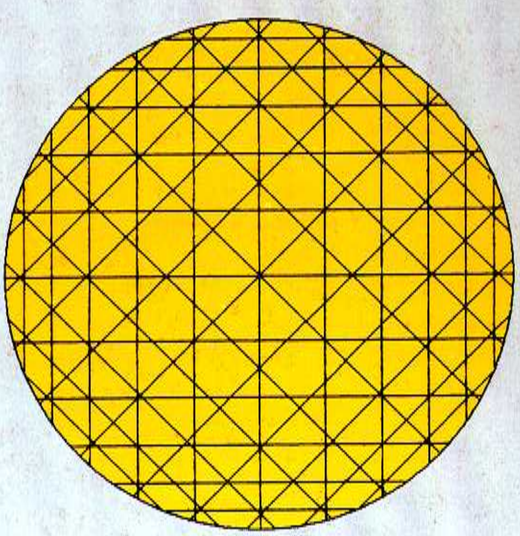
Solar Energy Concentrating Systems

Applications and Technologies



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Because this document covers a wide field of solar energy technologies and applications, it was necessary to ask many members of the solar community to provide information and to display their insights on solar concentrating systems. Significant contributions were made by various experts. A review provided valuable guidance and suggestions througout the writing of this document.

The editors and the authors would like to thank everyone who took the time to review and comment on the draft of this brochure. Reviewers and contributors from the USA and Europe are listed below.

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Preface

This brochure was edited under the auspices of the Deutsche Forschungsanstalt for Luft- und Raumfahrt e.V. (DLR) in Köln (Germany) and the National Renewable Energy Laboratory (NREL) in Golden, Colorado (USA). The intention is to provide up-to-date information on the status of solar concentrating technologies and applications. A previous document, *High-Temperature Technology and Applications,* published 1987, was primarily concerned with central receiver systems; it was used as a basis for this new brochure. We have chosen to expand the scope to include all solar concentrating technologies, i.e., the central receiver, the parabolic trough, and the parabolic dish systems.

Our intent here is not to provide a detailed technical discussion of all solar concentrating applications and technologies, but rather to introduce the reader to the possibilities for applying concentrated solar energy to a number of industrial processes. Instead of detailed discussions, we have included a list of references for further reading.

We may have neglected some technologies or applications either by providing only a brief discussion or no discussion at all. There are several reasons for this. First, some of these technologies are not being actively pursued at the present time. Second, information is not readily available for some areas, either because the technologies are too new, or because we made no contacts with the main participants. Finally, we had to choose a scope for this document and we chose to include only concentrating systems and their applications.
We believe that this document will be useful to those with a general interest in solar and renewable energy who wish to keep current with developments in the field, to students working their way into "solar," and to physicists, chemists, and practicing mechanical and chemical engineers who may wish to pursue specific applications for concentrating technologies. To address this diverse audience, we have kept the detailed technical discussions to a minimum. We also provide technical terms specific to the field of concentrating solar systems and a list of used abriviations/acronyms.

Chapter 1 comprises a general introduction to this document. After a quick historical view to the actual status of solar concentrating systems, the solar physics/irradiation, the available radiative energy and the interactions with technical processes are briefly discussed.

In *Chapter 2*, the existing or potential applications of concentrated solar energy are covered. By presenting this information first, we feel that the general-interest reader can quickly learn how the solar technologies may be used in industrial applications such as electrical power generation, process heat generation, and chemical processing. For each of these areas, we first give general information regarding the application and the potential benefits of using concentrated solar energy. We then discuss projects in which these applications have been examined in the field. For those applications in which feasibility, economic, or systems studies have been performed, we discuss the results of those studies and implications for the future of each application.

Chapter 3 describes in detail the technology required to exploit these solar applications. Here, we have divided the discussion along the lines of the major solar concentrating technologies: central receivers, parabolic troughs, and parabolic dishes. For each of these technologies, we provide a general introduction followed by a more detailed discussion of each important subsystem or major component.

Solar concentrating technologies cannot be applied everywhere. Determining locations where the technologies can be applied satisfactorily requires an understanding of the spatial and temporal variability of the solar resource. To that end, *Chapter 4* provides an introduction to solar resource assessment. Chapter 4 also describes the specialized instrumentation the solar engineer needs to assess the solar resource for a particular location or to assess the performance of a particular solar component.

Chapter 5 discusses existing test facilities where most of the research and development for the above-mentioned applications and technologies has been performed, respectively is currently performed. This section should give the reader an idea of where and how the work is done and of the specialized equipment necessary to perform the researchers' work. It is also intended as a compendium of important available test sites.

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1 Introduction

The sun *(Source: DLR)*

Classical applications of solar concentrating systems include the production of electricity and process heat. In these applications, the primary incentive for using solar energy as heat source is the avoidance of toxic goods as CO_2 and its potential low cost, even as compared to fossil fuels. The main technical challenge is to design equipment that can convert this free source of heat to usable forms without incurring excessive capital expenditures.

However, in the last few years, the cost of fossil fuels has stabilized, and in some areas has actually decreased, making it more difficult for concentrated solar radiation to compete in the near term in these applications. In response to this situation, solar research and development (R&D) has focused on finding the most cost-effective solar hardware possible and methods for minimizing operating and maintenance costs. This work has involved laboratory testing, field experiments, systems studies, and demonstration projects.

Increased worldwide attention to the environment has also affected the solar industry. One of the main advantages of concentrated solar radiation for all applications is the displaced consumption of fossil fuels and the related reduction in atmospheric pollutants. In some cases, environmental benefits have helped concentrated solar radiation compete with fossil fuels, and these benefits will continue to receive close attention.

Significant progress has been made in the solar engineering field, pushing various aspects of the technology toward, and in some cases into, beginning commercial implementation. This is true for all three major concentrating solar energy technologies: parabolic troughs, central receivers and parabolic dishes. This progress is demonstrated by various test facilities with small- and medium-scale experiments, e.g. at the Plataforma Solar de Almería in the South of Spain (Figure 1-1).

Additionally, a large amount of documented R&D work and numerous studies are available. The last few years have seen significant progress toward commercial acceptance in certain markets, including installation of 354 MW_e total capacity of solar electric generating system (SEGS) plants by LUZ International in California and construction of several successful process heat plants. The next phase of central receiver development, the 10 MW_e Solar Two project, is progressing in Barstow, California, where the existing 10 MW_e Solar One plant is being modified.
In the past few years, researchers have come to recognize that concentrated solar radiation can provide several advantages besides a clean, low-cost source of heat. These advantages include the ability of concentrated solar radiation to provide a safe source of energy that can be delivered at high radiant flux levels. This has opened the way to new materials production techniques, such as transformation hardening of steel, that require high-flux energy sources to produce rapid surface heating. Concentrated solar radiation also provides a convenient source of ultraviolet photons, and researchers are now examining photolytic and photocatalytic reactions that can take advantage of this (e.g. solar detoxification).

As a prerequisite for considering how to use solar radiant energy and solar thermal energy in industrial processes, the following basic principles should be understood:

- Solar physics and insolation
- Available direct insolation
- Interactions with technical processes.

1.1 Solar Physics and Insolation

Radiant energy produced by the sun is emitted from the sun's surface into space. This energy hits the earth in wavelengths ranging in the orders from 0.1 µm to 10 µm. Absorption and conversion of the solar radiation or insolation into heat are fundamental reactions on earth. The inexhaustibility and cleanliness of the insolation make it an ideal source of energy. Under extremely clean and clear atmospheric conditions, temperatures above 1000 °C can be reached for technical processes.

The conversion of the insolation into technically usable energy at required locations and needed time periods is an engineering challenge. The amount of insolation is not only a function of latitude, but also of general geographical, meteorological, and topographical conditions (see Figure 1-2). Local insolation data influence the main design aspects of a solar plant. Other important parameters are access to the plant, water needs, and different kinds of local services. Concentrating solar systems can make use only of the direct insolation, which means that a clear sky is needed. The reflection and concentration of the direct insolation is achieved by sun-tracking mirrors called collectors or heliostats. The concentrated solar radiation is focused on a solar heat exchanger, called a receiver, or, in the case of solar processing, on a receiver/reactor.

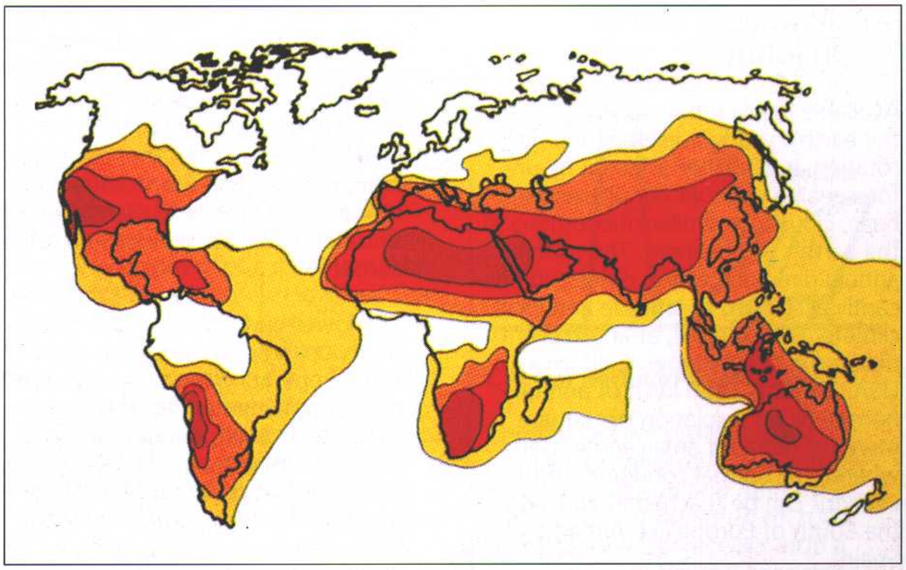


Figure 1-2. Global distribution of solar radiation intensity (Source: DLR)

Figure 1-1. View of the Plataforma Solar de Almeria in the South of Spain (Source: PSA)

1.2 Available Direct Insolation

Available insolation is dependent on the earth's yearly trajectory and daily rotation. It is further affected by unforeseeable weather conditions like haze, clouds, or similar phenomena in the earth's atmosphere. The usable annual direct insolation differs significantly according to latitude and local climate. For example, at an excellent desert site like Barstow, California, USA, 2400 to 2850 kWh of annual normal direct insolation per square meter of radiated area can be used, whereas at normal conditions 1800 kWh/m² can be reached at arid sites in the South of Europe like Almeria, Spain.

Since solar concentrating systems do not appear to be economical at sites with annual normal direct insolation below 1800 kWh/m² (equivalent to a horizontal global insolation of approximately 1700 kWh/m²), attractive potential sites are located in the area between the 40th north and south parallel of the earth.

1.3 Interactions with Technical Processes

Most established industrial processes require steady-state conditions, a requirement in conflict with the available solar energy during daylight hours. With proper design of a system for a particular application, a match between available solar energy and process requirements can be achieved. Three different ways are illustrated schematically in Figure 1-3:

- At the top of the figure, direct use of the nonsteady-state insolation is shown. A perfect coupling of the process to solar conditions is necessary to follow the insolation as it varies in time of the day (sun following mode).
- In the middle of the figure, a part of the usable solar energy provides thermal or chemical energy storage, from which energy is taken when no solar energy is available. Such systems are designed for solar-only operation modes. The storage may be used also to extend plant operation during cloudy periods and after sunset.
- The lower part of the figure shows the coupling of solar energy to constantly operating processes by applying supplementary fossil heating in nonsolar time periods. Such processes are maintained in solar/fossil hybrid operation. Fossil firing may be used also to supplement plant operation during cloudy periods and to enlarge the plant capacity factor as well as to fit the electricity or process heat generation to the users needs.

Current and future R&D efforts are and will be focused on key solar components (mainly the collector, receiver, and storage) and on the adoption of optimized solar processes as well as on demonstration of technically and economically feasible processes. Consequently, R&D and market introduction are often dependent on governmental and industrial support. The use of solar energy as an universal resource may help to meet the energy demand worldwide and therefore requires an international consensus to foster its development and promotion.

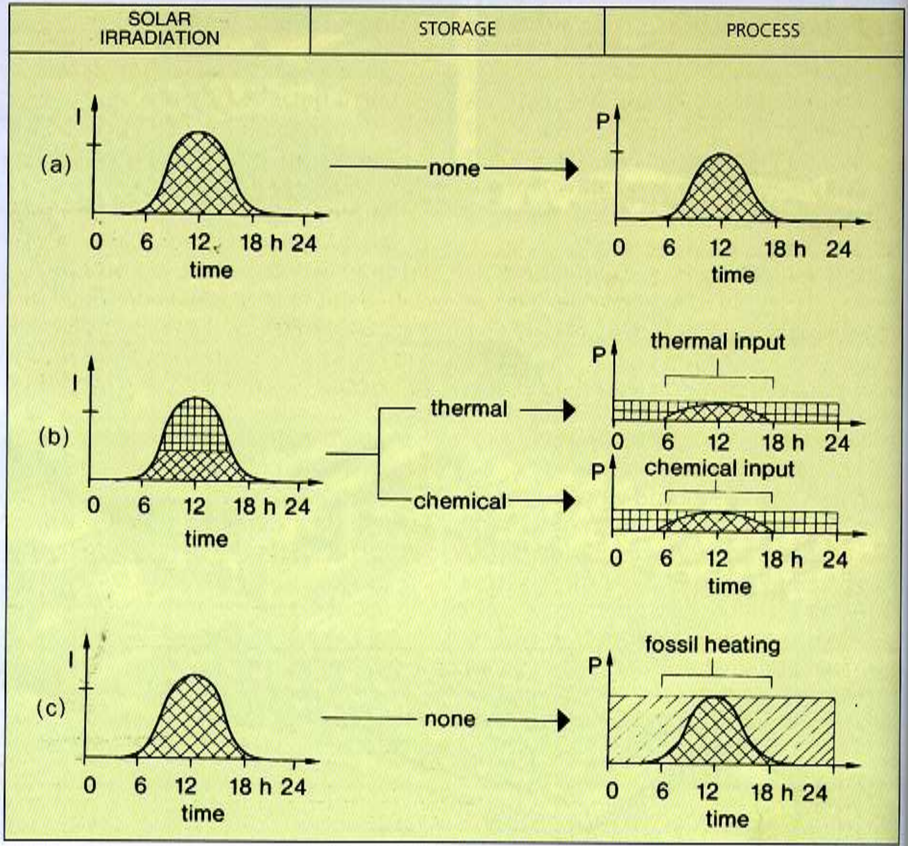


Figure 1-3. Coupling of time-dependent solar energy input with different processes (Source: DLR)

2 Applications

2.1 Electricity Generation

In less than 15 years, electricity generated by solar thermal power plants has developed from a subkilowatt novelty to a system of multimegawatt gridconnected power stations.

Solar power plants can be placed into two major categories: central plants that are connected to a grid and have a capacity greater than 30 MW_e, and distributed plants that supply power for remote uses, village electrification, and end-of-grid systems. Central plants can be designed as central receiver systems or as parabolic trough systems. Distributed plants are designed mainly as parabolic dish systems. Central receiver, trough, and dish systems have been built and operated as experimental facilities; trough systems also have been operated as commercial grid-connected plants delivering power up to the 80MW_e unit-level.

These solar technologies depend on the concentration of direct normal (i.e. nondiffuse) insolation. Using mirrors, solar radiation is collected and concentrated onto a receiver, which absorbs the radiant energy and transfers it into a suitable heat-transfer fluid. This creates high power fluxes up to 3000 times the intensity of normal sunlight (suns). Different heat-transfer media (steam, liquid sodium, molten salt, gas, heat-transfer oil) are used to transport the energy from the receiver to the power conversion system. To the extent possible, the power conversion system uses existing technologies applied in conventional power plants. Storage subsystems may be incorporated into the heat-transfer systems to make up for short interruptions in solar radiation caused by clouds, to adapt power production to the load profile, and to extend power production beyond daylight hours.

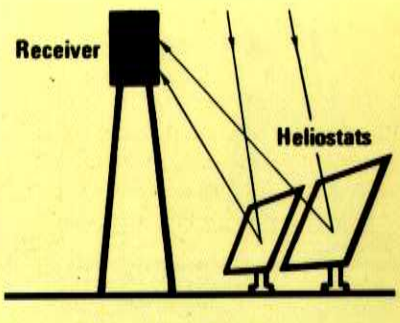
In response to rising interest in solar energy generation, several solar thermal facilities have been built, operated, and evaluated over the last approximately 15 years. Many of these facilities were designed for experimental or demonstration purposes. However, since the end-1980s, parabolic trough systems up to 80 MW_e per unit have been applied commercially in California (USA). These systems demonstrate that electric power from solar thermal is currently reliable and economical under good insolation and economic conditions.

The broad solar energy data base available today allows us, with reasonable confidence, to envisage future commercialized solar thermal plants with mature technology under favorable solar and infrastructure conditions.

2.1.1 Central Power Generation

2.1.1.1 State of the Art

Development of central receiver systems began in the early 1960s. One of the pioneers was Giovanni Francia in Italy, who experimented at Sant' Ilario near Genoa. Other small test facilities followed in the USA (Georgia Institute of Technology in Atlanta) and in France until the end of the 1970s. Then, in response to the sudden increase of oil prices, seven experimental central receiver power plants ranging from 500 kW_e up to 10 MW_e were designed, built, and operated in Italy, Spain, France, Japan, the USA, and Russia, at sites between 34 ° and 45 ° northern latitude. These projects



Central Receiver Systems

Central receiver systems (CRS) use heliostats (highly reflective mirrors) that track the sun and reflect it as well as concentrate it up to 1000 times to a central receiver atop a tower. The sun heats a heat-transfer medium in the receiver typically to temperatures up to a range of 500 to 1000 °C dependent on the concept used. The heated heat-transfer medium drives a turbine to produce electric power. Such a concept has been proven at the 10-MW_e Solar One system installed near Barstow, California, which used a pressurized water/steam receiver, and at various experimental plants in Europe (at Almería, Spain, Targasonne, France and Adrano, Italy), Japan and Russia. Through the experience with such systems, researchers are designing better and cheaper heliostats (such as the stretched-membrane heliostat), better receivers (molten salt and volumetric air receivers), and computerized controls that can run the solar thermal plant more cost effectively. Further, very high concentration may achieve temperatures up to 3000 °C for non-electric applications.

Name	Location	Country	Start of Operation	Electric Output (MW)	Heat-Transfer Fluid
SSPS	Almería	Spain	1981	0.5	Liquid Sodium
EURELIOS	Adrano (Sicily)	Italy	1981	1	Steam
SUNSHINE	Nio Town	Japan	1981	1	Steam
CESA-1	Almería	Spain	1983	1	Steam
THEMIS	Targasonne	France	1982	2-2.5	Molten Salt
Solar One	Barstow	USA	1982	10	Steam
SPP-5	Shchelkino (Crimea)	Russia	1986	5	Steam

Table 2-1. Experimental central receiver plants

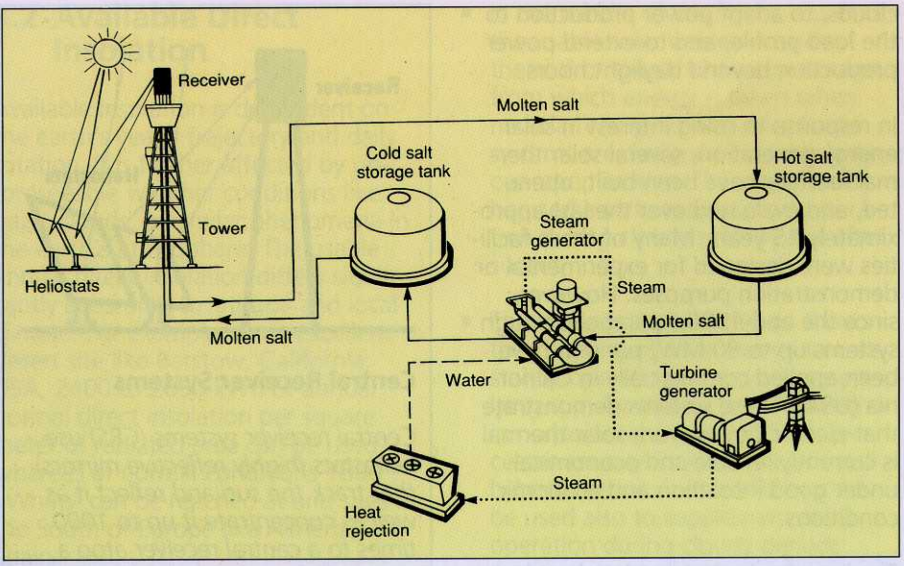


Figure 2-1. Schematic of a molten-salt central receiver system (Source: SNL)

received financial backing from their respective governments. Table 2-1 lists these facilities.

In spite of the fact that central receiver systems R&D started in the 1960s, and seven experimental plants up to 10-MW_e capacity demonstrated technological feasibility up to now, no large demonstration or commercial plant is now in place. One of the main drawbacks is the financing requirements of central receiver plants. Demonstrating systems in the 20-30 MW_e size range, which is the likely threshold for systems to be economical, will lead to commercial plants in the 100-200 MW_e size range at sites with favorable operating conditions (direct annual insolation of greater than approximately 1800 kWh/m^2).

Today, solar researchers and developers, mainly in the USA and Europe, undertake efforts for commercialization of the central receiver concept on the basis of experience gained by various experiments, technology programs, and experimental plants. One of the next important steps to reach the goal is the building and operation of demonstration plants. Mid-sized and large pilot experiments, e.g., the 10-MW_e molten-salt plant Solar Two in the USA and the 2.5-MW_t PHOEBUS technology program solar air receiver (TSA) in Europe, are important milestones to demonstration.

The central receiver system concentrates sunlight using heliostats that aim the radiation onto a central receiver on top of a tower. The plant typically has the following subsystems and components:

- Heliostat field
- Tower
- Receiver
- Heat-transfer system
- Thermal energy storage (optional)
- Supplementary fossil-fuel firing system (optional)
- Power conversion system (electric power generating system, comprising steam generator and turbine-generator)
- Plant control, auxiliary power supply, and heat rejection.

Figures 2-1 and 2-2 show the schematic diagram of modern solar tower plants using molten-salt respectively air as the receiver heat-transfer medium. These plants are suitable for power sizes up to approximately 200 MW_t for the solar-only operation mode and are equipped with a thermal energy storage using molten salt or e.g. ceramic spheres as the storage material. Fossil fuel firing may be used as a back-up system resulting in the solar-fossil hybrid operation mode.

Future central receiver systems will use molten salt or air as the preferable heat-transfer medium.

Seven experimental central receiver facilities are briefly described below.

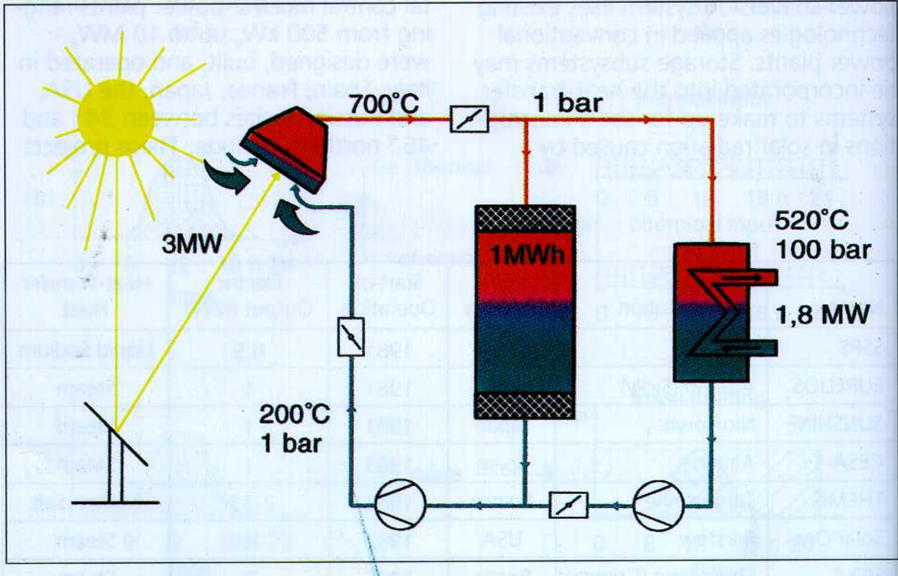


Figure 2-2. Technology Program Solar Air Receiver (Source: DLR/FDE)

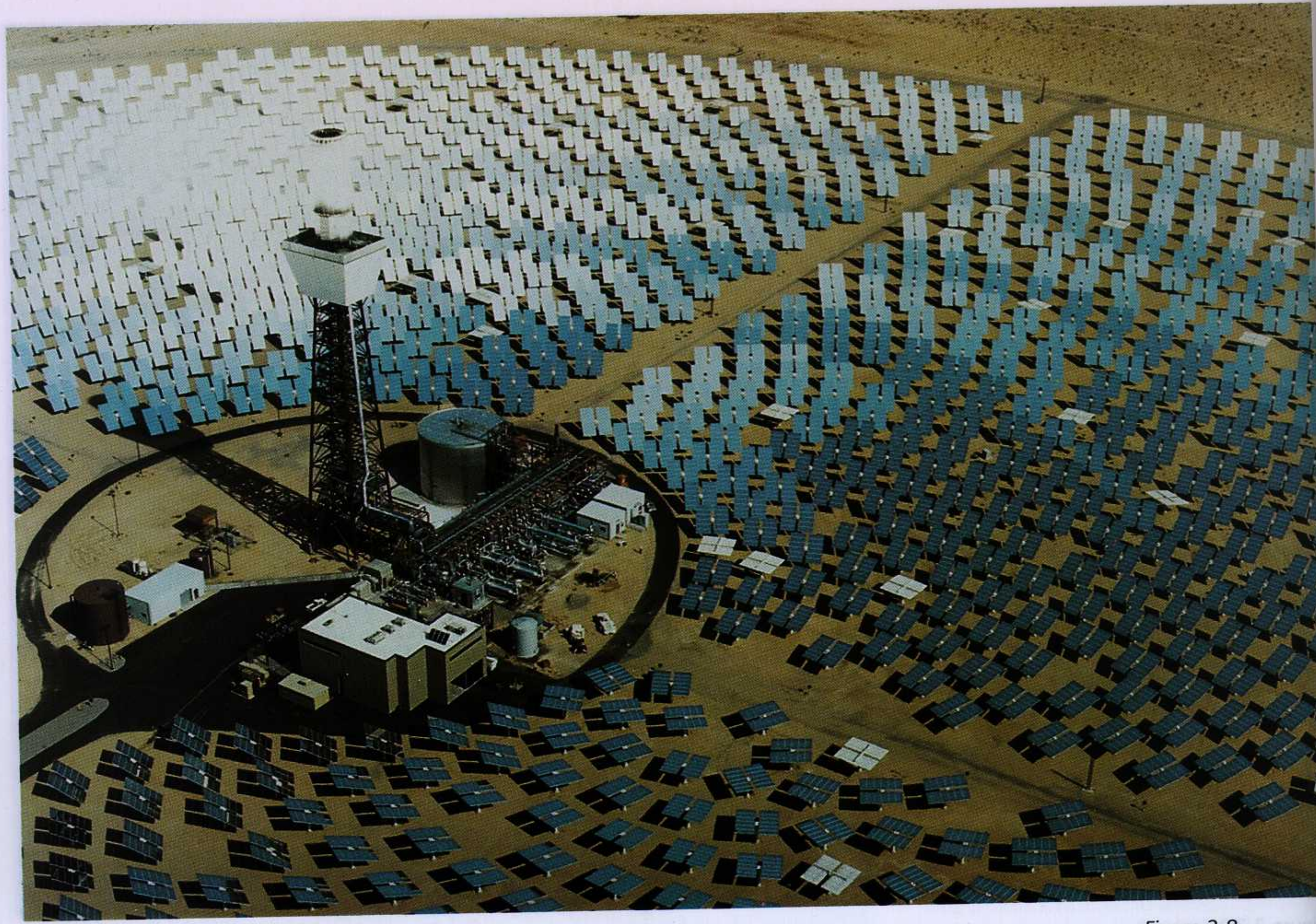


Figure 2-8.
Solar One, Barstow, California, USA
(Source: SNL)

Solar One, Barstow, California

The American 10-MW$_e$ Solar One (Figure 2-8; Table 2-7), the world's largest CRS power plant, was a cooperative effort of U.S. government, utilities, and private industry. The plant was constructed in the Mojave Desert near Barstow in California (34.9 ° northern latitude) and used a water/steam receiver system. It supplied energy to the Southern California Edison utility grid from April 1982 until 1988. The heliostat field comprised 1818 heliostat units of 39.3-m^2 reflective area each. After 6 years of successful operation, the experimental phase of Solar One was completed, and the plant became inactive. A U.S. group from utilities, industry, and research centers is currently rebuilding the plant (10-MW$_e$ Solar Two project) to operate on a molten nitrate salt system instead of the original water/steam system. Solar Two is planned to serve as a large-scale test facility on the way to a commercial CRS plant using molten nitrate salt as the receiver heat-transfer fluid as well as the storage medium.

Heliostat field reflective surface area	71,447 m^2
Receiver heat-transfer fluid	Steam
Receiver heat-transfer fluid temperature	516 °C
Storage medium Storage capacity (full power hours)	Oil/rock 3 hours
Electric output	10 MW$_e$

Table 2-7.
Design data for the Solar One plant (original plant)

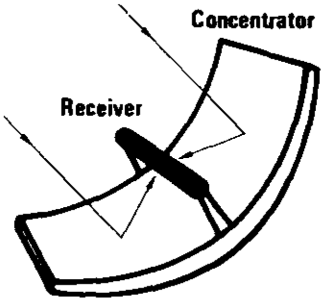
Russian Experimental Solar Power Plant (SPP-5)

The first Russian experimental solar power plant, SP-P5, is located near the settlement of Shchelkino on the Crimea (45 ° northern latitude) (see Figure 2-9). Project development and construction was undertaken following a 1978 decision of the Ministry for Power and Electrification of the former USSR. Plant construction was completed in 1986. The heliostat field (1600 heliostats of 25-m² reflective area each, arranged in 20 circular rows) surrounds the tower. Subsystem testing began in 1985. The plant was connected to the "Crimenergo" grid system in September 1985. The plant is still in operation, increasing its output each year. Some technical shortcomings were found during the testing phase and some improvements in design are needed to reach commercial operation criteria (Table 2-8).

Figure 2-9.
SPP-5, Shchelkino (Crimea), Ukraine
(Source: Sovelectro)

Table 2-8.
Design data for the SSP-5 plant

Heliostat field reflective surface area	40,000 m²
Receiver heat-transfer fluid	Steam
Receiver heat-transfer fluid temperature	250 °C
Storage medium Storage capacity (full power hours)	Water / steam not available
Electric output	5 MW_e



Parabolic Trough Systems

Most simple and mature among the solar thermal collector technologies are trough systems, which use parabolic reflectors in a trough configuration. Troughs concentrate the sun up to 80 times onto a fluid-filled receiver tube positioned along the line of focus in the trough. Heat can be produced efficiently up to 400 °C and is used as heat or to generate electricity. Troughs are modular, and many of them can be grouped together to produce more heat or power. Critical technology developed and applied to today's modern trough systems includes: reflective curved glass or reflective polymer films that cover the trough's primary collection surface; selective absorber coatings for receiver tubes that have a high absorptance for solar radiation but a low emittance for thermal radiation loss; and economical sun-seeking tracking sensors and controllers that use state-of-the-art optoelectronic devices and microelectronics. Industry is adopting and successfully implementing trough systems in the marketplace. More than 2 million square meter of parabolic trough collectors (approx. 350 MW_e) have been manufactured and are actually operated in California (USA).

The first solar thermal facility using line-focusing parabolic troughs to supply 35-kW shaft power to a heat engine was erected and successfully operated as early as 1913 in Egypt. However, the region's fledgling oil economy stopped further solar development efforts. Parabolic trough R&D activities started again in the mid-1970s, nearly simultaneously with central receiver development, in response to the sudden increase in world oil prices. In rapid succession, various R&D programs in the USA, Japan, and Europe were launched. These programs were financed by industry and governments in each country. Early demonstrations occurred in the USA for application to process heat in industry in the low- to medium-temperature range.

In late 1984, LUZ International Inc. began designing, building and operating the first commercial solar thermal power plant, the 13.8-MW_e SEGS I (Solar Electric Generating System) in California, USA. This was followed by construction of a series of improved, larger SEGS plants in California. One 13.8-MW_e, six 30-MW_e, and two 80-MW_e SEGS plants supply peaking power into the grid of the Southern California Edison utility resulting in 354 MW_e total electric capacity since 1991. Unfortunately, financial problems of LUZ stopped further development in 1991. The SEGS plants were designed, constructed, and operated by LUZ for third-party equity owners. Specific ownership structure varied from project to project, reflecting the tax provisions and the financial conditions at the time of construction. Equity owners were providing roughly half the capital with the remainder coming from various sources of nonrecourse debt. State and federal tax treatment changed considerably over the period of development, and, while the existing plants continue to be financially and technically successful, no additional plants were built in the USA because of short-term financial uncertainty caused by the delayed renewal of favorable tax provisions for solar systems. Other industries and entities are currently pursuing building new parabolic trough plants in the southwestern USA, in southern Europe, and in other parts of the world.

Progress in line-focusing collector technology for electric application is demonstrated in the following three examples:

- The 150-kW_e facility at Coolidge, Arizona, USA (1979), was the first solar thermal full-system experiment to demonstrate automated operation in an irrigation application environment.
- The 500-kW_e IEA-SSPS-DCS experimental plant in Almería, Spain (1981), was designed, built, and operated as a collaborative R&D project under the auspices of the IEA.
- The SEGS I-IX plants in California (1985-1990) with units up to 80 MW_e, were developed commercially by a group of American, Israeli, and German companies and marketed by LUZ International Inc.

Up to 25 % of the annual thermal energy supplied to the SEGS I-IX plants is by natural gas firing. This supplementary firing enables the plants to guarantee to deliver power consistently during peak electric demand periods.

The parabolic trough system is economic for peak power production under the favorable conditions in the southwestern USA. Like central receiver systems, parabolic trough systems need unit power sizes approaching 100 MW_e to be economical. High-efficiency collection of solar energy, comparable to central receiver systems, and large plant size make parabolic trough systems viable for utility-scale electric power generation at sites with favorable operating conditions (e.g., direct annual insolation of greater than approximately 1800 kWh/m^2).

The parabolic trough system concentrates sunlight using line-focusing parabolic collectors (troughs), which aim the radiation onto a straight tube acting as the receiver. The collector and the receiver form a geometrically stable unit. Many collectors are coupled to form straight parallel rows and are interconnected by piping. A field of collectors covers the ground like rows on a farm, which is why such plants are sometimes also called "farm systems."

The single plant typically comprises the following subsystems and components:

- Collector/absorber field
- Absorber tubes including vacuum insulation
- Heat-transfer system
- Thermal energy storage (optional)
- Supplementary fossil-fuel firing system (optional)
- Power conversion system (the electric power-generating system, comprising the steam generator and turbine-generator)
- Plant control, auxiliary power supply, and heat rejection.

Figure 2-10 illustrates (as an example) the flow diagram of the SEGS VIII-IX plants.

However, fossil-fuel heat-input became a key element in the SEGS plants operating in California to guarantee power generation and hence to maximize annual revenues and improve plant performance. The solar-only operation mode and solar-fossil hybrid operation mode are parts of the operational strategy determined by the local grid demand profiles.

For further improvements of the trough systems, direct water/steam generation in new advanced collector/receiver systems is being included in future R&D programs. If successful, this technology will be a "technological jump" for parabolic trough systems: higher plant efficiencies and improved cost/benefit ratios will be reached.

Some examples of existing parabolic trough systems are briefly presented below.

Figure 2-10.
Schematic of LUZ SEGS VIII-IX plants (Source: Flagsol)

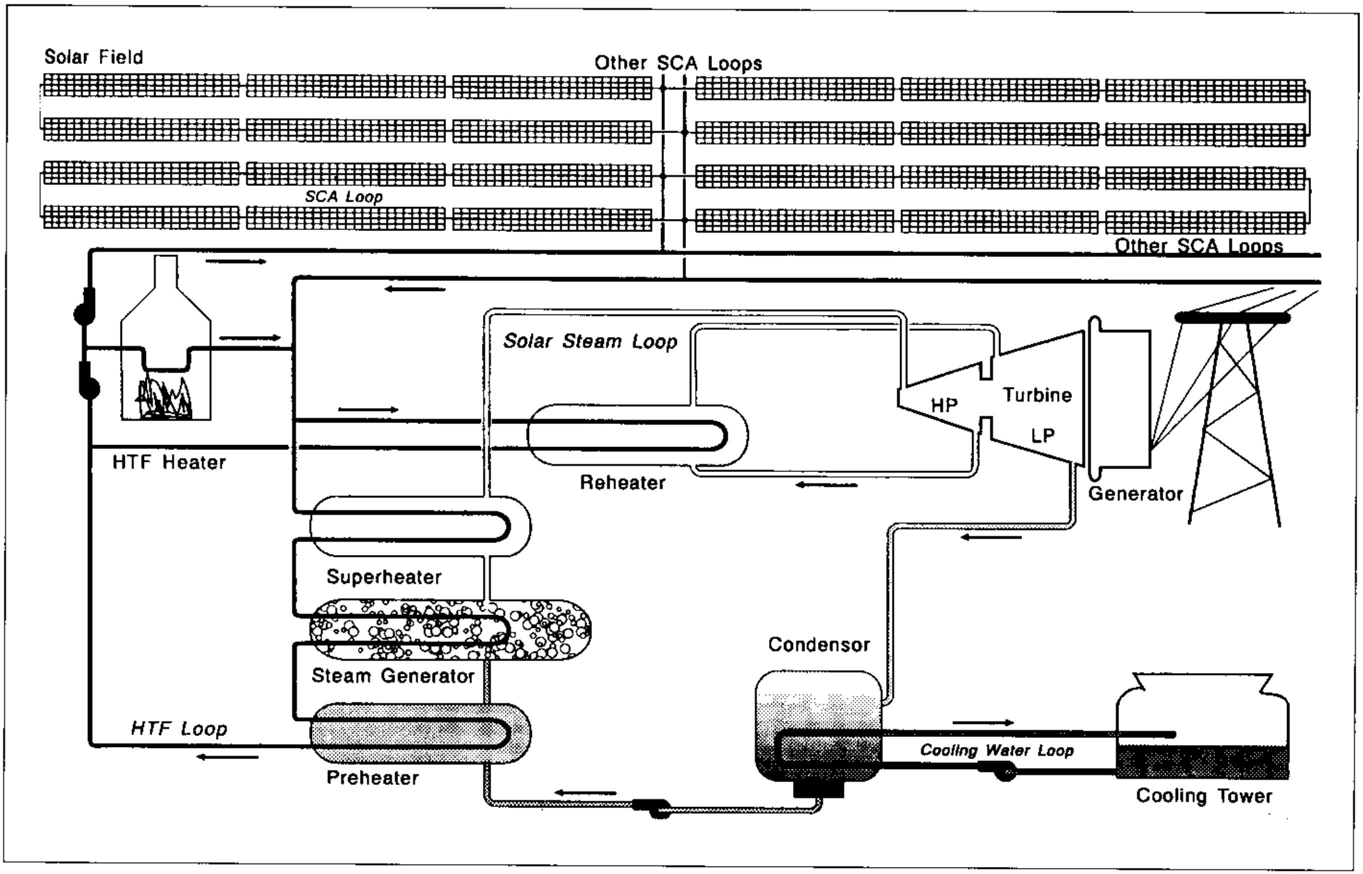


Figure 2-12.
Five 30-MW_e parabolic trough power plants, SEGS III-VII, at Kramer Junction in California, USA (Source: Flagsol)

SEGS Plants, California, USA

The LUZ SEGS plants were installed as nine separate plants totalling 354 MW_e of electrical capacity (Figures 2-12 and 2-13). Operation of SEGS I began in 1984, and that of SEGS IX began in 1990. The first plant has a power capacity of 13.8 MW_e and an energy storage of 119 MWh_t. The next six plants have a capacity of 30 MW_e each, and the last two plants have a capacity of 80 MW_e, but they are not equipped with energy storage. All plants are operated commercially in peak-load mode operation and supply energy to the Southern California Edison utility grid. The total collector reflective area for all nine plants is approximately 2.2 million m².

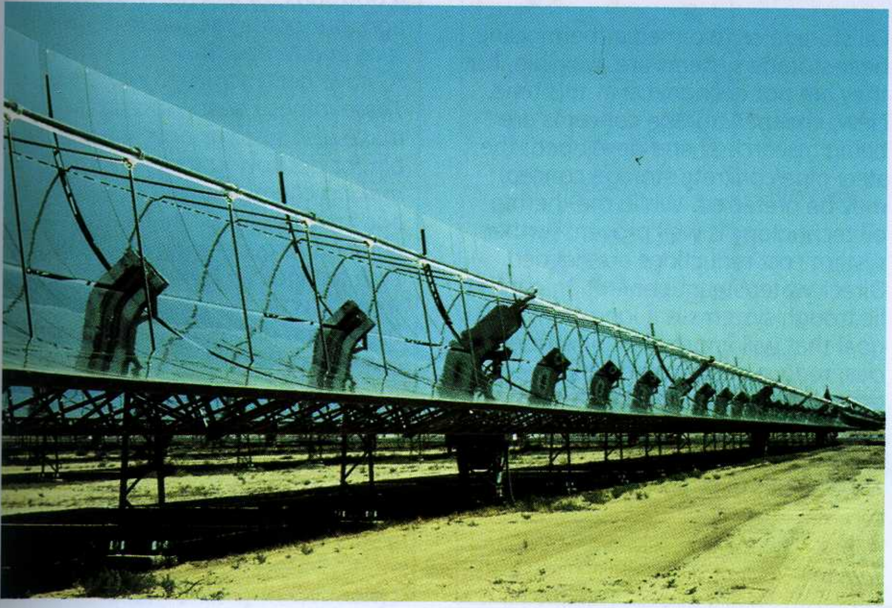


Figure 2-13.
First 80-MW_e parabolic trough power plant, SEGS VIII, at Harper Lake in California, USA (Source: Flagsol)

Currently, all parabolic trough systems use thermo-oil as a heat-transfer fluid. SEGS I uses mineral-oil-based thermo-oil (ESSO-500), limiting the receiver outlet temperature to approximately 310 °C. Since SEGS II, synthetic thermo-oil (Monsanto VP-1 or Dowtherm A) has been used that allowed the absorber outlet temperatures to be raised from 310 °C via 349 °C up to 393 °C (SEGS VI-IX), which allows generation of slightly superheated steam (100 bar, 371 °C). These higher temperatures also allow the use of modern single-reheat steam turbines of high efficiency (38.1% at design point). The SEGS plants were built in construction periods of 15 to 17 months (SEGS II-IV) and less than 1 year (SEGS VIII and IX). The locations in California are: Daggett (Barstow) for SEGS I and II, Kramer Junction for SEGS III-VII, and Harper Lake for SEGS VIII and IX. In 1991, the operation of the SEGS plants was taken over by different local operating companies.

2.1.1.2 Future Applications

Central Receiver Systems

Attempts are currently being made to commercialize the central receiver system, especially by U.S. companies and institutions for markets in the southwestern USA (e.g., the Solar Two project) and by European companies and institutions for export markets (e.g. the PHOEBUS project). A suitable demonstration project in the power range of at least 30 MW_e is considered to be the next step toward commercialization. However, the large capital investment required to develop the project has proven to be a hurdle.

Central receiver systems are economical in the 100-200 MW_e power range. The large plant size and high-efficiency collection of solar energy at high temperatures make these systems viable for utility-scale electric power generation at sites with favorable operating conditions (e.g., direct annual insolation of greater than 1800 kWh/m^2). Further technical development for fully commercialized plants may require some time and will depend on the success of demonstration plants.

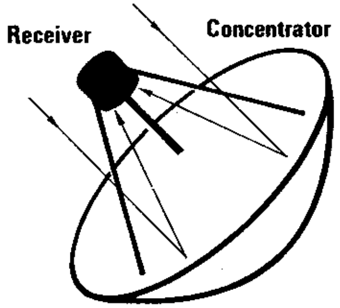
Different energy storage systems are available and experimentally proved: molten sodium or salt, ceramic bricks or ceramic spheres. Further system cost reductions are expected by low-cost molten salt storage systems and high-efficient ceramic spheres storage systems as well as by further R&D work with respect to use of phase change material or to thermo-chemical storage concepts.

A long-term R&D goal that will improve plant efficiencies and lower energy costs is to make use of the considerable potential of central receiver systems with respect to the upper process temperature lager than 500 °C, to the use of direct absorption receivers and of volumetric receivers as well as to combined gas/steam cycles.

Parabolic Trough Systems

Parabolic trough technology has reached economic competitiveness with conventional power plants in California under special financial conditions. Favorable economic situations in some countries will continue to encourage the use of this technology. Large-scale future applications depend on improvement of the technology with respect to more efficient cycles and the incorporation of a storage system to adapt the power generation to the load profile and to reduce the amount of supplementary fossil firing. The great success of the SEGS plants is a good starting point for further R&D to improve parabolic trough technology.

Oil storage or two-media thermocline heat-storage systems are available, but they are not economical at this time. New, cheaper storage concepts are being researched and developed; the steel pipe/concrete storage concept may be preferred. While the thermo-oil technology is well proven, further system cost reductions are needed. Direct water/steam generation parabolic trough systems is a long-term R&D goal that will improve plant efficiencies, reduce capital costs, and lower energy costs. This development could attract potential users in the fields of power generation and solar processing applications (e.g. process heat).



Dish systems use parabolic reflectors in the shape of a dish to focus the sun's rays onto a receiver mounted above the dish at its focal point. The solar energy heats a heat-transfer medium circulating through the receiver; the medium is pumped elsewhere for a variety of uses including electricity generation (the dish-central-engine concept), or a small engine/generator is mounted at the focal point of the dish (the dish-electric concept). Operating at up to about 800 °C, a single dish module may generate power in the kW_e-range, e.g. up to 50 kW_e using a Stirling engine-generator. Like trough systems, many dishes can be grouped together to produce more power. Dishes achieve the highest performance of all concentrator types in terms of annual system efficiency and peak solar concentration because they track the sun in two axes, keeping their aperture perpendicular to the sun at all times. Solar fluxes as high as 3,000 to 4,000 suns for electricity generation, but potentially up to 30,000 suns and temperatures up to 3000 °C have been achieved with dishes. These intense heat and solar fluxes make dish systems potentially suitable for destroying toxic wastes, making chemicals, producing fuels, and creating exotic materials in addition to generating electricity. Dish technology is not as mature as trough technology at the time being, and dish technology requires continued R&D on the concentrator, receiver, and conversion processes. The concept of stretched-membrane dish concentrators, currently being researched, holds great promise for reduced cost.

2.1.2 Distributed Power Generation

2.1.2.1 State of the Art

Parabolic dish collector systems (called "dish" systems) are the technology of choice for distributed electricity generation, i.e., remote power, off-grid power, village power supply.

A few concentrating parabolic collector systems were used in the USA in the 1800s for melting, calcining, and vitrifying metals. Among other applications in Europe, a dish system was presented by Augustin Mouchot with a steam engine to drive a printing press at the world exhibition in Paris in 1878. Most early dish systems were built to power steam engines, which could drive, for example, water pumps. These systems could not compete with much cheaper fossil-fired engines.

Since the beginning of the 1980s, efforts to develop dish systems have increased, in the USA, Europe and Australia, stimulated by the dramatic increase of world market prices for fuel oil. Various experimental parabolic dish systems have been designed, built, and tested as individual units or in a distributed field arrangement. These systems use diverse heat-transfer fluids, including organic fluids, water/steam, carbon dioxide, helium, and air.

In most dish systems the engine or turbine-generator is mounted on the dish and follows the dish movements. Solar energy may also be collected from a number of dishes working in parallel and piped to a central engine (e.g. water/steam turbine-generator). The single dish system may be small (e.g. 5 to 50 kW$_e$ with a 7-m to 17-m aperture diameter using a Stirling engine-generator), but a number of units may be arranged in field arrays up to the MWe range, and the electric power collected by cabling. The total output can easily be adapted to the demands of the utility because of the modularity of the dish field. Alternative power conversion systems are based on the steam Rankine cycle, the organic Rankine cycle, and the Brayton cycle engine. Systems using the dish-mounted Stirling engine-generator are being developed intensively, especially in the USA and Europe (mainly in Germany).

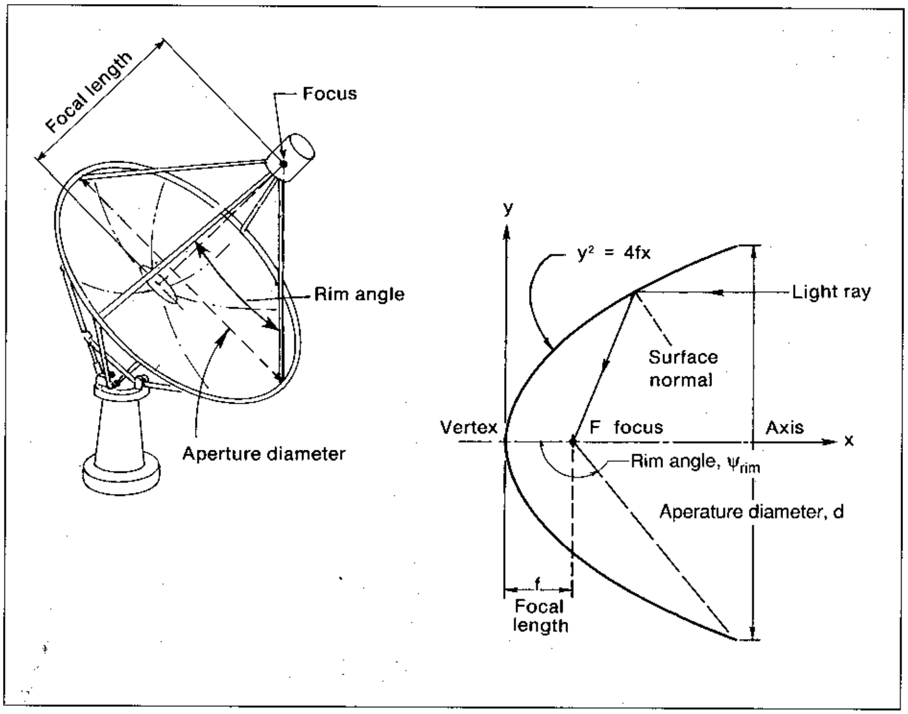
Demonstration plants with suitable modern and lowcost dish systems are the next step toward commercialization.
In Australia, a dish pilot facility (14 smaller dishes linked together) using a 25-kW$_e$ water/steam engine-generator was built and tested (White Cliffs Project). A 4-MW$_e$ dish pilot power plant is planned using a cluster of big dishes for the power supply in co-generation with an existing gas fired power station (Tennant Creek Solar Thermal Power Station). The dish units generate water/steam, which is ducted to a central steam engine- or turbine-generator. Plant concepts of 200 kW$_e$ (4 dishes, 1 steam engine-generator) and up to 100 MW$_e$ (792 dishes, 1 steam turbine-generator) have been investigated by the National University of Australia in Canberra. A 400 m^2 "Big Dish" has been built in Canberra and will be tested using a water/steam receiver for approximately 50 kW$_e$ output.

Because they are modular, respond quickly to changes in solar radiation, are easy to operate, and capable of high temperatures, the dish system is well suited for use in distributed energy systems. The excellent operational characteristics and flexible adaptability to site and grid requirements make the dish system a viable potential solar facility for commercial users at sites with an annual direct insolation even less than 1800 kWh/m^2. The reason is that the dish tracks on two axes, so the sun is always perpendicular to the aperture plane of the dish, ensuring maximum solar energy collection throughout the day. The dish system comprises the following main subsystems:

- Parabolic collector
- Receiver
- Supplementary fossil-fuel firing (optional)
- Engine/alternator (power conversion system)
- Tracking and control
- Auxiliary power supply, heat rejection.

Figure 2-14 illustrates the principle of the parabolic dish system. With the receiver/engine always fixed at the focal region, the system can be compared to a radio antenna tracking a satellite. Figure 2-15 shows various dish applications.

Figure 2-14. Principle of the parabolic dish system (Source: NREL)



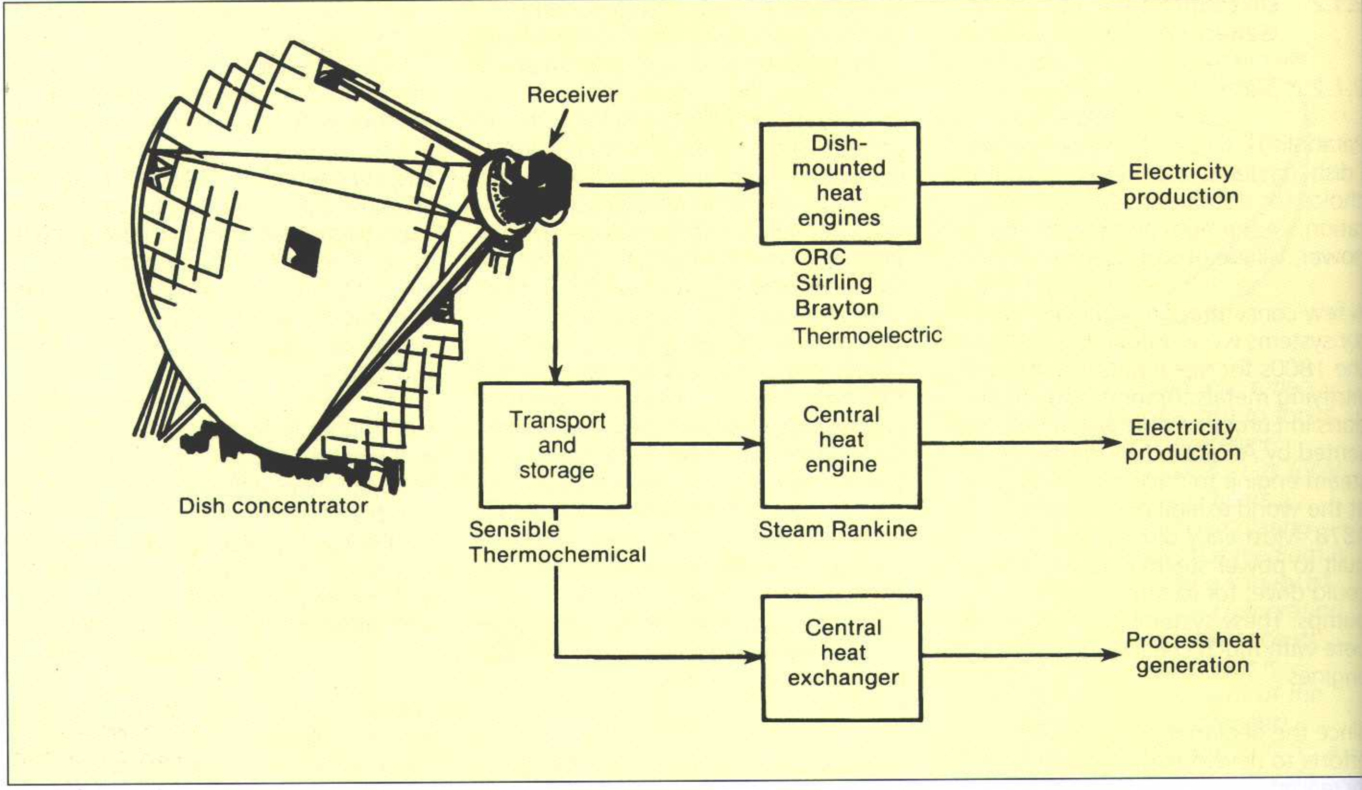


Figure 2-15. Schematic of different dish applications (Source: NREL)

The power output of a single dish unit using Stirling engines is typically in the range of 5-50 kW_e. The geometric concentration ratios (i.e., the ratio of solar collector area to heat absorber area) range from approximately 300 to 3000. Larger capacities up to the MWe range have been operated using a cluster of single dish units working in parallel and delivering their thermal

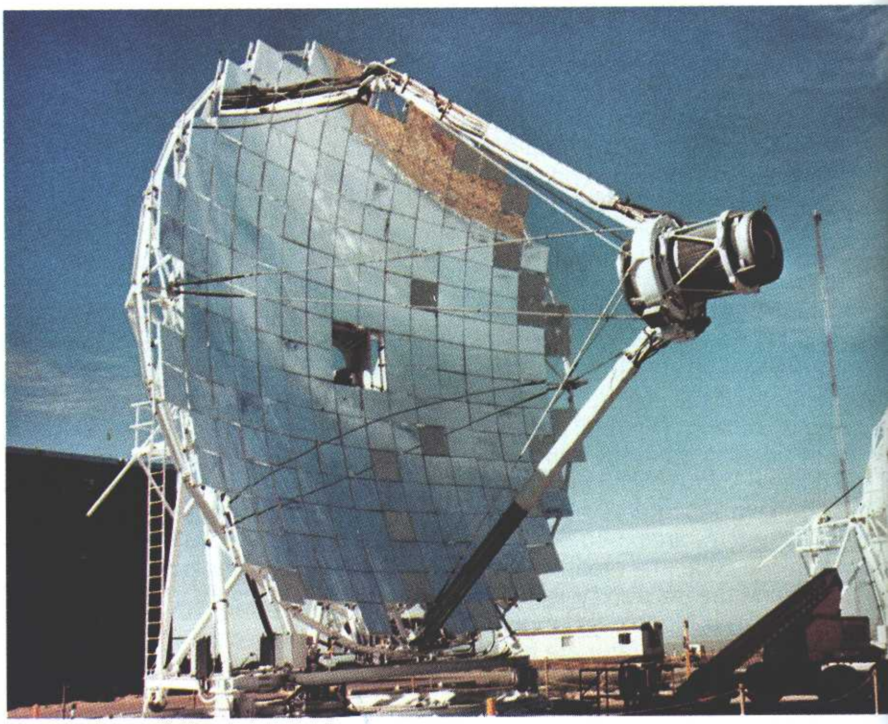
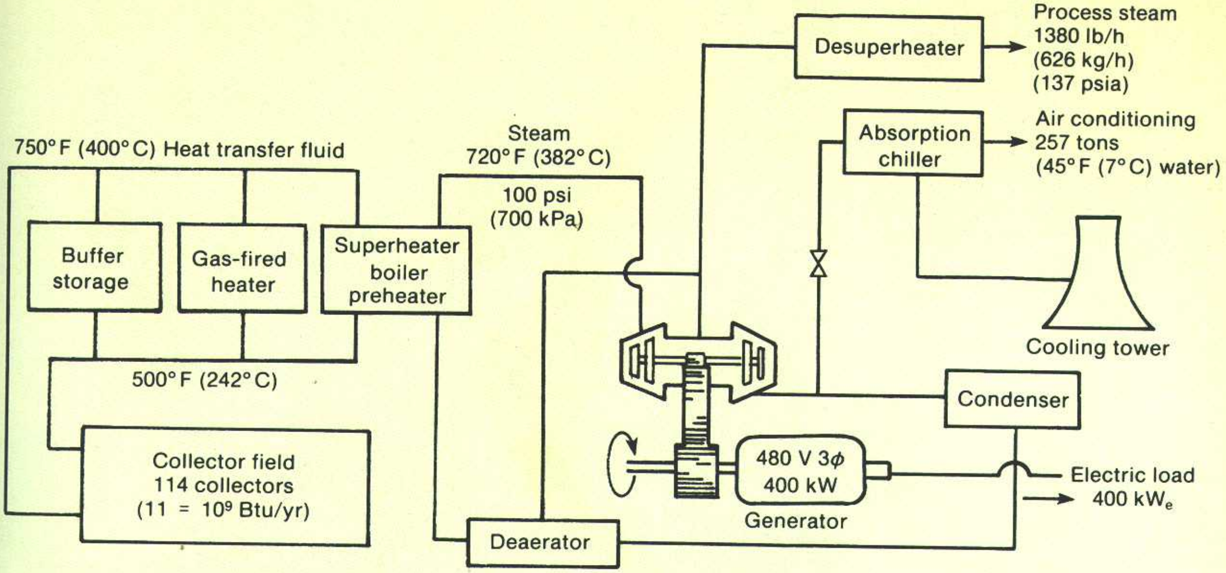


Figure 2-16. Test-bed concentrator (11-m diameter) designed for Jet Propulsion Laboratory shown testing an organic Rankine cycle engine (Source: SNL)

output to a central water/steam Rankine cycle (steam turbine generator). A fossil-fuel-fired back-up system may be used with a small gas turbine-generator (Brayton cycle or Stirling cycle generator set). Weight and dimension constraints restrict the use of a thermal storage system; therefore dish systems are foreseen mainly for peak-power generation in the solar-following mode. Supplementary fossil-fuel firing is a potential option for dish systems, too.

Figures 2-16 through 2-24 show examples of experimental dish facilities.

Figure 2-17. Solar Kinetics dish systems for Georgia Power Total Energy System in Shenandoah, GA, 400 kW$_e$ and 1065 kW$_t$ (Source: NREL)



2.1.2.2 Future Applications

Future parabolic dish systems are expected to favor the Stirling engine-generator as the power conversion system. The modularity and favorable operational characteristics of dish/Stirling systems will help penetrate the future market. Design and size requirements for the engine are similar to those for the automotive industry. A major difference is that the service life required for solar applications is more than ten times that for automotive applications. Demonstration of the Stirling engine's high reliability for solar systems is a prerequisite for future applications.

Improved receivers as well as low-weight and more effective reflective materials (stretched-membrane technology) will be used in future applications. Hybrid operation using fossil fuel as a back-up heat source is under development (SBP, CPG, USAB) and will significantly broaden the market for this technology. Higher process temperatures will improve the engine's efficiency, as has been demonstrated by the USAB 4-275 Stirling engine mounted on the 17-m SBP dish in Saudi Arabia (η peak = 45%) and by the Advanco and MDAC 4-95 Stirling dish (η peak = 42%). SBP is currently testing three dish systems using 9 kW_e SPS/SOLO V-160 engines on the Plataforma Solar de Almería with great success; goal is the demonstration of reliability with view to commercialization (see Figure 2-24).

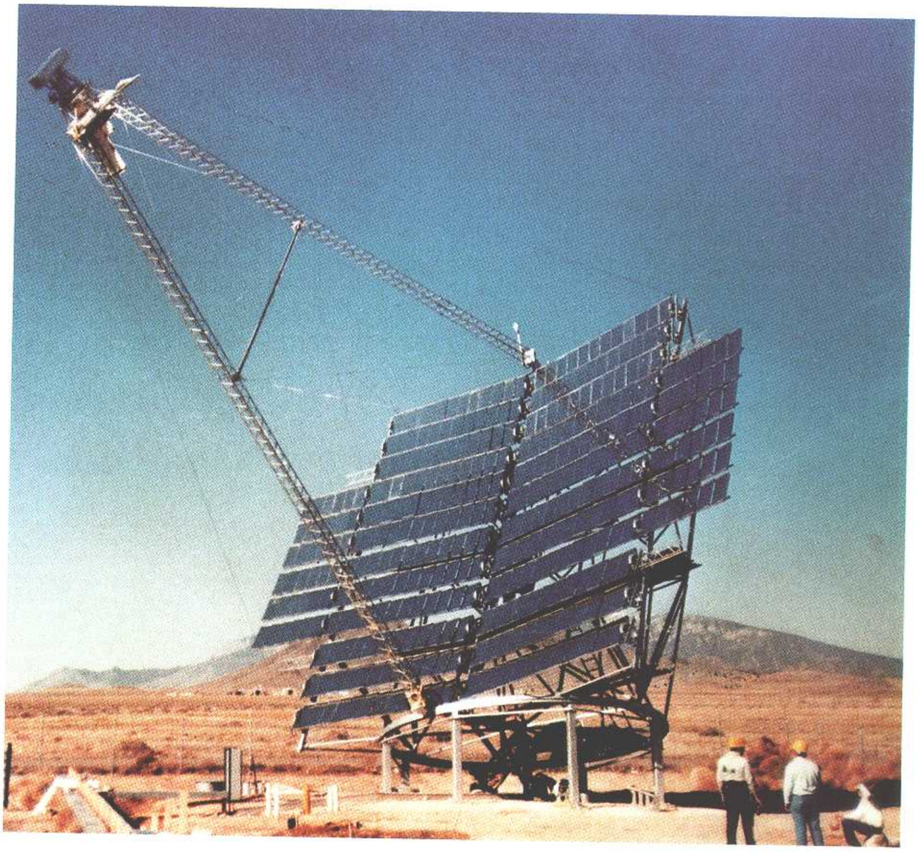


Figure 2-20. Power Kinetics, Inc. development concentrator (13.2-m diameter) powering the Barber-Nichols organic Rankine cycle engine (Source: SNL)

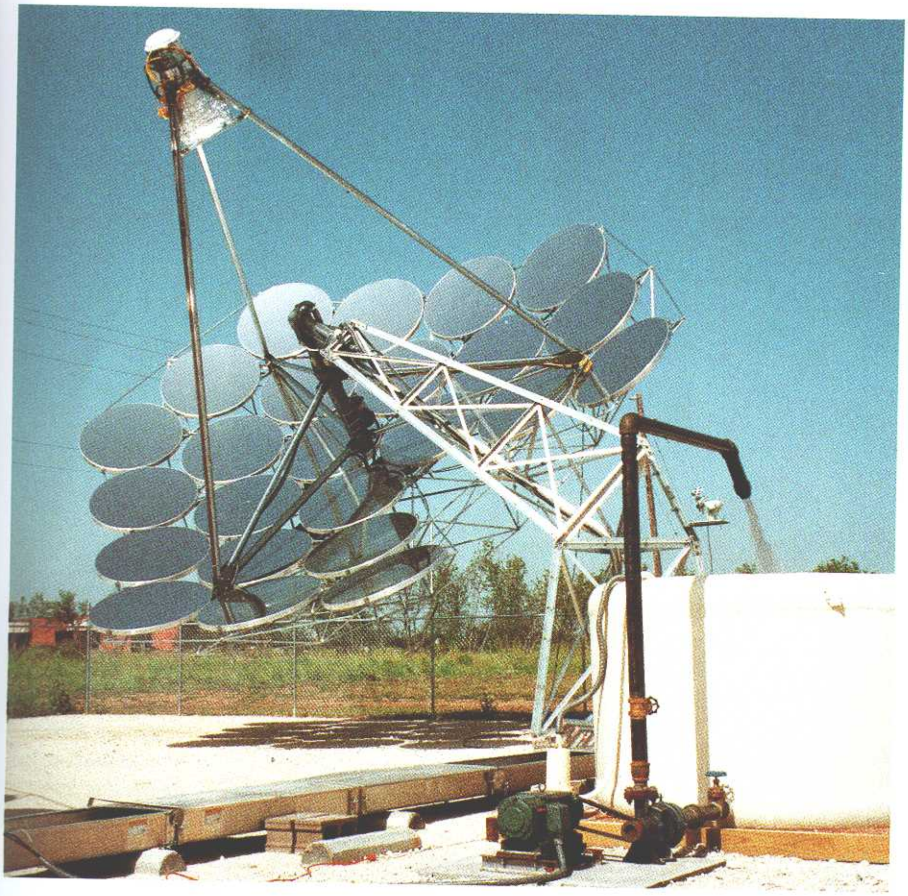


Figure 2-21. Cummins Power Generation, Inc. 5-kW_e prototype dish/Stirling system (Source: CPG)

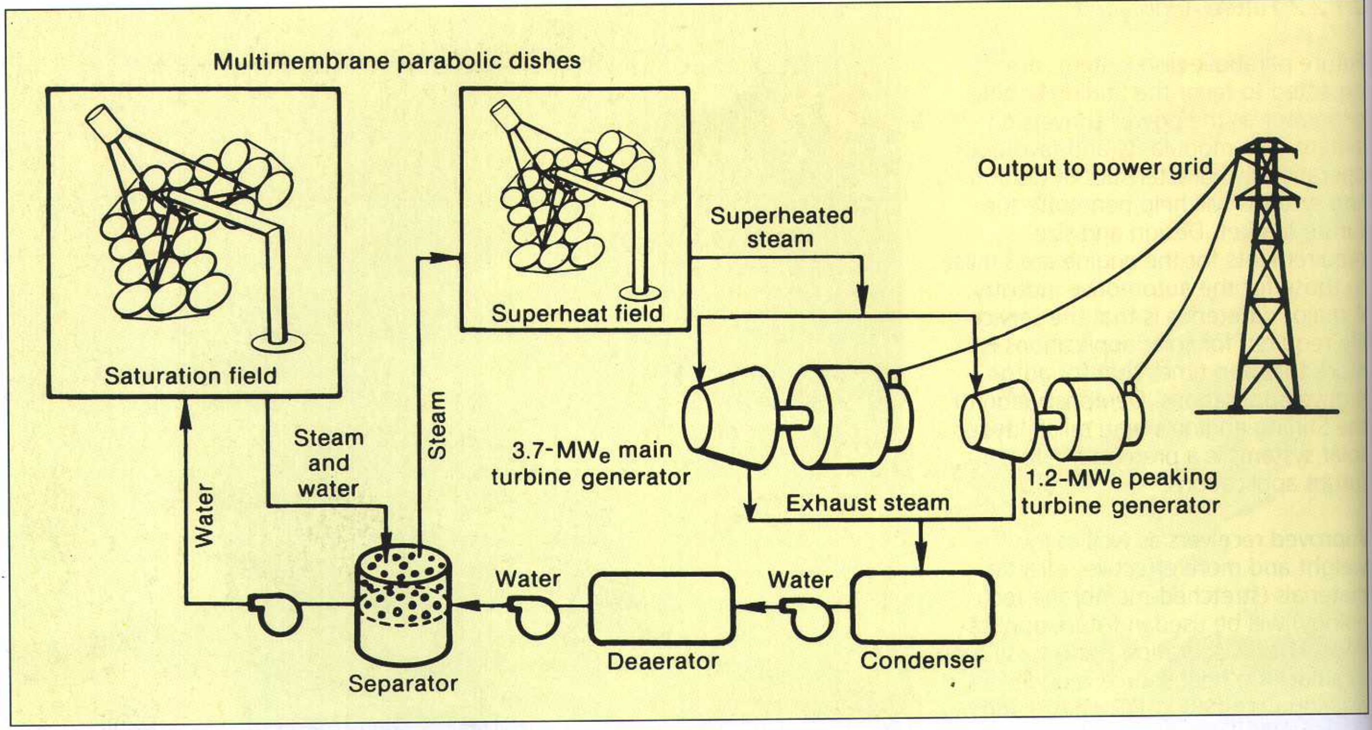


Figure 2-22. Solar One plant at Warner Springs, California, with total power of 4.9 MW$_e$ using 700 LaJet model LEC 460 multifaceted, stretched-membrane dish collectors (9.5-m diameter) (Source: NREL)

2.1.3 Application Studies

Several studies on potential applications of solar energy systems for electricity generation have been completed. The objectives of these studies are:

- To investigate systems from a technical and economic viewpoint in order to compare and prefer the most favorable system and to assess potential applications and markets.
- To demonstrate the feasibility and commercial benefit of constructing solar plants.

Technical specifications and predicted energy cost (levelized cost of generated electricity, LEC) are the two primary considerations.

In the following sections, important actual studies are described briefly. Figure 2-25 summarizes the energy cost (for both central and distributed power generation) of solar thermal power plants as estimated by several studies.

For reference, Figure 2-26 presents the energy cost of advanced central receiver power plants (second generation) and trough plants compared with that of fossil-fuel-powered plants in the 100-200-MW_e size range. The plants listed have annual capacity factors in the range of 25 % up to 63 %. Costs include parameters that are typical for investor-owned utilities in the USA, excluding inflation. The dotted line indicates the generating costs, if tax benefits expected in the USA and if environmental ("external") costs for emissions of fossil firing are incorporated. The addition of external costs for the emissions of fossil firing has been mandated by Nevada law and is being discussed by regulators within several other U.S. states. Clearly, inclusion of the environmental costs will help solar thermal electric plants to compete with the fossil-fuel alternatives.

Analysis and feasibility studies of solar thermal plants show that:

- The technologies needed to demonstrate commercial viability are ready today or will be ready in the near term.
- All technologies have remarkable development and market potential in the medium and long term.

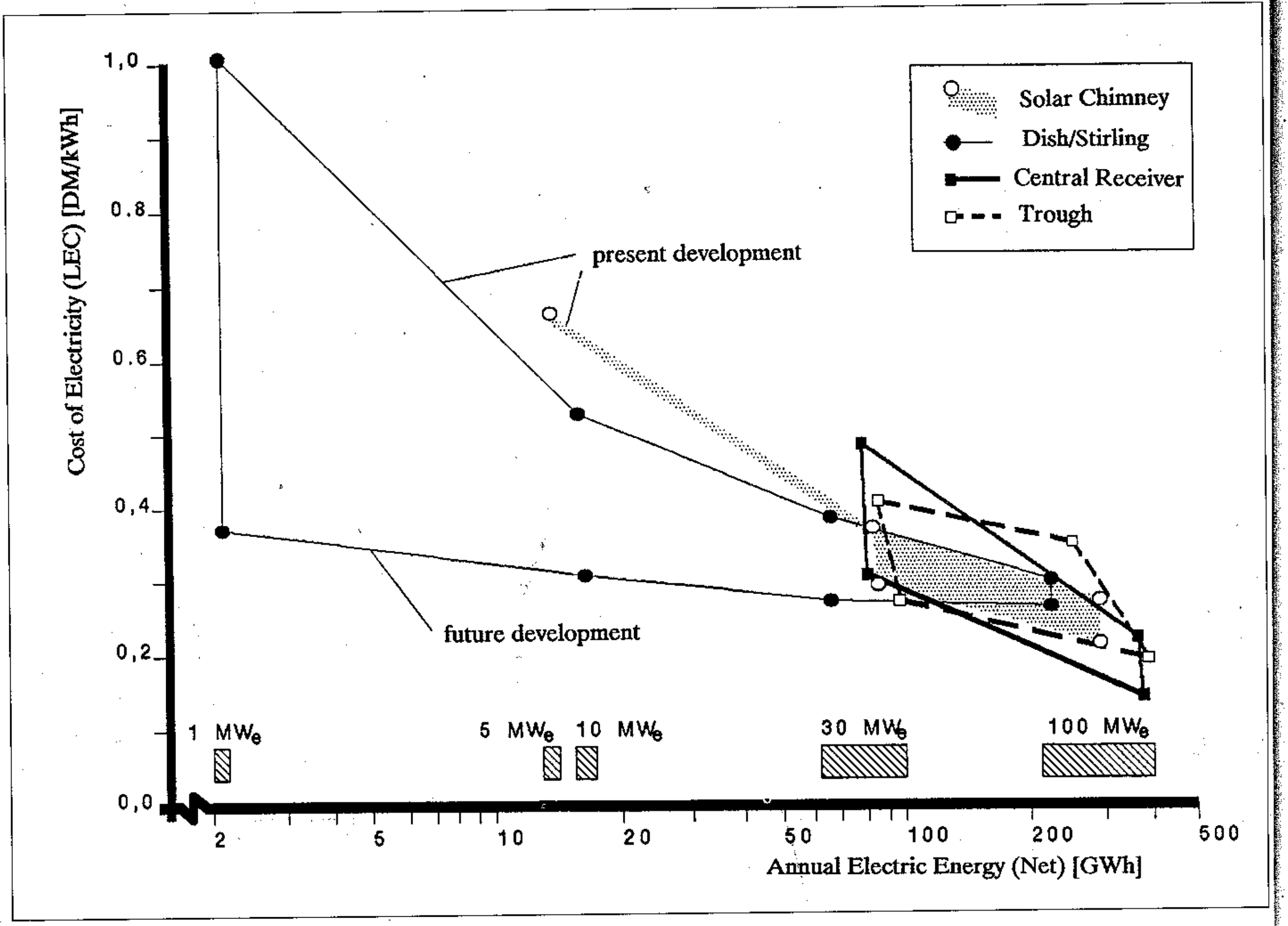


Figure 2-25. Energy cost of solar thermal technologies for electricity generation (solar-only mode, Barstow annual insolation 2850 kWh/m², 7% interest rate, 20 years depreciation, 1989 DM) (Source: DLR)

Strong R&D and financial efforts are needed to reach the demonstration and commercialization phase as soon as possible.

- The market potential for solar electric is highest in areas with high annual insolation (greater 1800 kWh/m^2).
- For *central* power stations of 100-200-MW_e:
  - Parabolic trough systems have a considerable mid-term potential for further development (direct steam generation) and further energy cost reductions to reach soon competitiveness.
  - Central receiver systems have the long-term potential to generate electricity at energy costs less than 10¢/kWh (1990 dollars) respectively less than 0.20 DM/kWh. Development towards mixed gas/steam cycles and towards direct absorption receiver systems may furthermore improve the competiveness.
- For *decentralized* power stations of small unit sizes (kW_e to MW_e range):
  - Parabolic dishes using a Stirling engine have the mid-term potential to cover the small power demands of remote villages or industries in countries with less than 40 ° northern/southern latitude.
  - Larger parabolic dish fields have the potential in the long term to possibly reach the energy cost regime of parabolic trough and central receiver plants. Energy costs of plants using this technology may be in the range of 18-25¢/kWh.

The studies identify the needed steps in the development of different solar technologies. Because these developments cannot yet be financed solely from potential profits on new technologies in the solar industry, the necessary R&D work and the introduction of mature solar technologies will require heavy support of governmental financing.

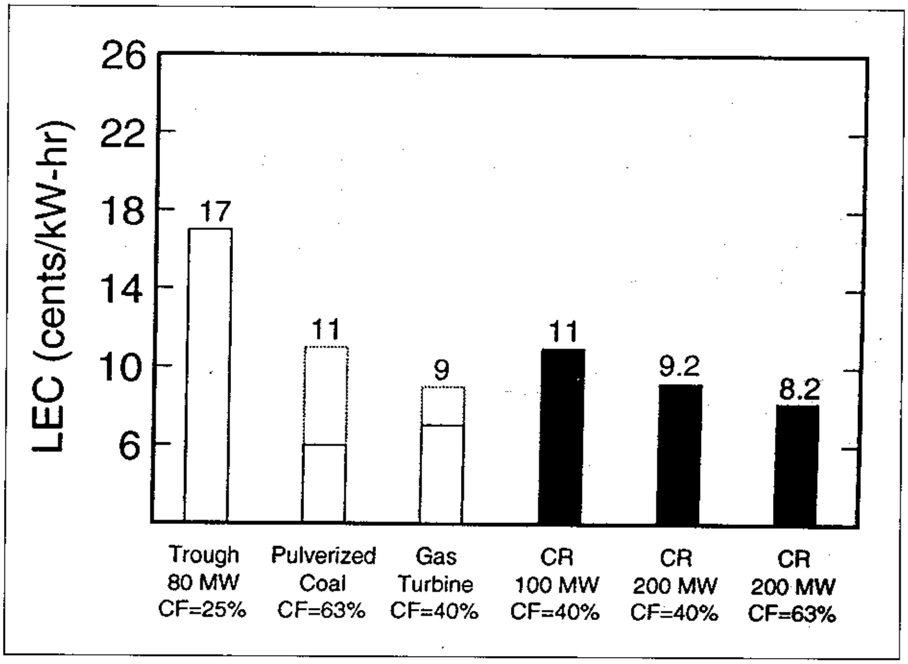


Figure 2-26. Energy cost prediction of solar thermal electric vs. fossil-fired alternatives (constant $, 7% interest rate, Barstow annual insolation 2850 kWh/m^2, 1990 $) (Source: SNL)

2.1.3.1 Technical and Economic Studies

Pacific Northwest Laboratory Study

A large number of alternative solar thermal concepts for generating electricity have been proposed. Pacific Northwest Laboratory (PNL) performed a study to provide a relative comparison of the thermodynamic and economic performance of several of the concepts that have been studied and developed in the U.S. Department of Energy (DOE) Solar Thermal Technology Program. The study was published in 1987. The projections in this study are for the late 1990s, based on the expected capabilities of improved technologies.

The following central receiver, dish, and trough concepts were compared:

- Molten salt cavity central receiver with salt storage
- Sodium external central receiver with sodium storage
- Sodium external central receiver with salt storage
- Water/steam external central receiver with oil/rock storage
- Parabolic dish with Stirling engine conversion
- Parabolic trough with oil/rock storage.

Annual plant energy output (1986 climate data for Barstow, California) and levelized energy cost were determined using the PNL code SOLSTEP. The levelized energy cost for the best solar thermal systems analyzed in this study ranged from 6 to 7¢/kWh (1984 dollars), which shows that the technology has considerable promise as an economical source of electricity. The lowest energy costs for the dish and central receiver systems ranged from 6 to 7¢/kWh for the 100-MW_e plant size. The lowest levelized energy cost for the trough system was much higher than that for the other technologies and occurred at the 30-MW_e plant size. Within the ground rules of this study, all of the central receiver systems and the dish systems analyzed show potential as economically competitive electricity-producing technologies.

Solar Energy Research Institute (SERI) Study

As part of the DOE Solar Thermal Technology Program, SERI (today: NREL) examined the technical and economic potential of high-temperature central receiver systems for electricity production. The study was published in 1988. High-temperature (1000-1400 °C) central receivers were chosen for study because significantly higher engine efficiencies result from operation at high temperatures, and near-term advancements in engine technology promise to raise these efficiencies even more. Innovative solar thermal receiver and heat exchanger designs are required to achieve these high temperatures. New receiver technologies may also be valuable in other applications that require high concentrations or high temperatures, such as direct chemical conversion.

The study examined three main designs and several permutations of the air heating systems:

- High-temperature direct absorption central receiver
- Particle injection central receiver
- Volumetric central receiver.

Each of these systems was coupled with an intercooled steam-injected gas turbine mounted on a tower. Study results indicated that advanced high-temperature central receiver systems have the potential to meet the Solar Thermal Technology Program's long-term cost goal for electricity production (5¢/kWh).

Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) Study

This study was performed under the direction of DLR-Köln by INTERATOM, Flagsol, SBP and DLR to compare the technical and economical performance of the currently available solar thermal plant technologies for electricity production. The study was published in 1992. Besides several technical considerations, levelized energy cost was the key comparison factor. The economic analysis was based on the climate data for Barstow, California, with annual insolation of 2850 kWh/m^2.

The following four systems (including hybrid permutations for the central receiver and trough systems) were compared:

- Central receiver (PHOEBUS volumetric air receiver, U.S. Utility molten-salt receiver, and the Solar One water-steam receiver) with storage (500-800 °C, 30-100 MW_e)
- Parabolic trough with oil (LUZ SEGS LS-3 collector) and direct water/steam generation (LUZ SEGS LS-4 collector) with and without storage (400 °C, 30-100 MW_e)

- Parabolic dish with Stirling engine of SBP (700 °C, dish cluster 1-100 MW_e)

- Solar chimney of SBP (5-100 MW_e).

The results indicated that, under the assumptions of the study, most of the investigated technologies have the potential to reduce in the mid term the levelized energy costs (LEC) below 0.30 DM/kWh (1989 dollars, exchange rate 1.7 DM/$). Levelized energy costs below 0.20 DM/kWh are possible for future large commercialized parabolic trough and central receiver plants (Figure 2-25; Table 2-9).

Sandia National Laboratories (SNL)/ Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) Study

SNL and DLR performed a study of second-generation central receiver systems. The study was published in 1993. This study was an international team effort, codirected by SNL and DLR, under the IEA SolarPACES Project. Central receiver technologies relating to existing systems were quantified, logical next-step systems were characterized, and future potential advances were identified. The advanced 30 and 100 MW_e central receiver concepts investigated included:

- Molten salt central receiver systems (U.S. types):
  - Salt-in-tube receiver
  - Molten salt film receiver

- Volumetric air central receiver systems (European variations of the PHOEBUS type).

The study also used data from the U.S. utility study and the PHOEBUS feasibility study, but focused on more advanced receiver technologies and on cost reductions resulting from competitive bidding in order to show the potential for reduced levelized energy costs (Table 2-10).

The results indicated that increased scale and improved technologies in central receiver systems will result in lower costs of energy, which tend to be more favorable than those for trough systems. The results showed that future 100-MW_e commercialized central receiver systems can potentially

Facility Status	Central Receiver	Parabolic Trough	Dish/ Stirling	Solar Chimney
Present				
30 MW	0.49*	0.41 +	0.38*	0.38*
100 MW	0.22*	0.35 +	0.30*	0.27*
Future				
30 MW	0.31**	0.27**	0.28 ++	0.29 ++
100 MW	0.14**	0.19**	0.26 ++	0.22 ++

\+ Present status, 5th facility
* Present development, 1st facility
++ Future development, nth facility
** Future development, 5th facility

Table 2-9. Summary of electric energy cost in DM/kWh of 30-100 MW_e solar thermal technologies; solar-only operation, Barstow annual insolation 2850 kWh/m^2, 1989 DM (Source: DLR)

2nd Generation CR Technology	Cap. Cost[1] ($ M)	Ann. Cap. Cost ($ M)	Ann. 0 & M Cost ($ M)	Total Ann. Cost ($ M)	Plant Availability (%)	Ann. Electr. Energy[2] (GWh$_e$)	Capacity Factor[2] (%)	LEC (¢/kWh$_e$)
* 30-MW$_e$ SIT, Solar-Only SM = 1.4 4.5 h-Stor.	95.3 (77.6)	10.0	2.6	12.6	91.0	81.7	31.1	15.4
* 30-MW$_e$ SIT, Hybrid (25%) SM = 1.4 4.5 h-Stor.	99.5 (81.0)	10.4	3.5	13.9	91.0	109.0	41.5	12.8
* 30-MW$_e$ Air, Solar-Only SM = 1.2 3 h-Stor.	99.4 (81.0)	10.4	2.5	12.9	91.5	78.9	30.0	16.4
* 30-MW$_e$ Air, Hybrid (25%) SM = 1.2 3 h-Stor.	101.3 (82.6)	10.6	3.2	13.9	91.5	105.2	40.1	13.2
* 100-MW$_e$ SIT, Solar-Only SM = 1.6 7 h-Stor.	227.7 (182.7)	23.9	4.5	28.5	91.0	336.3	38.4	8.5
* 100-MW$_e$ DAR, Solar-Only Mod. Field SM = 1.5 6 h-Stor.	211.9 (169.9)	22.2	4.3	26.5	91.5	340.4	38.9	7.8
* 100-MW$_e$ DAR, Solar-Only SIT-Field SM = 1.5 6 h-Stor.	222.3 (178.3)	23.3	4.4	27.7	91.5	369.9	42.2	7.5
* 100-MW$_e$ Air, Solar-Only SM = 1.8 8 h-Stor.	272.7 (218.7)	28.6	4.4	33.0	91.5	335.6	38.3	9.8

[1] In brackets: direct capital cost
[2] Includes plant availability

Table 2-10. Summary of cost estimates and LEC calculations using cost data in 1990 $ (Source: DLR/SNL)

reach levelized energy costs less than 10 ¢/ kWh (1990 dollars) respectively less than 0.20 DM/ kWh in the solar-only mode under favorable boundary conditions (e.g. high annual insolation greater 2500 kWh/m^2, good infrastructure). Considering external costs, solar thermal plants become even more competitive with fossil fuel plants (Figure 2-26). It is expected that this second generation represents a significant step toward commercialization of central receiver systems.

2.1.3.2 Feasibility and Commercialization Studies

U.S. Utility Studies

Two U.S. utility teams, Pacific Gas and Electric (PG&E) and Arizona Public Service (APS), conducted a cooperative study cofunded by DOE, the Electric Power Research Institute (EPRI), and the utilities. The studies were published in 1987/1989. The teams assessed the feasibility of commercial central receiver systems for gridconnected electricity generation in the southwestern USA. Two plants were investigated: a 100-MW$_e$ first commercial plant and a 200-MW$_e$ commercial plant representing the fifth through tenth plant built, i.e. mature technology.

In Phase I, each utility team performed trade studies and compared conceptual designs under a common set of guidelines to determine the most appropriate central receiver technology for utility application using projected utility power values and commercial operational boundary conditions in the 1985 climate of Barstow, California. In Phase II, the teams developed a recommended strategy to bring the selected technology to commercial readiness, including the possible need for component and system tests.

Important design features of the near-term commercial plants investigated include:

- 150-m^2 stretched-membrane heliostats (75-100 $/m^2)
- Surround heliostat field layout
- External cylindrical receiver configuration with salt-in-tubes absorber
- Molten nitrate salt (60% NaNO$_3$, 40% KNO$_3$ heat-transfer and storage fluid)
- Six hours of rated output from thermal storage
- Innovative dry-heat rejection design.

Cost and performance data for the two plants were optimized for utility financing and assumed Barstow (California) site parameters. Annual net electric output was calculated using a detailed annual simulation of plant operation, including scheduled and forced outages, start-up and steady-state losses, and overnight losses. Assuming that both plants have a capacity of 38%, are operated in solar-only mode, and are cooled by dry-heat rejection systems, the levelized energy cost was estimated at 11¢/kWh (1987 dollars) for the 100-MW$_e$ plant and 8¢/kWh for the 200-MW$_e$ plant.

PHOEBUS Feasibility Study

Starting in 1986, a group of European companies took up an initiative of the Swiss SOTEL group and the German DLR research establishment to commercialize the volumetric air receiver technology. These companies established the PHOEBUS Group, with the intention of undertaking all activities required for the detailed design, construction, commissioning, operation, and financing of a 30-MW_e power plant. In 1988, an international consortium of 19 German, Swiss, Spanish, and U.S. companies, called PHOEBUS, was formed under the leadership of Fichtner Development Engineering (FDE) for the purpose of continuing the work to commercialize solar thermal central receiver (tower) technology by designing, constructing, and operating a 30-MW_e volumetric air receiver power plant.

In the first phase of the feasibility study, several designs and receiver heat-transfer fluids for a 30-MW_e plant were evaluated. The volumetric air receiver concept was found to offer the best opportunity for commercial application in the envisaged host countries. Researchers designed the plant to include a ceramic checker storage system with 3 hours full-load capacity. A project siting analysis of 58 countries (funded by the German Ministry of Research and Technology (BMFT)) led to the selection of Jordan as the host country. In the final phase of the study, the technical, financial, and organizational basis for the PHOEBUS project was established.
The study was documented by Fichtner Development Engineering (FDE) in Stuttgart (Germany) in 1990.

The plan for financing this first-of-a-kind solar tower plant in Jordan was based on a combination of grants, development loans, and partner equities. The 30 year financial analysis of the plant cash flows predicts a required power sales price of 0.112 DM/kWh (6.6 ¢/kWh levelized energy cost, in 1989 prices) over the life of the plant (30 years). Negotiations with the Jordan Electricity Authority regarding the actual terms of a power purchase agreement were planned to take place during the project development phase. Unfortunately, the project was stopped because of the Gulf War in 1991.

In the meantime, R&D work took place concerning the PHOEBUS volumetric air system (TSA technology program, compare chapter 3.1.2). A review of the PHOEBUS feasibility study has been performed by the TSA consortium (FDE, LCS, DIDIER) in 1994, in order to define a data base for new acquisition efforts with a view to the erection of a first 30-MW_e demonstration plant. Various modified 30-MW_e PHOEBUS concepts were investigated with respect to reduce the capital investment costs. The favorite concept for market introduction uses a solar/fossil hybrid mode; an energy storage is not incorporated. The compact integrated system is placed on a tower platform, with exception of the steam turbine-generator being mounted on ground level. Low-cost 150-m^2 stretched metal membrane heliostats are arranged in a surrounding circular field irradiating a volumetric air receiver of circular cross sections. Energy costs of less than 0.20 DM/kWh (12 ¢/kWh) result potentially from the economic evaluation depending on the solar/fossil share and under the study boundary conditions (1985 Barstow insolation).
Further R&D efforts will concentrate on minor technical improvements and optimization, mainly concerning the control, the operational behavior and the energy storage, and on a low-cost stretched metal membrane heliostat.

DLR/INTERATOM/SBP/ZSW Mediterranean Study

A German study group of DLR, INTERATOM, SBP and ZSW investigated the potential of solar thermal technologies to penetrate the power-generating market in Mediterranean countries in both the mid term (approximately until the year 2005) and the long term (approximately until the year 2025). The study was published in 1992.
A large amount of basic data from 19 countries was evaluated to quantify and classify the different national market characteristics. The results showed that:

- There is an extraordinarily large market potential for solar thermal power generation, both central and distributed.
- Levelized energy costs below 20¢/kWh in the mid term and below 15¢/kWh in the long term may be reached (Figure 2-27).
- Dish/Stirling systems open the market for decentralized power stations.

If development efforts in Europe are increased, a total capacity of approximately 13,500 MW_e in the mid term and 63,000 MW_e in the long term could be potentially built up. This would require a total capital investment of 15-60 billion DM until the year 2005 and 90-220 billion DM in the period 2005 to 2025. This level of development would contribute greatly to the reduction of CO_2 emissions in countries using solar thermal technologies.

Actual feasibility studies are under preparation by international teams regarding commercial parabolic trough power plants on the basis of the LUZ technology for potential sites, e.g. in Morocco and South of Spain (including the Canary Islands).
Additionally, studies are currently carried out investigating conventional power plant concepts using thermal energy supplied by a parabolic trough or central receiver system (advanced hybrid plant concepts) for sites in the South of Europe.

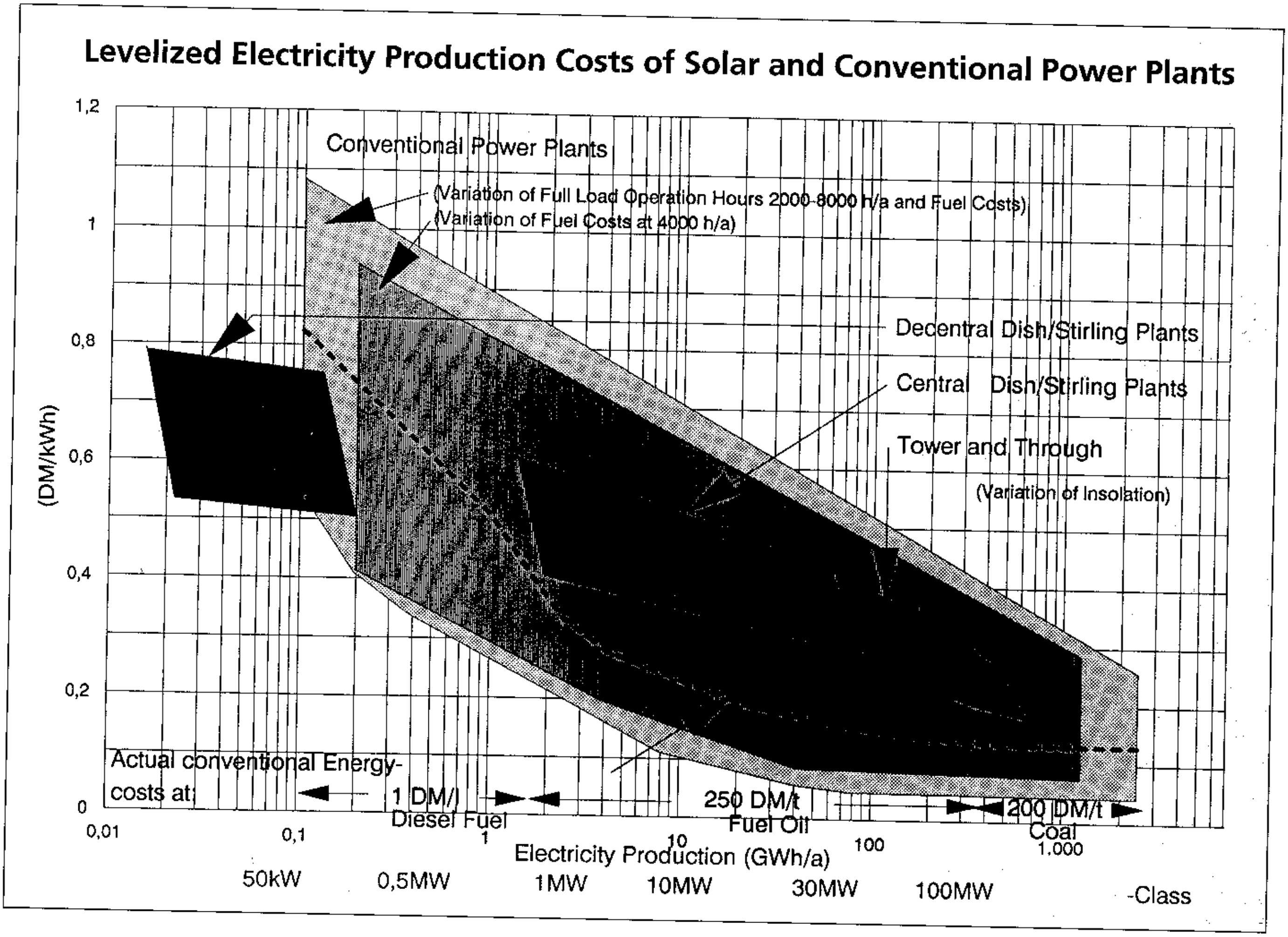


Figure 2-27. Summary of electric energy cost (LEC) in DM/kWh of solar and conventional power plants in the Mediterranean area (upper bound: 1750 kWh/m² year; lower bound: 2500 kWh/m² year) (Source: DLR/ZSW)

2.2 Process Heat Generation

Solar process heat systems provide thermal energy for industry, commerce, agriculture, and public facilities and operations. The principal applications (actual and potential) are:

- Water preheating
- Process hot water
- Process steam
- Process hot air.

Solar process heat technology can be applied to numerous industries employing processes with temperatures ranging from about 20 °C (in the case of water preheating or low-temperature process hot air) to 550 °C (for high-pressure steam), and perhaps higher than 1000 °C in the future (for high-temperature process hot air). Depending on the application and temperature, solar process heat systems can use flat-plate, evacuated-tube, or concentrating solar collectors (parabolic trough, parabolic dish, or central receivers) to collect solar radiation and convert it to heat. Solar process heat systems using flat-plate and parabolic trough collectors have been available for commercial use in the USA, Australia, and Europe since the late 1970s. In the future, solar thermal process heat is expected to impact very high-temperature applications such as preheating steel, melting copper, and manufacturing glass, most likely by the use of a solar furnace.

2.2.1 State of the Art

In the following sections, some examples of process heat projects are described, projects mainly been established in the USA and in Europe.

2.2.1.1 Process Hot Water

Figure 2-28 shows the solar process heat system owned and operated by Gould, Inc. in Chandler, Arizona, USA. This system, which has operated since 1983, uses 5620 m^2 of parabolic trough solar collectors and supplies the foil plant with process hot water at 95 °C. Sunlight falling onto the parabolic troughs heats a heat-transfer oil to temperatures of 200 °-230 °C. The heated oil is transported to a liquid-to-liquid heat exchanger where the water is heated. At design conditions, the system has a peak production capacity of 8700 GJ per year. Gould Inc. has estimated that the electrical energy savings from this system is approximately $120,000 per year.

Figure 2-28. System supplying process hot water to the Gould, Inc. foil plant in Chandler, Arizona, USA (Source: SKI/SNL)

Figure 2-29 shows the process heat system at the California Correctional Institution in Tehachapi, California, USA. This system, operated since late 1990, is owned and operated by private investors. The California Department of Corrections buys energy from the system at a rate below what it would pay for natural gas through a long-term purchase agreement. The solar system uses 2677 m^2 of parabolic trough collectors. Thermal energy collected by the system provides heat to a pressurized high-temperature water loop that distributes energy throughout the facility for showers, kitchen operations, a laundry, and space heating. Domestic hot water is produced by means of a separate loop. No thermal storage is provided. Collector output temperature at design conditions is 146 °C. The system is designed to deliver approximately 7160 GJ annually and to meet about 80% of the summer thermal load at peak conditions.

Figure 2-29. System supplying process hot water to the California Correctional Institution in Tehachapi, California, USA (Source: IST/NREL)

2.2.1.2 Process Steam

In the Solar Total Energy Project (STEP), a field of 114 parabolic dish concentrators provided both process heat and electricity to a textile mill in Shenandoah, Georgia, USA. This experimental plant was started up in 1982 and was operated until 1989 when its mission was completed. A heat-transfer oil circulated through the dish field and was heated to 400 °C. The hot oil

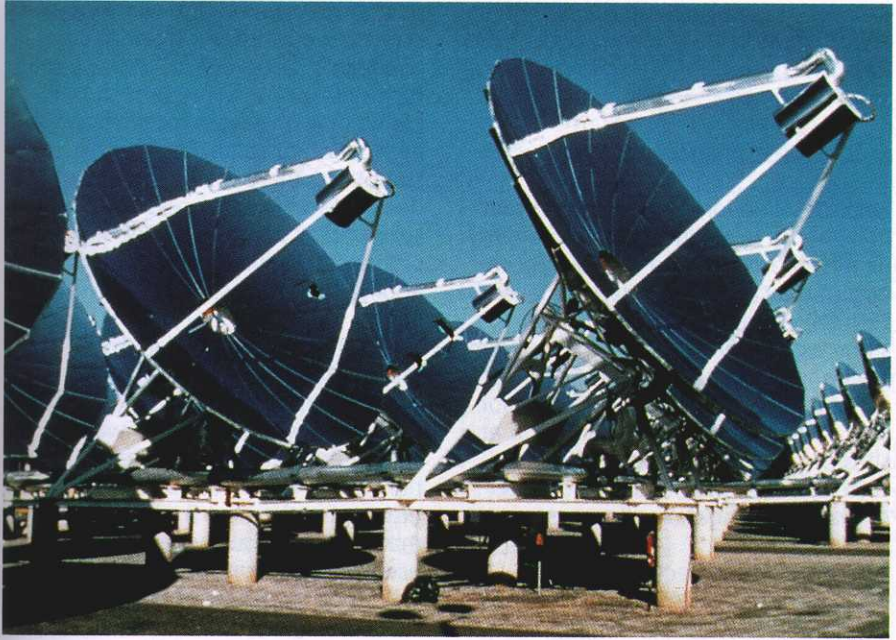


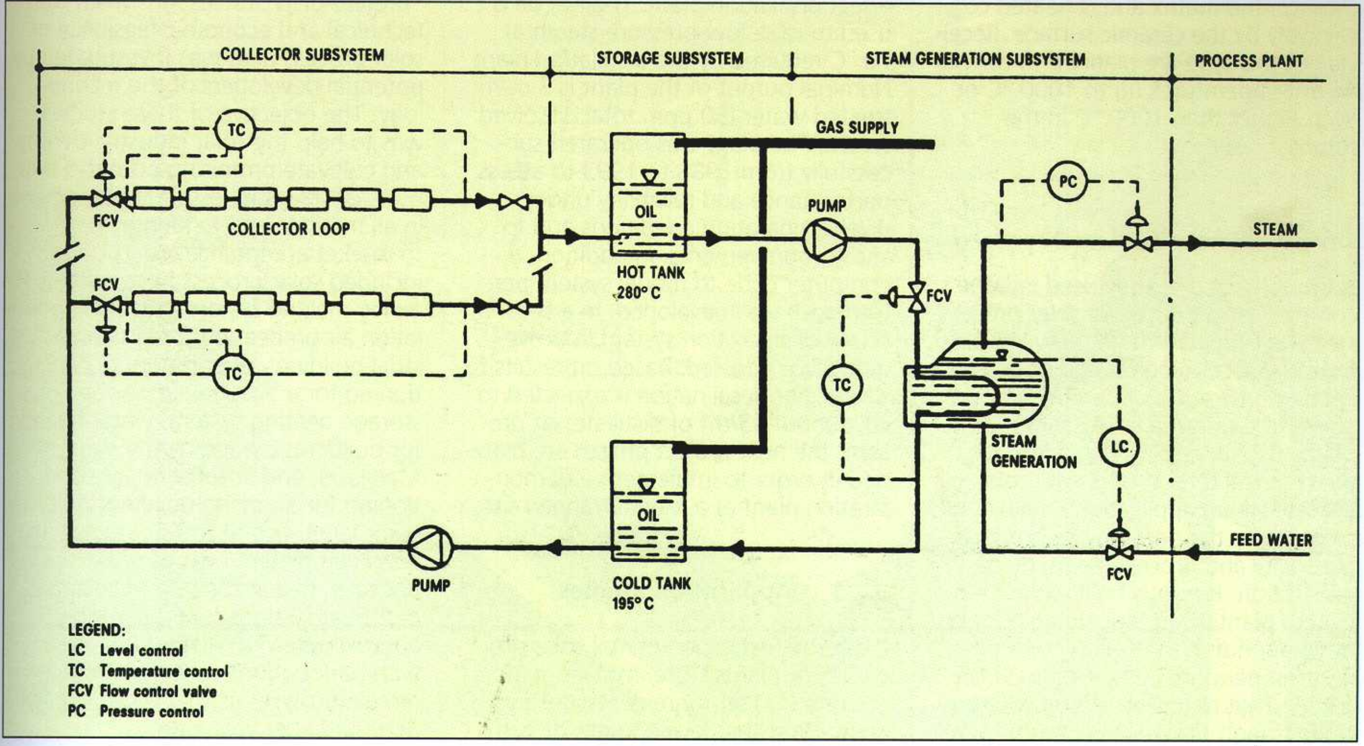
Figure 2-30. Field layout of the Solar Total Energy Project in Shenandoah, Georgia, USA (Source: SNL)

generated superheated steam in a boiler, which in turn drove a steam turbine to produce electricity (see Section 2.1.2.1; Figure 2-17). Extraction steam was used to supply process steam for the mill, and exhaust steam from the turbine was used to drive an absorption chiller. A fuel-oil fired heater allowed the plant to operate in the hybrid mode. The plant generated 400 kW of electrical power and supplied 2000 kW of thermal energy.

Figure 2-30 shows the layout of the dish field (see also Figure 2-17).

The German company MAN Technologie AG installed several experimental solar process steam plants using the MAN parabolic trough technologies (HELIOMAN 3/32 and HELIOMAN M 480 collectors). In these plants, a heat-transfer oil is heated in a field of troughs to a maximum of 260 °C and is pumped to a steam generator. A 400 m³/day water desalination plant (solar part 300 kW_t, 640 m² HELIOMAN M 480) started operation in the Arabian Emirates in 1984. A 560-kW_t process steam plant for a Portuguese dairy (750 kg steam per hour of 12 bar/188 °C, 1280 m² HELIOMAN M 480) began operation in Aguas de Moura in 1985. The MAN trough technologies also had been used for small power production facilities in Almería (500-kW_e IEA-SSPS-DCS together with Acurex collectors), in Saudi-Arabia (five collectors for a small steam turbine generator at the Jeddah University), and in India near New Delhi (50-kW_e steam turbine generator). Figure 2-31 shows a typical process flow diagram for the MAN process steam plants.

Figure 2-31. Typical process flow diagram for a MAN solar process heat generator (Source: MAN)



2.2.2 Future Applications

2.2.2.1 *Process Hot Air*

Although not presently used in commercial applications, solar process hot air is expected to impact several high-temperature process heat markets in the future. Air is the leading candidate for high-temperature solar process heat because of temperature limitations associated with other heat-transfer fluids, such as oils, water, and molten salts. High-temperature process air can be produced in heat exchangers, but heat-transfer limitations associated with air have so far limited commercial potential. The most promising means for producing high-temperature process air will be direct heating of the air either in a tube receiver (metallic or ceramic tubes for temperatures up to approximately 1000 °C) as has been demonstrated by the GAST Technology Program (see Section 2.3.2.1) or in a volumetric receiver similar to those discussed in Section 3.1.2. In the volumetric receiver concept, a ceramic matrix with very high surface area per unit volume is located near the focus of a concentrating collector. The ceramic surface is located so that the solar radiation is absorbed more-or-less volumetrically, that is, the surface area is distributed throughout the volume of maximum solar flux. Air is drawn through the matrix and is heated convectively by the ceramic surface. Receivers of this type are planned to deliver air at temperatures up to 1000 °C or even higher than 1000 °C in the future.

2.2.2.2 *Process Steam*

Although not presently used in large commercial applications, solar process steam is expected to get new impulse from the technological and operational demonstration of parabolic trough plants in California, USA. These SEGS plants use thermo-oil up to 400 °C, which is the reason to review solar process steam applications: such plants have the potential to produce electricity and process steam by cogeneration. Previous built experimental trough plants were not suitable for cogeneration due to the far lower process temperature compared to SEGS plants. That might be reason why previous trough plants designed for pure process steam production were not able to demonstrate commercial viability.

2.2.2.3 *Desalination*

Solar desalination of water using thermal energy or electric pumping energy (reversed osmosis) is a typical application of concentrating systems. Several concepts have been studied. Only some experimental facilities have been built and tested up to now. Solar desalination is expected to play an important role in future solar application at sites of resources of sea or brackish waters, but of lack of drinking water or water for irrigation purposes.

As mentioned in Section 2.2.1.2, MAN Technologie AG developed and built a parabolic trough field of HELIOMAN M 480 collectors supplying solar process steam to the multistage flash desalination facility at a capacity of 400 m^3 per day in the Arabian Emirates.
In Spain, solar thermal desalination is under investigation by CIEMAT at the Plataforma Solar de Almería and cofinanced by CIEMAT and DLR. The process plant includes parabolic trough collectors of the former SSPS-DCS facility (Acurex troughs; Figure 2-32) that deliver hot oil to a thermocline thermal storage tank and a multi-effect distillation plant. The hot oil is used to raise low-pressure steam at 70 °C required by the distillation plant. Nominal output of the plant is 3 m^3/h treated water (50 ppm total dissolved solids). The plant was operated successfully from 1988 to 1993 to assess performance and reliability under diverse operating conditions and to study improvements. In addition, a computer code to model system performance was developed. In a second phase of operation system improvements were tested. Based on results to date, solar desalination is expected to cost about \$3/m^3 of distillate. At present, the next project phases are planned in order to implement a demonstration plant at a Mediterranean site.

2.2.3 Application Studies

After the first experimental solar process heat plants were installed and operated under more or less testing conditions, the development of such plants has stopped due to the lack of economic success. As mentioned above in chapter 2.2.2.2, the trough technology of the well proven LUZ plants may give new impulses to the application of solar process heat. Doubtless, there is a large future demand for solar process heat in sunny areas worldwide. The following sections describe examples of actual application studies.

The status of commercial process heat in California was reviewed and the potential impact of the technology in the future was assessed. It was estimated that approximately 5000 GJ per year of installed systems were practical in the next 5 years. Approximately 34% of all industrial energy is used for temperatures below 200 °C. The study results were published by Kulkarni in 1991 (see References).

Another study evaluated the potential U.S. market for solar process heat. The study team concluded that there is the potential of supplying 5 billion GJ per year by the year 2030, assuming that an expanded R&D program is pursued to introduce parabolic dish technology to the market. The study was published by Demeter and Gray in 1990 (see References).

A NREL study published in 1992 (see References) described a series of six "prefeasibility studies" in which the technical and economic feasibility of solar process heat was investigated by potential developers of the technology. The objective of these studies was to help the solar industry identify and cultivate promising potential end users of solar process heat equipment in all markets and to identify barriers to market acceptance. The studies included solar process heat systems for an ice-making system in Mexico, ventilation air preheating for large industrial buildings, absorption air conditioning for a hospital, an asphalt bulk storage heating system, water heating for buildings owned by the state of Maryland, and absorption air conditioning for an office building. As of early 1993, five of the six studies had been completed. Two of these studies have resulted in the sale of solar process heat systems that will supply approximately 10,000 GJ per year, with negotiations continuing on remaining systems that could supply 36,000 GJ per year.

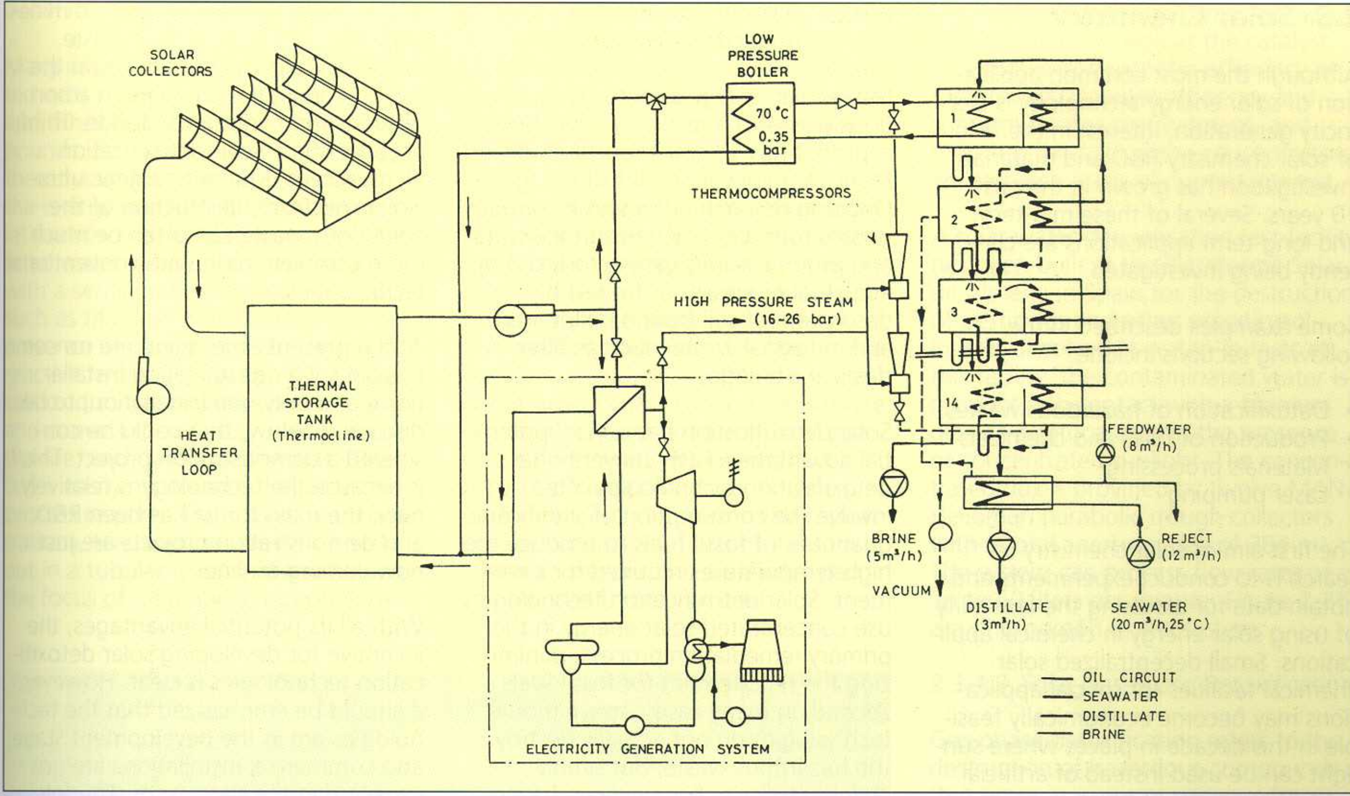
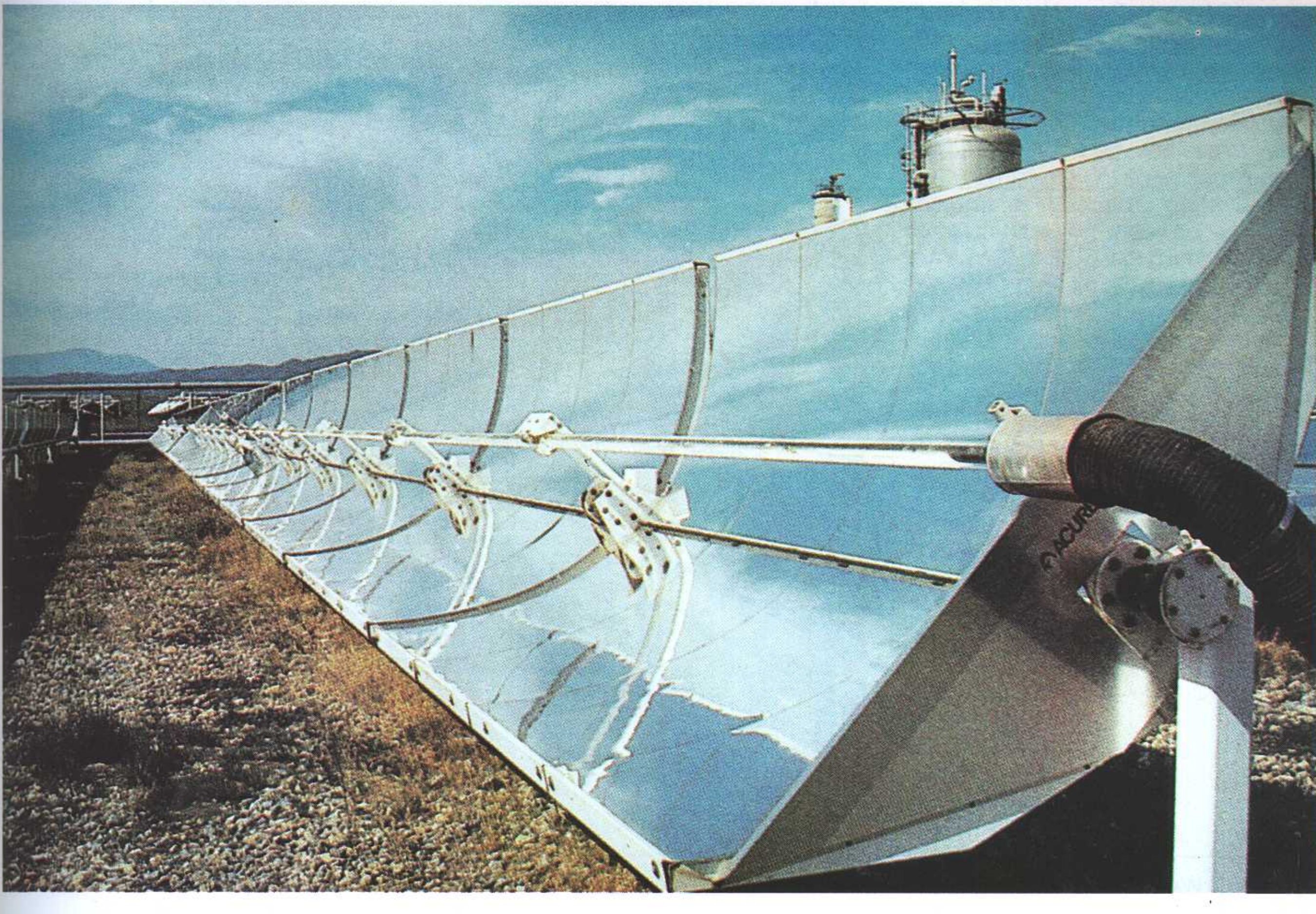


Figure 2-32. Solar thermal desalination test facility at CIEMAT using ACUREX troughs on the PSA (Source: CIEMAT)



2.3 Solar Chemistry

Although the most common application of solar energy technology is electricity generation, interest in the field of solar chemistry R&D and materials investigation has grown in the past 10 years. Several of these mid-term and long-term applications are currently being investigated.

Some examples described in the following sections include:

- Detoxification of hazardous wastes
- Production of fuels and chemicals
- Materials processing
- Laser pumping.

The first aim of solar chemistry research is to conduct experiments and obtain data for assessing the feasibility of using solar energy in chemical applications. Small decentralized solar chemical facilities for special applications may become economically feasible in this decade in places where sunlight can be used instead of artificial light sources.

The solar technologies required by solar chemistry can be derived from the existing equipment developed for thermal and electric energy generation.

2.3.1 Detoxification of Hazardous Wastes

Using solar energy to detoxify hazardous wastes is a relatively new concept that has several important advantages over conventional technologies. Ongoing research addresses hazardous wastes found in polluted surface water and ground water, gases produced by industrial processes or from the desorption of soil-bound pollutants, and industrial wastes such as filter dusts and sludges.

Solar detoxification has several potential advantages. First, conventional detoxification technologies often involve the consumption of significant quantities of fossil fuels to produce the high temperatures required for treatment. Solar detoxification technologies use concentrated solar energy in the primary remediation process, minimizing the requirement for fossil fuels. Second, in many cases, conventional technologies do not actually destroy the hazardous waste, but simply change its form. For example, hazardous organic solvents are often stripped out of contaminated water and vented to the air. Even in cases in which destruction of the waste is attempted, by-products are produced that are often more hazardous than the original waste. Solar technologies aim at the complete destruction and mineralization of the hazardous waste. Often the only by-products from the solar technologies are water, carbon dioxide, and hydrogen chloride. Third, because some solar detoxification technologies use the energetic ultraviolet spectrum, destruction of the hazardous waste can often be much more complete than with conventional technologies.

At the present time, there are no commercial solar detoxification installations, and only one installation, to be discussed below, that could be considered a demonstration project. This is because the technology is relatively new; the main thrust has been R&D, and demonstration projects are just now coming on-line.

With all its potential advantages, the incentive for developing solar detoxification technologies is clear. However, it should be emphasized that the technologies are in the development stage, and commercial installations are not expected in the short term. The following sections describe in more detail solar detoxification technologies and applications of these technologies.

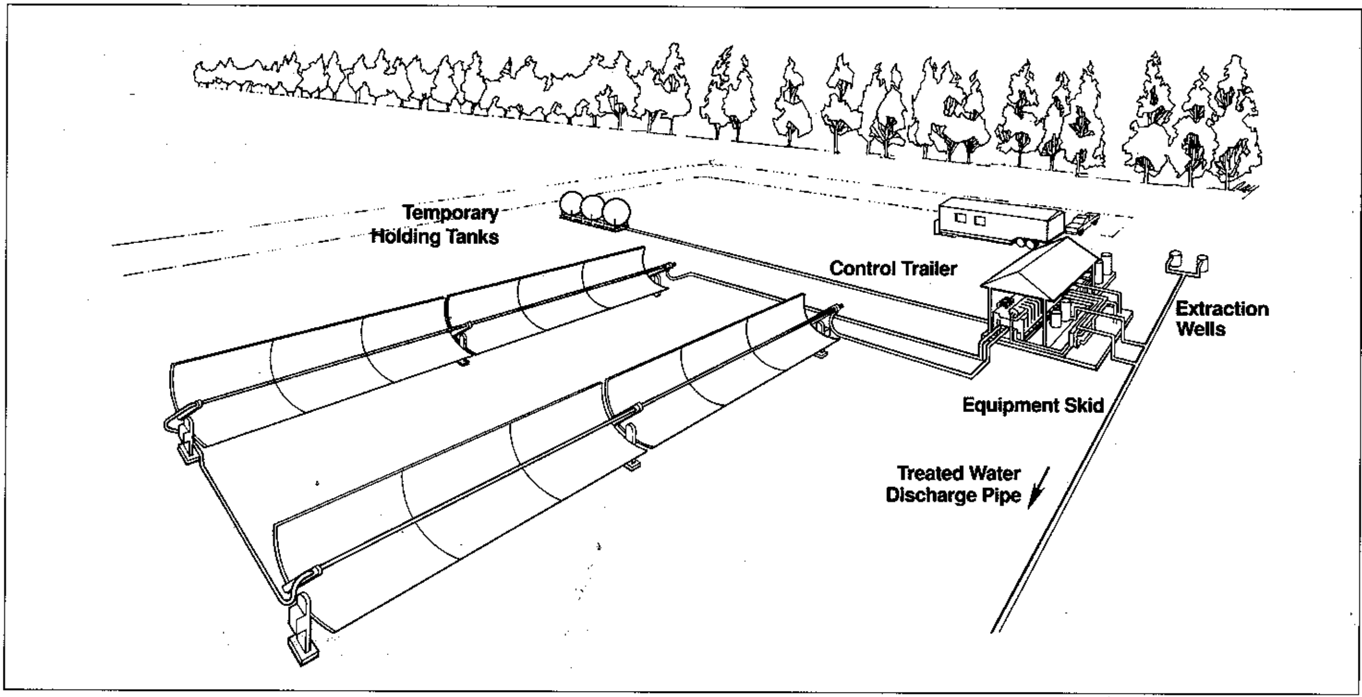


Figure 2-33. Water detoxification field demonstration plant at Lawrence Livermore National Laboratory in Livermore, USA (Source: NREL)

2.3.1.1 Solar Water Detoxification

Many of our water resources are polluted with solvents, dioxins, pesticides, and other hazardous chemical compounds. Solar detoxification destroys these hazardous chemicals by using the energy available from the ultraviolet portion of the solar spectrum. Polluted water is brought into contact with a semiconductor photocatalyst, such as titanium dioxide, which in the presence of sunlight creates highly reactive hydroxyl radicals. These radicals oxidize the organic contaminants and convert them into water, carbon dioxide, and hydrogen chloride. The last is easily neutralized. Because the process requires low solar-flux concentrations, the reaction can be carried out in a tubular reactor aligned along the focus of a parabolic trough concentrator (Figure 2-34). The small particles of titanium dioxide catalyst in the glass reactor tube can be mixed in the water in the form of a slurry or can be fixed in the reactor on a catalyst support.

Figure 2-33 shows a field demonstration plant developed by the National Renewable Energy Laboratory (NREL), SNL, and Lawrence Livermore National Laboratory. The plant was tested in Livermore, California, USA, has a total aperture area of 154 m², and is capable of processing 110 liters per minute of water contaminated with 400 ppb of trichlorethylene. Ongoing R&D focuses on improving overall system performance and lowering the capital cost of systems. Portions of the solar spectrum beyond the ultraviolet part can be used by using mixed titanium/iron oxide particles instead of pure titanium dioxide as the catalyst. This should enhance the efficiency of the process. Catalyst efficiency and supports, water pretreatment, and reducing the cost of the concentrators are research areas of current interest.

A solar water detoxification test facility has been built at the Plataforma Solar de Almería in Spain for the destruction of pesticides and other organic pollutants dissolved in water. In tests at this facility, the contaminated water is brought into contact with a titanium dioxide photocatalyst in the presence of concentrated sunlight. The concentrated flux is provided by twelve MAN Helioman parabolic trough collectors with a total aperture area of 384 m². The system can process flow rates of up to 50 liters per minute. Figure 2-35 is a photograph of the system.

2.3.1.2 Solar Gas-Phase Detoxification

Gas-phase detoxification refers to the destruction of hazardous compounds that occur in vapor or gaseous form. These are produced as off-gases in some industrial processes when volatile compounds are removed from contaminated soil or when contaminants are stripped from activated carbon. Chlorinated and nonchlorinated organic solvents, dioxins, polychlorinated biphenyls (PCBs), and explosives are a few of the possible candidate compounds suitable for destruction in the gas phase. For many applications, the compounds will occur as dilute constituents of an air stream, in the range from ten to a few thousand of parts per million by volume. Other compounds, such as those stripped from activated carbon, may occur in a steam environment.

Figure 2-34. Parabolic trough used for detoxification of water contaminated with trichlorethylene (Source: NREL)

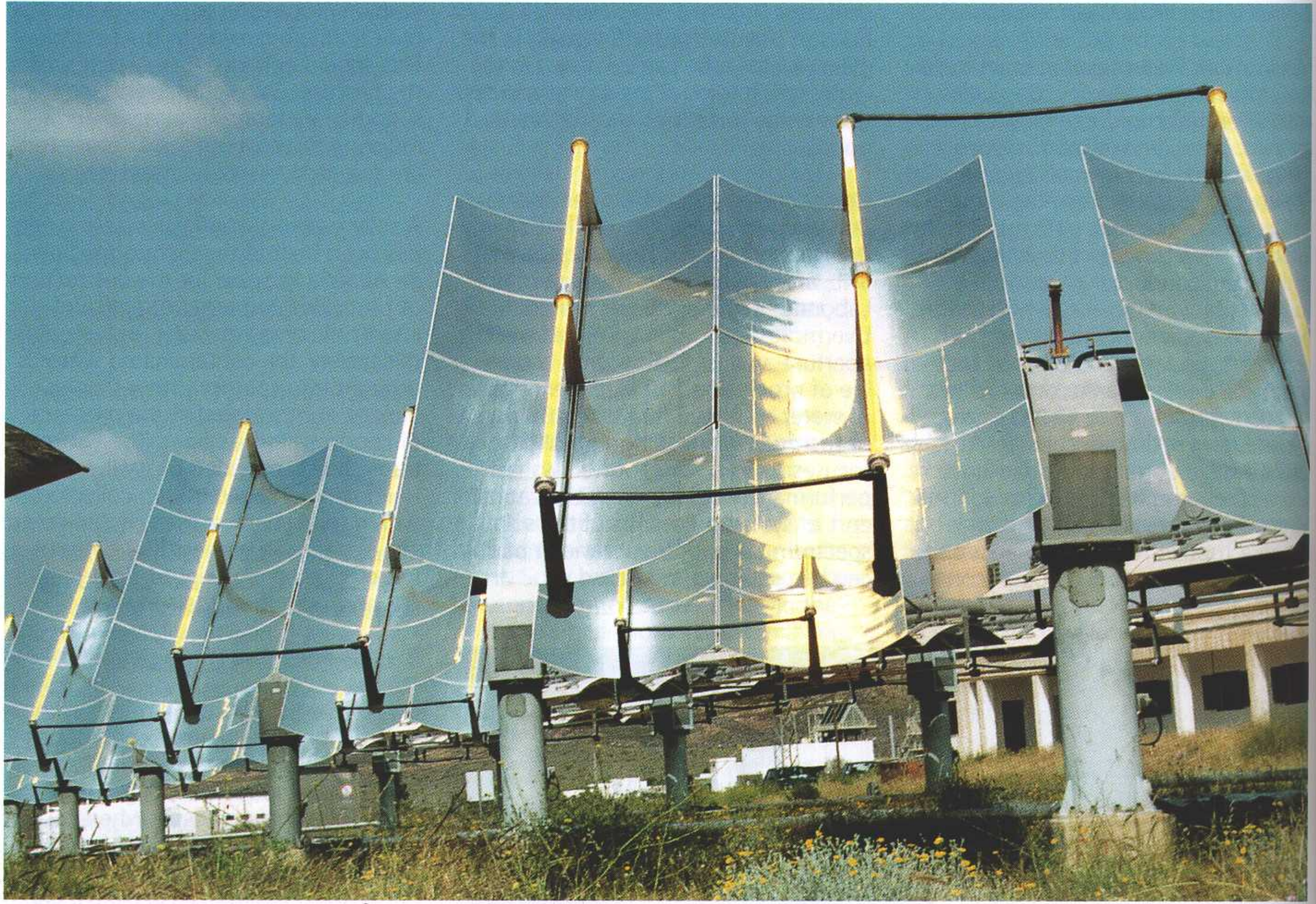


Figure 2-35. Water detoxification test loop on the Plataforma Solar de Almería (Source: CIEMAT)

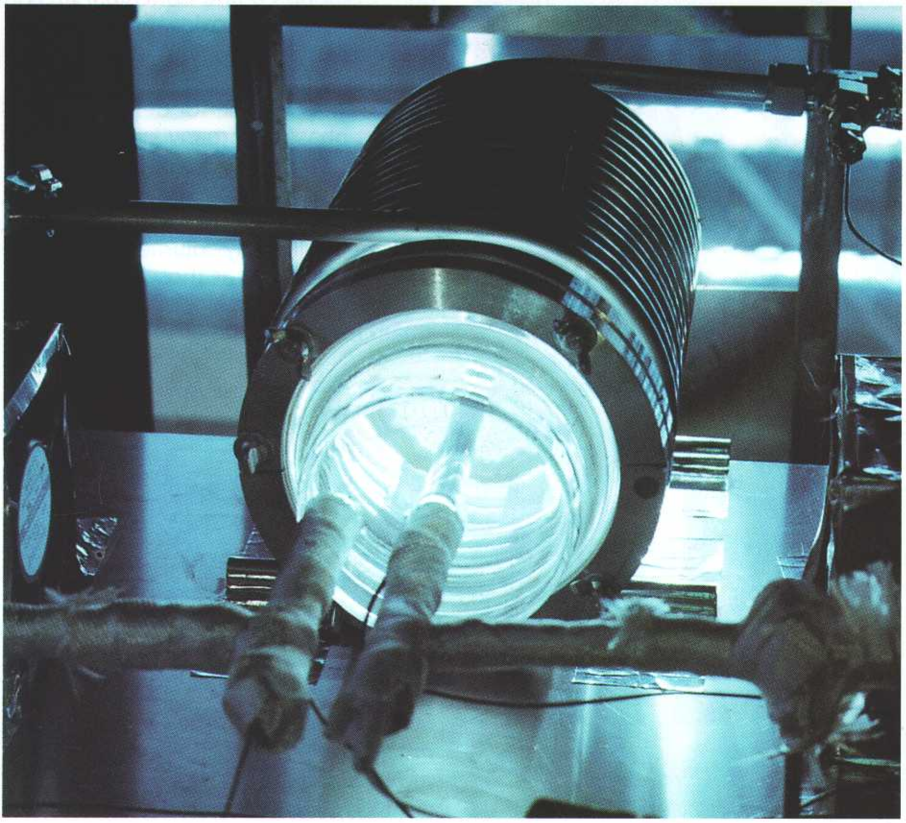


Figure 2-36. Experimental gas-phase detoxification reactor (Source: NREL)

Currently, there are three technologies for solar gas-phase detoxification. The first is a high-flux photothermal process in which the entire solar spectrum plays a role. Energy in the visible and near-infrared part of the spectrum provides heat to the gas stream, and energy in the ultraviolet part of the spectrum helps to initiate the destruction reactions. These two energy sources work together to oxidize the organic compound at temperatures far below that required by conventional incineration temperatures. Figure 2-36 shows an experimental gas-phase solar detoxification reactor developed by NREL that was used in early experiments to destroy 1,2,3,4-tetrachloro dibenzodioxine, trichlorethylene, and methylene chloride. Experiments showed that solar energy destroyed hazardous chemicals at lower temperatures and more thoroughly than conventional techniques.

The second solar gas-phase detoxification technology utilizes a supported photocatalyst in the receiver tube of a trough collector for the destruction of organic compounds in humid air. Only the ultraviolet part of the solar spectrum is employed in this system as it operates at near-ambient temperature. Interaction of the ultraviolet photons with the photocatalyst produces reactive hydroxyl radicals that promote the oxidation of the organic waste. This technology is attractive because it operates at low temperature and has the potential for being more economically competitive than conventional technologies. NREL has used the trough shown in Figure 2-33 to prove the concept of photocatalytic destruction of trichlorethylene in air.

The third technology is a thermal catalytic steam-reforming process, which is a high-flux, high-temperature process. A catalyst such as rhodium is exposed to concentrated sunlight. The contaminants and steam are then passed through the reactor over the catalyst, where the contaminants react with the steam to form products typical of the steam-reforming reaction and hydrogen halides. This process is well suited for destruction of halogenated hydrocarbons. This technology can exceed 99.9999% destruction and removal efficiencies without the production of hazardous by-products or the consumption of fossil fuels. Figure 2-37 shows an experimental steam-reforming reactor for gas-phase detoxification developed by Sandia National Laboratories.

Solar pyrolysis and catalytic reforming of chlorinated organic compounds in the gas phase are under investigation at the Plataforma Solar de Almería (PSA) in Spain. These studies are being carried out using a solar simulator, a 1-m-diameter Fresnel concentrator, and the high-flux solar furnace of the PSA.

The gas-phase technologies are expected to become important tools for the environmental remediation and waste management industries by the late 1990s.

2.3.1.3 Treatment of Solid Wastes

The solar thermal high-temperature treatment of solid wastes is being investigated in Germany. A film of molten solids is exposed to concentrated solar radiation in a rotary kiln-type receiver/reactor, destroying organic material associated with the solid waste. Volatile heavy metal salts are evaporated and collected in subsequent condensers and filters, and the remaining glass-like solids can be used as building materials. The receiver/reactor is intended for use on the top of a central receiver type facility.

2.3.1.4 Solar Recovery of Waste Sulfuric Acid

The recycling of diluted waste sulfuric acid is a highly endothermic process because of the high specific energy demand for water evaporation, dehydration and optional sulfur trioxide splitting. Only a fraction of the energy can be recovered. Practical studies with organically contaminated waste acid and direct exposure to concentrated sunlight showed a flux-density-dependent increase of the oxidation rate of the organic substances. Sulfur trioxide decomposition studies proved a correlation between the ultraviolet radiation intensity and a shift toward higher decomposition rates. Thus, direct solar radiation treatment is a promising technique for the removal of organic matter and generation of fresh sulfuric acid.

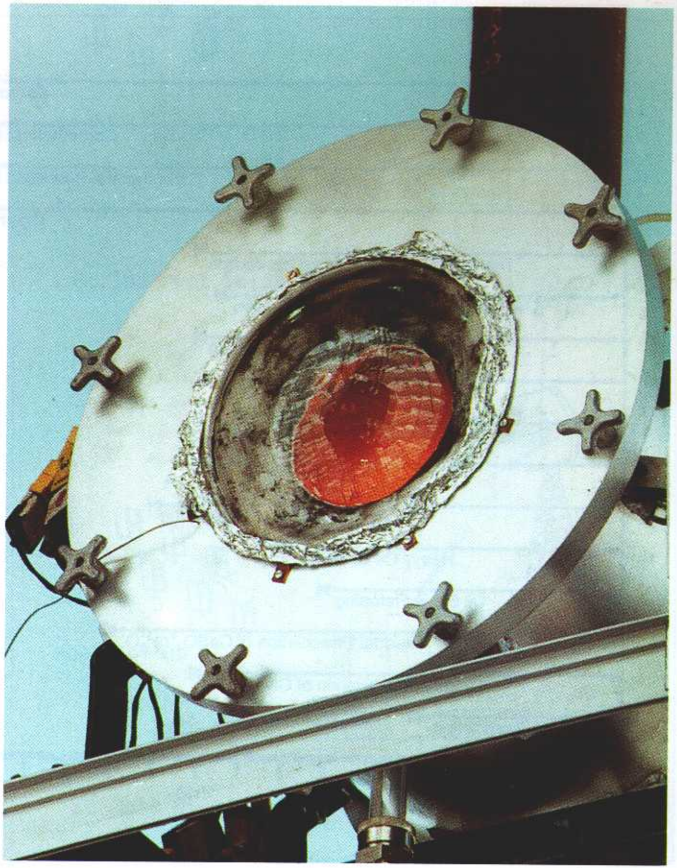


Figure 2-37. Experimental steam-reforming reactor for gas-phase detoxification (Source: SNL)

2.3.2 Production of Fuels and Chemicals

An important goal of solar chemistry is the use of solar radiation for the production of fuels and chemicals. As a general guideline for innovative solar chemical R&D, routes for the direct conversion of hydrocarbons to chemicals should be found to reduce both the primary energy input and the equipment costs. Much of the potential for solar chemical reactions concerns direct photoconversions that can avoid or reduce expenditures for the indirect activation, the feed condition, or the product separation.

In general, solar energy can be used for chemical processes by three different paths:

- Thermochemical (by use of thermal energy)
- Photochemical (by use of radiant energy)
- Electrochemical (by conversion of the solar energy to electricity and its subsequent use in electrochemical processes).

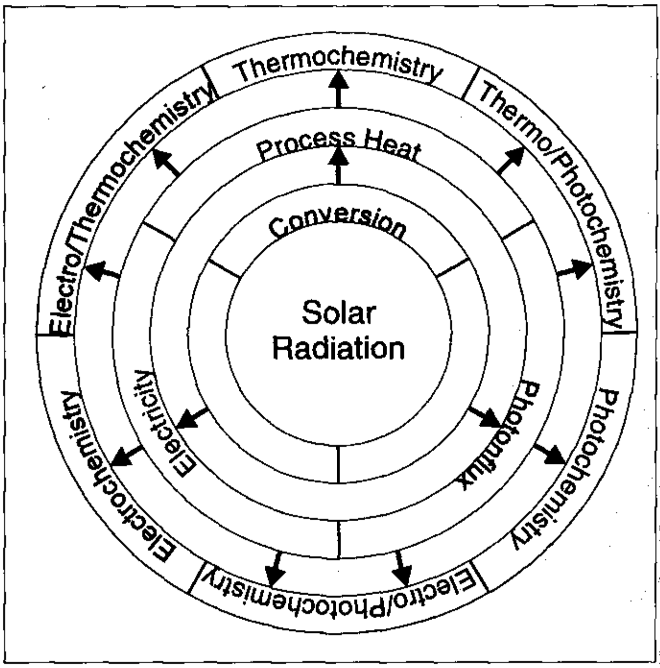


Figure 2-38. Conversion pathways in solar chemistry (Source: University of Munich)

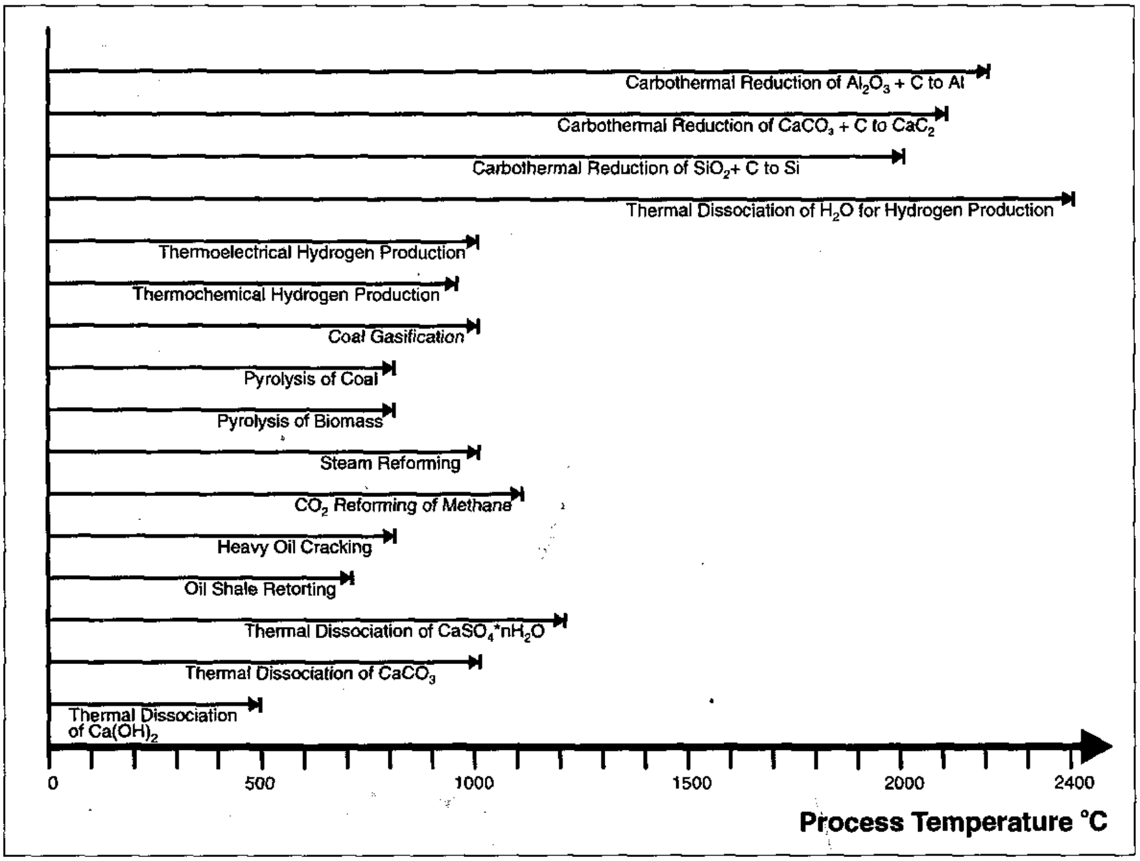


Figure 2-39. Potential process applications for high-temperature thermochemical conversion for the application of solar energy (Source: DLR)

Figure 2-38 illustrates these conversion pathways in a circular schematic.

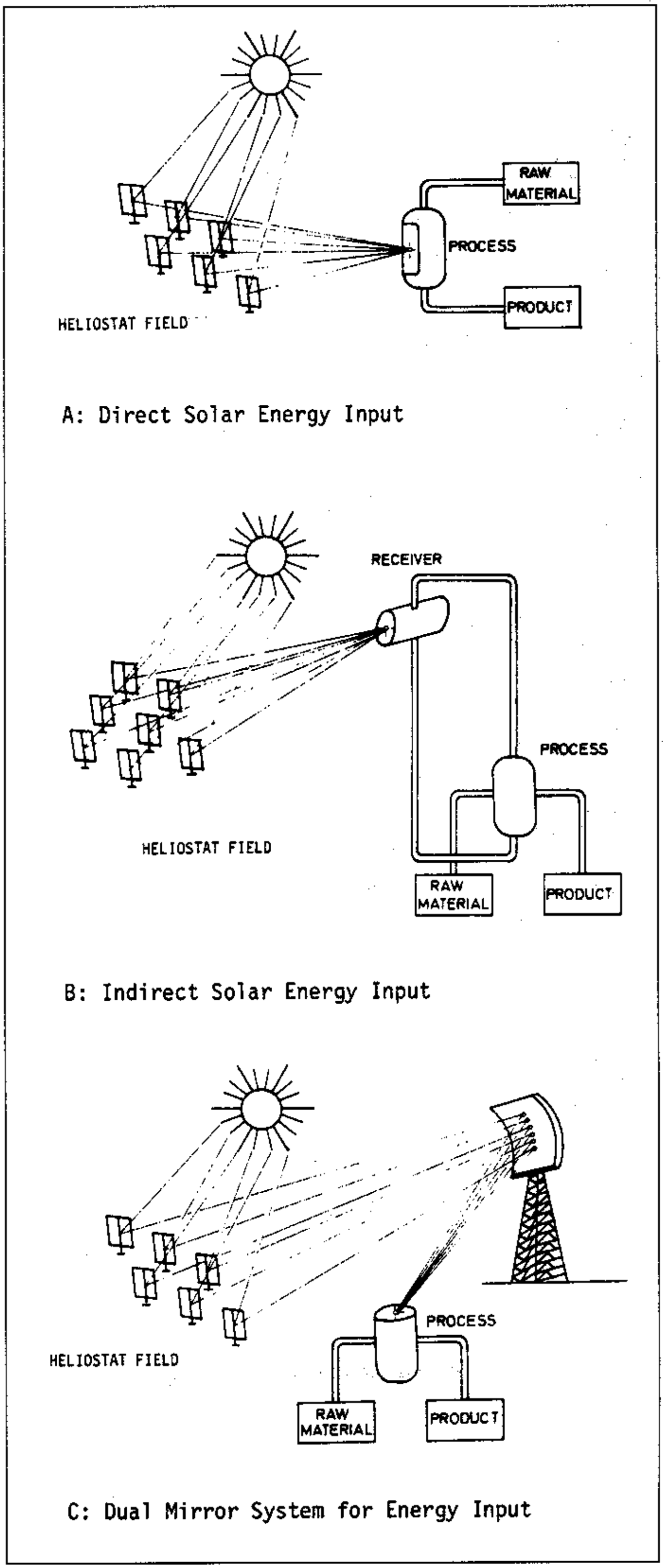
An important task for solar chemistry is to substitute fossil fuels in established industrial processes for the production of fuels and chemicals. Thus the two functions of the fossil fuel fed to the process – raw material for the production of chemicals, and fuel for the processing of the production steps – can be decoupled. Figure 2-39 lists potential process applications over the range of the process temperatures. These processes are powered by fossil fuel energy today. The processes can be categorized as follows:

- Production of synthesis gas
- Refining or upgrading of products from coal and hydrocarbons
- Production of hydrogen
- Production of bulk inorganic materials.

A few basic materials are of increasing demand in the chemical industry: synthesis gas, ammonia (as fertilizer), methanol (as synthetic fuel), and hydrogen. Today, most of these products are generated from fossil fuels, which will inevitably become more difficult to tap, and hence will become much more expensive in the foreseeable future. Therefore, it is increasingly important to be able to demonstrate that solar energy is an excellent substitute for fossil fuel energy in chemical processes. Solar reforming of methane is one of the most promising examples of solar-powered thermochemical reactions, as will be discussed. However, R&D in this field has just begun, and economical feasibility is probably many years away.

Several technologies exist to couple solar energy to thermochemical processes. In each case, concentrating technologies (i. e. central receiver systems or parabolic dish systems) are required to generate high-flux radiation and/or high-temperature heat.

Figure 2-40 shows three principal approaches to collecting solar energy from a heliostat field. In Part A of Figure 2-40, solar energy is reflected directly from the heliostat field into the processing system. The complete processing unit must be located on a tower unless a natural slope can produce the same elevation effect. In Part B of Figure 2-40, the solar energy is introduced into the process via a receiver using a heat-transfer medium



A: Direct Solar Energy Input

B: Indirect Solar Energy Input

C: Dual Mirror System for Energy Input

Figure 2-40. Different pathways for energy transfer into a solar chemical process (Source: DLR)

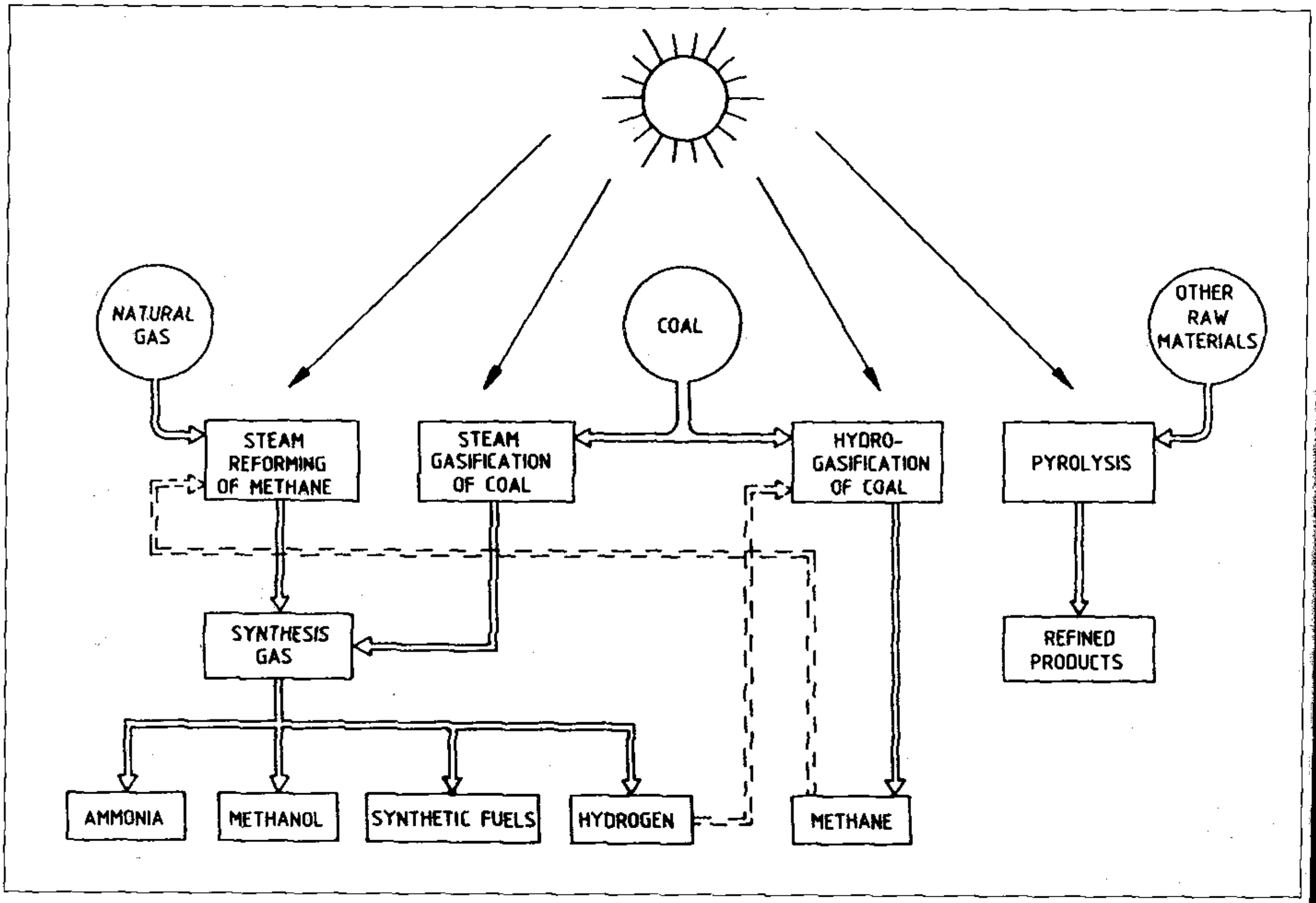


Figure 2-41. Examples of upgrading raw materials by the application of high-temperature energy (Source: DLR)

such as gas, liquid, or solid particles. Here, the receiver must be located on a tower. In Part C of Figure 2-40, the solar energy is directed via a secondary concentrator to the ground. This mechanism could be necessary for extensive industrial plants. In each case, the processing systems might be combined with storage and other hybrid systems.

Figure 2-41 shows examples of upgrading raw materials using solar energy. Upgrading processes require energy that may amount to more than 30 % of the energy content of the process feed.

2.3.2.1 Methane Reforming

Today, process heat for conventional chemical applications is generated by the combustion of fossil fuels. In the future, renewable energy resources may be widely substituted to reduce the consumption of fossil fuels and the production of air emissions.

Steam or carbon dioxide reforming of methane is a candidate process for the demonstration of solar thermal energy applications in chemical processing. These processes are of primary interest and are commonly practiced by the chemical industry worldwide. Both reforming processes are catalytic endothermic high-temperature reactions.

Synthesis gas from methane reforming is a gas mixture containing carbon monoxide (CO), carbon dioxide (CO_2), and hydrogen (H_2) with minor concentrations of other components such as methane. The synthesis gas can be used as the major feedstock in the production of other chemicals and fuels. The ratio $H_2/(CO + CO_2)$ is important with regard to the subsequent synthesis of special chemical products. Natural gas, petroleum liquids, biomass, and coal may all be completely converted or partially oxidized to produce synthesis gas suitable for further processing.

Steam reforming of methane to produce synthesis gas for methanol production, hydrogen for ammonia synthesis, or hydrogen for other processes is practiced commercially worldwide. The reforming of methane using steam or carbon dioxide has been proposed as the basic step for a novel energy transport system. For large-scale energy transport over long distances, carbon dioxide reforming has significant advantages over steam reforming. These advantages include the higher reaction enthalpy for carbon dioxide reforming and smaller energy losses than steam generation.

For solar methane reforming, several technologies have been investigated. These technologies can work separa-

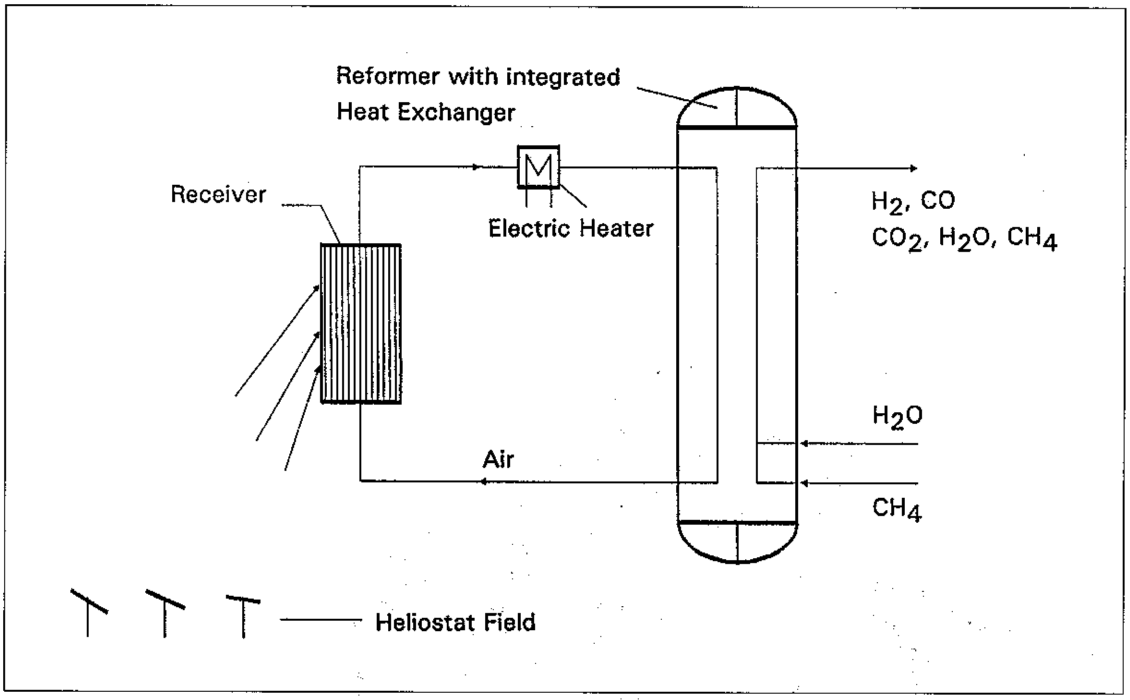


Figure 2-42. Simplified process flow diagram of the ASTERIX experiment (Source: DLR)

tely in a system in which the solar receiver is linked to a chemical reactor by an intermediate gas loop. Or they may be integrated, with the reforming reactor placed directly within the solar receiver (receiver/reactor).

For the steam reforming of methane, the ASTERIX (Advanced Steam Reforming in Heat Exchange) experiment was defined and built on the PSA in Spain as part of a joint German/Spanish R&D program. Tests performed by a joint DLR – Köln and PSA team showed very promising results. A simplified process flow diagram is shown in Figure 2-42. The equilibrium composition of the synthesis gas is given in Figure 2-43.

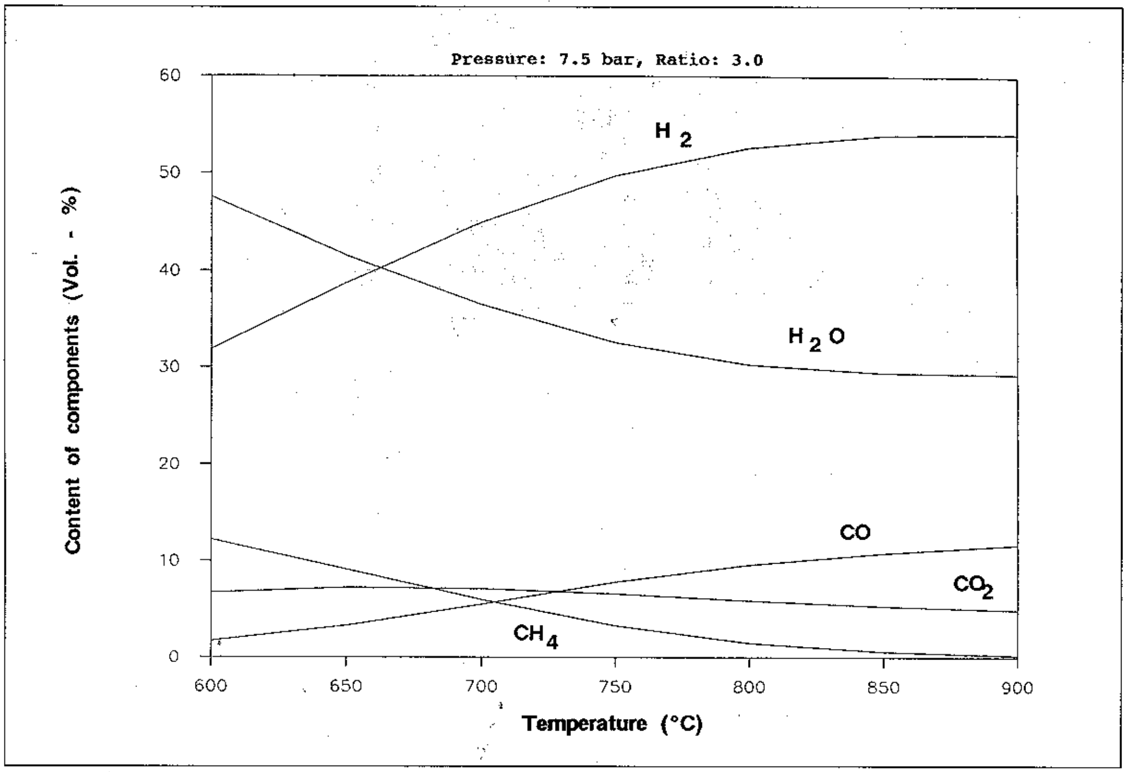
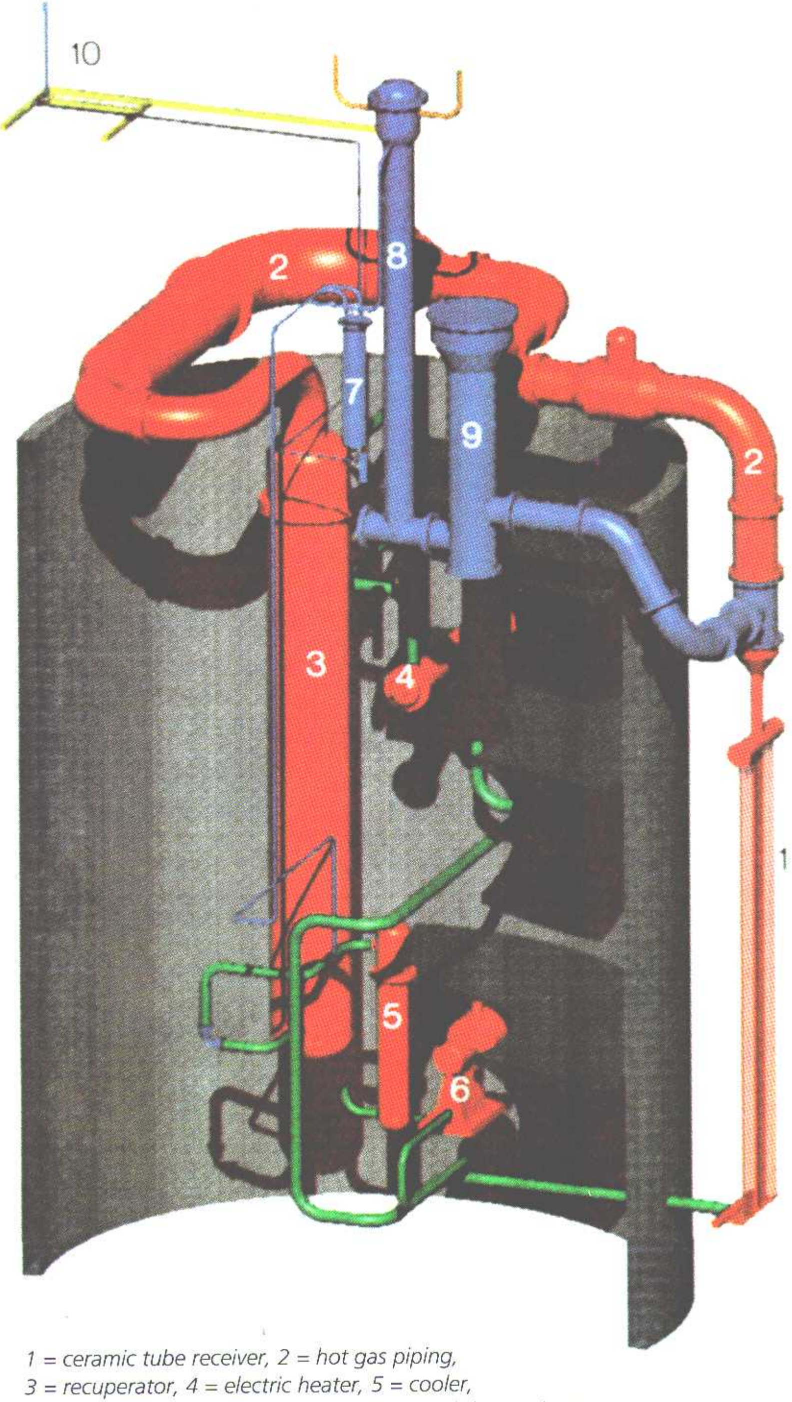


Figure 2-43. Equilibrium composition of gases for steam reforming of methane for a steam/methane ratio of three (Source: DLR)



1 = ceramic tube receiver, 2 = hot gas piping,
3 = recuperator, 4 = electric heater, 5 = cooler,
6 = compressor, 7 = cooler, 8 = reformer with heat exhanger,
9 = electric heater, 10 = torch

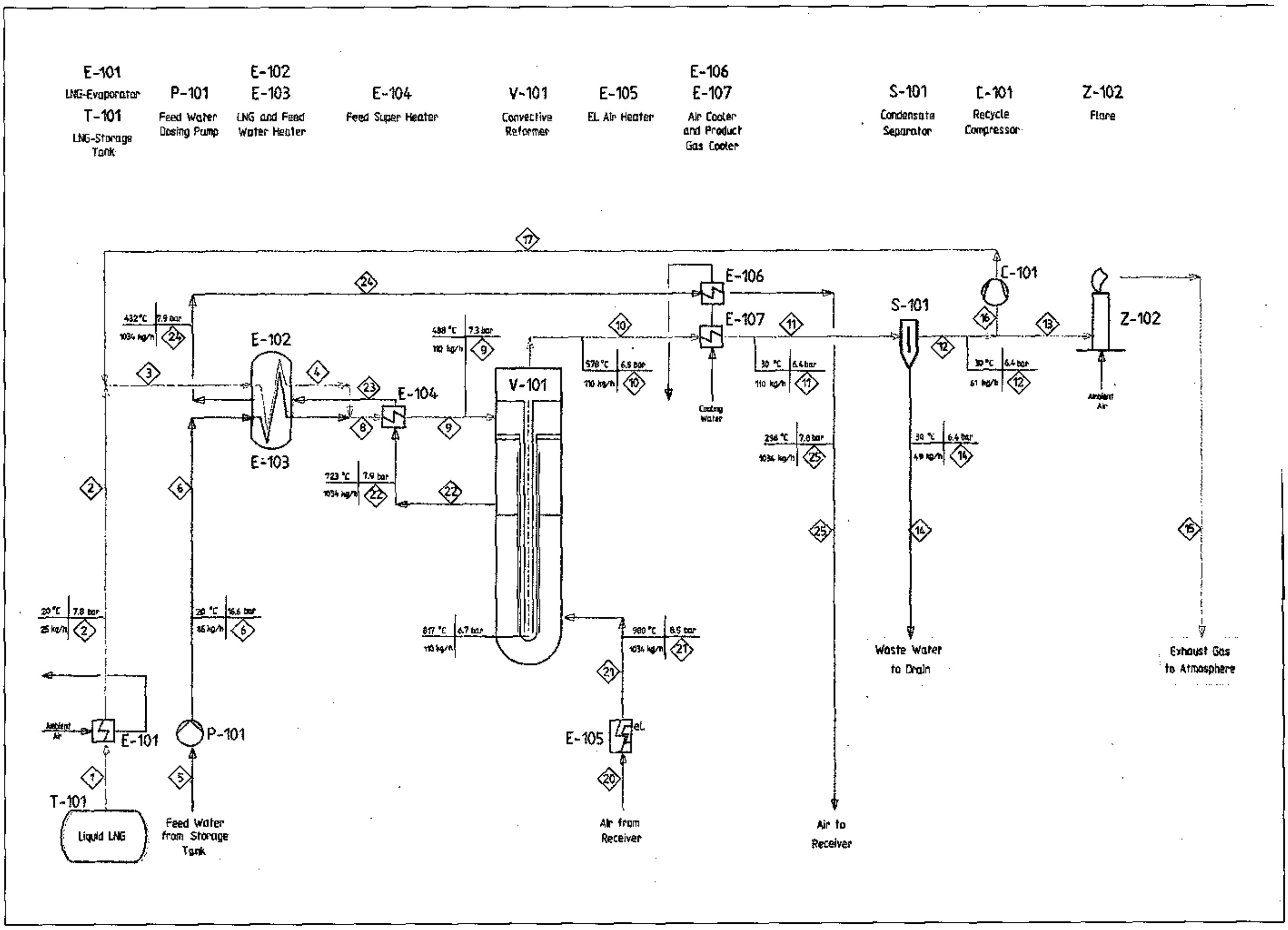


*Figure 2-45.
Process diagram of the ASTERIX experiment (design case)
(Source: LCS)*

◀ *Figure 2-44.
Three-dimensional view of the ASTERIX experiment and GAST hot air cycle
(Source: LCS)*

High-temperature heat for the process was provided by solar energy using a ceramic receiver on top of the CESA-1 tower of the PSA. This receiver, developed within the joint German-Spanish GAST Technology Program, was able to heat air at 9 bar and temperatures up to 1000 °C. A large part of GAST cycle hot air was used to drive a separate steam reformer. This air was then fed back into the GAST cycle. The necessary equipment for the ASTERIX experiment was designed and built by the German company, L&C Steinmüller, in cooperation with the Spanish company Technical and under the directory of DLR. Figures 2-44 and 2-45 illustrate the facility arrangement and the details of the process.

For economic reasons, commercial plants aim for higher pressures and lower steam/methane ratios.

A remarkable potential exists for substituting fossil fuel with solar energy in the methane reforming process. With increasing energy output and storage capacity, the solar plant will shift from a fuel saver to a system in which the total energy demand for the reforming process is supplied by solar energy.

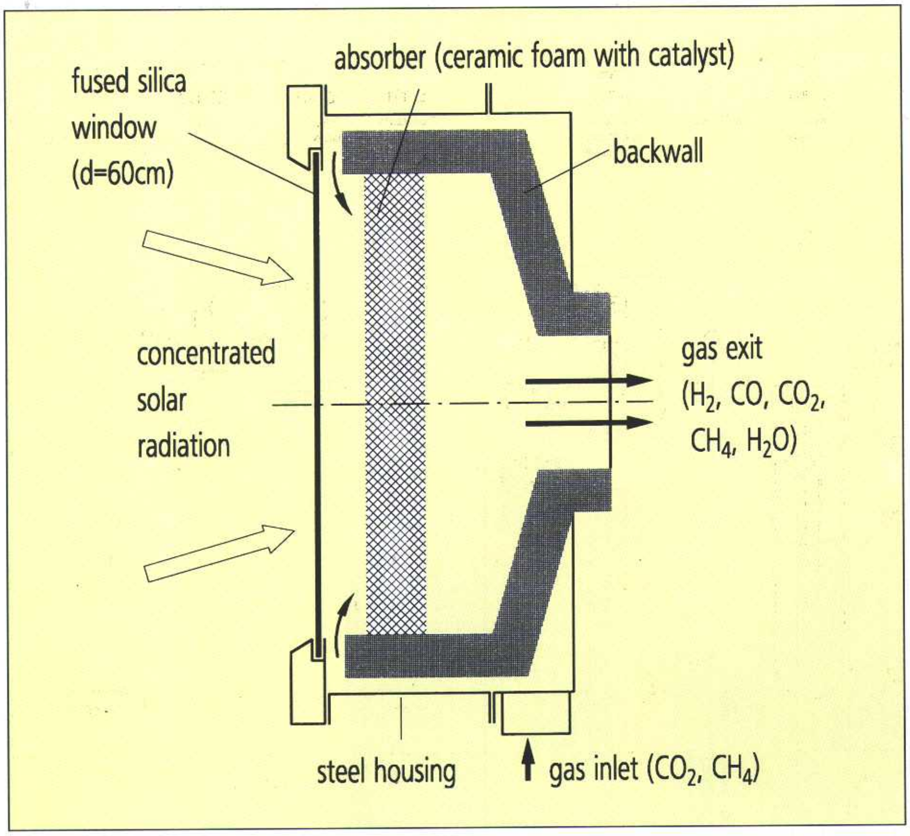


*Figure 2-46.
Principle of the CAESAR experiment and schematic of the volumetric receiver/reactor (Source: DLR)*

Carbon dioxide reforming of methane has been proposed mainly for energy transport. The feasibility of a solar receiver reactor system has been demonstrated by open-loop experiments using a windowed volumetric receiver/reactor. These tests were performed by DLR in Stuttgart using the parabolic dish test facility PAN at Lampoldshausen, Germany, as part of a joint DLR/SNL solar experiment called CAESAR (Catalytic *E*nhanced *S*olar *A*bsorption *R*eceiver) within the IEA-SSPS project. Figure 2-46 shows the conversion principle of the CAESAR experiment, which is a typical integrated process because the receiver and reactor are the same unit. Figure 2-47 shows the test facility at Lampoldshausen in operation. Tests have shown very promising results, but some technical problems still remain to be solved. A closed-loop CO_2 reforming experiment has been successfully performed at SNL in Albuquerque, New Mexico, USA.

*Figure 2-47.
PAN test bed concentrator at Lampoldshausen (SBP parabolic dish) with CAESAR volumetric receiver/reactor (Source: DLR)*

Within a joint project between the Weizmann Institute of Science (WIS), Israel, and DLR-Stuttgart, Germany, a solar methane reforming experimental loop using a volumetric receiver as the solar chemical reactor (SCR) was developed. A schematic of the SCR volumetric receiver/reactor is shown in Figure 2-48. The receiver has a quartz glass window and a secondary reflector. The main component is the directly irradiated alumina foam absorber, which is coated with rhodium as the catalyst for the reforming reaction. Figure 2-49 shows the principle of the SCR experimental loop at the WIS test center in Israel. The center's goal is to demonstrate the closed-loop operation of a reversible chemical storage and energy transportation system.

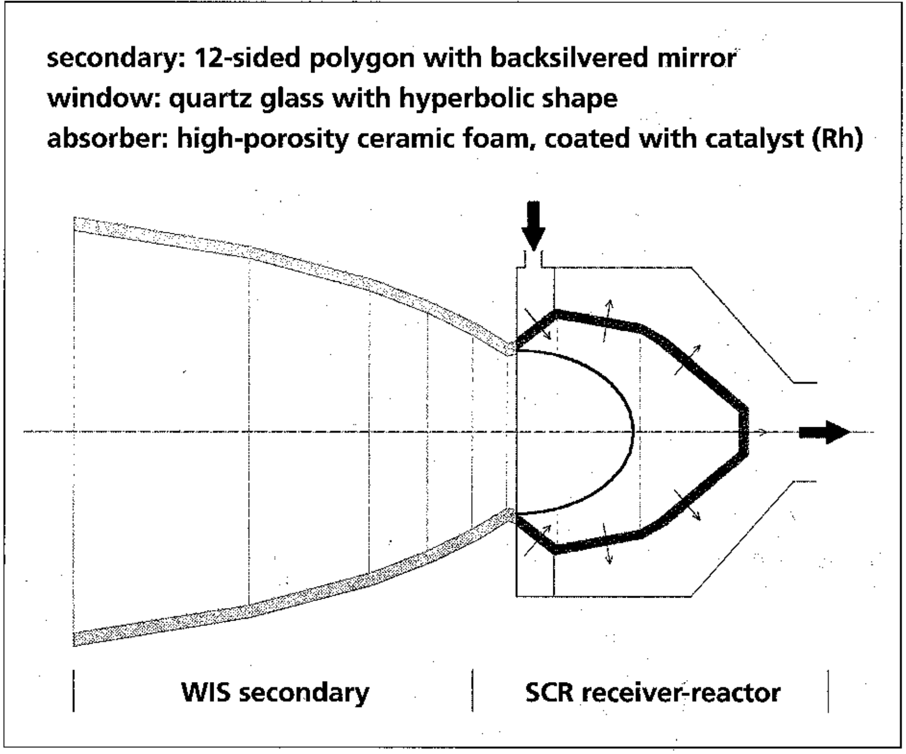
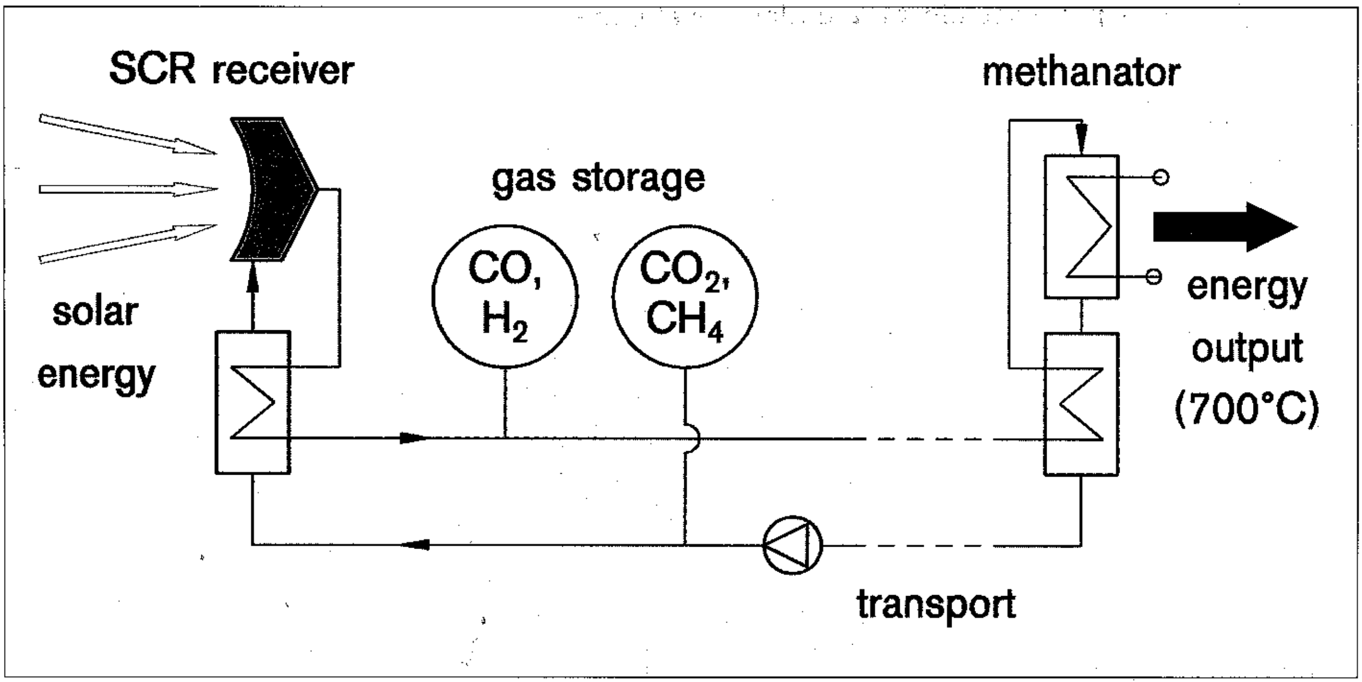


Figure 2-48. Schematic of the SCR volumetric receiver/reactor (Source: DLR)

Figure 2-49. Principle of the SCR experimental loop at the WIS test center (Source: DLR)



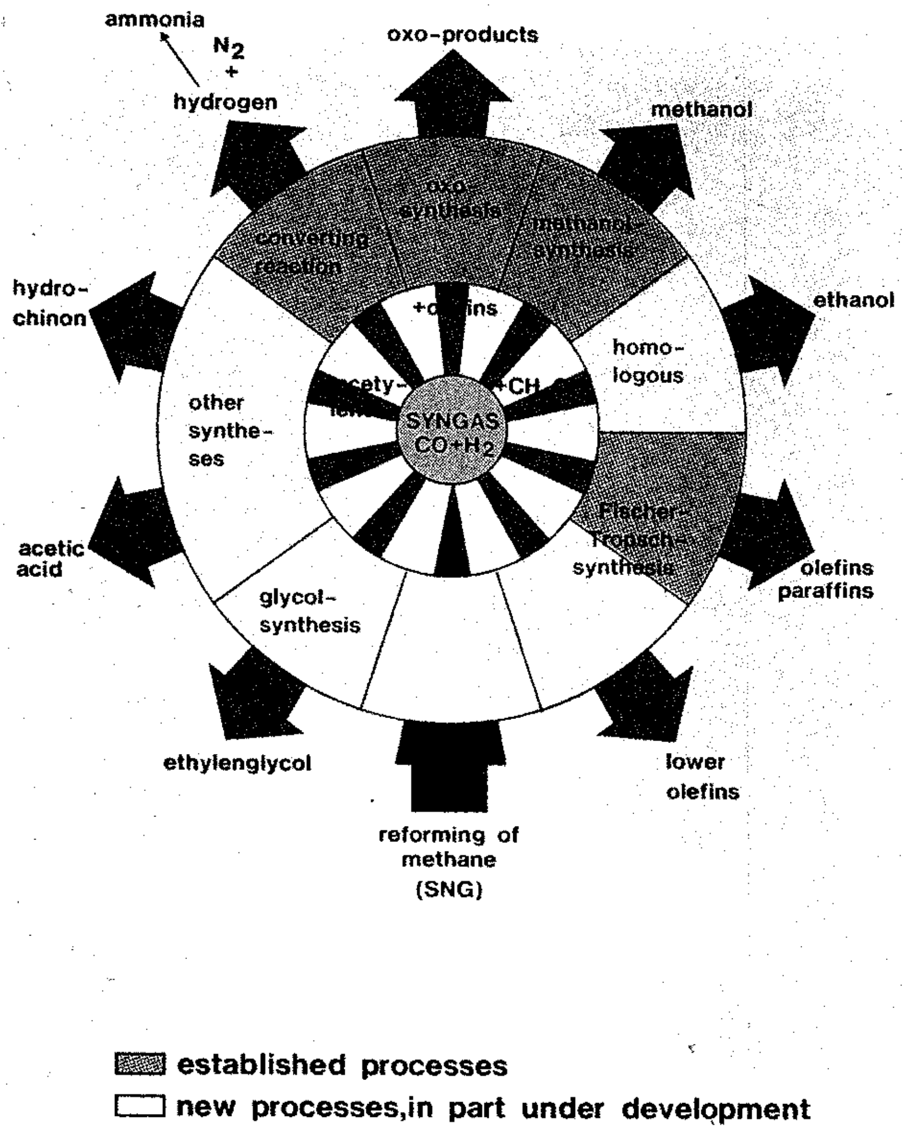


Figure 2-50. Chemical products on the basis of synthesis gas (Source: MAN)

The most important products of synthesis gas are shown in Figure 2-50.

2.3.2.2 Coal Gasification

The conversion of raw materials into chemical products requires energy, mainly in the form of process heat. Hard coal and lignite can be gasified by reacting either with hydrogen (hydrogasification) or with steam or carbon dioxide. The use of solar energy would proportionately improve the yield of synthesis gas compared to alternative coal gasification processes. Reducing the use of coal in gasification processes also reduces many associated environmental problems. Essentially, a solar-powered coal gasification process has the dual advantage of upgrading coal to a more easily utilized form of fuel and of chemically storing solar energy.

Solar gasification of coal can be carried out by several techniques: (1) hydrogasification and steam reforming, (2) pyrolysis, and (3) direct solar coal gasification.

The hydrogasification process is an exothermic reaction with coal and hydrogen (or hydrogen-containing gases) occurring at temperatures of about 800 °C and pressures as high as 80 bar (Figure 2-51). At these high pressures, methane is produced:

$$C + 2H_2 \rightarrow CH_4 + 87 \text{ kJ/mol}$$

Part of this methane is steam reformed in a solar steam reformer (see Chapter 2.3.2.1 for more details). The gas produced in the steam reformer is separated into methane and a mixture of hydrogen and carbon monoxide, which is used as the gaseous reactant in the hydrogen-reaction unit. Excess reactant gas produced during daylight hours can be stored for nighttime operation of the hydrogasification unit. Hydrogasification is also suitable for sulfur-containing coal because the sulfur can be removed in an elementary form.

The pyrolysis process is the initial step in most coal gasification processes. Coal is decomposed into fuel gases, tars, and residue of char, as in the Lurgi-Ruhrgas Process (Figure 2-52), using a fluidized bed reactor. Here, the solar reeiver is integrated with the reactor. Concentrated solar radiation (e.g. from a heliostat field) enters the reactor through an aperture. As they pass the focal area, the coal particles absorb the radiation. The products can then be integrated into existing production structures, e.g. a refinery. The pyrolysis process is followed by coal gasification. This combination of coking and gasification couples solar energy into the process and minimizes contamination of the environment. In addition, the technology can be used to upgrade oil shale and tar sand.

The direct solar coal gasification process uses pulverized coal, which can be gasified by reaction with steam (or carbon dioxide) in the focal plane of a solar central receiver plant. Because the overall reaction is highly endothermic, the product gas has a greater heating value than the initial coal. The necessary energy to drive the endothermic reaction is provided by focused solar energy. Solar energy is thus converted into chemical energy at the same time coal is gasified.

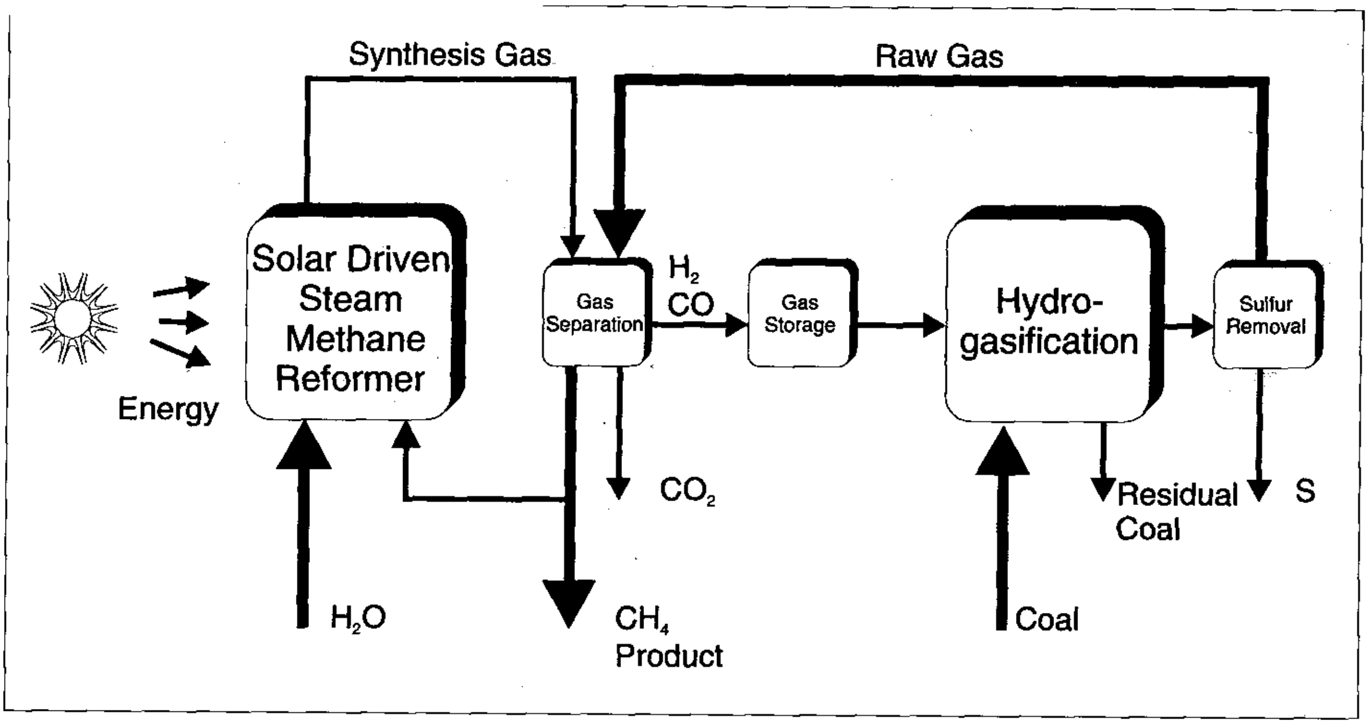


Figure 2-51. Principle of a solar-driven coal hydrogasification plant (Source: Lurgi/DLR)

2.3.2.3 Hydrogen Production from Water

Hydrogen has many applications in the chemical industry, and hydrogen fuel is likely to play a major role in the long-term energy supply. In use, it is converted back to water and is, therefore, environmentally benign. The following processes are suitable for solar hydrogen production from water:

- Electrolysis: hydrogen production process using an electrolyzer and electricity generated by solar thermal or photovoltaic systems
- High-temperature steam electrolysis: hydrogen production process using steam and electricity, which are generated by a solar thermal system
- Thermochemical conversion cycles: hydrogen production process using numerous sequences of two or more chemical reactions using energy generated by a solar thermal system.

For electrolysis, the electricity needed could be generated from solar thermal electric systems described earlier (Chapter 2.1). High-temperature solar heat sources are principally attractive for high-temperature electrolysis and thermochemical conversion processes. High-temperature steam electrolysis is a special thermal/electric electrolytic process, referred to as "HOT ELLY." The process operates at temperatures above 800 °C with solid electrolytes.

Figure 2-52. Principle of a solar-driven Lurgi-Ruhr-gas process (Source: Lurgi/DLR)

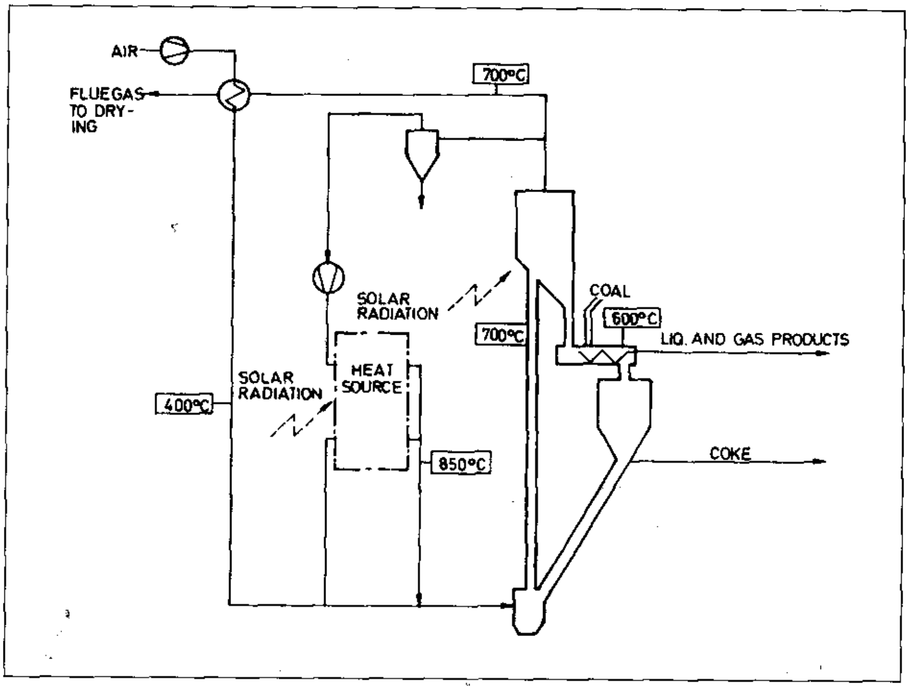


Figure 2-53. Model of the high-temperature steam electrolyzer for hydrogen production, HOT ELLY (Source: Lurgi/Dornier)

Such a high temperature is necessary to secure sufficient ionic conductivity of the solid electrolyte; it is also desirable because the theoretical and practical cell voltage decreases with increasing temperature. Operating temperatures are limited by the strength of the construction materials available today.

Key elements of the electrolyzer are the anode, the solid electrolyte, and the cathode in the form of concentric tubes, electrically connected in series by annular conducting and insulating materials. Steam flows at a high temperature through the electrolysis tubes and is enriched with hydrogen during operation, while the oxygen leaves the anode through the outside surface. The electrolysis tubes are combined to modules. A model of an electrolyzer with this module concept is shown in Figure 2-53. Such a model may be built having a 1000 Nm³ H_2/h production capacity.

For thermochemical conversion cycles, water can be dissociated at temperatures well below the thermal dissociation temperature in a sequence of two or more chemical reactions. Hydrogen (H_2) can be generated from water (H_2O) by bonding the oxygen to a reducing agent A to form another oxide AO_x. If a reaction can be found in which AO_x is reduced back to A and Oxygen (O_2) is set free, the net result is a thermochemical water splitting with the regained reducing agent A. This reaction sequence is advantageous if moderate reaction conditions can be chosen. A common feature of thermochemical cycles is the potential for high process efficiencies (50% and more).

The sulfur-iodine process developed by the General Atomic Company (GA) in the USA is the most advanced among many proposed approaches. A principle of a solar-driven GA process using a volumetric receiver at gas temperatures in the range of 900-1200 °C is shown in Figure 2-54.

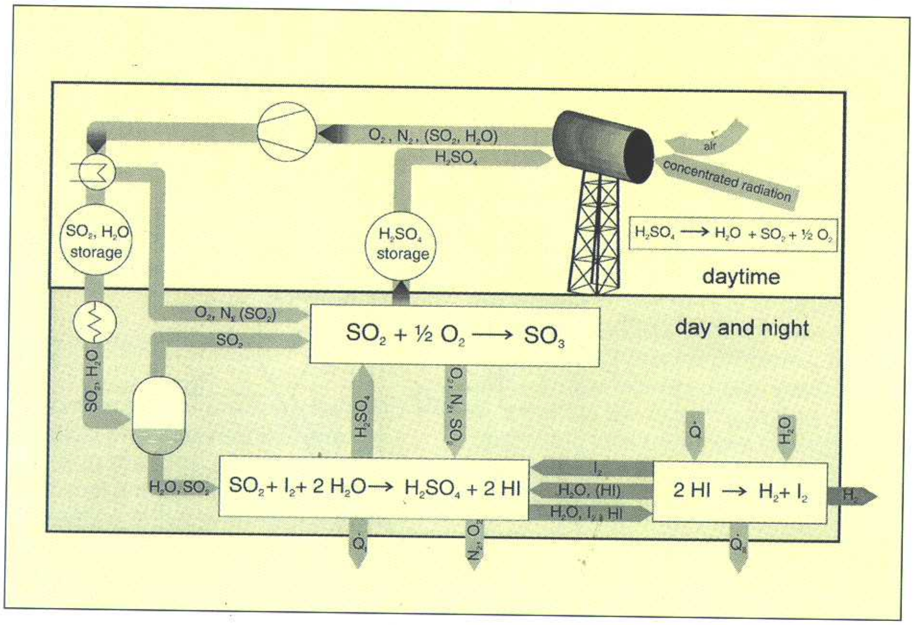


Figure 2-54. Principle of the solar-driven General Atomic process for hydrogen production (Source: RWTH/DLR)

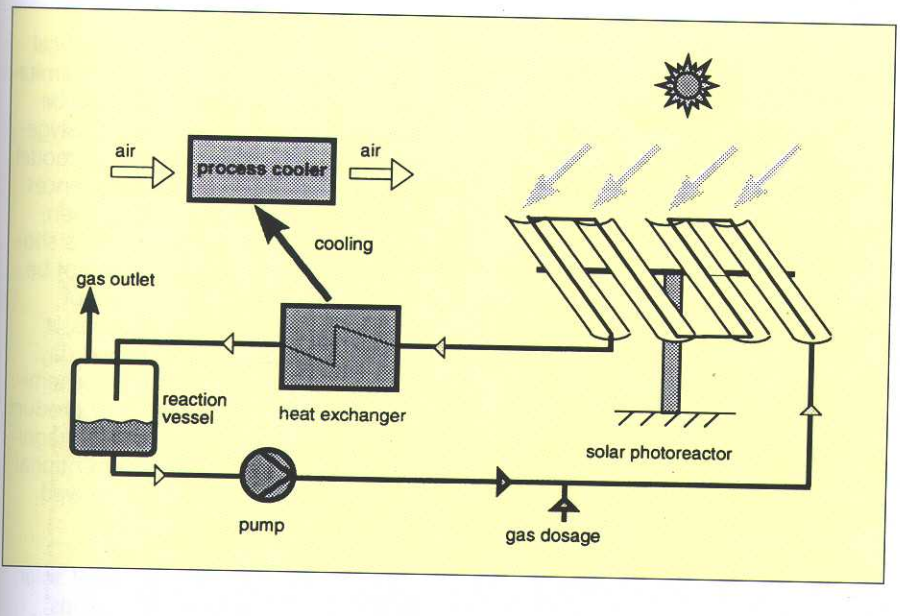


Figure 2-55. Schematic of the PROPHIS test facility for solar photochemical syntheses of chemicals (Source: DLR)

2.3.2.4 Synthesis of Fine Chemicals

The solar photochemical synthesis of fine chemicals can become one of the most promising near-term industrial applications. Today, photochemical syntheses only play a minor role in the chemical industry, and only in some special cases. The main reason is that the operation costs (lamps and electricity) are extremely high. However, photochemical syntheses often proceed very selectively, and some compounds of interest can be produced economically by photochemical means. Energetically and exergetically the conversion of a fossil fuel via electricity to artificial light is very inefficient, if the photochemical system could utilize near-ultraviolet or visible light. Solar radiation can be used directly for the refinement of basic or intermediate chemicals in applications where the artificial light costs are a substantial fraction of the total production costs.

In 1994, DLR in Köln constructed the PROPHIS test facility (parabolic trough facility for solar photochemical syntheses of chemicals) shown in Figures 2-55 and 2-56. The aim of the facility is to prove the feasibility of small-scale photochemical production using a modified MAN Helioman parabolic trough collector. A previous experiment of solar photochemical syntheses of fine chemicals (SOLARIS) was successfully performed by joint cooperation of DLR in Köln and the Technical University of Aachen (RWTH) on the Plataforma Solar de Almería in

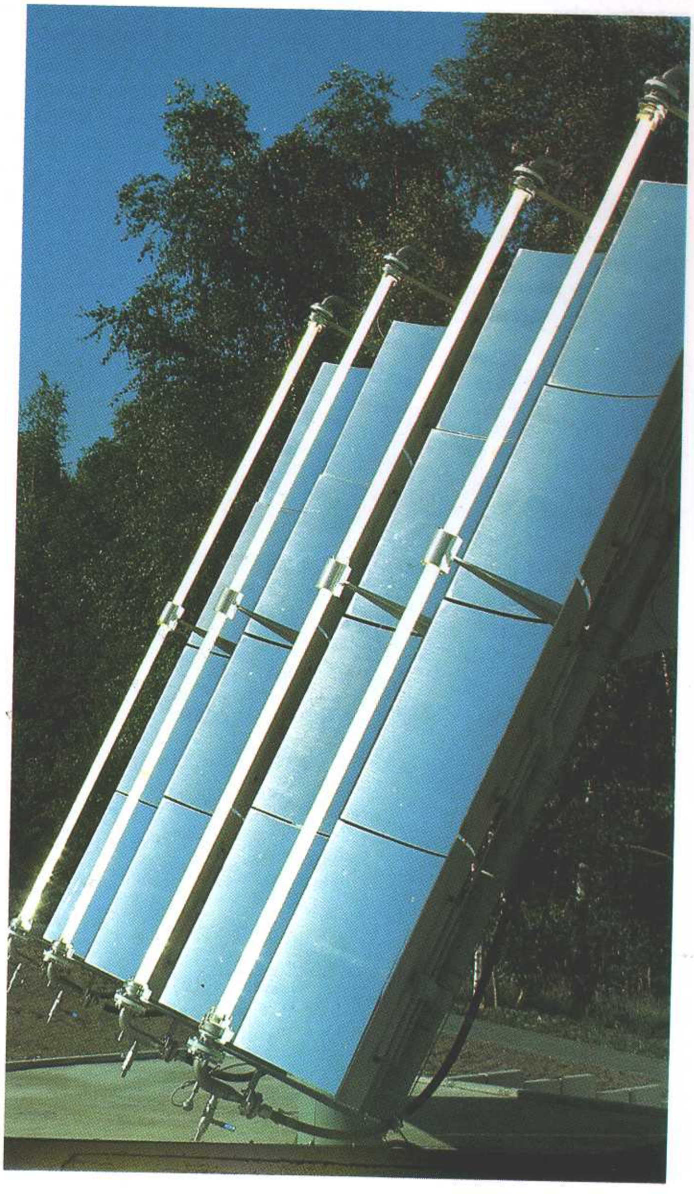


Figure 2-56. The PROPHIS test loop at DLR in Köln (Source: DLR)

Base Material	Reaction	Temperature Range	Product
$CaCO_3$	Thermal Dissociation	900 – 1100 °C	$CaO + CO_2$
$2CaSO_4 \cdot nH_2O$	Thermal Dissociation	1200 °C	$CaO + SO_3 + H_2O$
$Ca(OH)_2$	Thermal Dissociation	500 °C	$CaO + H_2O$
$CaO + 3C$	Carbothermal Reduction	1900 – 2100 °C	$CaC_2 + CO$
$2Al(OH)_3$	Thermal Dissociation	1200 – 1300 °C	$Al_2O_3 + 3H_2O$
$Al_2O_3 + 3C$	Carbothermal Reduction	2000 °C	$2Al + 3CO$
$SiO_2 + 2C$	Carbothermal Reduction	2000 °C	$Si + 2CO$
$SiO_2 + 3C$	Compound Formation	2200 – 2400 °C	$SiC + 2CO$

Table 2-11. List of high-temperature reactions for potential solar energy applications (Source: DLR)

"solarized" photoreactions, practical knowledge of the feasibility and limitations of solar photoreactions will be studied. For example the photooxygenation of furfural served as one model reaction. Total production efficiences with wavelengths $\lambda < 700$ nm were approximately 15%. Experiments showed that if the reaction could not be completed in one day because of insufficient insolation conditions, it could be started again the next day. Data show that for solar photochemical reactions, energy per kg of product needed is in the same order of magnitude as is needed by the conventional process using artificial light derived from electric energy.

Based on experience, the use of solar radiation instead of electric lamps looks very attractive for photoreactions. Additional promising applications are the syntheses of fragrances such as rose oxide, terpineol, myrthenol, and of vitamins, which are produced industrially in quantities of several tons per year. Additional tests are being prepared to improve the technique and modify the reacting systems.

2.3.2.5 Other Upgrading Processes

Several other high-temperature reactions may be adapted in the future for solar thermochemical applications (see Table 2-11). Highly absorbing compounds and reaction temperatures above 800 °C are necessary to benefit from the high-temperature capabilities of solar energy.

Calcium oxide (CaO), an important raw material for the ceramics and building material industries, can be produced by thermal dissociation of limestone ($CaCO_3$), calcium sulfate ($CaSO_4 \cdot nH_2O$) or calcium hydroxide ($Ca(OH)_2$). Cement can also be produced by mixing the calcic base material with oxides (SiO_2, Al_2O_3, Fe_2O_3), or with clays (e.g. hydrous alumina silicate) before the thermal reaction takes place.

The reactions listed in Table 2-11 could be used principally in solar calcination processes, e.g. by employing a solar beam in the precalcining stage of a modern cement production factory. Solar energy would save fuel, but would not completely replace fossil fuel in this application. Decarbonation

Figure 2-57. Testing the atmospheric open solar cyclone reactor on the 60-kW parabolic test bed concentrator of PSI for decarbonation of limestone (Source: PSI)

of $CaCO_3$, an endothermal reaction that takes place at 900 °C, has been identified as a potential candidate for solar energy application.

In Switzerland, at the Paul Scherrer Institute (PSI), the solar thermal decomposition of $CaCO_3$ was examined. This endothermal reaction has been selected as a model gas-solid reaction in order to demonstrate the feasibility of an atmospheric open solar cyclone reactor (Figures 2-57 and 2-58). This new reactor concept offers a high energy transport efficiency and allows a continuous mode of operation with respect to reactant feed and product separation as well as removal.

The cement production process is another possible solar energy application. In this process, the raw mixture of minerals is preheated in cyclones by exhaust gases and enters a rotary kiln at about 800 °C, where it is first calcinated and then sintered to klinker brick.

Although the decarbonation process of limestone has been selected by PSI as a model reaction to get some insights in the design of solar reactors containing a gas/particle-suspension,

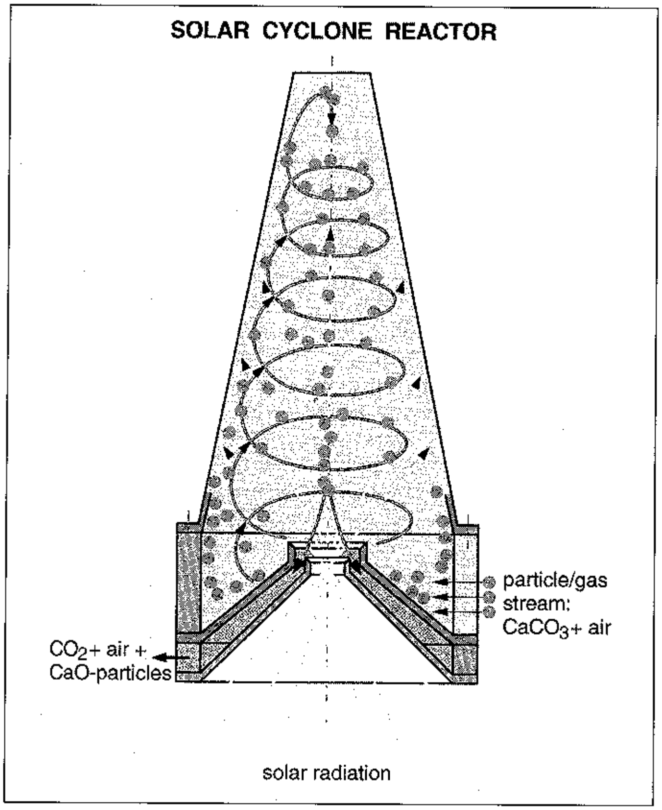
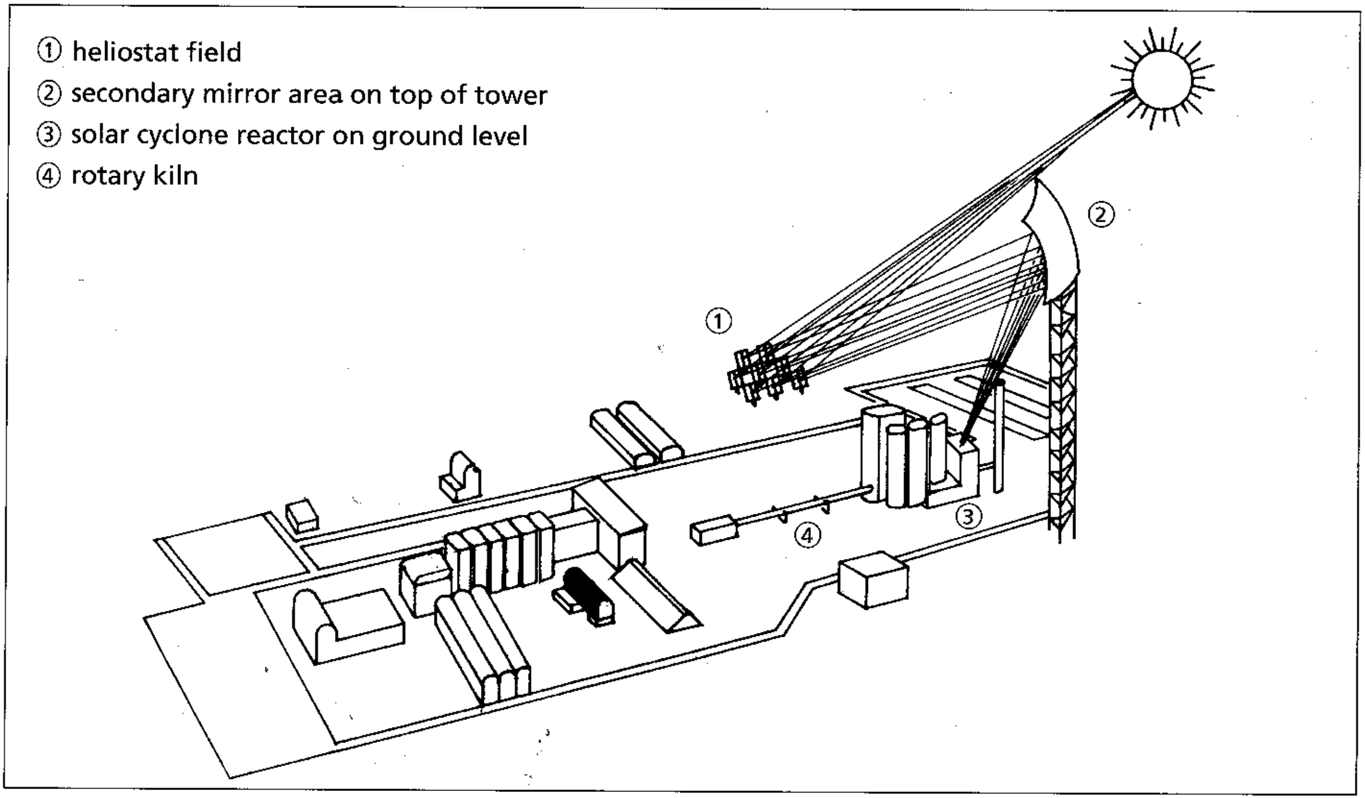


Figure 2-58. Schematic of the open solar cyclone for test on the 60 kW parabolic concentrator at PSI (Source: PSI)

Figure 2-59. Concept of solar calcinator plant (Source: PSI/DLR)



this process might be of some interest for the cement industry in third world countries, where good boundary conditions (raw materials, solar radiation, etc.) are given. A concept for a combined solar/fossil fired precalcinator is shown in Figure 2-59. The calcinator unit is modified for use as a solar reactor placed inside the plant. The solar radiant beam will be reflected into the reactor (e.g. solar cyclone reactor) by a secondary mirror area mounted on the top of a tower. The interior design of the solar reactor has to act as ideal cavity.

A conventional cement-producing installation works around or slightly below atmospheric pressures. The process may be modified so that the radiation inlet aperture of the receiver/reactor can be left open. The incident beam would be absorbed partly by the mixture of raw material and air (particle cloud) suspended in the beam and partly by the rough surface of the brick walls of the cyclone. The nonabsorbed part of the radiative energy would be reflected almost isotropically, thus creating a more homogeneous flux distribution in the cyclone reactor.

Other opportunities for upgrading raw materials using solar concentrating technologies may involve heavy oil, tar sand, biomass, oil shale, and natural gas. However, R&D work in these areas has just begun.

2.3.3 Materials Processing

Solar materials processing using highly concentrated solar radiation generated by a solar furnace is a new field of solar applications. Researchers at NREL in Golden, Colorado, have investigated the use of their High-Flux Solar Furnace (HFSF; see Chapter 5) for processing advanced materials and coatings. Advanced materials synthesis and processing in a solar furnace are particularly attractive when the only way to achieve the desired product is to employ radiant sources of energy. Typically, these processes are surface-specific, use extremely high temperatures, or both. A further advantage of a solar furnace is the possibility of applying very high temperatures in oxidizing environment which is not possible or at least not easy to realize in conventional furnaces. Several capabilities have been successfully demonstrated, including surface hardening, cladding, controlled decomposition of organometallic precursors, initiation of self-heating synthesis (SHS) reactions, thermal treatment of preapplied coatings, and film growth via cold-wall chemical vapor deposition. Each of these processes and its importance in advanced materials is briefly reviewed below.

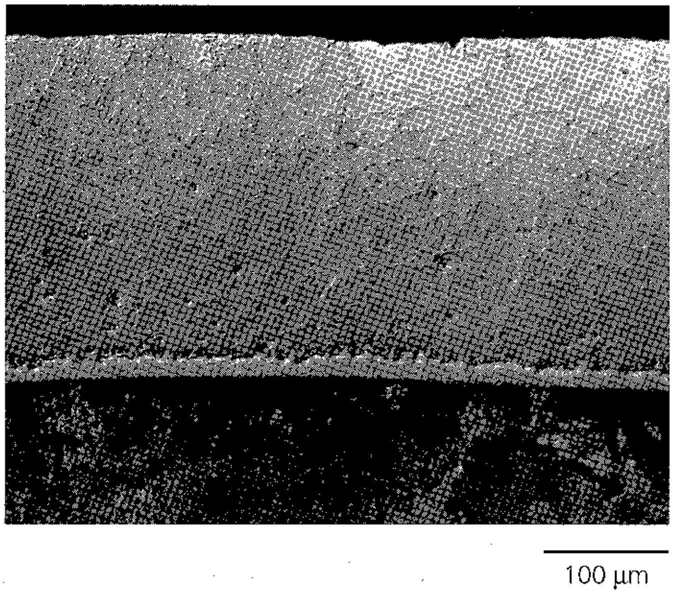


Figure 2-60. Cladding of preapplied powders using a solar furnace (Source: NREL)

2.3.3.1 Transformation Hardening of Steel

Transformation hardening is the process of transforming steel to martensite. For some applications, a hard, wear-resistant surface with a softer ductile matrix is desirable. Examples are plow blades, roll mills, cylinder liners for reciprocating engines, camshafts, bearings, and wear plates. To achieve this, it is necessary to preferentially heat the surface. Typical methods of applying heat to the surface include flame, induction, or laser heating. A new technique for surface hardening of steel, laser transformation hardening, is now being used by the automotive industry for engine and drive-train components. Industry acceptance of laser transformation hardening encouraged solar researchers to develop a data base for the solar hardening of steel. Experimental confirmation of surface hardening of steel using concentrated solar radiation and a favorable economic comparison between a laser facility and a solar furnace further encouraged an examination of this application for solar furnace technology.

2.3.3.2 Cladding of Preapplied Powders

It is sometimes desirable for a material's surface to exhibit particular properties that may either be incompatible with desired bulk properties or too costly to achieve throughout the material. Examples are valve seats and stems used in corrosive or abrasive environments, aircraft and steam turbine blades subject to high-temperature erosion, bearings subject to high loads and excessive wear, corrosion-resistant containers, cutting blades, and dies. To achieve this result, techniques such as plasma spray coating, laser melting of powders, and shock cladding have been developed to apply desired surface coatings. Although these techniques can be used to apply a powder or other substance to a surface, post-processing may be necessary to improve the adherence of the films to the substrate, close or mitigate porosity, or cause solid-state chemical reactions to take place in the film to form the desired phases. A solar furnace can be used to melt powders onto substrates as well as post-process films applied by other means. Figure 2-60 shows an example of an aluminum powder applied to a steel substrate using a solar furnace. In this example a steel substrate has been clad with a combination of aluminum (middle layer) and powder (top layer) showing that multiple metallic layers can be applied in a single-step process.

2.3.3.3 Self-Heating Synthesis

Some mixtures of powders will react with the release of energy. Once initiated, the exothermic reaction becomes selfsustaining and will propagate through the reaction mixture. The self-heating synthesis (SHS) initiation has been demonstrated in the high-flux solar furnace using powders of aluminum and nickel and multiple layers of vacuum-deposited thin films. When exposed to thermal pulses in the solar furnace, such powders and films add their reaction heats to the solar beam, allowing temperatures to reach the melting point of refractory metals and ceramics. High-quality thin films with very narrow heat-affected zones can be produced in this manner.

Modern high-performance ceramics offer unique combinations of properties that make them attractive materials for many applications. Processing techniques are critical for emerging ceramics applications in high-temperature and high-stress environments. Indeed, developing novel techniques for coating and joining ceramic composites is listed as one of the future needs in the ceramics industry. Numerous applications exist for ceramic coatings requiring retention of mechanical properties at high temperature, tribological properties, and corrosion resistance to high-temperature fluids. The use of concentrated solar radiation to initiate and sustain the SHS processes to produce these coatings may provide solutions to the processing problems currently encountered in the ceramics industry.

2.3.3.4 Plasma- and Flame-Sprayed Coatings

Plasma- and flame-sprayed coatings are widely used throughout the industry to provide high-performance coatings and repair worn and eroded parts. A significant shortcoming of these techniques is the porosity of the coating. This porosity results in less than optimum corrosion resistance on many metal components. Also, cracks are initiated and propagated along these voids, resulting in delamination and failure. Another problem with these coatings is adhesion; because of the deposition method, these coatings are attached mechanically, with no chemical bonding at the interface. This provides an easy avenue for chemical or mechanical failure that results in delamination of the coating. Laser-beam treatment of these coatings has been successful but sometimes produces cracking. A logical extension of the solar melting of powders previously described is to use solar beams to remelt, densify, and metallurgically bond preapplied plasma- or flame-sprayed coatings. Preliminary work exploring this possibility has been completed.

2.3.3.5 Metalorganic Deposition

Metalorganic deposition technology is a rapidly growing alternative to electroplating and chemical vapor deposition (CVD) techniques for forming certain types of thin films on solid substrates. Of particular interest are high-quality metal and ceramic films that can be grown using this technique. The organometallic solutions are easily applied, using spray, dip, brush, spin, or ink-jet processes. Ceramic, glass, or metal substrate materials are coated with organometallic solutions that are subsequently pyrolyzed in controlled atmospheres to produce the desired coating. The decomposition products given off in the reactions are normally benign, and there is little or no waste of expensive or strategic materials designed for use in the finished coating. Patterning and control of film thickness and uniformity are easily accomplished. Concentrated solar flux from a furnace can provide the heat necessary for the pyrolysis step. As seen in Figure 2-61, beryllia coupons have been metallized with palladium, platinum, gold and copper. The samples shown indicate the ability to easily apply uniform layers of metal to a ceramic substrate with a unique organometallic/ solar process.

Figure 2-61. Metalorganic deposition using a solar furnace (Source: NREL)

2.3.3.6 Rapid Thermal Chemical Vapor Deposition

Rapid thermal chemical vapor deposition (RTCVP) is a relatively new process whereby radiant energy is directed at the substrate material to control the temperature during an otherwise conventional chemical vapor deposition (CVD) process. Heating with radiant energy provides an extremely clean (cold-wall) environment and very rapid thermal response of the target surface. A variant of this process has been explored by NREL researchers, using a concentrated solar beam as the radiant input for the CVD process. Figure 2-62 shows a vacuum chamber and apparatus at the high-flux solar furnace. The vacuum chamber allows for both high-vacuum and controlled atmosphere experiments. A gas manifold system provides flow and pressure control of gas mixtures into the chamber. A quartz window admits the concentrated sunlight. The system is primarily used for ceramic metallization and diamond-like thin film experiments. The solar-induced process has several advantages: the energy can be delivered over very large areas, it can be shaped to match a process line or piece of work, it can use much higher fluxes than those available in conventional rapid thermal processing systems, and the radiation comes in a broad band extending from 0.5 to 4.0 eV. In addition, system studies indicate that the delivery of energy to the target is cost effective, compared with that of more conventional radiant sources.

An application area of RTCVD processing that looks particularly promising for the use of solar radiation is the growth of diamond films and other ultrahard coatings. These coatings are used in a number of technological areas in which hardness, abrasion resistance, maintenance of cutting edges, and extreme optical, electronic, or thermal performance is necessary. The coatings add a large value to their substrate materials, and often can be fabricated only by using relatively exotic (expensive) techniques that are very energy intensive. Initial experiments at NREL conducted under conditions similar to those required for producing some of the ultrahard coatings have been successful. For example, diamond-like carbon films have been produced in the solar furnace. A significant opportunity exists for improving the synthesis and processing of ultrahard coatings, including thin diamond films. Films such as SiC, TiB_2, TiN, BN, and diamond have been identified as candidates for solar-based CVD processing.

2.3.4 Laser Pumping

The ability to generate high flux at reasonably high power levels will open a variety of new applications and enhance the prospects for solar-pumped lasers. With the improved efficiency and high-output power made possible by solar pumping, lasers can become a competitive source of energy compared to electrical or laser pumping for a wide range of photochemical applications that are not economically feasible now. Solar pumping is expected to have the potential to be more efficient than does electrical or laser pumping. Solar-pumped

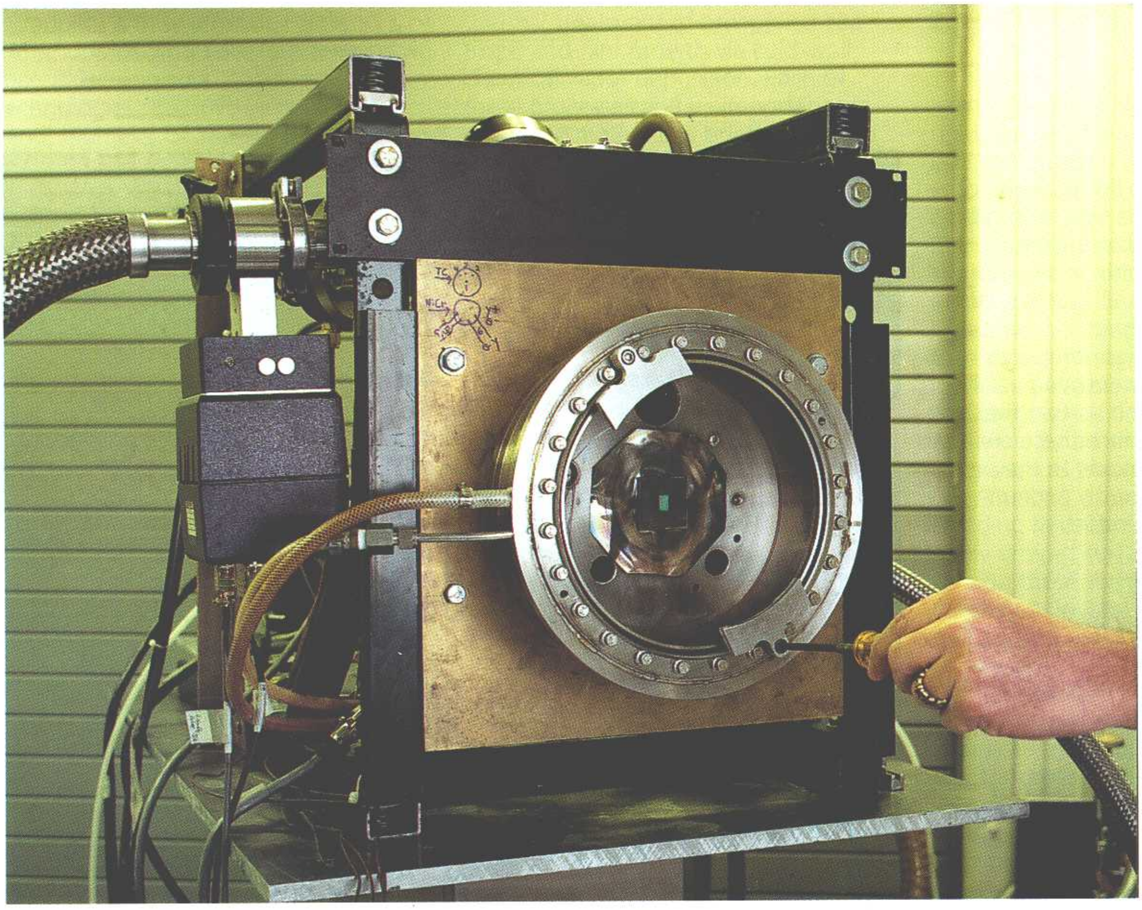


Figure 2-62. Vacuum chamber used with a solar furnace for chemical vapor deposition at NREL (Source: NREL)

lasers could be larger, as well. Israel's Weizmann Institute of Science (WIS) has demonstrated a continuous wave laser at a peak power output of 100 W. WIS erected a test set-up for simultaneous pumping of a solar laser and solar cells (Figure 2-63). This test was placed in the WIS solar tower test facility and used a secondary concentrator with a 1-m diameter. Even larger lasers are feasible with the high-threshold flux that is possible using high-index secondary reflectors. Solar concentrators to deliver high-input power (for a laser) are entirely feasible and can be made relatively inexpensive. More R&D is needed, however, to define the appropriate coupling between the concentrator, the high-index secondary reflector, and the laser crystal. With continued research in this area, a new set of opportunities in laser applications could become accessible.

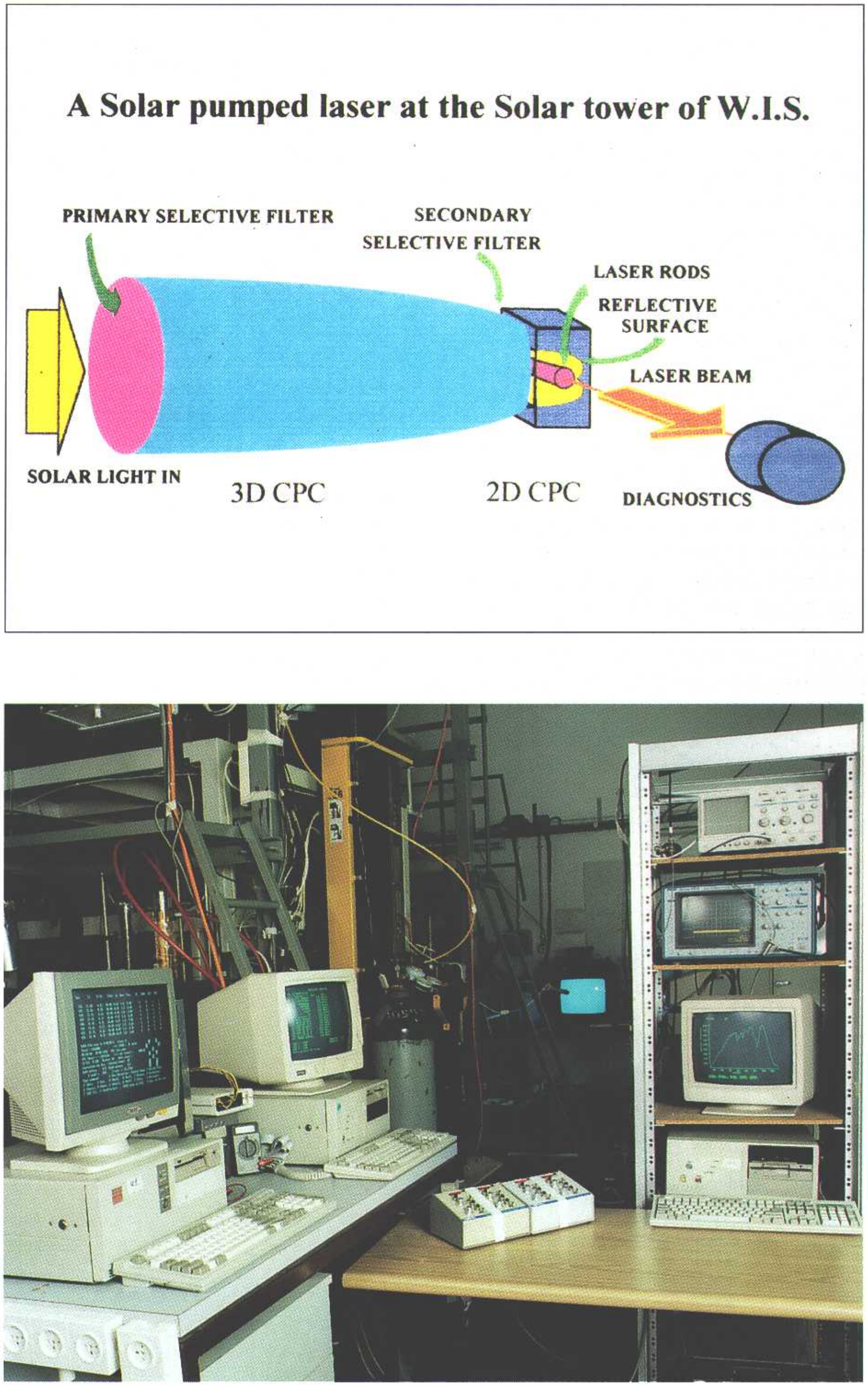


Figure 2-63. Schematic and test set-up of solar laser pumping at WIS (Source: WIS)

2.3.5 Application Studies

Since the beginning of solar thermal power plant development in the late 1970s, the high-temperature, high-flux energy of concentrating systems (central receiver and parabolic dish) has been studied for technological application in producing solar fuels and chemicals. Besides solar chemistry applications, the low and medium-temperature solar process heat (particularly of the low-concentrating parabolic trough system) has been studied for industrial applications such as food, clothing production, and oil refining.

Over the years, many reports of experiments, tests, and studies have been published, covering the entire field of solar process heat and solar chemistry. This field of R&D is growing each year, and attractive applications of solar energy and solar flux have been proposed. Critical R&D work continues, particularly in the USA (e.g. at NREL and SNL) and in Europe (e.g. Germany: DLR, various universities; Spain: CIEMAT; France: CNRS; and Switzerland: PSI). Many of the solar chemistry technologies studied concern long-term applications for which challenging technological problems related to high-flux and high-temperature requirements are yet to be investigated, and better understanding of the phenomena is needed.

3.1 Central Receiver Systems

Chapter 2 described central receiver systems and their applications from system and operating plant viewpoints. In the following sections, central receiver systems are described from a technology viewpoint; their subsystems, particularly the solar-specific components, are explained in some detail. The central receiver plant comprises the following main subsystems:

- Heliostat field (a large array of heliostats including control equipment)
- Receiver, where the incident solar energy is absorbed; mounted on top of a tower at the focus of the heliostat field
- Heat-transfer system, which transports the thermal energy from the receiver to the electric power generating system
- Thermal storage (if applied), where solar energy is stored and discharged when required
- Supplementary fossil-fuel firing system (if applied)
- Electric power generating system comprising the steam generator and the turbine-generator (if used for electricity generation)
- Plant control, auxiliary power supply, and heat rejection.

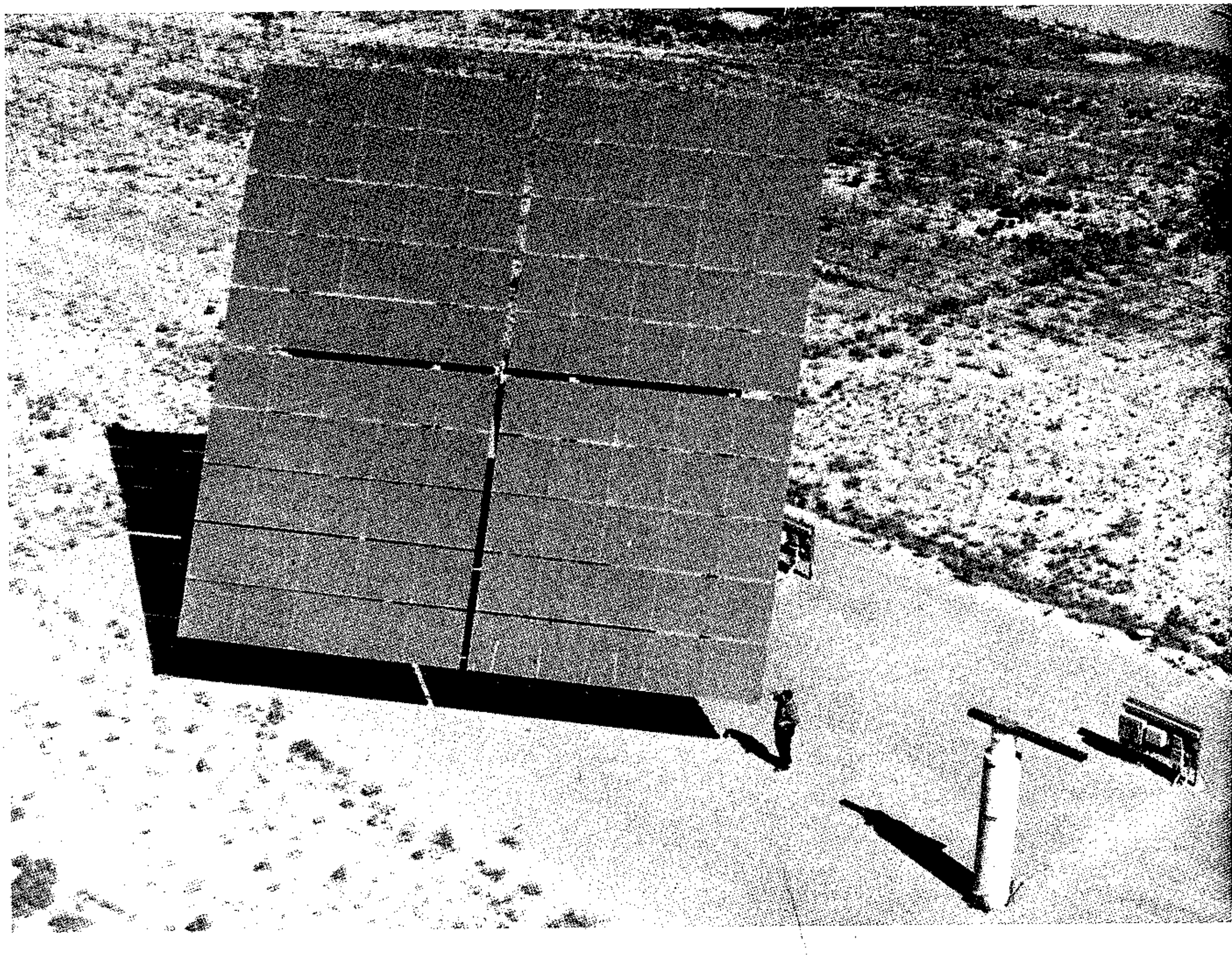


Figure 3-1.
The 150-m² glass/metal heliostat test unit of ATS (USA) at SNL (Source: SNL)

3.1.1 Heliostat Technologies

The heliostat field is the largest single capital cost item of a central receiver system. While R&D aims for lower cost and highly efficient designs, two main heliostat designs are currently considered to be economically favorable:

- The glass/metal heliostat type for current and near-term applications (Figures 3-1 and 3-2)
- The stretched-membrane heliostat type for future applications (Figures 3-3 and 3-4).

Many alternative designs for glass/metal heliostats (back-silvered glass mirrors supported by a metal structure) have been built and tested, mainly in the USA and Europe. The glass/metal heliostat is the more developed of the two designs. Proven heliostats of up to 150-m² reflective area are available today. A heliostat prototype of 200-m² reflective area (SPECO) was the largest unit tested up to now at SNL in Albuquerque (USA). The stretched-membrane heliostat is an innovative design currently under development for future low-cost heliostats. The stretched-membrane heliostat uses light-weight materials and structural design concepts to reduce capital costs. Two approaches are being evaluated. In one, a reflective polymer film membrane is attached to the front side of a thin pretensioned metal membrane structure, while in the other back-silvered thin glass mirrors are glued to a thin pretensioned metal membrane. The membranes form a self-supporting low-weight structure in conjunction with the metal frame by forming a slight vacuum in the plenum between two membranes (Figure 3-5). A special vacuum control ensures exact focusing of the beam onto the receiver and allows easy defocusing by increase of pressure.

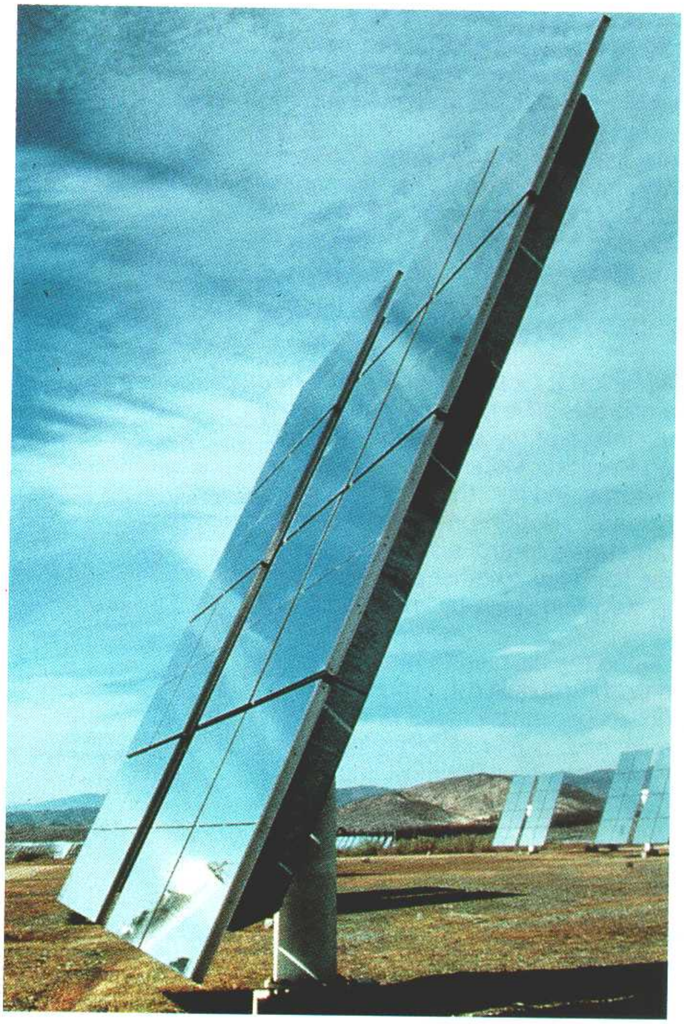


Figure 3-2.
The 52-m² glass/metal heliostat test series units (MBB, ASINEL) of the GAST Technology Program (Germany/Spain) on the PSA; 65-m² GAST units (ASINEL) also on site (Source: DLR)

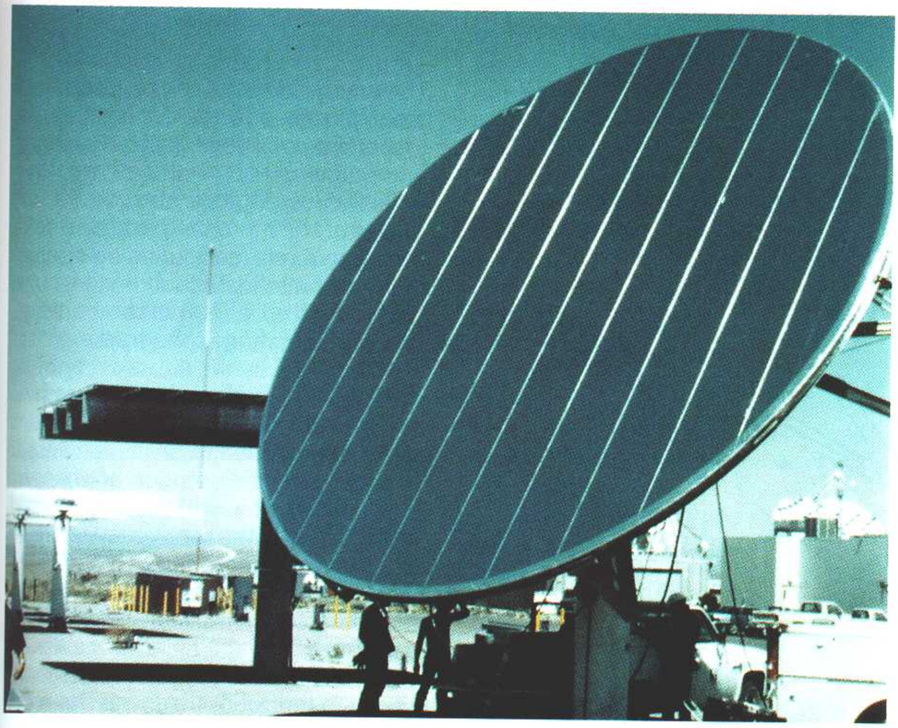


Figure 3-3.
The 50-m² stretched-membrane heliostat prototype of Solar Kinetics, Inc. (USA) at SNL (Source: SNL)

An actual test program comprises three large-area heliostat test units of 100-m^2 respectively 150-m^2 reflective area, which are being erected and tested by Spanish and German industrial teams on the Plataforma Solar de Almería (PSA): two 100-m^2 glass/metal units of different design (CIEMAT, Jupasa, Pujol); one 150-m^2 stretched-membrane unit (LCS, SBP, FDE). This program aims at the 30-MW$_e$ PHOEBUS power plant project.

All heliostat types currently in use have a two-axis drive mechanism to keep the image of the sun on the receiver. An electronic system controls each heliostat and also the total heliostat field to track the sun on the receiver target. The control system also moves the heliostats to other positions, such as stow and stand-by, as needed.

During the past ten to fifteen years the heliostat capital cost, expressed in dollars per square meter of reflective area, have been reduced remarkably (see Figure 3-6). The most important features of this evolution are the continual design cost reduction and the increase of the reflective mirror area.

Figure 3-4.
The 44-m^2 stretched-membrane heliostat prototype of SBP (Germany) on the PSA
(Source: DLR)

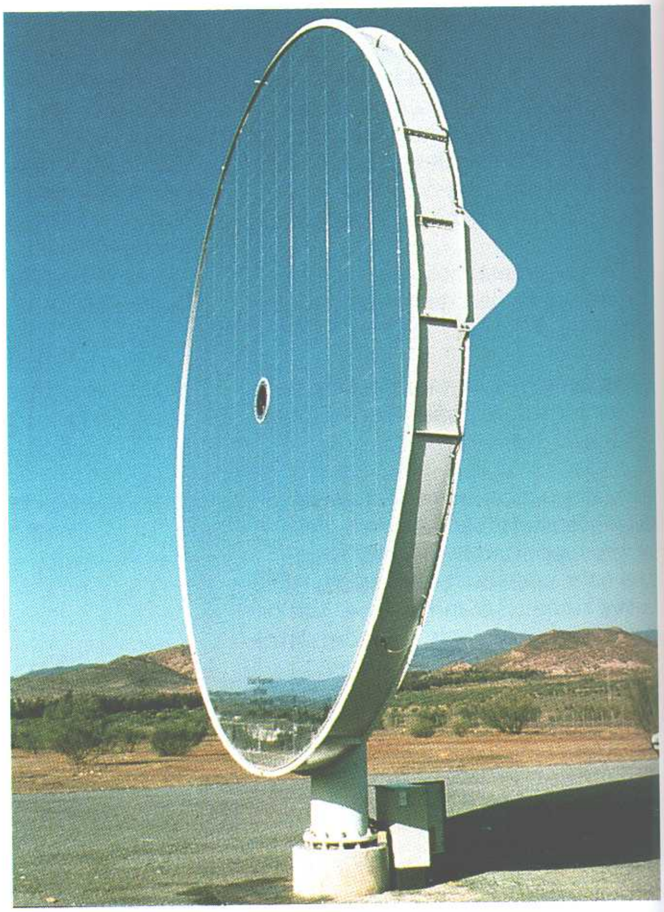
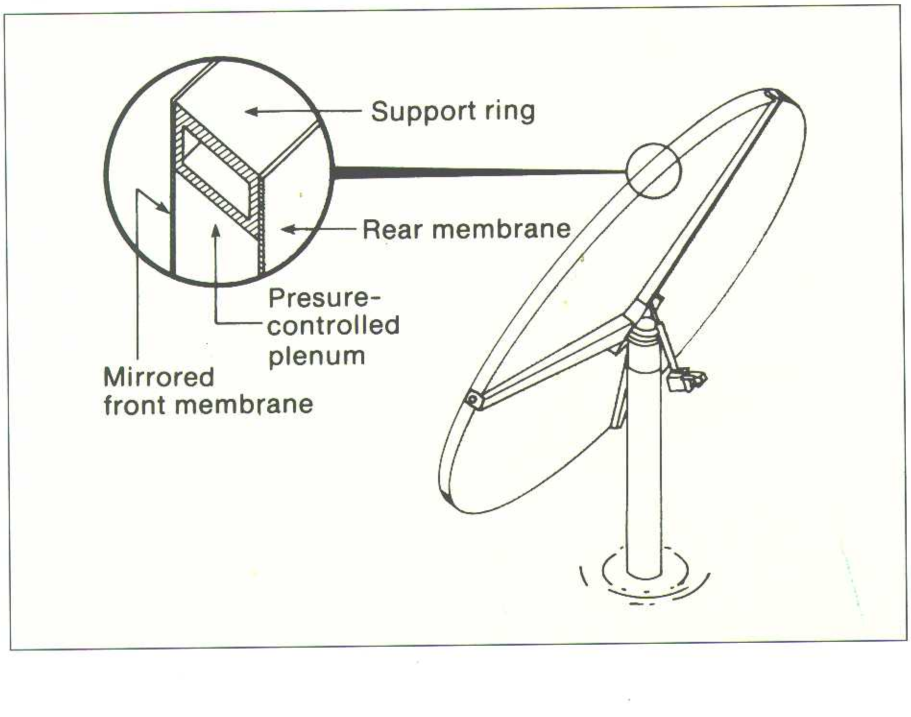


Figure 3-5.
Principle of stretched-membrane heliostat
(Source: NREL and SNL)



The energy losses of the heliostat field are determined by the cosine losses (depending on the angle of incoming and outgoing rays on the mirror), the reflective losses (depending on the quality of the mirror and its cleanliness), the beam errors (depending on enlargement of the reflected sun image, caused by the optical heliostat quality and the slant range), the tracking errors (caused by the two-axis controls), the blocking/shading (interactions between the heliostats because of the spacing), and the atmosphere (caused by atmospheric absorption of energy in the reflected beam). Additional field losses occur at the receiver aperture, where the concentrated beam enters the aperture with less than 100% of the beam energy (spillage losses). The performance of the heliostat field is expressed in terms of the field efficiency to represent the losses incurred.

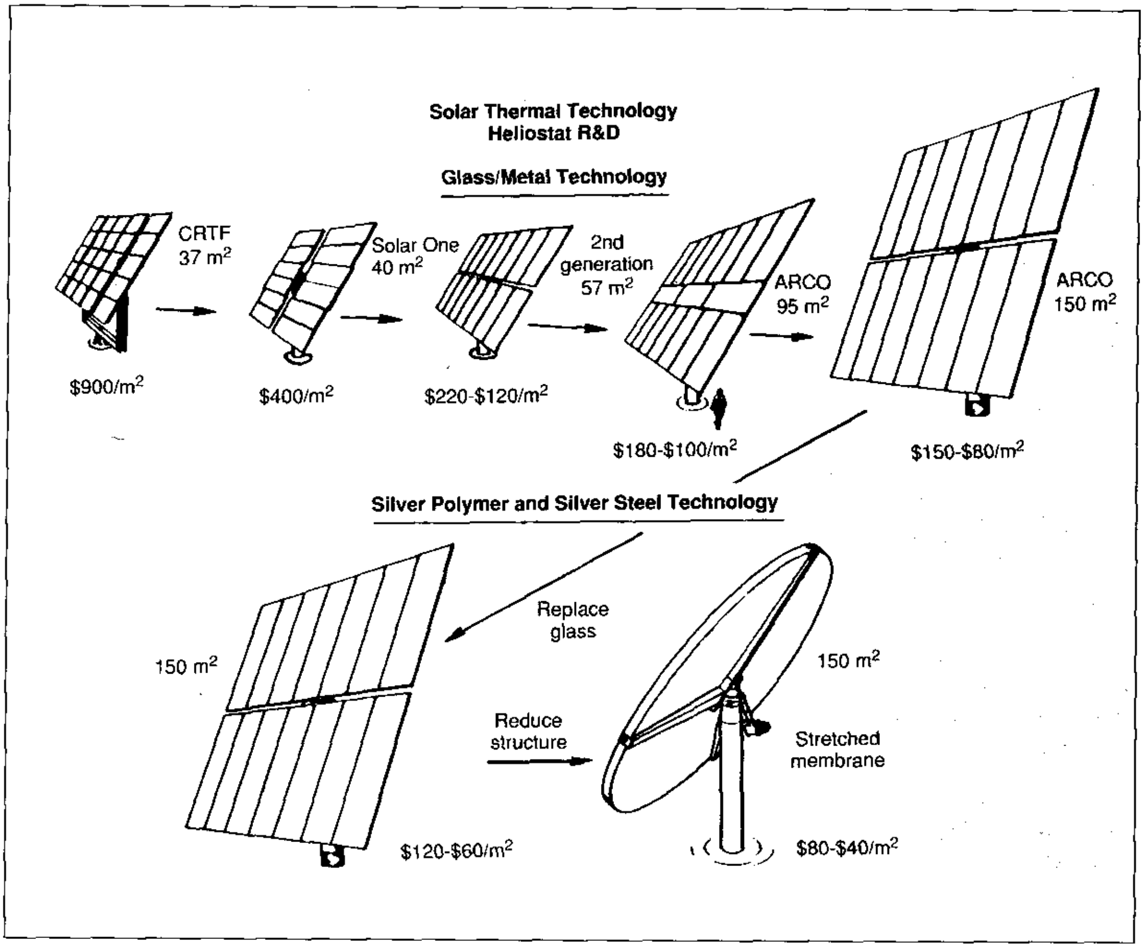


Figure 3-6. Pictorial representation of heliostat development, prices in 1986 $ (Source: SNL)

3.1.2 Receiver Technologies

The solar receiver absorbs concentrated radiation, which causes much higher heat-flux densities than conventional industrial heat exchanger technologies. Because passing clouds cause rapid operating transients, receiver design is a major technical challenge. Hence, receiver development and its operational reliability are the most important R&D activities for central receiver systems today. Until some years ago the tube receiver, similar to an industrial heat exchanger, was the mainly used receiver type. Various experimental designs have been built, tested, and operated; the designs use different receiver heat-transfer media such as water/steam, molten salt, liquid sodium, and air.

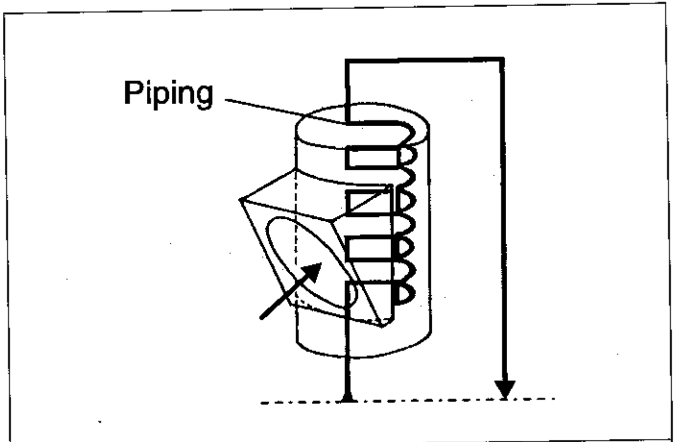
In the central receiver system, a single receiver is used. Unlike heliostats, whose cost reduction can also be achieved by mass production, capital cost reduction in receivers will result from improved design, increased receiver efficiencies, the use of highly efficient materials, high reliability, and low maintenance costs. Receiver design depends considerably on the ratio of the concentration of radiation, the type of heat-transfer medium, the range of working medium temperatures (approximately 500 °C up to more than 1000 °C), and the method of energy transfer from the receiver to the power conversion system or the end user of the thermal energy.

The energy losses of the receiver are mainly determined by reflection, re-emission, and absorption of energy in the concentrated beam reaching the receiver. The absorbed energy is thermal energy that is transferred by the heat-transfer medium to the end user.

Typical principles are illustrated in Figures 3-7 and 3-8.

Two tube receiver designs have been evaluated. One, in which an absorber made from tubes is placed within a shell (cavity type), and the other in which the tubes form the surface (external type) of the receiver body. Fluids (molten salt, liquid sodium, water/steam) and air are used to cool the absorber tube panels by removing the absorbed solar energy. These types of receivers are the most common today. When the tube panels are housed in a cavity with an aperture facing the heliostat field, re-emission losses are reduced (mainly caused by infrared radiation being emitted from the hot absorber surface). Cavity type receivers were used at the Thémis, IEA-SSPS-CRS (Sulzer receiver), and the CESA-1 experimental plants. External-type receivers allow more design flexibility in the arrangement of the heliostat field and the size of the plant. External receiver types were used at the Solar One plant, IEA-SSPS-CRS (Agip/Franco Tosi receiver), and

Cavity
Conduction through Tube Wall



External
Conduction through Tube Wall

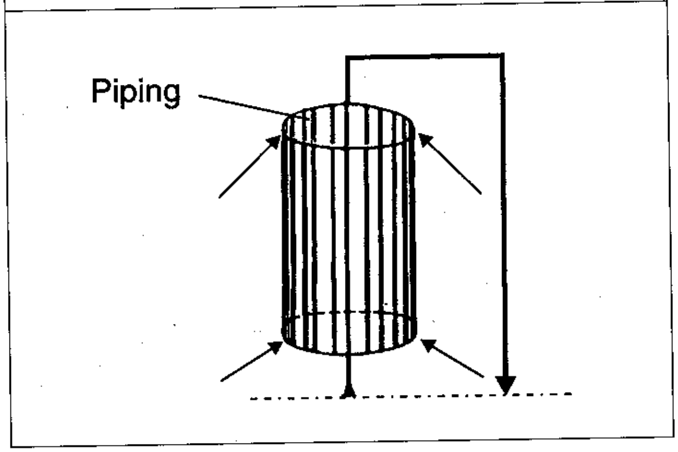
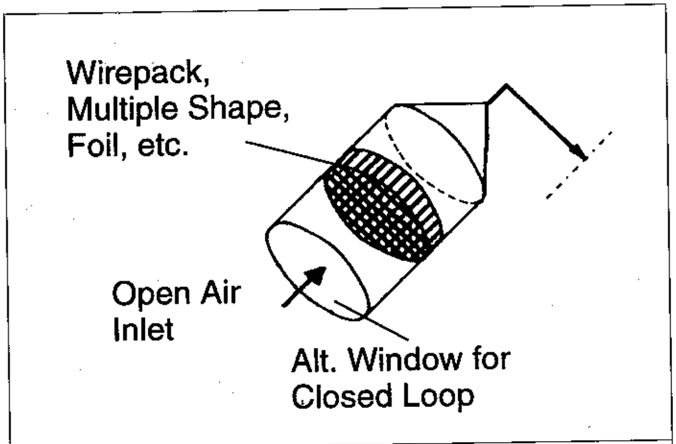


Figure 3-7.
Tube receiver principles
(Source: DLR)

Volumetric
Convection Back from Wall



Particles and Liquids
Direct Absorption

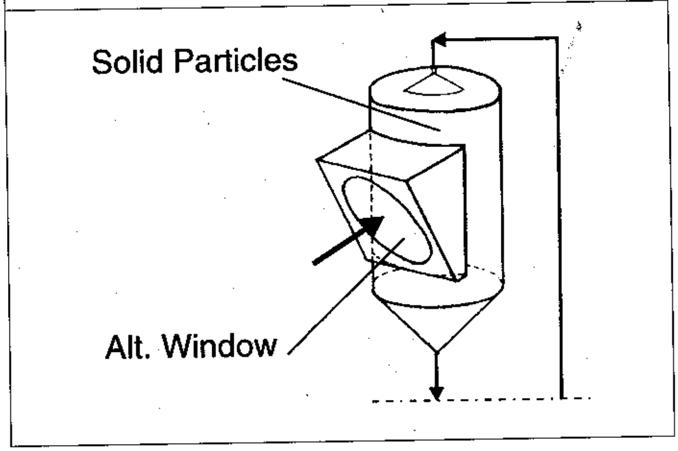


Figure 3-8.
Advanced receiver principles
(Source: DLR)

Fluid	Water/Steam	Liquid Sodium	Molten Salt	Volumetric Air
Heat Flux Density (MW/m²)				
• Average	0.1-0.3	0.4-0.5	0.4-0.5	0.5-0.6
• Peak	0.4-0.6	1.4-1.5 (2.5)	0.7-0.8	0.8-1.0
Range of Fluid Outlet Temperature (°C)	490-525	540	540-565	700-800 (> 800)

Table 3-1. Characteristics of receiver development (Source: DLR, SNL and NREL)

the U.S. molten-salt experimental facility. Based on experience and trade-off studies, future commercial plants are likely to have external receivers.

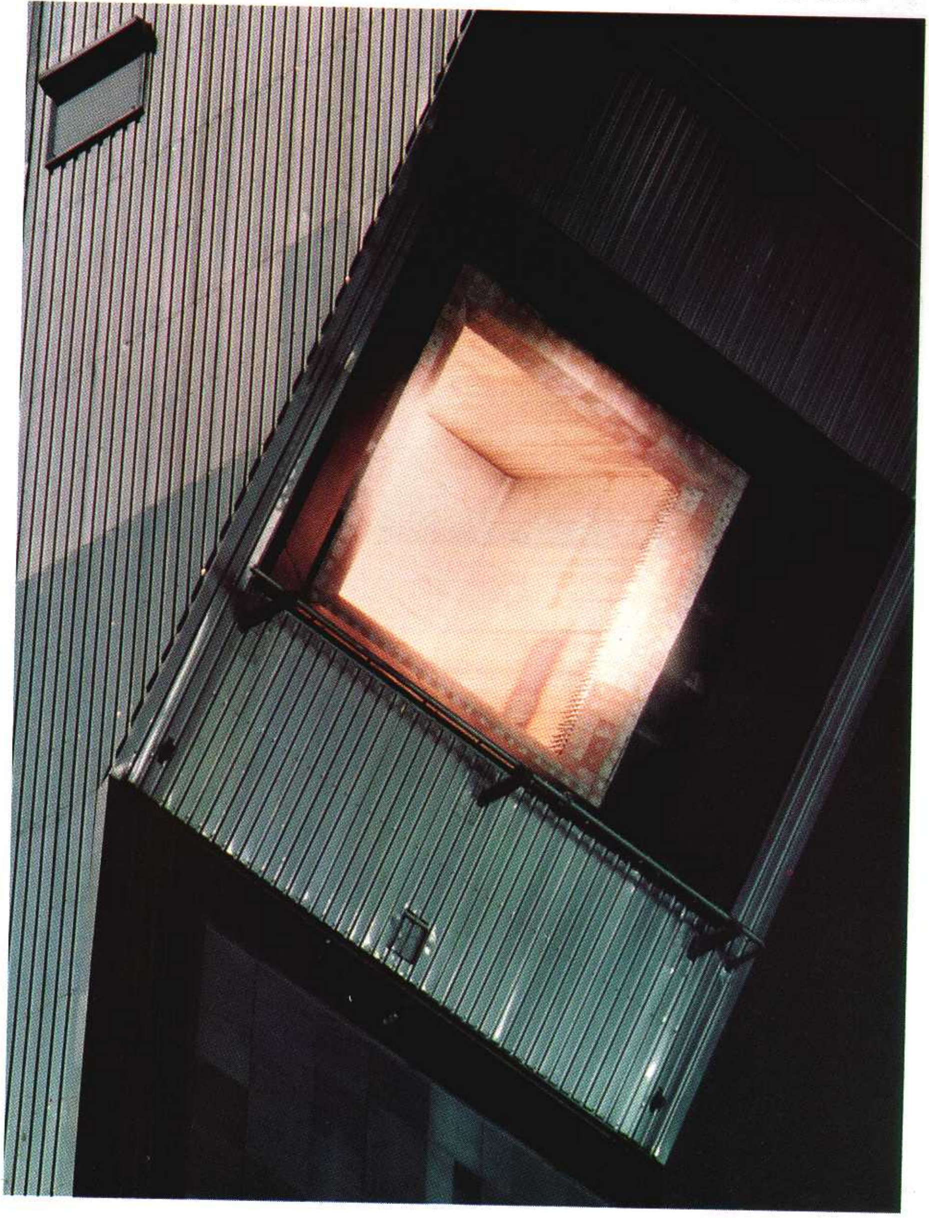
Two advanced and innovative receivers use the volumetric- and the direct-absorption principles. Their development is aimed to improve receivers from an energetic, operational, and economic viewpoint. The volumetric receivers absorb radiant energy in a volumetric arrangement of the absorber material. Air is used as a the heat-transfer medium, and open or closed heat-transfer cycles are possible. The volumetric air receiver is currently under development, mainly in Europe (PHOEBUS technology program solar air receiver TSA). The direct absorption receiver uses a liquid (e.g. molten-salt film) or solid particle media (e.g. silicon carbide or carbon particles) to directly absorb the concentrated beam radiant energy. R&D on the solid-particle-based receiver is just beginning, whereas the molten-salt-film-based receiver is advancing to the prototype design and testing stage.

Typical characteristics of receiver development are summarized in Table 3-1.

The following sections describe those receivers in more detail that have played and will play an important role in the development of central receiver plants. Molten-salt and volumetric air receivers are expected to have great potential for future central receiver plants.

Molten-salt receivers may employ a salt-in-tube design (external or cavity type) or molten-salt film design. The salt-in-tube receivers are well proven in a power range up to 9 MW_t (Figure 3-9 and Figure 3-10). The salt-in-tube receiver of large commercialized tower plants may have an external cylindrical absorber. This type of receiver is the favored receiver concept in the USA. As described in Chapter 2, the 10-MW_e Solar Two project relies on this type of receiver.

Figure 3-9. 9-MW_t Thémis molten-salt receiver (Source: CNRS)



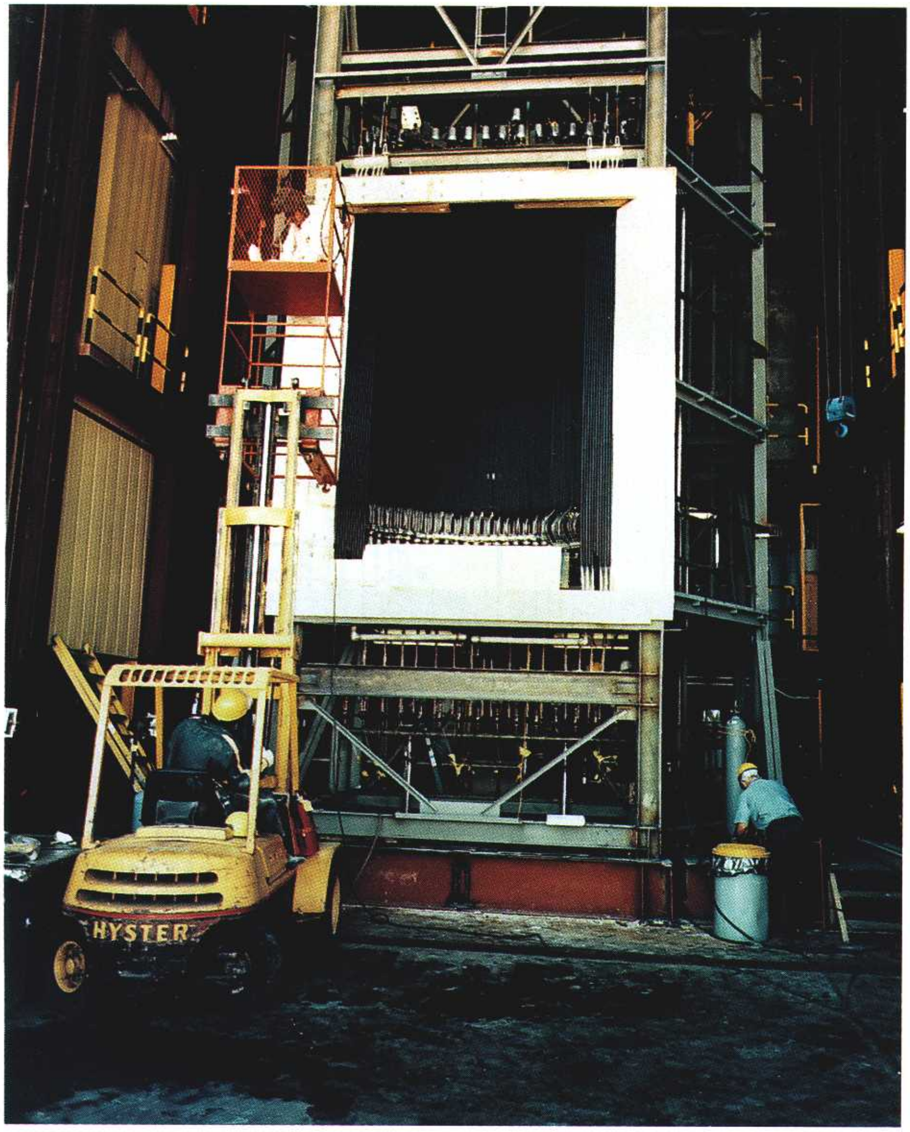


Figure 3-10.
5-MW_t experimental molten-salt receiver at SNL
(Source: SNL)

R&D on the molten-salt film receiver with the film on the front side of the absorber plate was conducted at NREL to develop basic design data. It is currently under development at SNL; the molten-salt film absorbs the radiation when flowing over the surface of a metal support plate (Figure 3-11). This receiver concept mainly offers the advantage of absorbing extremely high radiant flux densities, resulting in a small absorber area, and, therefore, achieving high receiver efficiencies and lower costs. Rapid response to radiant transients is possible. Another design uses the molten-salt film on the rear side of the absorber plate. It is now being developed by CIEMAT in Spain (Figure 3-12).

Typical nitrate-based molten-salt temperatures are 450 °C to 565 °C. HITEC salt (53% KNO_3, 40% $NaNO_2$, 7% $NaNO_3$) or nitrate salt (60% $NaNO_3$, 40% KNO_3; preferred for future applications) are used. Molten salt is also an excellent thermal energy storage medium.

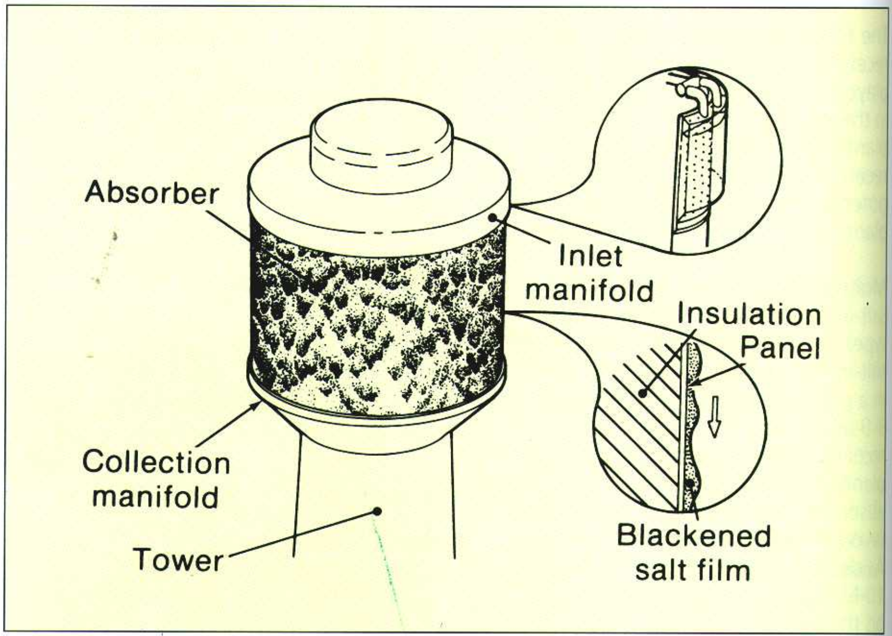


Figure 3-11.
Molten-salt film receiver concept
(Source: SNL)

The volumetric air receiver uses the volumetric absorber principle (Figure 3-13). The receiver heats ambient air up to 700-800 °C (metallic absorber material) or more than 1000 °C (ceramic material). Besides the high-temperature air, other advantages are: easy-to-handle heat-transfer medium and operability, good efficiency, rapid response to radiant transients, fast start-up, and high availability. The arrangement of a 115-MW$_t$ open volumetric air receiver with metallic absorber material from the 30-MW$_e$ PHOEBUS power plant project (PHOEBUS feasibility study) is shown in Figure 3-14.

Figure 3-12. Spanish experimental molten-salt film receiver on the PSA (Source: CIEMAT)

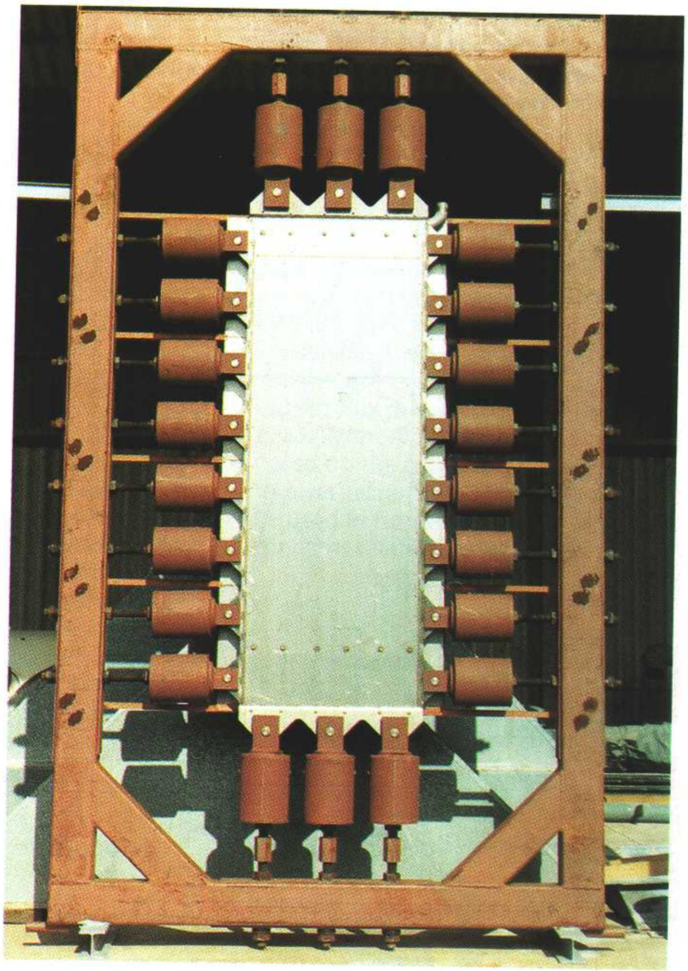
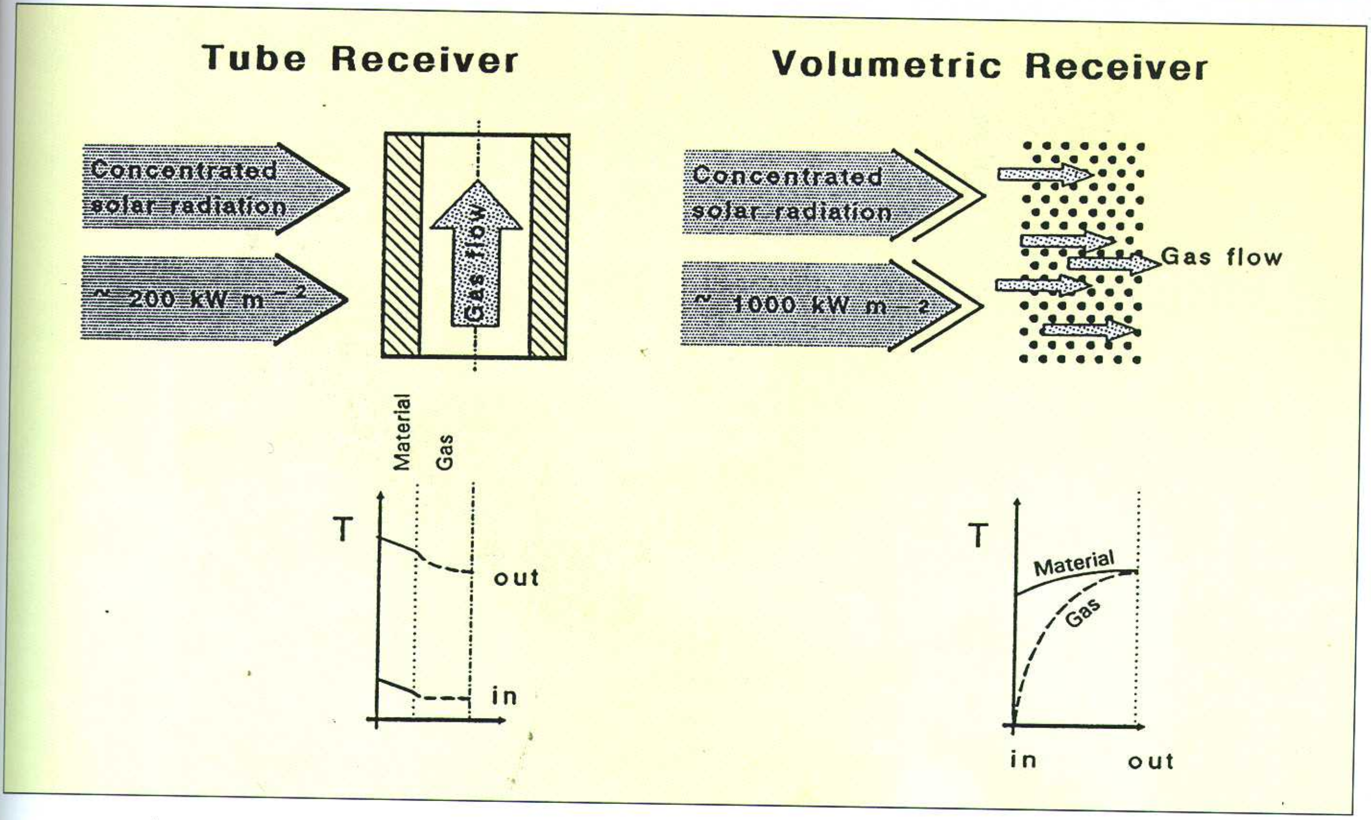


Figure 3-13. Principle of the volumetric air receiver compared with that of the air tube type (Source: DLR)



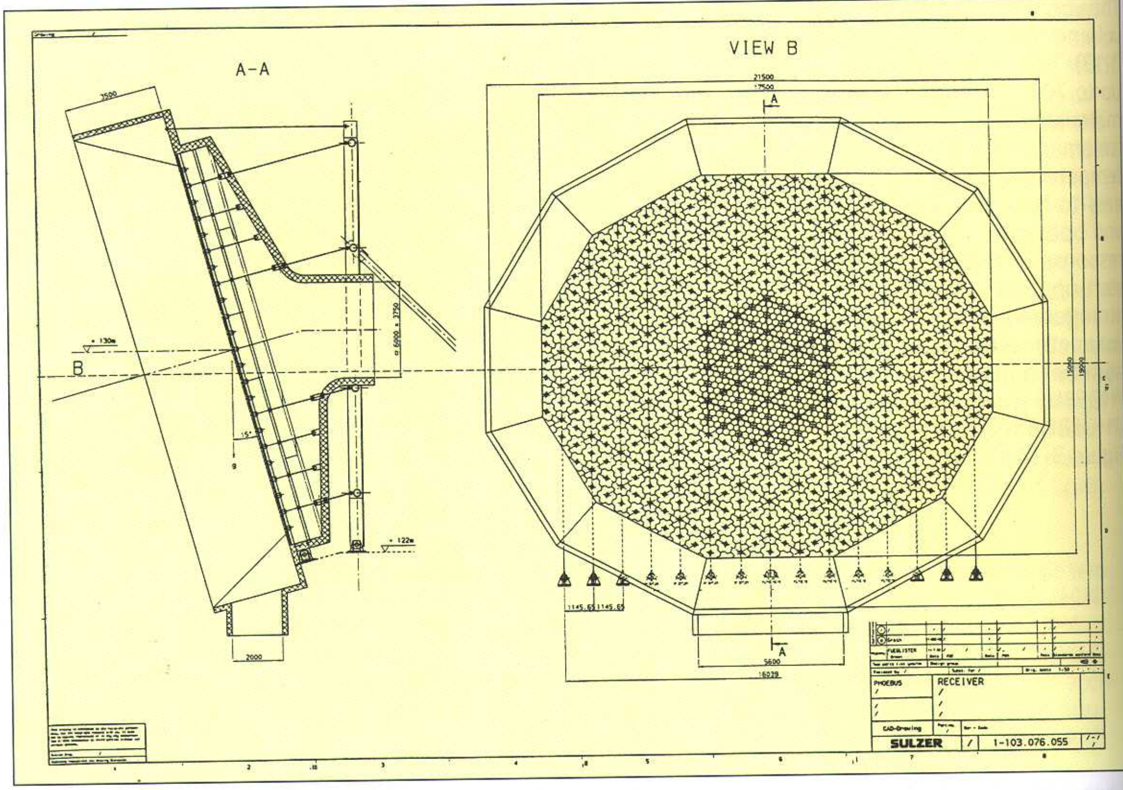


Figure 3-14.
115-MW$_t$ volumetric air receiver arrangement of PHOEBUS (feasibility study, status 1990) (Source: SULZER)

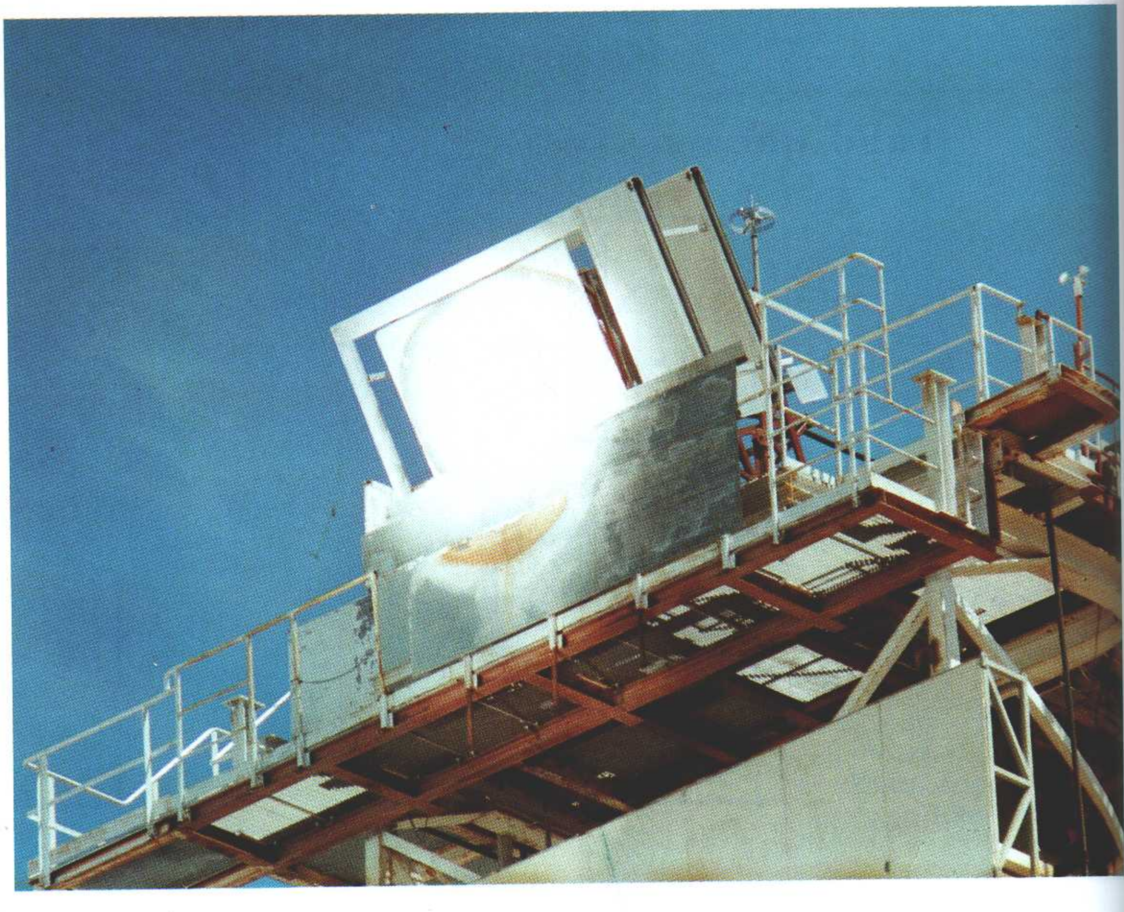


Figure 3-15.
200-kW$_t$ experimental volumetric air receiver on the PSA (Source: DLR)

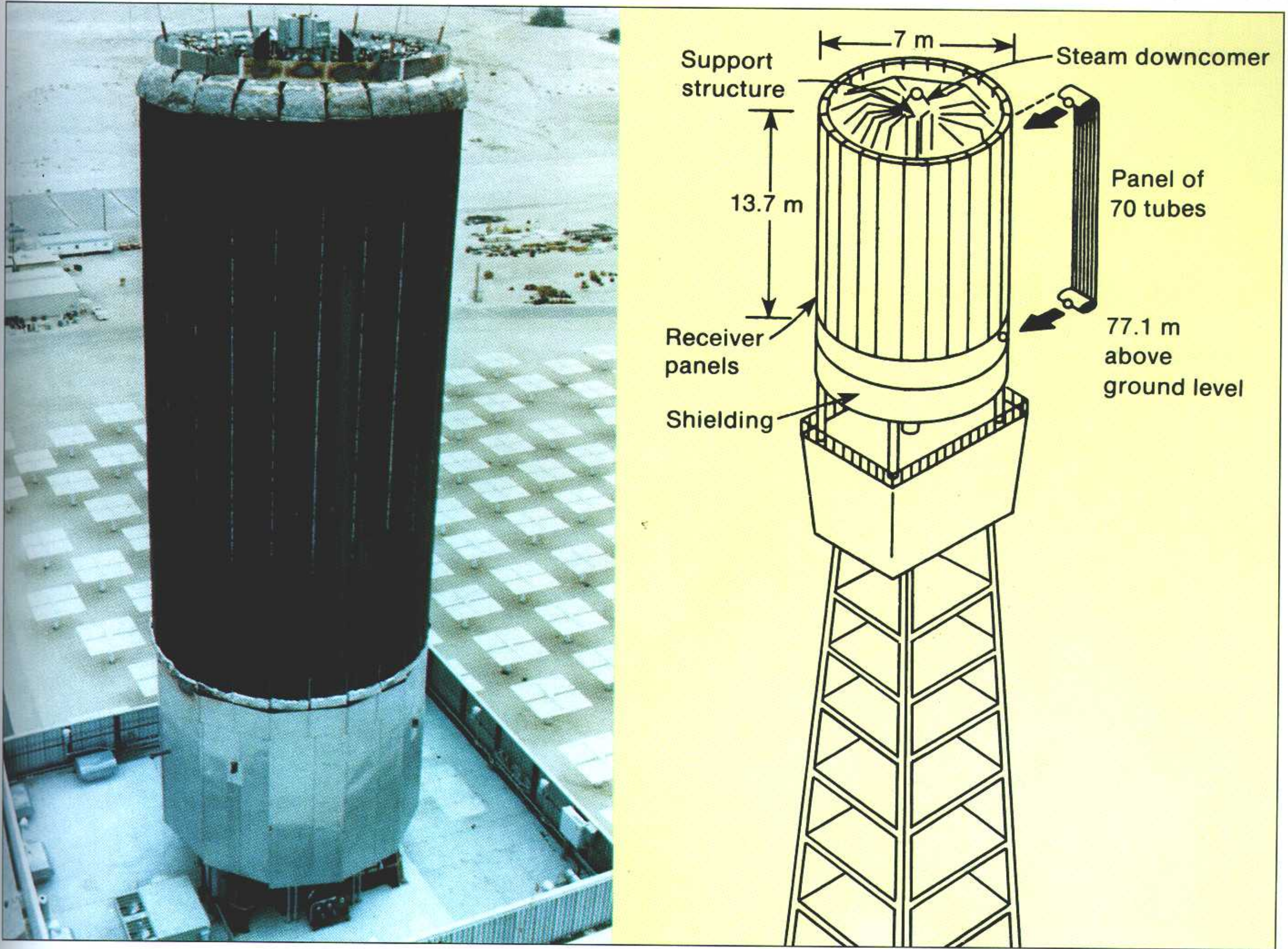
Tests of the various volumetric air receiver types are currently conducted on the Plataforma Solar de Almería using the 200-kW$_t$ SULZER volumetric receiver as a test bed. Different absorber materials (ceramic, metal) have been or are currently tested. The results show good characteristics in the temperature range up to approximately 750 °C, but generating hot air above 800 °C has not been demonstrated and remains a materials and design challenge. The German 2.5-MW$_t$ PHOEBUS technology program solar air receiver (TSA) has been successfully performed in 1992 to 1993 (Figure 3-15). The TSA test facility comprises a complete volumetric air system including energy storage and a steam generator. The facility uses the CESA-1 plant as a test site. Air temperatures of up to 750 °C behind the absorber have been reached using a metal wire mesh absorber. Ongoing testing since 1994 has proved the receiver and system performance. Such tests have been mainly carried out in order to improve and optimize the control and the operational behavior of the TSA test facility.

In the case of a closed air cycle, the receiver requires a closed aperture using a quartz glass window, which is under development.

An example of a steam receiver, the 43.4-MW$_t$ external receiver of Solar One is shown in Figure 3-16. The receiver was designed to generate superheated steam (100 bar, 515 °C) in one pass through the tube, which can be fed directly to the steam turbine-generator or to the thermal energy storage. The flux-absorbing tube panels are arranged at the circumference of a cylinder. The optimum height-to-diameter ratio of the cylindrical receiver absorber results from an analysis of receiver cost versus spillage losses (a portion of radiation passes the absorber). Based on the Solar One (USA), CESA-1 (Spain), EURELIOS (Italy), and Nio (Japan) experience, the steam receiver with steam superheating will probably not be favored for future plants.

Two sodium receiver designs, a 2.4-MW$_t$ semicavity receiver of SULZER (Switzerland) and a 2.5-MW$_t$ advanced external receiver of Franco Tosi (Italy), were successfully tested in the 500-kW$_e$ IEA-SSPS experimental plant in Almería. The advanced sodium receiver achieved extremely high radiant flux densities up to approx. 2.5 MW/m^2 absorber area. But based on the experiences, the sodium receiver technology will probably not be used in future plants due to safety concerns related to the sodium.

Figure 3-16. Solar One's 43.4-MW$_t$ external water/steam receiver at Barstow (USA) (Source: SNL)



3.1.3 Storage Technologies

Energy storage systems increase the capacity of solar power plants by extending daily operation times. Also, they allow power generation to be adapted to power demand (load profile, tariffs), and they simplify the operation of the plant. Although the development and application of storage systems do not appear to be critical, the equipment is costly. Future solar power plants will be equipped with a storage system to optimize the solar power generation, to reduce, or to avoid supplementary fossil fuel firing. In the phase of the market introduction of solar power plants and for niche market applications, solar/fossil hybrid plants without storage systems may be attractive for potential users.

Three different storage principles are applicable for central receiver systems:

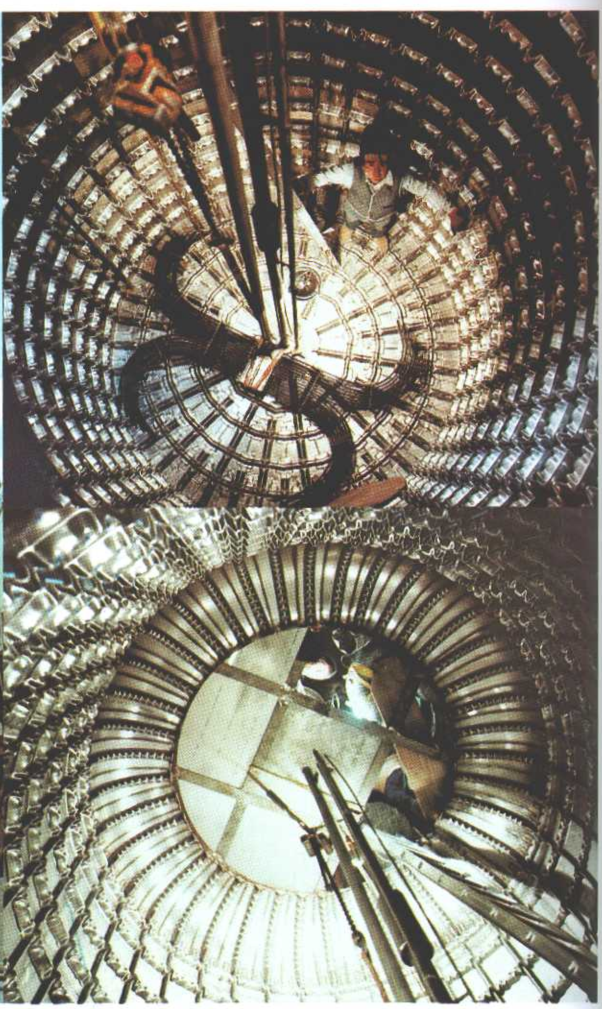
- Sensible heat storage system using either receiver heat-transfer fluid (molten salt, liquid sodium) or solids (ceramic bricks or spheres, oil/rock, steel plates, etc.) as the storage material
- Phase-change storage system
- Thermochemical storage system.

Experimental heat storage systems have been built and operated or are currently under development (particularly the advanced storage systems for use in volumetric air receiver plants). The phase-change and the thermochemical storage systems, which offer technical and operating advantages, are in the early R&D stage for future applications.

Analyses and trade-off studies in the USA and in Europe indicate that molten-salt storage will be applied for commercial molten-salt receiver systems (e.g. Solar Two project in the USA), and ceramic storage will be applied for future volumetric air receiver systems (e.g. PHOEBUS feasibility study). If the optimal storage capacity is applied, systems with storage have lower power generating costs than solar plants without storage. The optimal capacity depends on the plant concept, the application, and specific storage capital costs in question; it may be in the range of one to three hours of full turbine-generator load or even up to 15 hours in order to reach high plant capacity factors.

Thermal storage systems have been tested in all of the seven experimental central receiver plants described in Chapter 2. Some of these used the receiver heat-transfer medium for storage in tanks (liquid sodium, molten HITEC salt) or a special vessel filled with a suitable storage medium (molten HITEC salt, oil/rock) heated by condensating steam or simply pressurized water/steam in tanks.

Figure 3-17 shows the 7-MWh$_t$ advanced molten-nitrate salt storage



system comprising a hot and a cold tank, which was operated very successfully at SNL for application in molten-salt central receiver systems (compare flow diagram in Figure 2-1). The 250-MWh_t PHOEBUS storage system is illustrated in Figure 3-18. The more advanced TSA experimental storage with 0.5-1 MWh_t useful capacity has a bulk of ceramic spheres (approx. 10 mm diameter) as storage material. Figure 3-19 shows the 18-MWh_t molten HITEC salt storage of the CESA-1 plant.

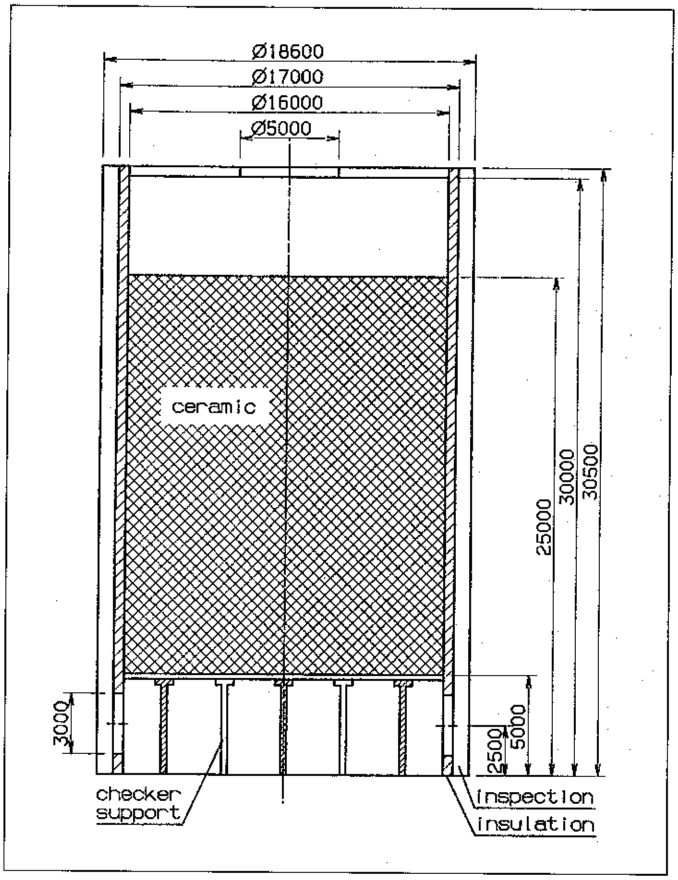


Figure 3-18. 250-MWh_t ceramic brick storage of the 30-MW_e PHOEBUS project (feasibility study, status 1990) (Source: DIDIER)

◀ *Figure 3-17. 7-MWh_t molten-nitrate-salt thermal storage test facility at SNL (Source: SNL)*

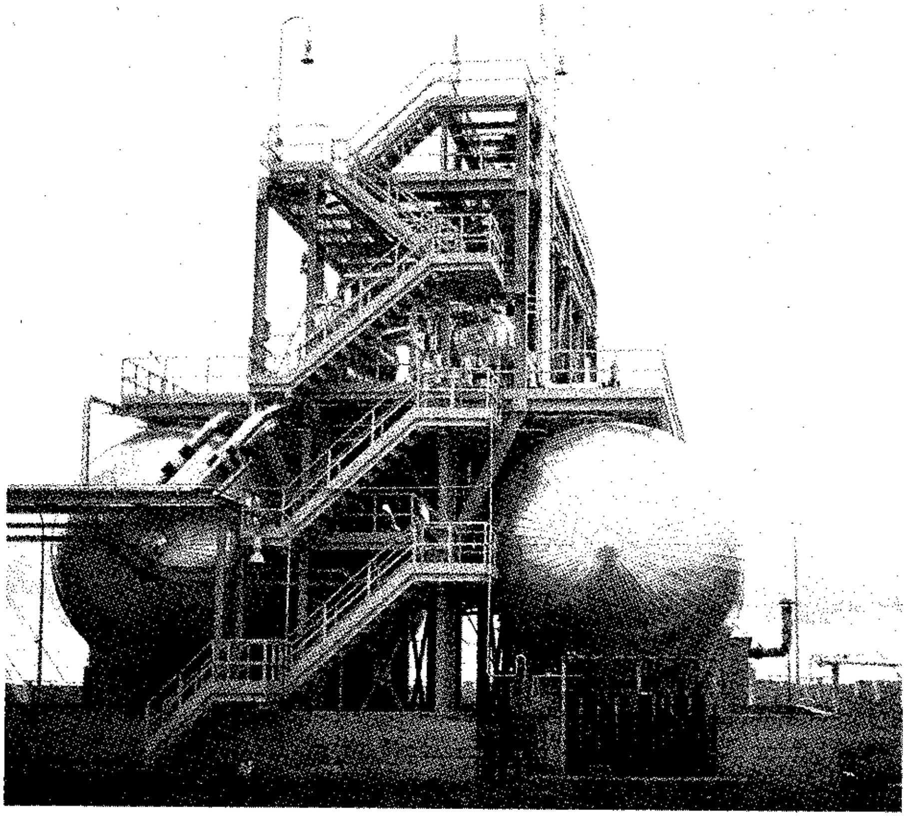


Figure 3-19. 18-MWh_t molten HITEC salt storage of the CESA-1 experimental plant on the PSA (Source: CIEMAT)

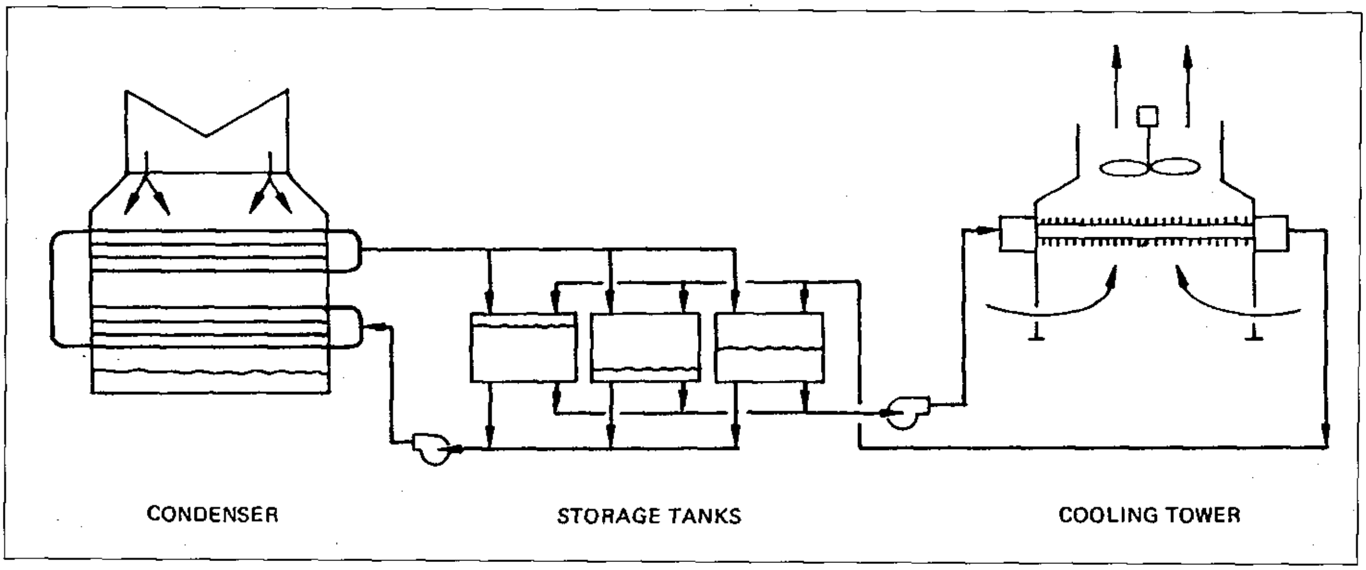


*Figure 3-20.
Innovative closed-circuit cooling water system
(Source: PHOEBUS/Bechtel)*

3.1.4 Balance of Plant Technologies

Electric power generation including steam generation, plant control, auxiliary power supply, and heat rejection uses conventional technologies to take advantage of commercially available equipment. Steam turbine-generators usually are applied to convert solar thermal energy to electricity. For this reason, practically no component development for the mentioned systems took place apart from the integration of these components into the full solar system experiments. However, some adaptation of conventional systems to solar-specific operation conditions is required. Particularly for the heliostat field control system significant R&D has been performed, and alternative control concepts have been tested at the previously mentioned experimental facilities.

Salt-heated and sodium-heated steam generators were built and tested. These steam generators showed adequate performance; however, this equipment is not available as standard items from manufacturing companies. Steam generators for the volumetric air system can be derived from conventional waste heat boiler technology, with some adaptation to the larger air volume flows.

Supplementary fossil fuel firing systems are available commercially. They can be added to all of the diverse central receiver concepts. The receiver heat-transfer medium can be heated, the steam generator can be equipped with fossil fuel burners, or an additional steam generator can be added to the system.

With regard to the heat rejection system of the turbine-generator, dry cooling is a valuable solution for solar plants intended for desert regions. Figure 3-20 illustrates an innovative dry cooling concept. Here, the cooling water is stored in large neoprene tanks and is cooled down in a closed circuit by an air fan-cooling tower at night. This process allows low cooling water temperatures for operation during the day because of the efficient dry cooling at night at low air temperatures typical of the desert environment.

3.2 Parabolic Trough Systems

Parabolic trough systems were described in Chapter 2 from system and operating plant viewpoints. In the following sections, these systems are described from a technological viewpoint; their subsystems, particularly the solar-specific components, are explained in some detail.

Parabolic trough systems comprise the following main subsystems:

- Collector field, which is an array of a large number of parabolic troughs (each trough comprises the reflective concentrator, the receiver tube, and relevant axis drives, as well as tracking controls)
- Heat-transfer piping system, which transports the thermal energy from the receiver tubes to the electric power generating system (thermo-oil is commonly used, but direct steam generation in receiver tubes is being developed)
- Thermal storage system (optional), in which solar energy is stored and discharged when required
- Supplementary fossil-fuel firing system (optional)
- Electric power generating system comprising the steam generator and the steam turbine-generator
- Plant control, auxiliary power supply, and heat rejection.

3.2.1 Concentrator/Structure Technologies

The collector field is the largest capital cost item of a parabolic trough plant. Consequently, ongoing R&D is aimed at lower costs and more efficient designs. An example of the state of the art is the parabolic trough design used in the LUZ SEGS plants with peak power ratings up to 80 MW_e.

The concentrator/structure of a parabolic trough system comprises several components; these are illustrated by the most widely used collector, the LUZ Company's LS-3 (Figures 3-21 and 3-22):

- Steel pedestals with foundations and the bearings of the horizontal axis on top
- Steel structures at the back of the reflective concentrator and mounted to the horizontal axis for support of the mirrors
- Drive system for slewing the concentrator and for tracking the sun.

The sun sensor and the local controller belong to the field control system. In the case of LS-3, the solar collector array is 99 m long and is assembled by linearly combining 8 trough collector units. A total of 224 back-silvered curved, low-iron white glass mirrors are mounted to the structure. The collector is curved in a parabolic shape to reflect the sun onto the receiver tube which is placed in the line-focus. The aperture width of the LS-3 is 5.76 m, and the total reflective area is 545 m². A flex hose tube connects the receiver tube entrance and exit with the heat-transfer piping system in the solar field.

Trough collectors of larger aperture width than of the LS-3 collector are envisaged concerning direct water/steam generation parabolic trough systems. The long-term R&D goal is to improve plant efficiencies, reduce capital costs, and lower energy costs.

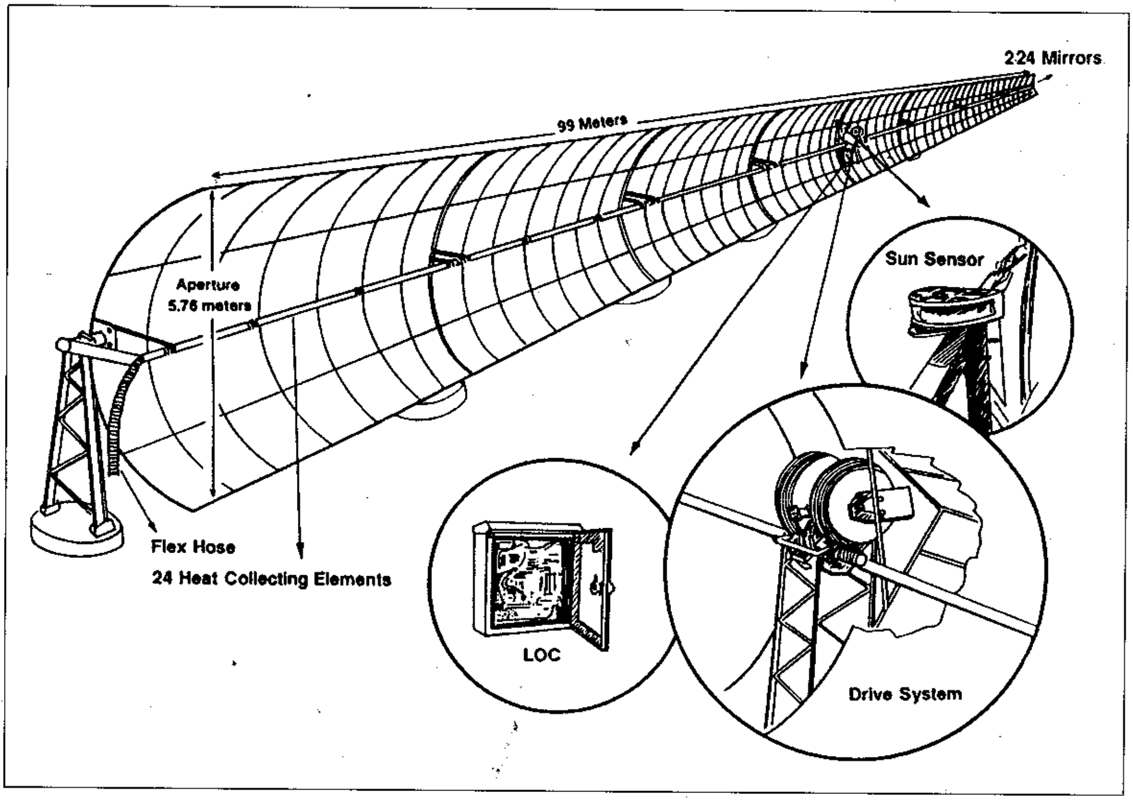
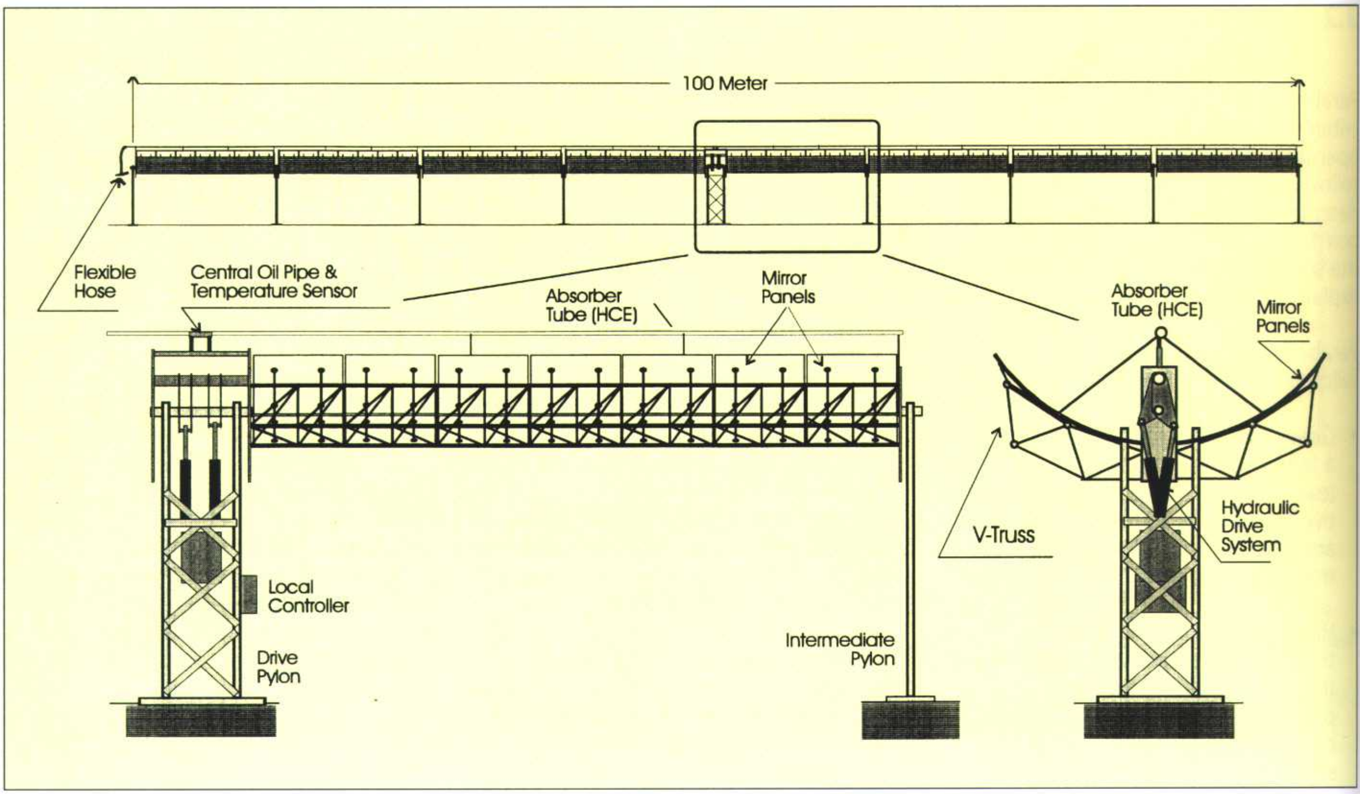
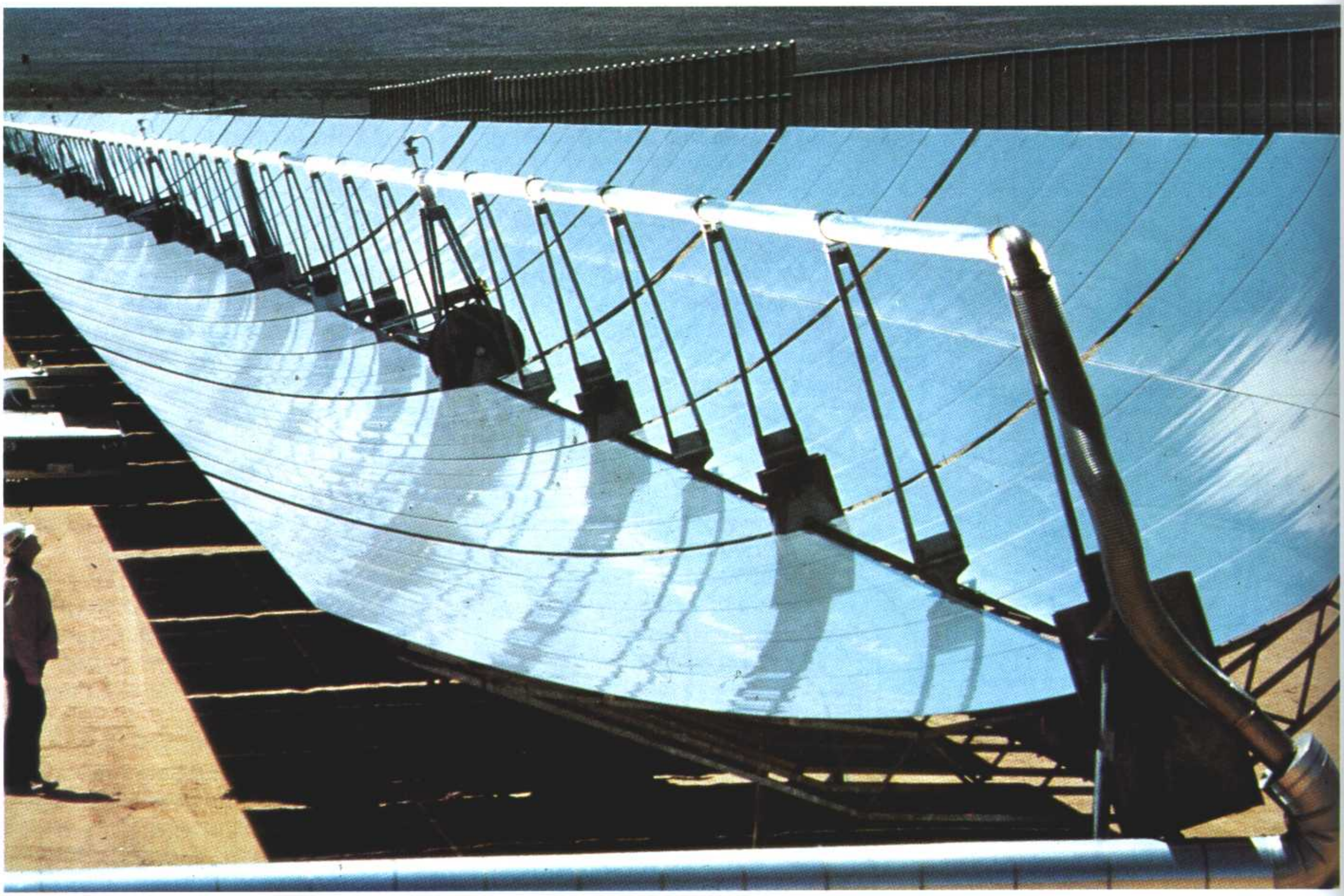


Figure 3-21. Schematic arrangement of the LUZ LS-3 collector (Source: Flagsol)


100 Meter
Flexible Hose
Central Oil Pipe & Temperature Sensor
Absorber Tube (HCE)
Mirror Panels
Absorber Tube (HCE)
Mirror Panels
V-Truss
Hydraulic Drive System
Local Controller
Drive Pylon
Intermediate Pylon



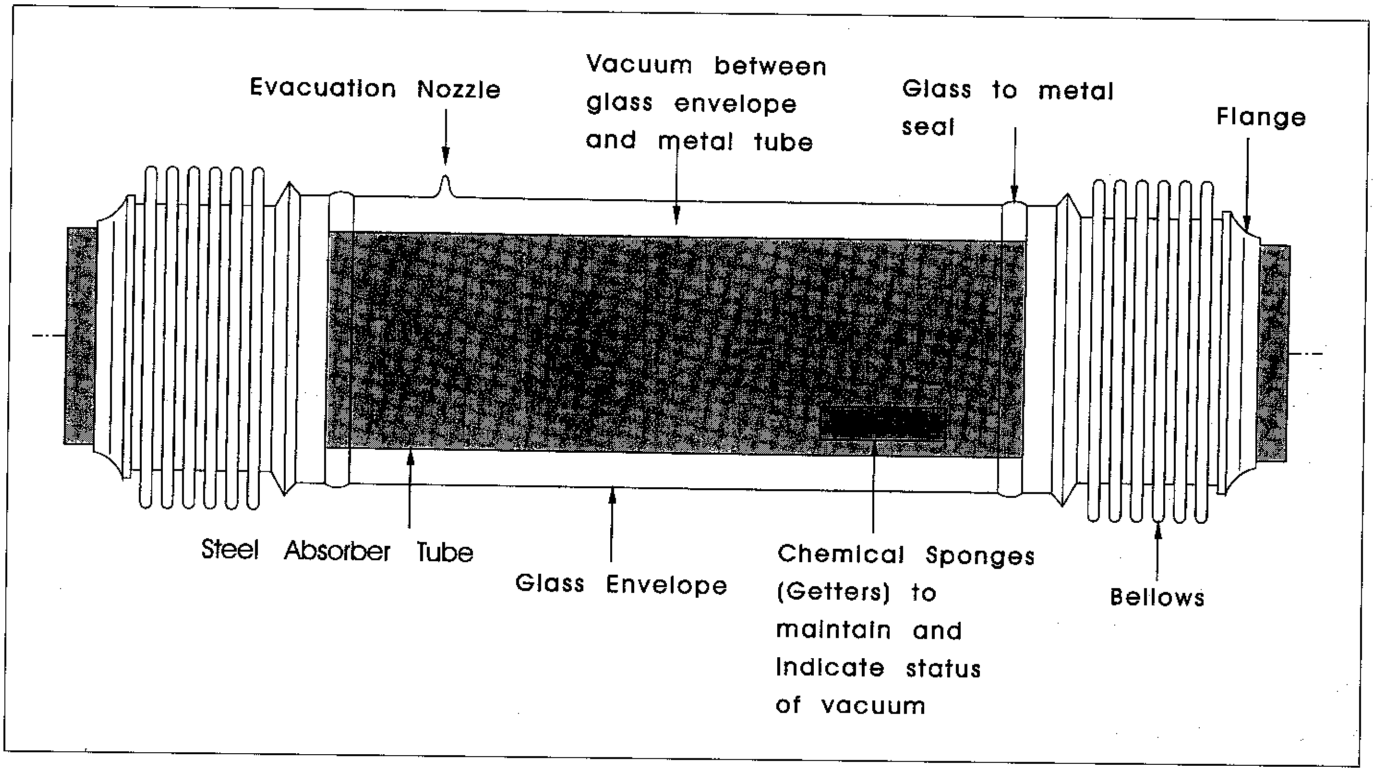


Figure 3-23: Details of the LUZ LS-3 receiver assembly (Source: Flagsol)

The collectors are usually oriented in a north-south direction, although east-west orientation is an alternative. The most favorable orientation depends on the latitude of the specific site. The north-south orientation is preferred for improved plant performance during summer and for locations near the equator. Inclining the troughs by a few degrees will reduce cosine losses, but will result in higher capital costs for the structures.

◀ *Figure 3-22. The LUZ LS-3 collector (Source: Flagsol)*

3.2.2 Receiver Technologies

Because the focus is placed along a line rather than on a point, the concentration of the radiation is lower for parabolic troughs than for central receivers and dish receivers (40-80 suns).Hence, trough systems produce thermal energy at relatively low temperatures (typically up to 400 °C using thermo-oil).

Trough receiver technology using thermo-oil is fully developed and commercialized today, as demonstrated at the SEGS plants. The receiver is made from a tube with a high-absorptivity, relatively low-emissivity coating on the outside surface. Approximately 87.5% of incident radiation reaches the receiver tube (absorber) at the design point load. The ratio of aperture and absorber tube diameter (also called concentration ratio) is 82 to 1 for the LS-3 collector. The LS-3 absorber tube is 70 mm in diameter, made from stainless steel, and coated with a highly selective layer. This tube is housed in a glass tube of high transmissivity (95%) that is connected to the absorber tube by a flexible bellow to allow for differential expansion of metal and glass and to maintain a tight seal of space between the absorber tube and the glass tube. The volume between absorber and glass tube is put under vacuum to reduce the thermal losses. Figure 3-23 shows some details of the LS-3 receiver assembly.

Receiver technology for direct steam generation parabolic trough systems is a long-term R&D program which has just started. Various improvements are expected, e.g. concerning increase of the absorptivity by advanced selective coatings and decrease of thermal losses.

In the return piping carrying the heated fluid, vacuum insulation is also used for the tubes connecting the collector rows to the field loops to reduce thermal losses from the collector field. However, here a metal tube is used in place of the glass tube.

3.2.3 Storage Technologies

The discussion of energy storage systems for central receiver plants is generally applicable to parabolic trough plants as well, with one significant difference. Storage systems are not as economically feasible for parabolic trough plants. The thermo-oil storage medium reaches only 390 °C and does not have the excellent storage properties of molten salt. Therefore, the temperature difference between storage inlet and outlet is much smaller than that for the tower systems, resulting in much larger (and more expensive) storage vessels. Additionally, the oil is relatively costly and may have some adverse environmental effects if leaks occur.

Some storage systems have been built and qualified in experimental trough plants. They are based on either the single-tank thermocline principle or the two-tank principle. Examples of these plants are:

- The 4-MWh_t single-tank storage system (dual medium: oil/cast iron) of the 500-kW_e IEA-SSPS-DCS plant in Almería, Spain
- The 5-MWh_t single-tank storage system (single-medium: oil) of the 150-kW_e Coolidge solar irrigation facility, USA
- 117-MWh_t two-tank storage system (single medium: oil) of the 13.8-MW_e SEGS I Plant, USA.

Figure 3-24 shows the successfully tested advanced single-tank thermocline storage system of the SSPS-DCS plant in Almería. This tank contains cast iron plates (see Figure 3-25) in order to improve the storage capability and to save costly oil used as the storage medium.

For broad marketing of parabolic trough plants capable of producing power after sunset in a solar-only operation mode, development of an effective and low-cost storage system is required. R&D efforts are currently under way to make such storage systems available in the near future. One near-term concept, developed by an international study group for application in SEGS plants, has been selected for tests using a small experimental unit in Europe (see Figure 3-26). The design is a concrete thermal storage system: the steel pipes ducting of the oil is cast in the concrete.

More advanced concepts for mid- or long-term trough applications may be based on more advanced materials made from, for example, a combination of ceramic and nitrate salt bricks using the phase-change principle. Those storage systems may be applied to future commercialized parabolic trough plants based on direct steam generation, which allows the generation of slightly superheated steam during discharging for improved system efficiency.

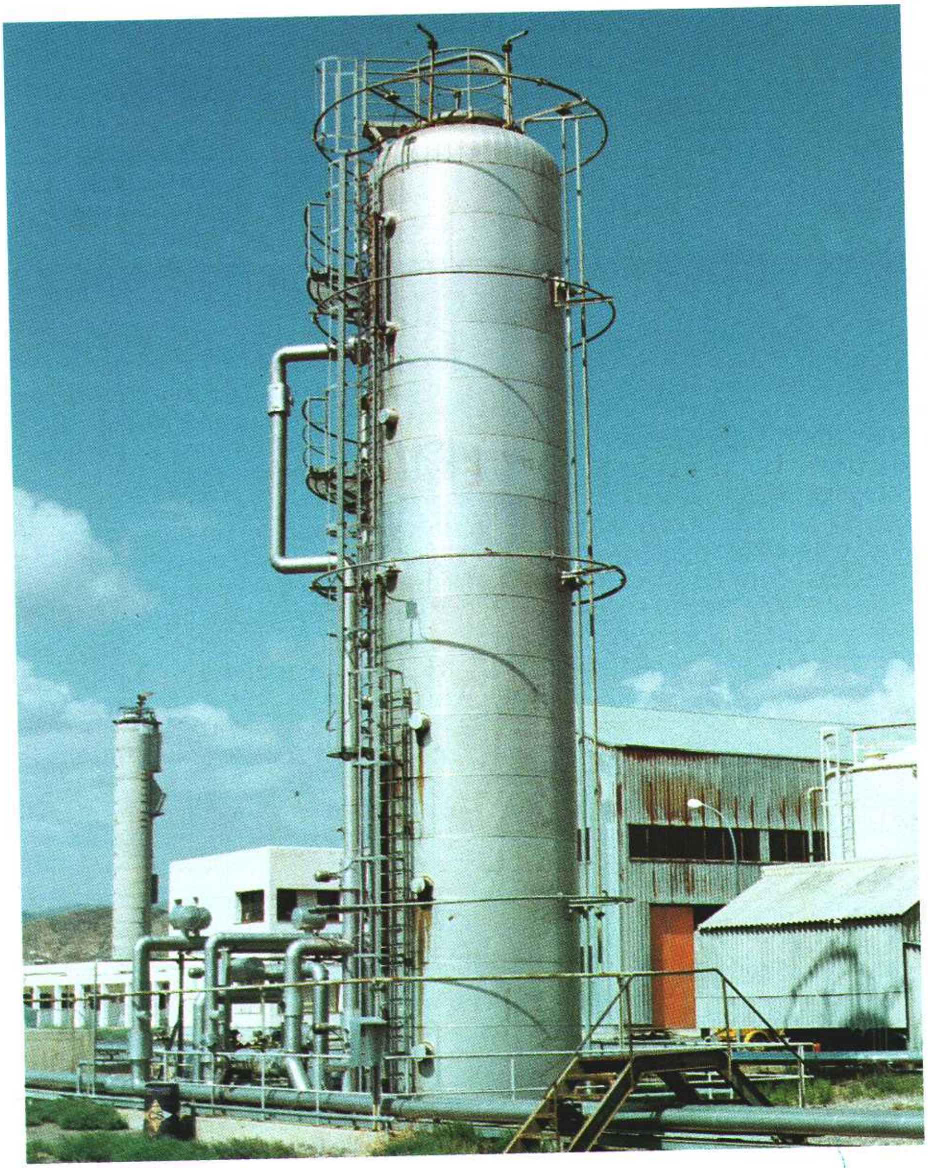


*Figure 3-24.
4-MW_t single-tank storage system of SSPS-DCS plant in Almería (dual medium: oil, cast iron)
(Source: PSA).*

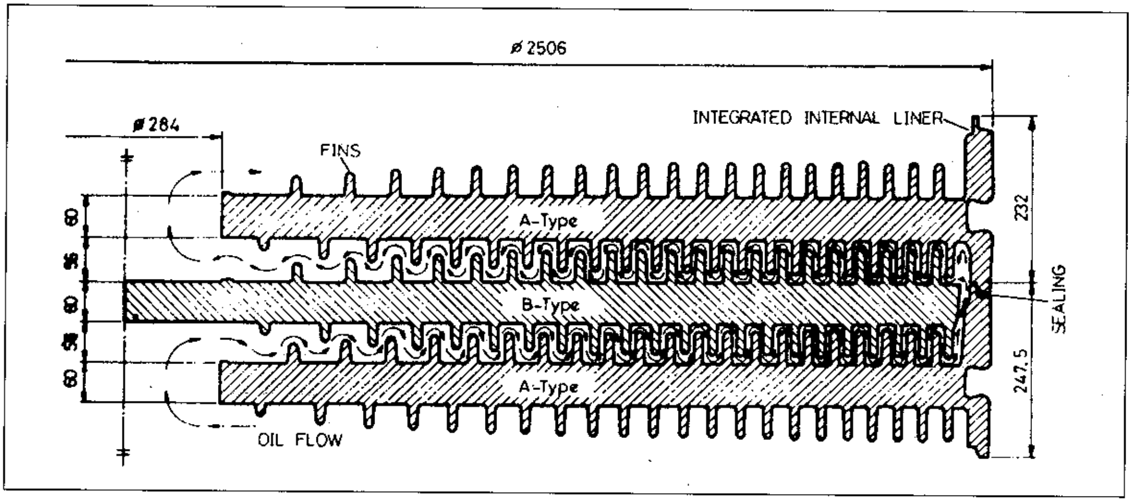
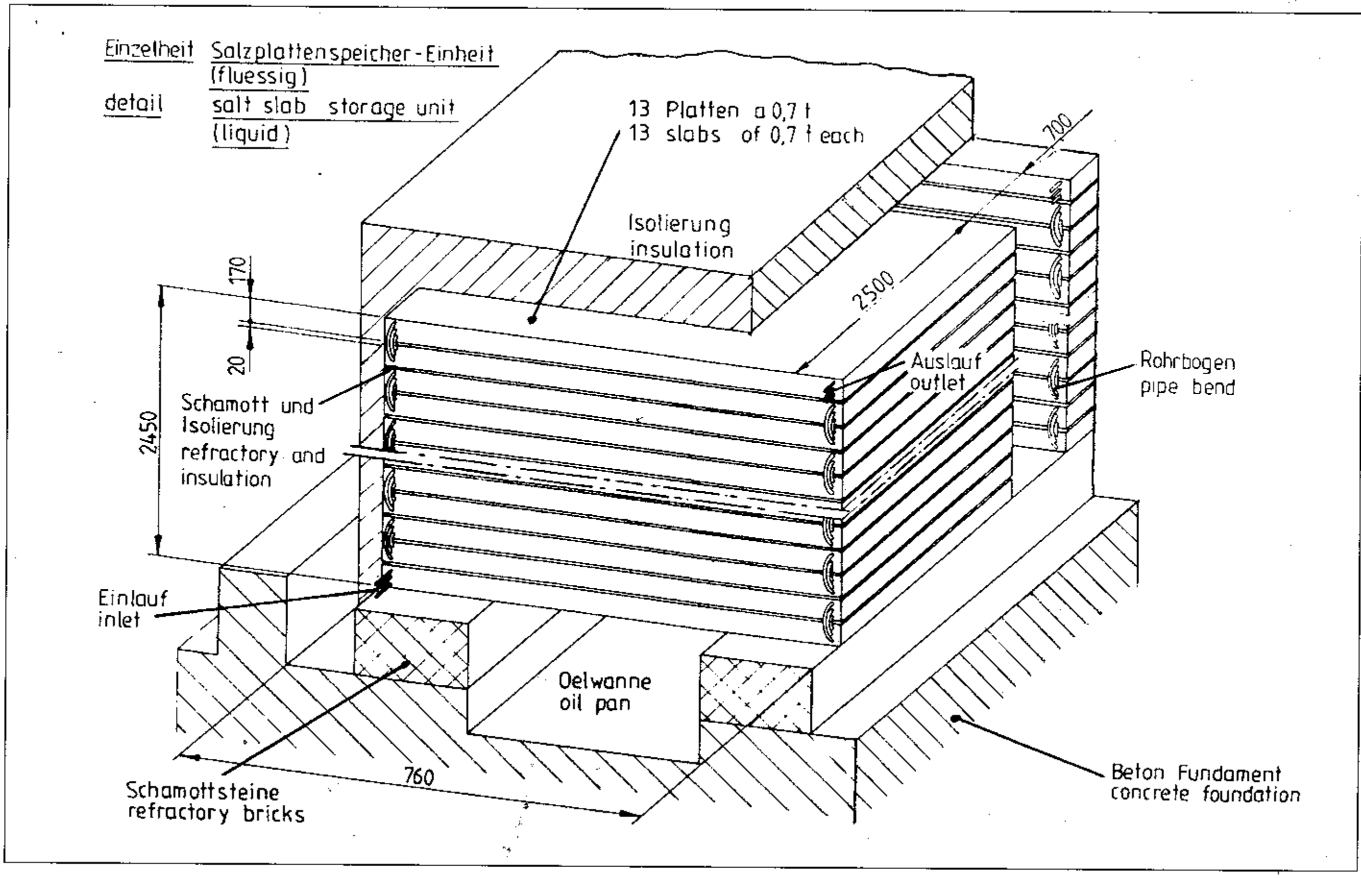


Figure 3-25. Detail of cast iron plates assembled in the SSPS-DCS dual-medium storage vessel (Source: Siempelkamp)

3.2.4 Balance of Plant Technologies

In general, balance of plant technologies are similar for central receiver systems and parabolic trough systems. Both systems use a similar thermodynamic cycle to heat a steam generator that feeds a steam turbine-generator. The main difference is that the trough system generates less superheated steam in solar mode (e.g. SEGS plant maximum temperature: 370 °C; maximum pressure: 100 bar) compared with the central receiver system (maximum temperature: 540 °C; maximum pressure: 140 bar). Hence, the electric power generating system of the SEGS trough plant has an inherently lower annual efficiency (typical: 36%-38%) versus the central receiver system (typical: 38%-42%).

Figure 3-26. Schematic of a concrete thermal storage system with cast-in steel piping (Source: University of Essen)



The 30- to 80-MW_e SEGS plants use a single-reheat turbine, which was derived from proven industrial turbines and adapted to the solar-specific, low-superheating temperature. Good design point efficiencies of 37.5% (30-MW_e SEGS VII) and 38.1% (80-MW_e SEGS VIII) were achieved in the solar-only mode. Turbine-generator efficiencies tend to increase with increasing plant power rating. The direct steam generation process, which is currently under development, is expected to improve turbine efficiency to about 40%.

Other balance of plant systems for plant control, power supply, and heat rejection were derived from conventional plant technologies. The collector field control system is somewhat simpler than the heliostat field control of central receivers because of the lower number of single collector units and the lower accuracy requirements of the tracking control.

The oil-heated steam generator is fully commercialized in the SEGS plants. Supplementary fossil-fuel heating is performed by conventional natural gas-fired steam generators added to the solar-heated steam generators. In the fossil mode, the turbine can be operated with a steam temperature of 510 °C (SEGS II through SEGS VII); the most advanced SEGS VIII and SEGS IX designs use 370 °C for both the solar and fossil mode to simplify the Rankine cycle.

The SEGS plants use wet cooling for heat rejection. In principle, the dry cooling concept may be applied to trough systems as well to save the groundwater resources in arid regions.

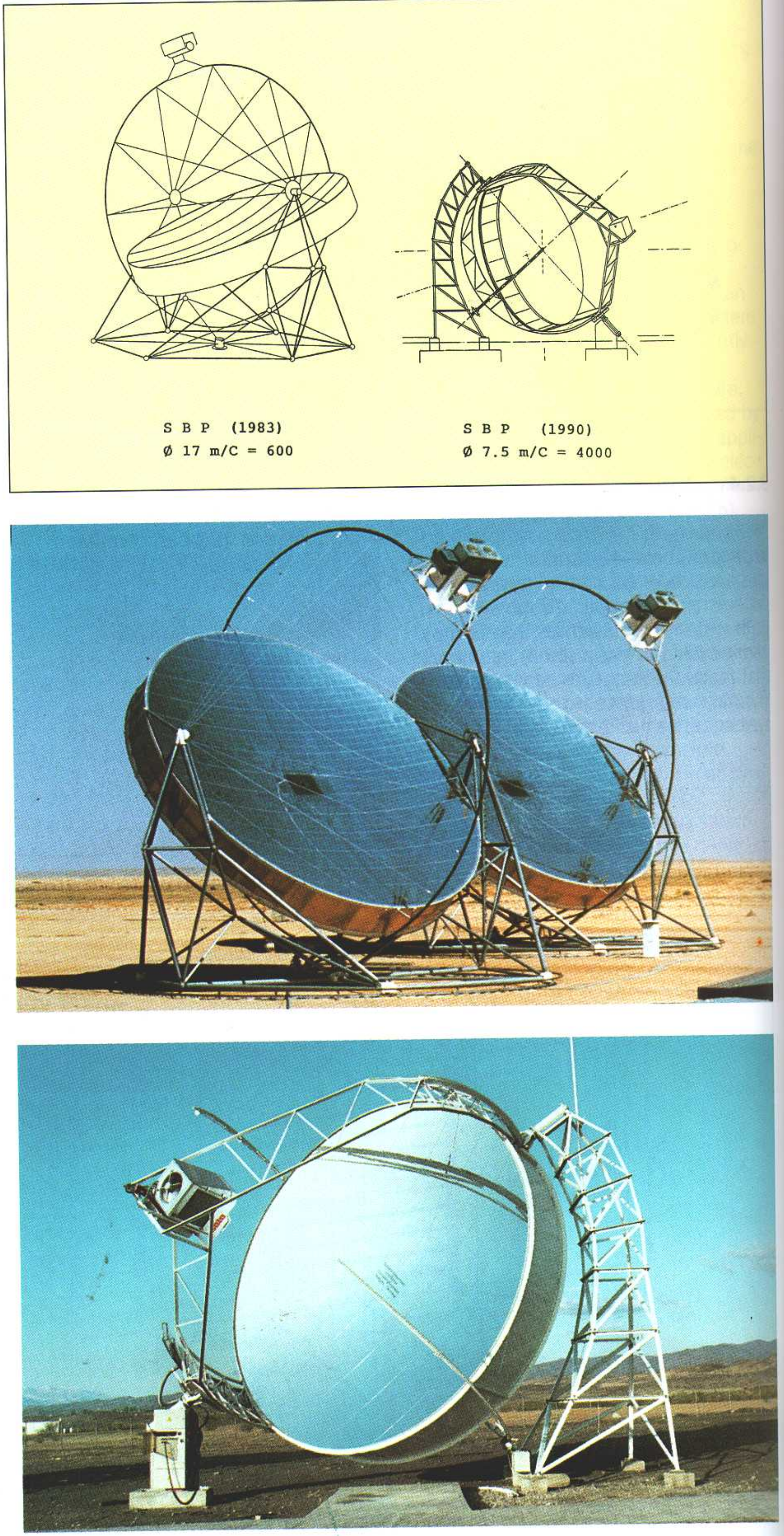


Figure 3-27. Stretched-membrane dish concentrator/structure technology of SBP in Saudi Arabia near Riyadh (17-m diameter) and on the PSA (7-m diameter) (Source: SBP)

3.3 Parabolic Dish Systems

Parabolic dish systems were described in Chapter 2 from system and operating plant viewpoints. In the following sections, these systems are described from a technological viewpoint; their subsystems, particularly the solar-specific components, are explained in some detail.

Parabolic dish systems comprise the following main subsystems:

- Dish reflective collector system, including the supporting structure
- Receiver system mounted on the dish at its focus
- Supplementary fossil-fuel firing (optional)
- Stirling engine-generator mounted adjacent to the receiver system (or alternative electric generating systems, such as turbine-generators or steam engines)
- System control, power supply, heat rejection (normally coupled directly to the dish-mounted engine- or turbine-generator).

Usually, dish systems are applied for power supply at remote sites, for small villages and off-grid consumers. If larger capacities are requested, e.g. some MW_e total electric output, single-dish systems of the kW_e power range may be arranged in a field array. Two alternatives of such "farm" systems are:

- Distributed dish-mounted electric power generation systems (e.g. Stirling engine, Rankine steam engine, gas turbine, and organic steam engine). These systems use a closed-coupled packaged assembly. Power cables and electric installations connect the dishes with a central switching station.
- Central electric power generation systems (e.g. Rankine steam turbine and organic steam turbine). A piping system connects the dishes with the central turbine-generator. Energy storage systems may be applied.

Selection of the preferred dish system depends on the client's requirements, including power demand, load profiles, and tariffs. The dish/Stirling system is generally preferred because it is more developed and has excellent operational characteristics. The key aim of current development efforts is to demonstrate reliable operation of the Stirling engine, receiver, and dish-drive mechanisms.

Dish systems normally do not have energy storage systems because of a lack of space and weight considerations if mounted near the dish focal region. However, the dish systems mentioned above that use a central power generation system may be equipped with a storage system installed near the central power generation system. Both centralized and decentralized dish systems can be equipped optionally as hybrid plants with a supplementary fossil-fuel firing system.

3.3.1 Concentrator/Structure Technologies

The objective of concentrator/structure technologies is the same for all solar thermal technologies: to concentrate sunlight onto a receiver with high reflectivity and weatherability and to use an efficient and light-weight structure to support the reflective optical surface.

Several designs have been used in experimental dish systems to combine the optical and structural requirements. The main difference between

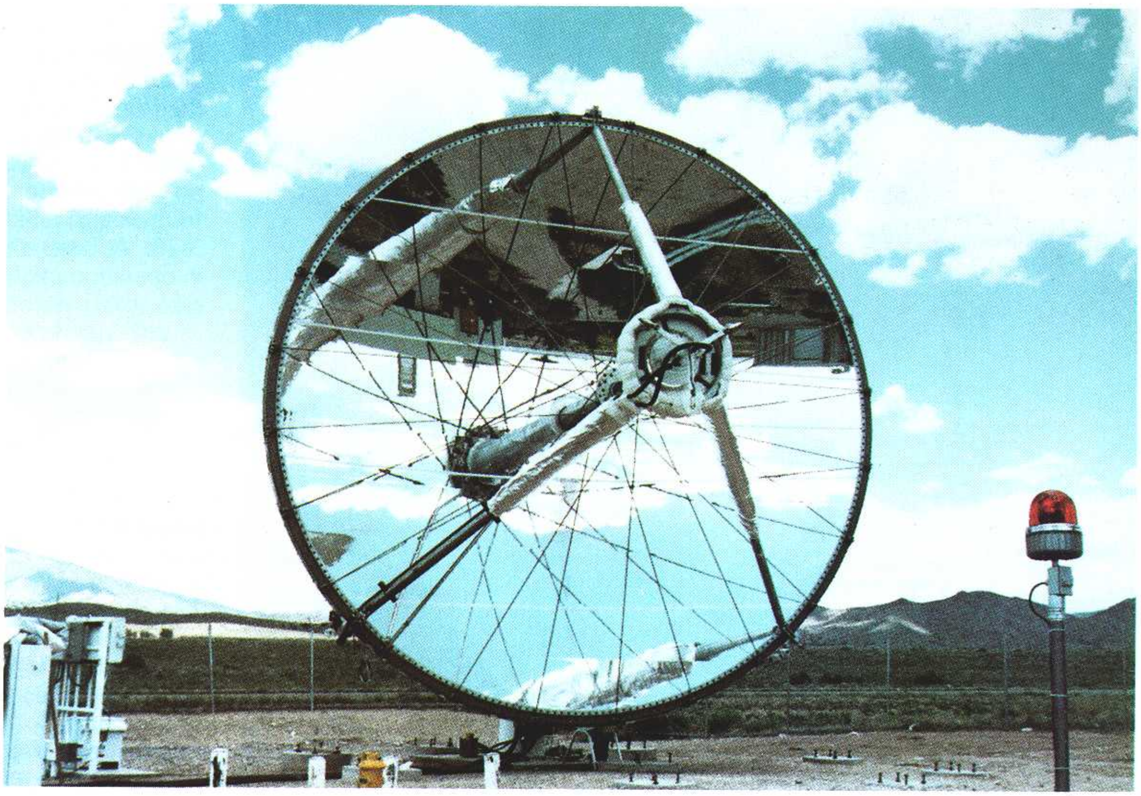


Figure 3-28. Stretched-membrane dish test unit at SNL (Source: SKI)

dish systems and other solar thermal technologies is the 3-dimensional parabolic shape of the concentrator. The parabolic shape can be manufactured as a single reflector unit, as a facet, or as a reflector assembled from many small facets. Some of the parabolic concentrator designs developed to date are described below.

(a) Single stretched-membrane concentrator (example: SBP and SKI)
(b) Multifaceted stretched-membrane concentrator, (example: CPG, SAIC)
(c) Focused-facet concentrator (example: MDAC)
(d) Slat concentrator (example: Power Kinetics)
(e) Fix-focus concentrator (example: HTC-Solar)
(f) Refractive concentrator.

Design (a) uses a single-front stainless-steel membrane and another single stainless-steel membrane on the back side (see Figures 2-23, 2-24, and 3-27). Both membranes are stretched around a hoop. To form the optical shape and provide rigidity, a slight vacuum is created in the space between the membranes by a pump system. This design, in combination with optimized support structures and drive mechanisms, holds promise as a light-weight, inexpensive concentrator. The SBP dish test facilities in Saudi-Arabia, Almeria, and Stuttgart used thin back-silvered white glass mirrors glued onto the membrane surface on the front. They demonstrated good results with concentration ratios up to 4000 suns. The SKI design uses a thin polymer reflector membrane on the front side to reflect the sun (see Figure 3-28). A 7-meter-diameter test unit is in operation at SNL, Albuquerque, USA.

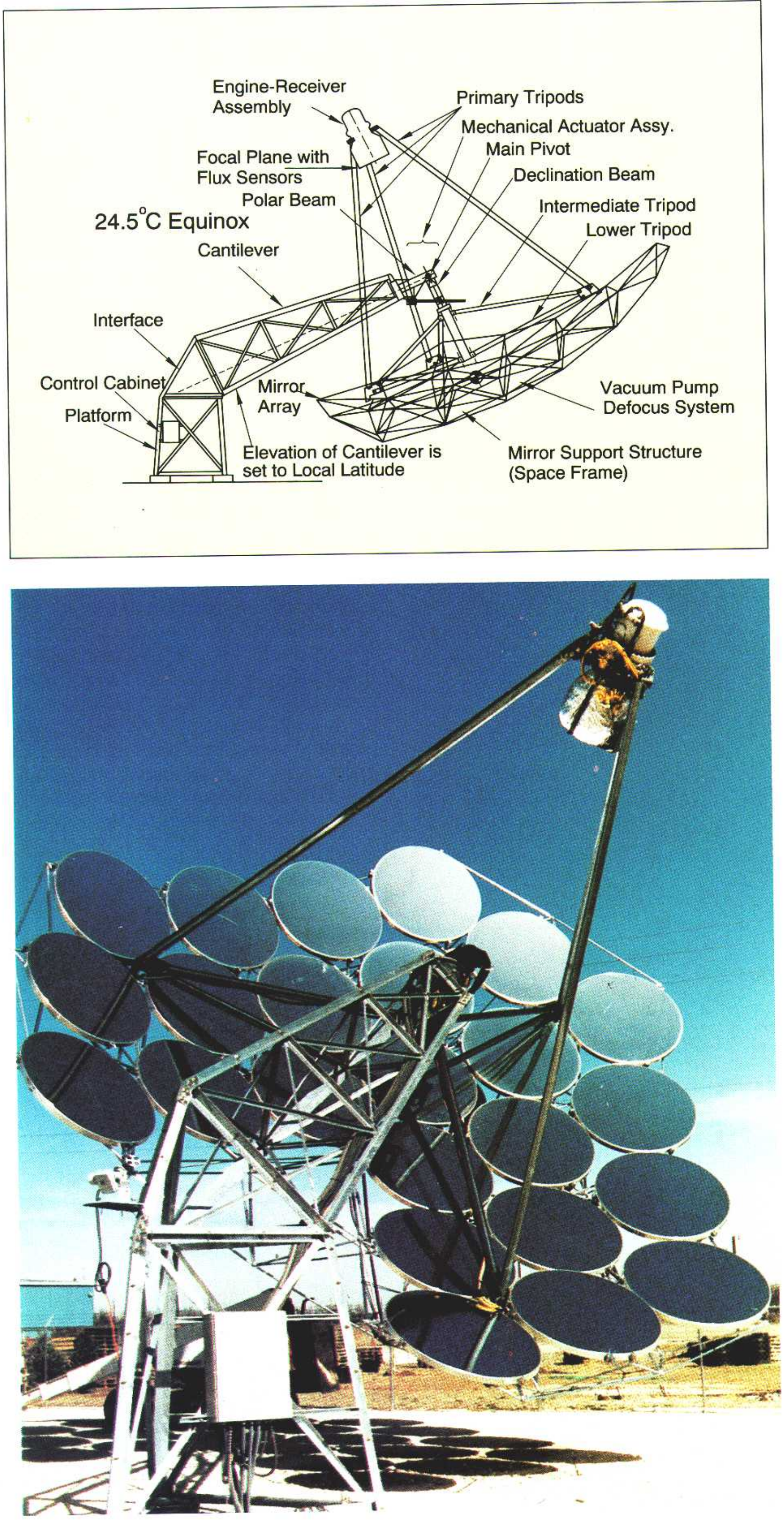


Figure 3-29. Concentrator/ structure of the 5-kW$_e$ Cummins dish/Stirling prototype system 460B (Source: CPG and SNL)

Design (b) uses a principle similar to design (a), but subdivides the reflective area into many facets of typically 1.5-m diameter. As an example, the Cummins Power Generation, Inc. (CPG) dish type 460B (based on LaJet development) has 24 facets (see Figure 3-29). Reflective polymer film (aluminized Mylar) is used for the front membrane and another polymer film for the rear membrane. Using polymer film membranes (another example is the aluminized or silvered-acrylic polymer film) keeps the concentrator weight low. A major drawback of metallized polymer films is today that they have not been experienced in solar applications for expected lifetime with regard to resistance against mechanical washing. However, the films are relatively inexpensive to be replaced.

Design (c) divides the reflective surface into several small glass mirror facets; each facet is fabricated and attached to a steel frame that holds them in place in the paraboloid. This design allows individual facets to be adjusted to a common focus, thus forming a paraboloid. Developers of the JPL test-bed concentrator (see Figure 5-2) chose the focused-facet design in order to reach a high concentration ratio (3000). This design was further developed for commercial manufacturing by McDonnell Douglas (MDAC), shown in Figure 3-30. But this design resulted in higher manufacturing expenses and labor costs to focus the facets and assemble them on the metal frame.

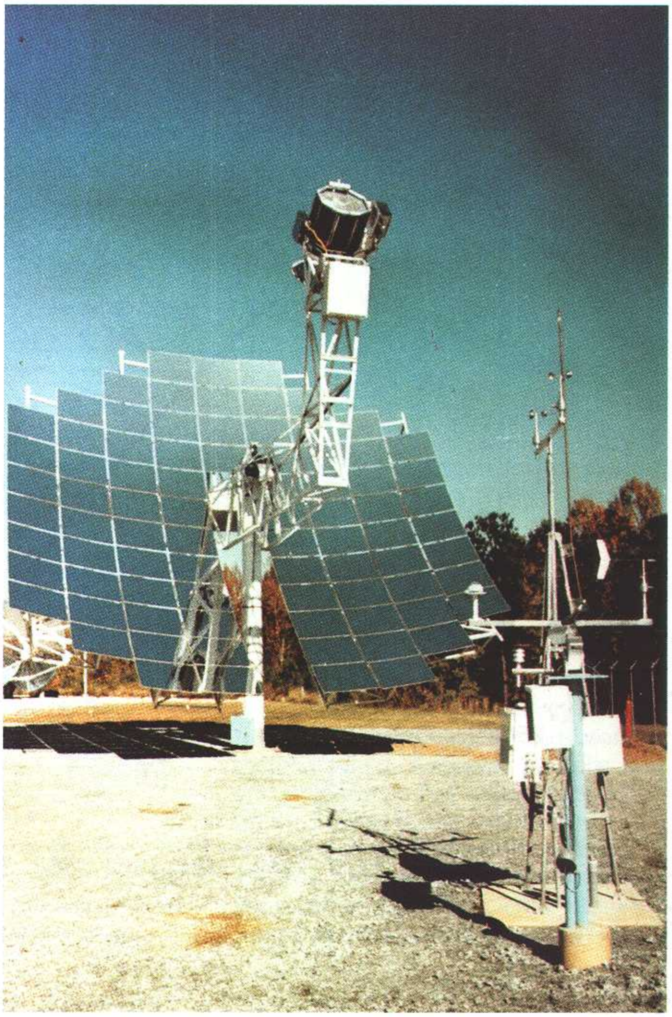


Figure 3-30. Faceted dish collector design by MDAC (Source: MDAC)

Designs (d), (e), and (f) are alternative methods to concentrate sunlight. Designs (d) and (e) employ small moveable facets placed on a large area and aimed to a common focus. The fix-focus dish of HTC-Solar is shown in Figure 3-31. Design (f) uses Fresnel lens optics (from glass or plastic) to concentrate sunlight on the focus.

New R&D programs in Australia concerning dishes of large reflective area up to 400 m² per unit have been mentioned in Chapter 2.1.2.1.

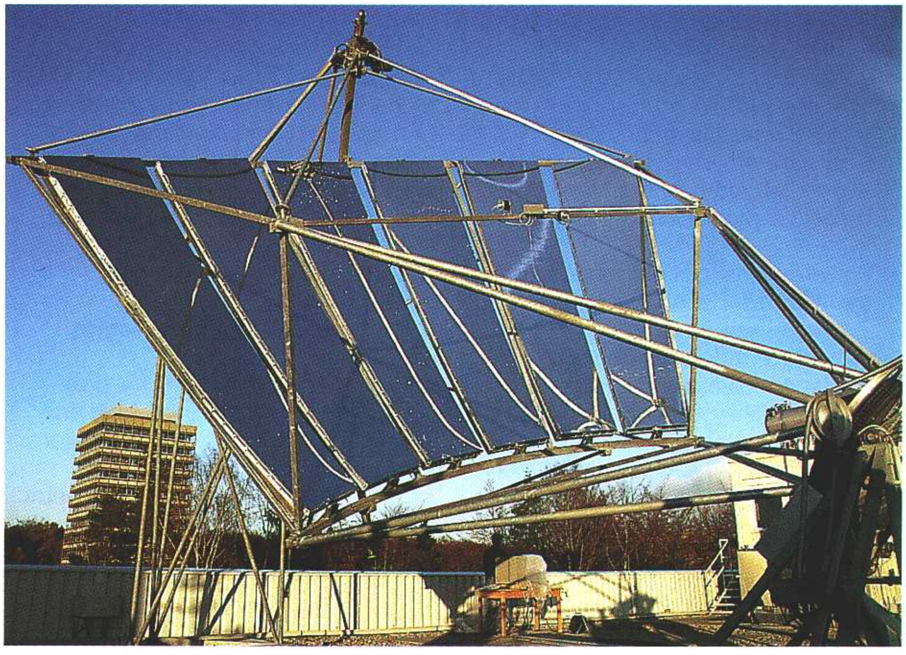


Figure 3-31. Fix-focus dish concentrator/structure (Source: HTC-Solar)

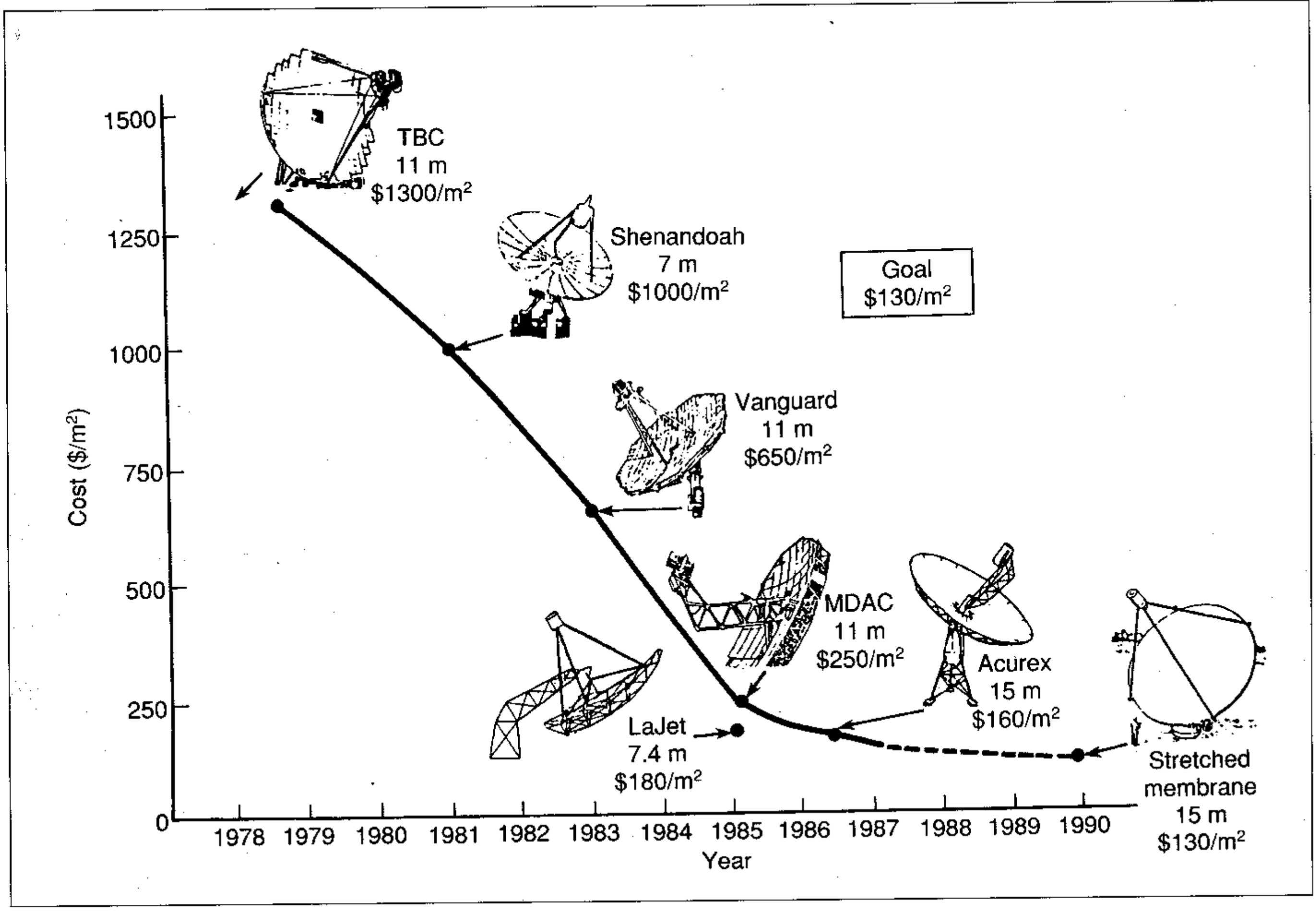


Figure 3-32. Cost improvements of parabolic dish systems during the past 10-15 years (Source: SNL)

Designs (a) and (b) have good potential for future commercial applications. The stretched-membrane concentrator design offers the advantage of a lightweight, efficient structure. The reflective membrane may be of two different types:

- Thin stainless-steel metal sheet with a glued reflective material (thin back-silvered white glass or reflective metallized polymer films) or a reflective silver coating (sol-gel)
- Polymer films/foils with a reflective metallized surface.

Front surface reflectors are subject to degradation from mechanical washing procedures. They require a surface-hardening coating that has high radiant transmissivity, such as the sol-gel coating with a SiO_x protective film. The back-silvered white glass technology has already been developed, while the polymer film technologies are currently under development. Developments in light-weight reflective materials and new structural concepts have progressed remarkably, so that current concentrator designs are promising in terms of both performance and cost (see Figure 3-32).

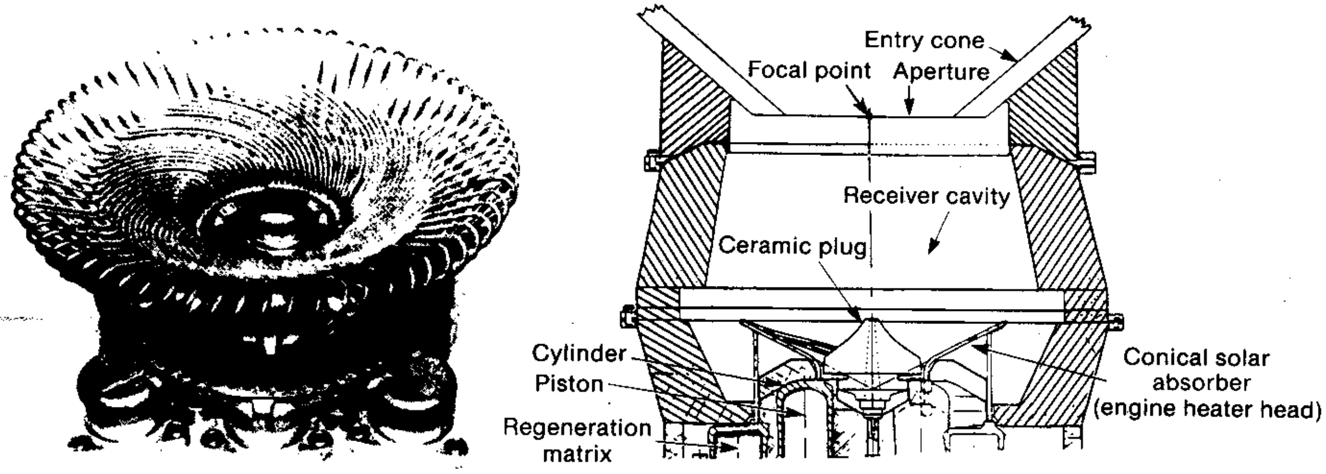
Dish collector systems may use either two-axis tracking to follow the sun as it changes elevation and azimuth, or one-axis tracking about the polar axis with slow correction of the declination axis. Two-axis tracking is more commonly used because of weight and cost advantages.

3.3.2 Receiver Technologies

Different receiver designs for dish/Stirling systems have been built and tested. The three concepts of major interest are tube receivers (cavity receiver, external receiver), volumetric receivers, and heat pipe receivers. Although the tube receiver is the most developed design, the advanced volumetric and liquid-metal reflux receivers are currently under development.

While the tube receiver may be used simply as an external receiver to heat a fluid or to vaporize water or organics, the advanced receivers heat gases or liquids. Different thermodynamic cycles may be applied:

- Stirling cycle (helium or hydrogen piston engine)
- Brayton cycle (gas turbine)
- Water/ steam Rankine cycle (steam turbine)
- Organic cycle (organic steam turbine).



Stirling engine heater head

Cross section of solar receiver with a Stirling engine

Figure 3-33.
Cavity receiver incorporating the 25-kW$_e$ United Stirling engine heater head
(Source: USAB)

Current advanced receiver designs are directed toward increasing the receiver operating temperature achievable from the high concentration in a dish system, and, therefore, increasing the engine-generator efficiency. In this regard, the receivers for the Stirling and Brayton engine cycles have the best potential for future power-generating applications.

The first Stirling receiver concept was a tube type with a cavity. The receiver and the heat engine/generator form a compact unit mounted on the dish. The circular bundle of the small-diameter tubes is the heat exchanger for the Stirling engine and is located at the back of the insulated receiver cavity housing. The working gas (helium or hydrogen) passes through the tube bundle and is heated to approximately 700-800 °C. The main shortcoming of a directly illuminated tube receiver is the risk of short tube life caused by nonuniform flux distribution; this can possibly be solved by further development and experience. Development of this first receiver led to receiver concepts using heat pipes and pool boiling as discussed below.

A tube receiver was used on the Advanco dish to set a world record for solar-to-electric conversion efficiency of 29% (peak) (see Figure 2-18; Figure 3-33).

Another dish receiver concept is based on the heat pipe principle using liquid sodium or potassium with a cavity. Liquid flows along the capillary structure (wick) at the back of the absorber material where it absorbs the solar flux and evaporates. The vapor condenses on the Stirling heater head tubes mounted at the back of the receiver. Because the liquid covers the absorber, the receiver is able to tolerate nonuniform flux from the concentrator.

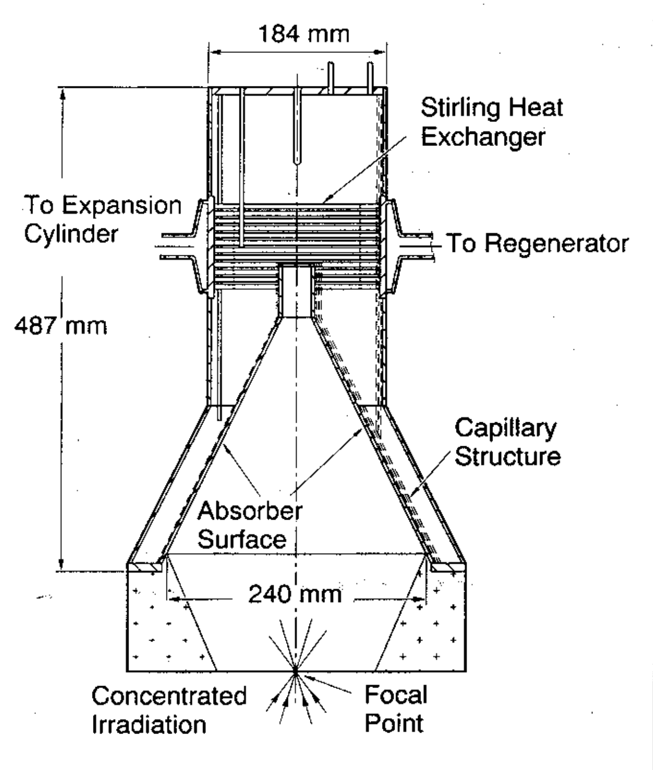


Figure 3-34.
Sodium heat pipe receiver for Stirling application
(Source: DLR)

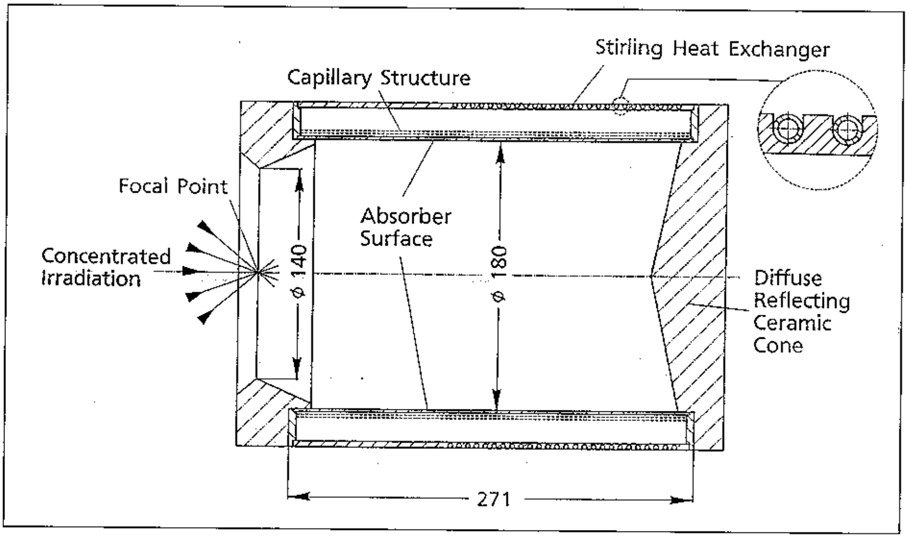


Figure 3-35.
Heat pipe receiver design of the second generation
(Source: DLR)

Receiver working temperatures are in the range of 500-800 °C. A heat pipe receiver of the first generation at DLR in Stuttgart showed promising test results (Figure 3-34). Figure 3-35 shows the DLR design of the second generation heat pipe receiver. Cummins Power Generation Inc., USA, has recently concluded a successful 500-hours on-sun durability test of a heat pipe receiver (see Figure 3-36).

Another dish receiver concept utilizes the reflux pool boiling principle using liquid sodium or sodium/ potassium with a cavity (see Figure 3-37). Solar irradiance is absorbed by a dome located at the back of the cavity; the dome is cooled by the boiling liquid metal. The metal vapor condenses on the Stirling engine heat exchanger tube bundle and drains back to the pool by gravity.

Receiver temperatures of approximately 650-850 °C (similar to those for the heat pipe receiver) are reached. SNL has recently tested a NaK reflux pool boiling receiver.

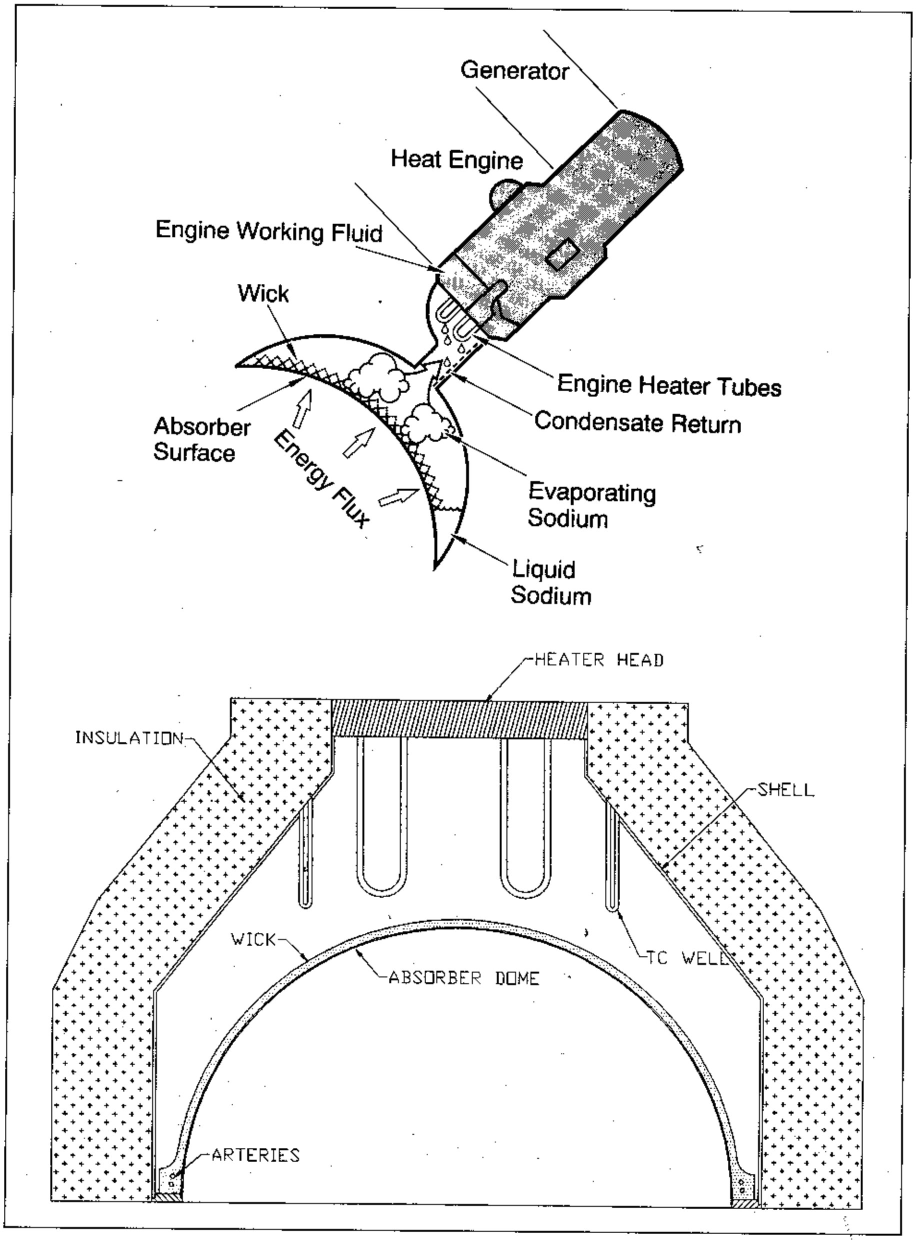
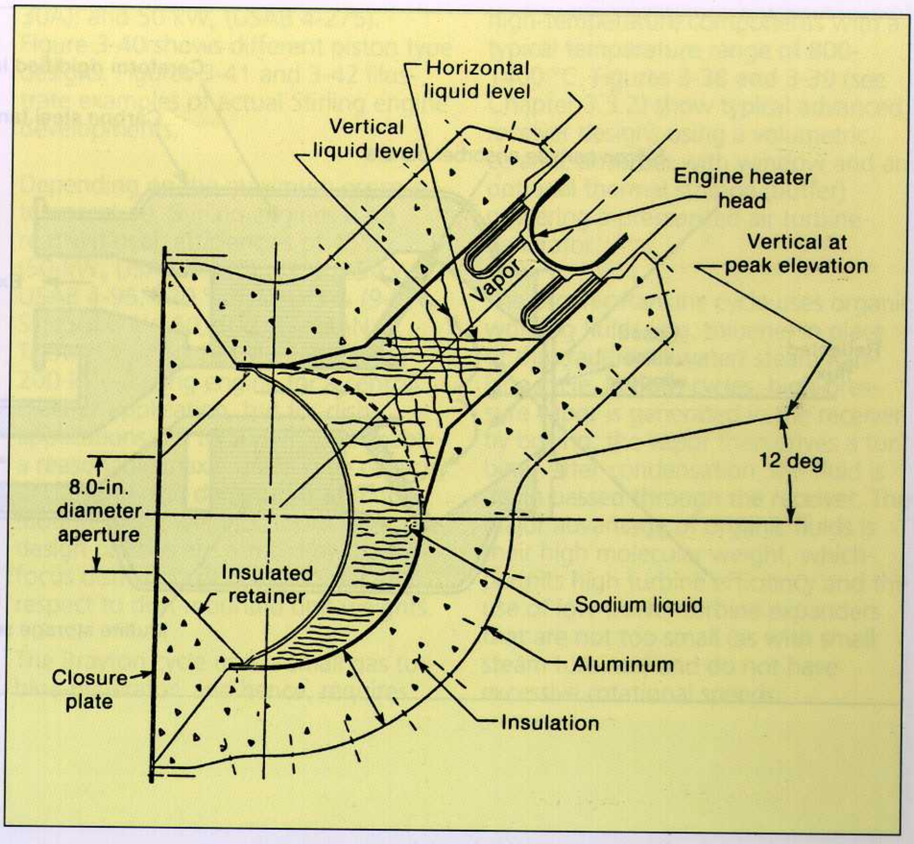


Figure 3-36.
Sodium heat pipe receiver for Stirling application
(Source: CPG/Thermacore)

Figure 3-37.
Reflux pool boiling receiver for Stirling application
(Source: SNL)



The volumetric receiver for dish-mounted gas turbine (Brayton cycle) uses a ceramic volumetric absorber similar to the central receiver application (see Figures 3-38 and 3-39).

The heat-transfer medium (e.g. air) is heated by the volumetric absorber, which is usually made from ceramic material (e.g. foam, honey comb structure). In the case of the Sanders receiver, ceramic material is installed within the hot gas duct to function as a heat buffer storage. For the purpose of a closed pressurized gas cycle, a quartz window is applied at the receiver aperture. The window suffers from thermal transient stresses, which is the reason why further development for use in solar receivers is needed.

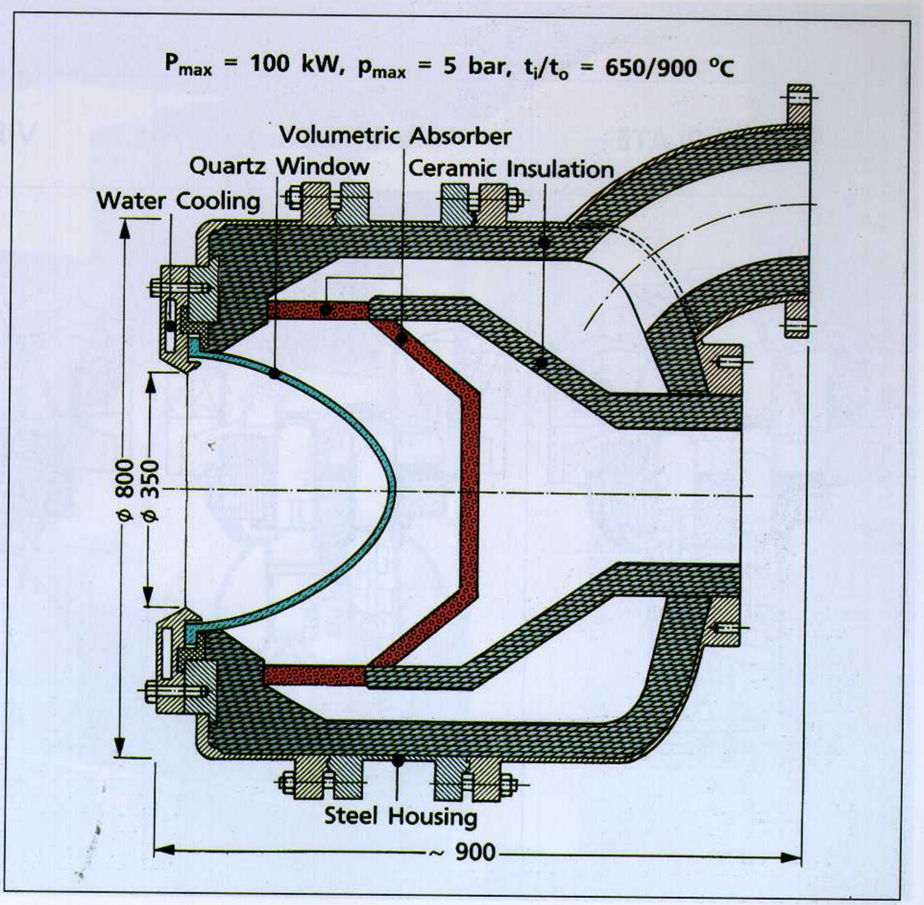


Figure 3-38.
Volumetric ceramic receiver using pressurized air and a gas turbine (Brayton) cycle
(Source: DLR)

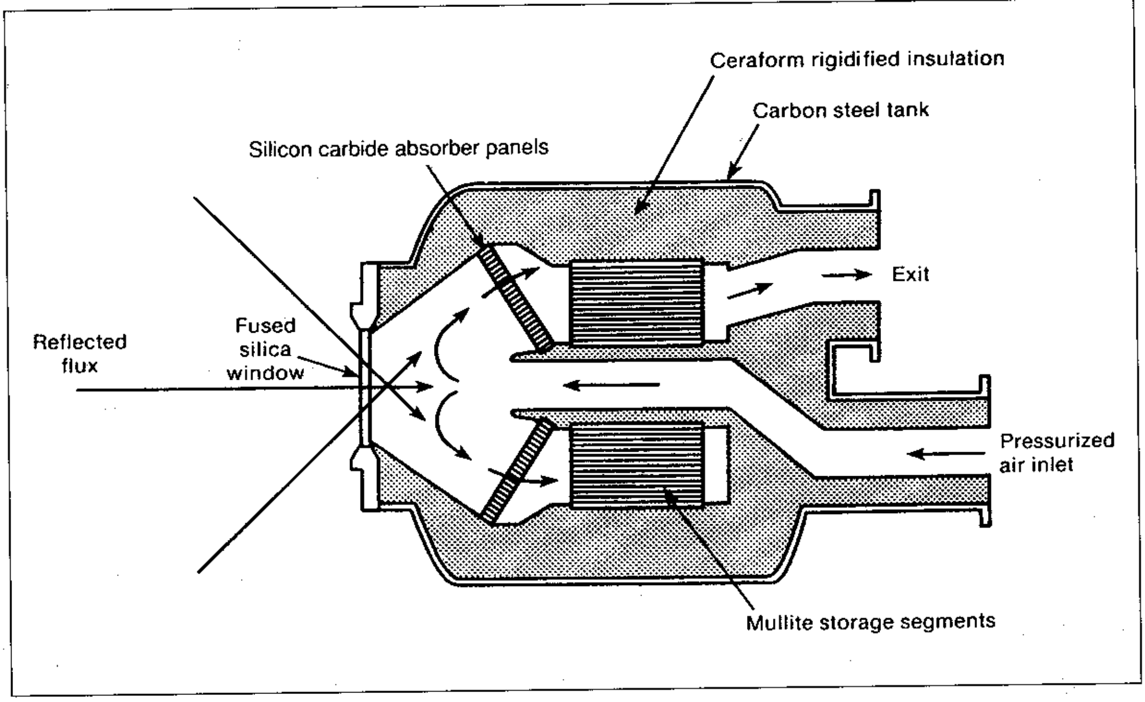


Figure 3-39. Sanders volumetric ceramic receiver for Brayton cycle using pressurized air turbine of Garrett Turbine Engine Company (Source: Sanders)

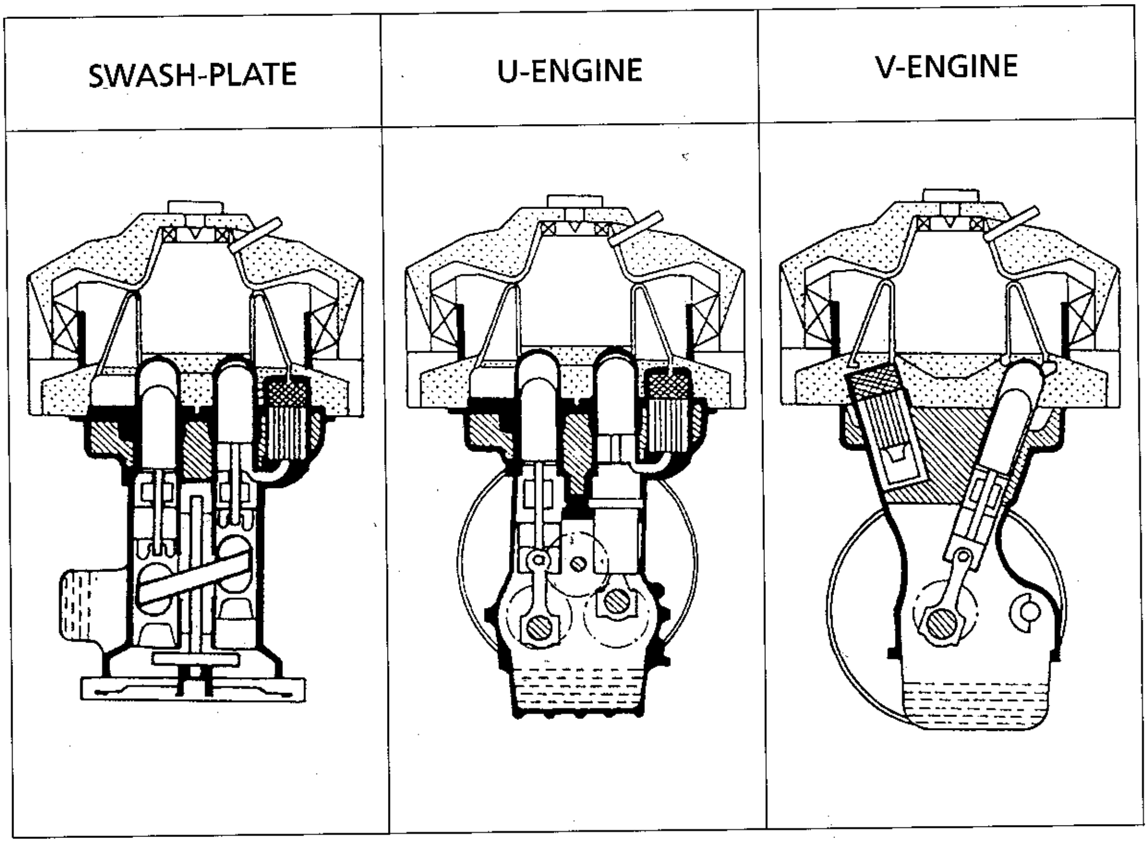


Figure 3-40. Different piston type Stirling engines (Source: SBP)

3.3.3 Engine Technologies

As mentioned in Chapter 3.3.2 for dish receiver types, parabolic dish systems use various power conversion technologies. The Stirling engine is the primary focus of current dish research in the USA and Europe because of its technical and economical potential for power generation. Two types of Stirling engines have been developed and tested in experimental automotive and solar facilities: the piston/crankshaft (kinematic) type with rotating alternator and the free-piston type with linear alternator.

The working gas may be helium or hydrogen and may reach 700-800 °C at maximum pressures of 15 MPa. The unit power size of existing Stirling engines and of current developments is 5/9 kW_e (CPG); 9 kW_e (SBP, SPS/SOLO V-160); 25 kW_e (USAB 4-95, STM 4-120); 30 kW_e (Aisin Seiki NS 30A); and 50 kW_e (USAB 4-275). Figure 3-40 shows different piston type designs. Figures 3-41 and 3-42 illustrate examples of actual Stirling engine developments.

Depending on the maximum process temperature, Stirling engines have reached peak efficiencies of 45% (50-kW_e USAB 4-275); 42% (25-kW_e USAB 4-95, 720 °C); and 31% (9-kW_e SPS/SOLO V-160, 500 °C). MAN Technologie AG has studied a large 200-kW_e Stirling engine for a central receiver application, but for dish applications, 25 to 50 kW_e is probably a reasonable maximum engine capacity because of dish dimensions and dish-mounted unit weights. More favorable design options are offered by the fix-focus dish concept of HTC-Solar with respect to dish-mounted unit weights.

The Brayton cycle uses a small gas turbine-generator, and hence, requires high-temperature components with a typical temperature range of 800-1400 °C. Figures 3-38 and 3-39 (see Chapter 3.3.2) show typical advanced receiver designs using a volumetric ceramic absorber with window and an optional thermal storage (buffer) powering a pressurized air turbine-generator.

The organic Rankine cycle uses organic working fluids (e.g. toluene) in place of the traditional water/ steam Rankine cycle. In both cycles, high-pressure vapor is generated in the receiver by boiling; the vapor then drives a turbine. After condensation, the fluid is again passed through the receiver. The major advantage of organic fluids is their high molecular weight, which permits high turbine efficiency and the use of low-power turbine expanders that are not too small (as with small steam turbines) and do not have excessive rotational speeds.

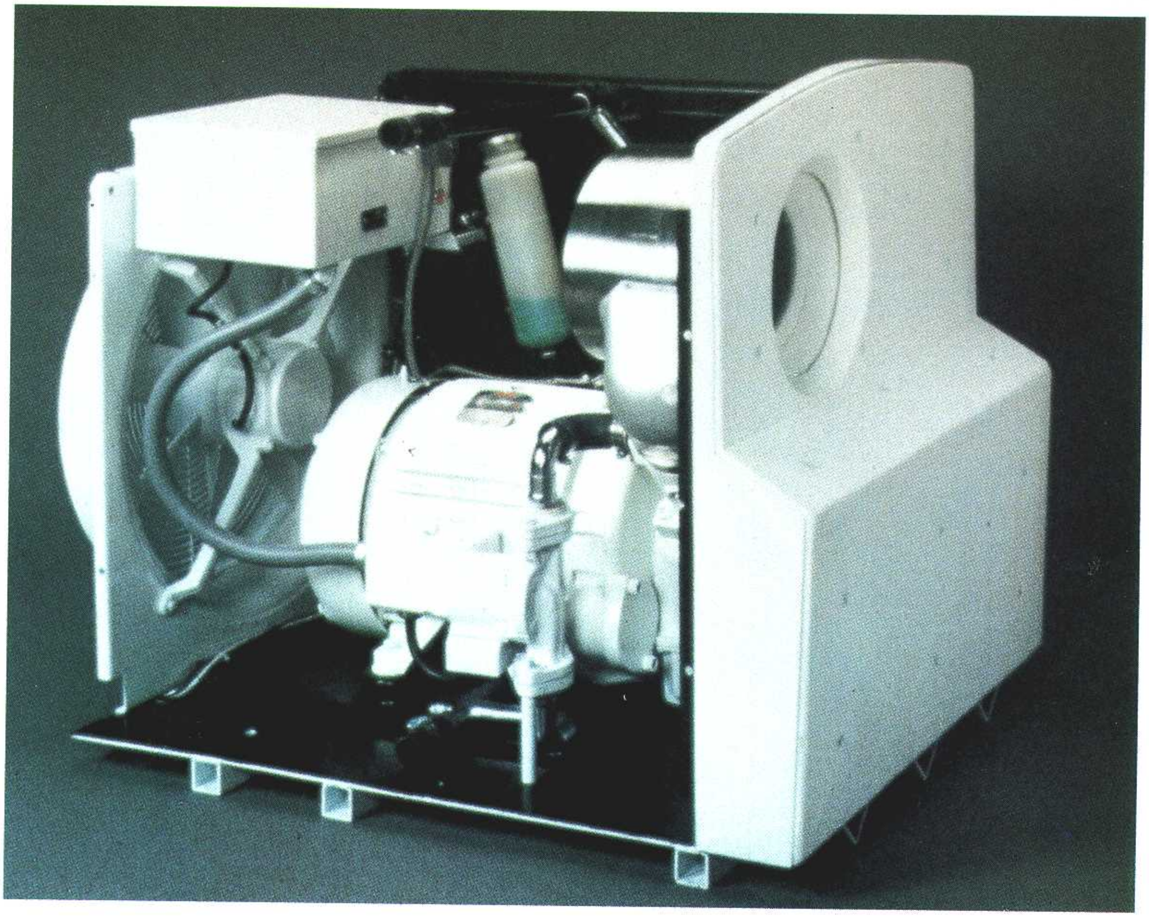


Figure 3-41. Stirling engine SPS/SOLO V-160 unit including receiver and heat rejection (Source: SBP/SOLO)

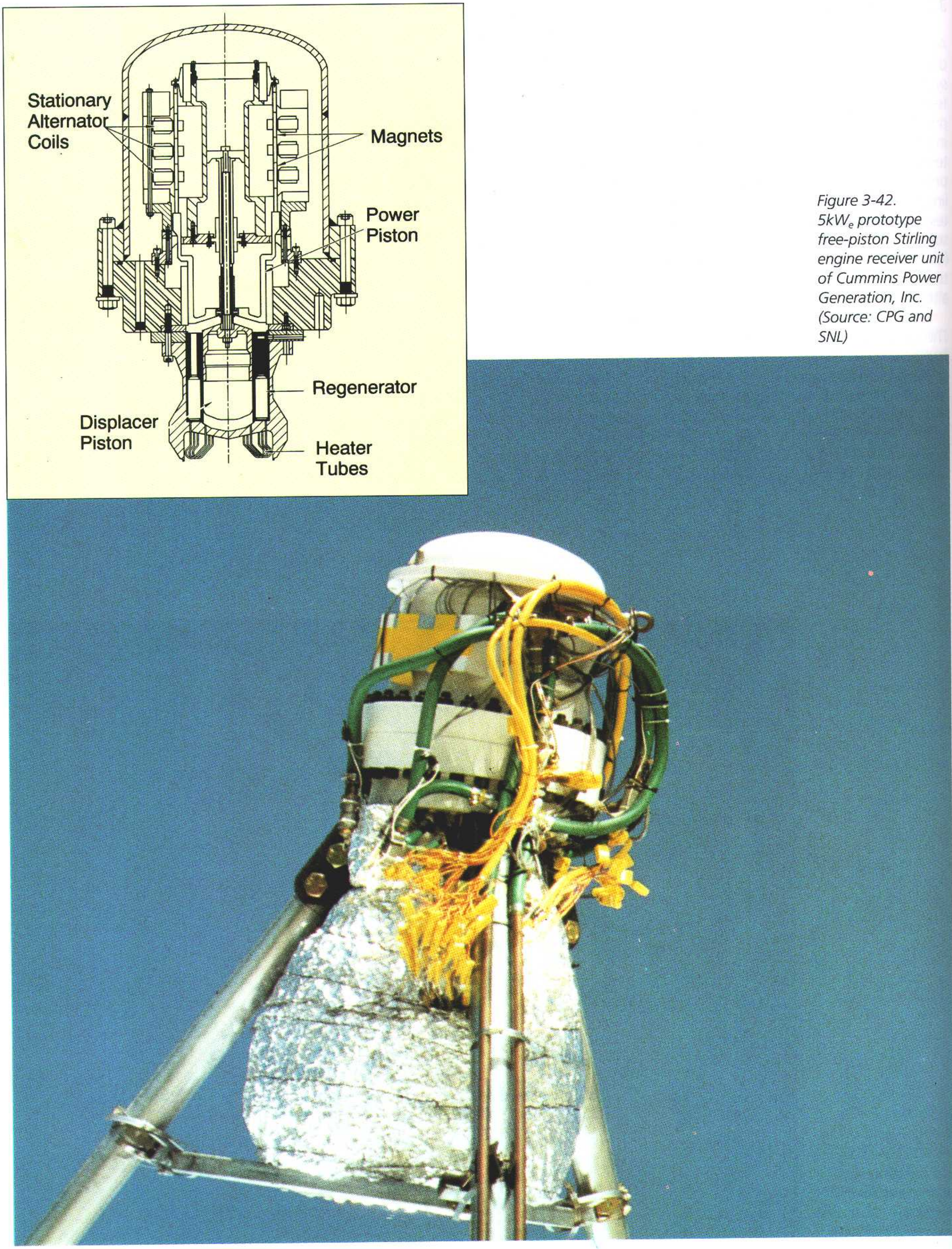


Figure 3-42. $5kW_e$ prototype free-piston Stirling engine receiver unit of Cummins Power Generation, Inc. (Source: CPG and SNL)

4.1 Solar Resource Assessment

Solar resource assessment is a fundamental area of activities in solar energy research. Researchers strive to understand and quantify the variations in solar radiation levels that occur across the surface of the earth. Long-term trends and variations in radiation levels for a given region are the basis for design and selections of solar energy systems. The output power or energy delivery achieved by a solar-based system is a direct function of how well suited that system is for exploiting the ambient radiation trends in the operating environment. Considerations such as system location, size, output fluctuations, back-up and storage requirements, and peak-use periods all are derived from knowing the solar resource characteristics at a particular site.

Energy from the sun travels unimpeded through the vacuum of space, and radiant energy flux decreases inversely as the square of the distance from the sun. At any given distance from the sun, the level of solar radiation remains fairly uniform, with small, temporary fluctuations caused by solar flares, sun spots, and other solar events. This relative uniformity is lost as solar radiation travels through the earth's atmosphere. Large spatial, temporal, and spectral variations over the surface of the earth greatly affect the composition and intensity of solar radiation.

Spatial, or geographic, variability plays a critical role in solar resource assessment. Spatial variability research attempts to understand such interrelated factors as altitude, latitude, weather patterns, geographic features, climate, and atmospheric constituents. The combination of these factors can produce marked variations in solar radiation over short distances or, conversely, can produce vast areas of uniform solar coverage.

The amount of solar energy reaching a point on the earth changes remarkably over the course of a day, a month, a season, a year, and even longer cycles. The success of many solar energy systems is heavily dependent on whether peak use periods coincide with peak solar resource availability. For example, a solar-based air conditioning system would experience peak energy loads at mid-day, which, in many instances, coincides with peak solar radiation levels.

The spectral variability of solar radiation reaching the surface of the earth is also a critical component of resource assessment research. A large portion of the solar radiation passing the atmosphere is absorbed and scattered as it interacts with air molecules, aerosols, and water vapor. Specific wavelengths within the solar spectrum react differently to the various constituents within the atmosphere. For example, the shorter wavelengths are susceptible to molecular and aerosol scattering, while radiation in the longer-wavelength portion of the spectrum is more readily absorbed by water vapor. Spectral variability is influenced primarily by changing atmospheric conditions and optical path length through the atmosphere.

The usable solar radiation incident on the earth's surface falls into two categories: direct-beam radiation and diffuse radiation. Direct-beam radiation is the solar radiation that reaches the surface of the earth without being scattered or absorbed in the atmosphere. Because the radiation retains its directionality, it can be collected and concentrated by focusing solar energy systems. Diffuse solar radiation refers to scattered radiation reaching the surface of the earth. Nonconcentrating, (e.g. flat-plate) collectors can make use of diffuse as well as direct-beam radiation. The sum of the two types of radiation is known as global solar radiation.

Figure 4-1 and 4-2 show how the solar radiation varies with location in the United States and in Europe, respectively. From the standpoint of solar resource assessment, distinguishing

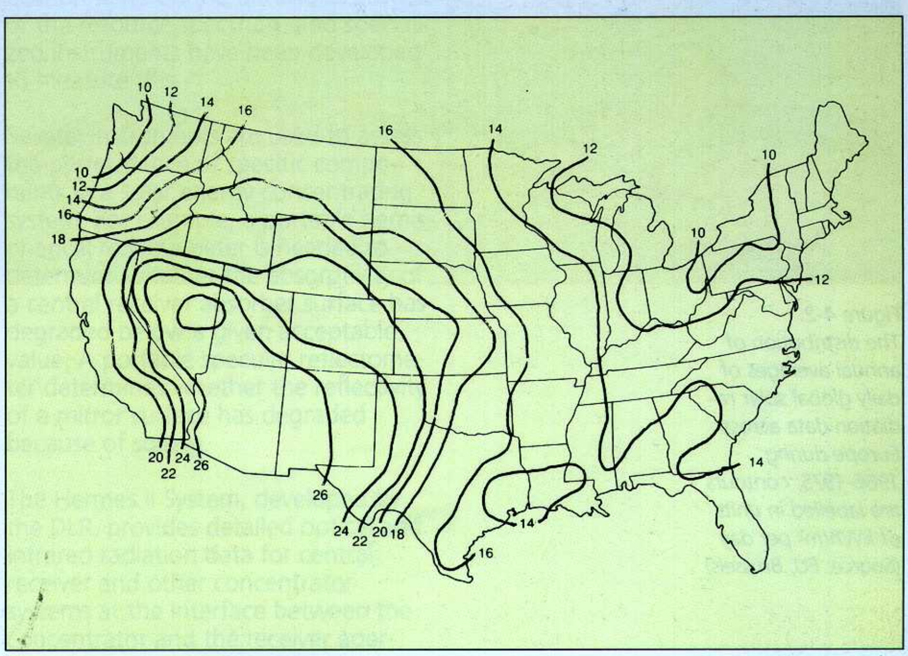


Figure 4-1. The distribution of annual averages of daily solar radiation data across the United States for the direct-beam component of solar radiation; contours are labelled in units of MJ/m² per day (Source: NREL)

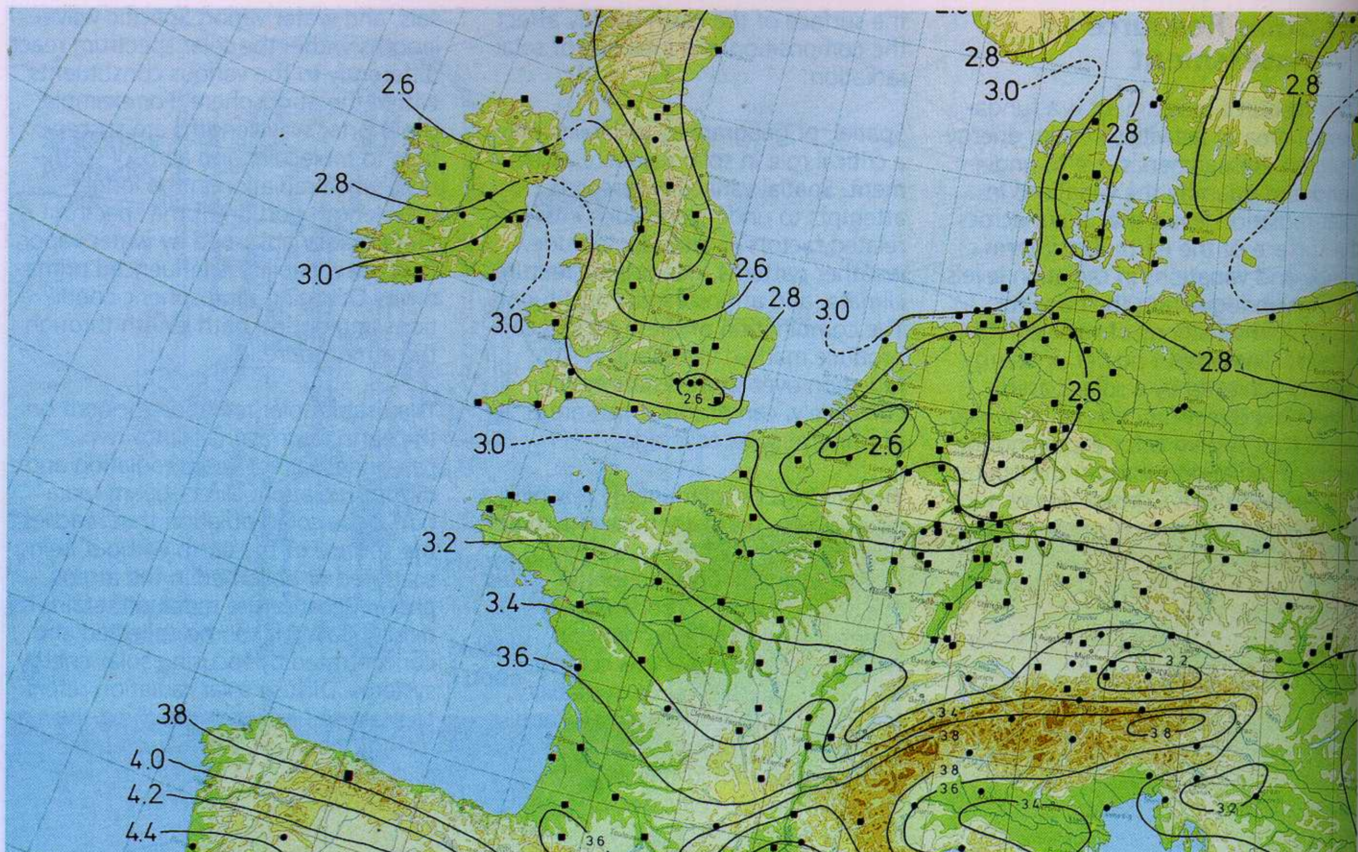


Figure 4-2.
The distribution of annual averages of daily global solar radiation data across Europe during 1966-1975; contours are labelled in units of kWh/m² per day (Source: EU, Brussels)

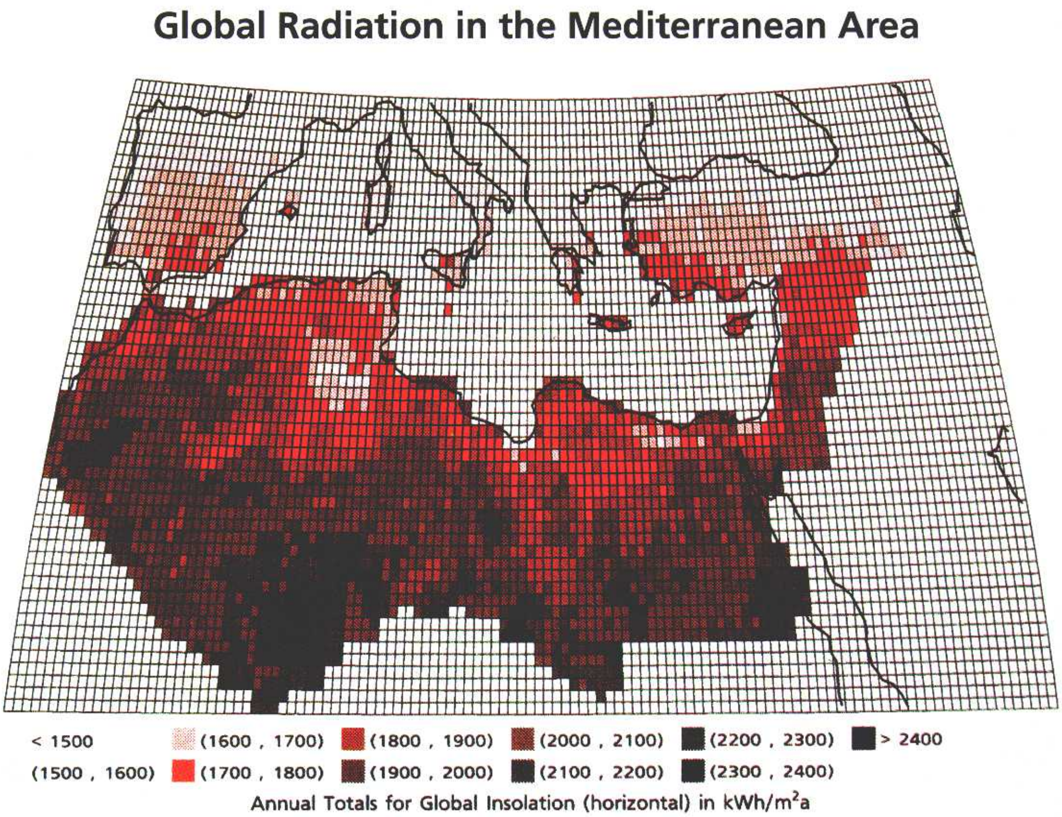


Figure 4-3.
The distribution of annual averages of solar global radiation in units of kWh/m² for the Mediterranean area (Source: DLR/ZSW)

between the two types of radiation is important because an area abundant in one type may not necessarily be abundant in the other. The availability of direct-beam radiation in a region is of primary importance when selecting a concentrating solar technology. As an additional example, Figure 4-3 shows the distribution of the annual averages of the solar radiation in countries of the Mediterranean area.

4.2 Instrumentation

Instrumentation associated with concentrating solar energy systems is used either to help to assess the solar resource or to characterize the performance of the hardware. The local solar resource is typically measured using two important instruments: a pyranometer and a pyrheliometer. A pyranometer (see Figure 4-4) measures the global solar radiation incident on a horizontal surface at a given location. A pyrheliometer (see Figures 4-5 and 4-6) measures the direct beam component of the resource available at a given location. This instrument is tracked in order to follow the moving sun position. Specialized applications may require more detailed resource information. For example, solar detoxification relies on the ultraviolet portion of the resource spectrum, and specialized instruments have been developed to measure this.

Several instruments are used to assess the performance of specific components in a solar energy concentrating system. For example, a portable hemispherical reflectometer is needed to determine whether the absorptivity of a central receiver absorber surface has degraded below a given acceptable value. A portable specular reflectometer determines whether the reflectivity of a mirror surface has degraded because of soiling.

The Hermes II System, developed by the DLR, provides detailed optical and infrared radiation data for central receiver and other concentrator systems at the interface between the concentrator and the receiver aper-

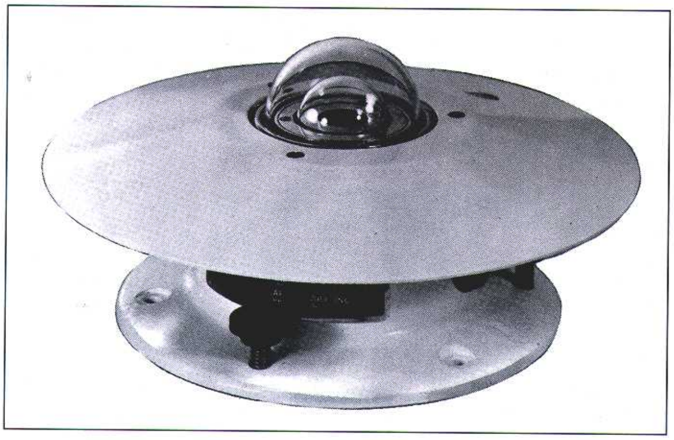


Figure 4-4.
Pyranometer used to measure global solar radiation (Source: NREL)

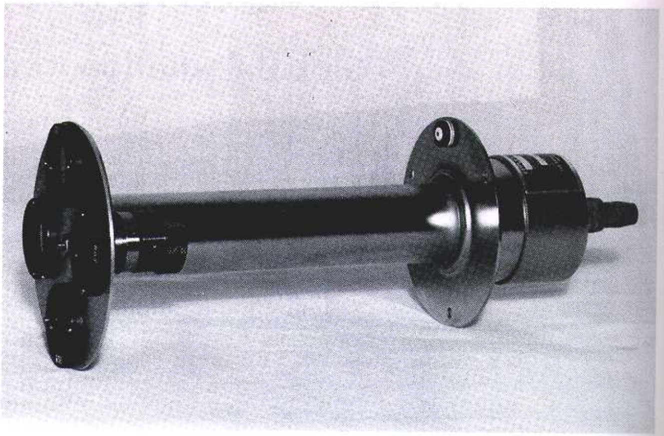


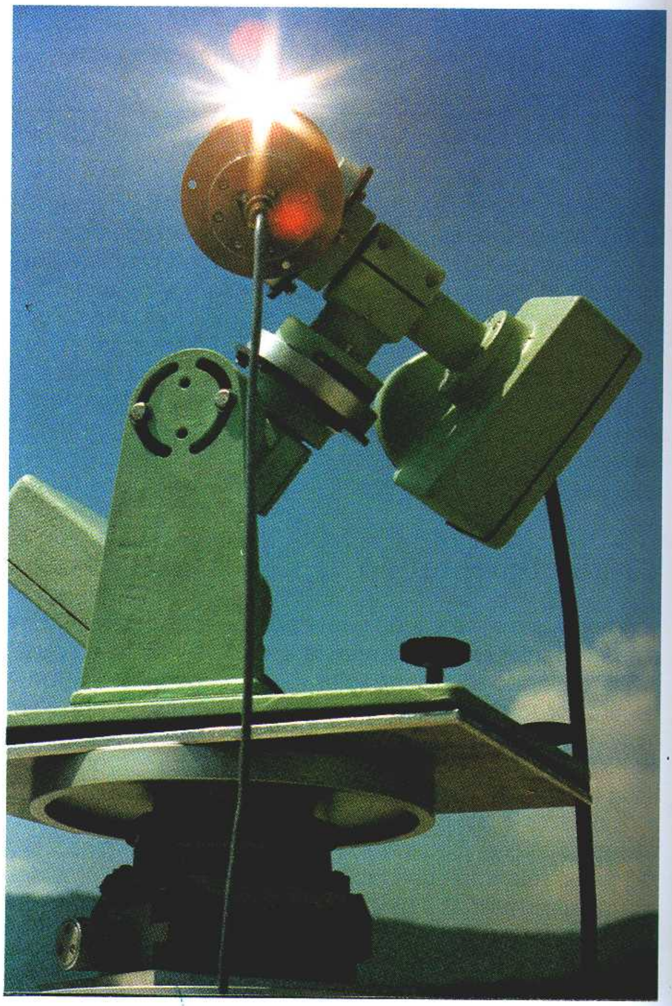
Figure 4-5.
Pyrheliometer used to measure direct beam solar radiation (Source: NREL)

ture. Included in the data that can be provided by the system are focal plane radiance power, receiver radiant flux, reflected radiation, heliostat characterization, and receiver surface temperature distribution by evaluation of the infrared radiation emitted from the receiver surface.

A schematic of the system is shown in Figure 4-7. Data in the visible spectrum are provided by passing a diffuse reflector through the focal plane and by measuring the radiation reflected from it with a video camera. An absolute intensity measurement is provided by a calorimeter or a radiometer. Temperature is inferred by measuring the infrared radiation emitted from the receiver surface with an infrared-wavelength camera. Determining temperature requires a knowledge of the surface emissivity. The system also provides local meteorological data, including the aforementioned global and direct radiation level as well as wind speed, wind direction, temperature, and humidity. Figure 4-8 shows typical output data from the Hermes II System in optical and infrared photographs.

Another instrument characterizes the optical surface and performance of large-aperture dish-type solar concentrators for use in terrestrial and space applications. The Scanning Hartmann Optical Test (SHOT) instrument is unique in its ability to acquire surface slope data at a high spatial resolution over a short time and can be used to test dish concentrators. When interfaced with associated optical ray-trace software, the system predicts the flux distribution and assesses the optical performance at a user-specified target plane.

Figure 4-6
Pyrheliometer mounted on solar trackers (Source: PSI)



A large-aperture, near-specular imaging reflectometer (LANSIR) was designed and built for performing optical surface quality tests on laminate mirror specimens. LANSIR can quantify the extent of reflective light-scattering from the surface of mirrors.

Various instrumentations for the different specific requirements in the field of solar energy have been developed or are yet under development, e.g. to assess the quality of the curvature of concentrators, to measure the radiant flux of a concentrated beam, to align the correct position of individual mirror facets of a concentrator, to characterize the optical performance of stretched membranes.

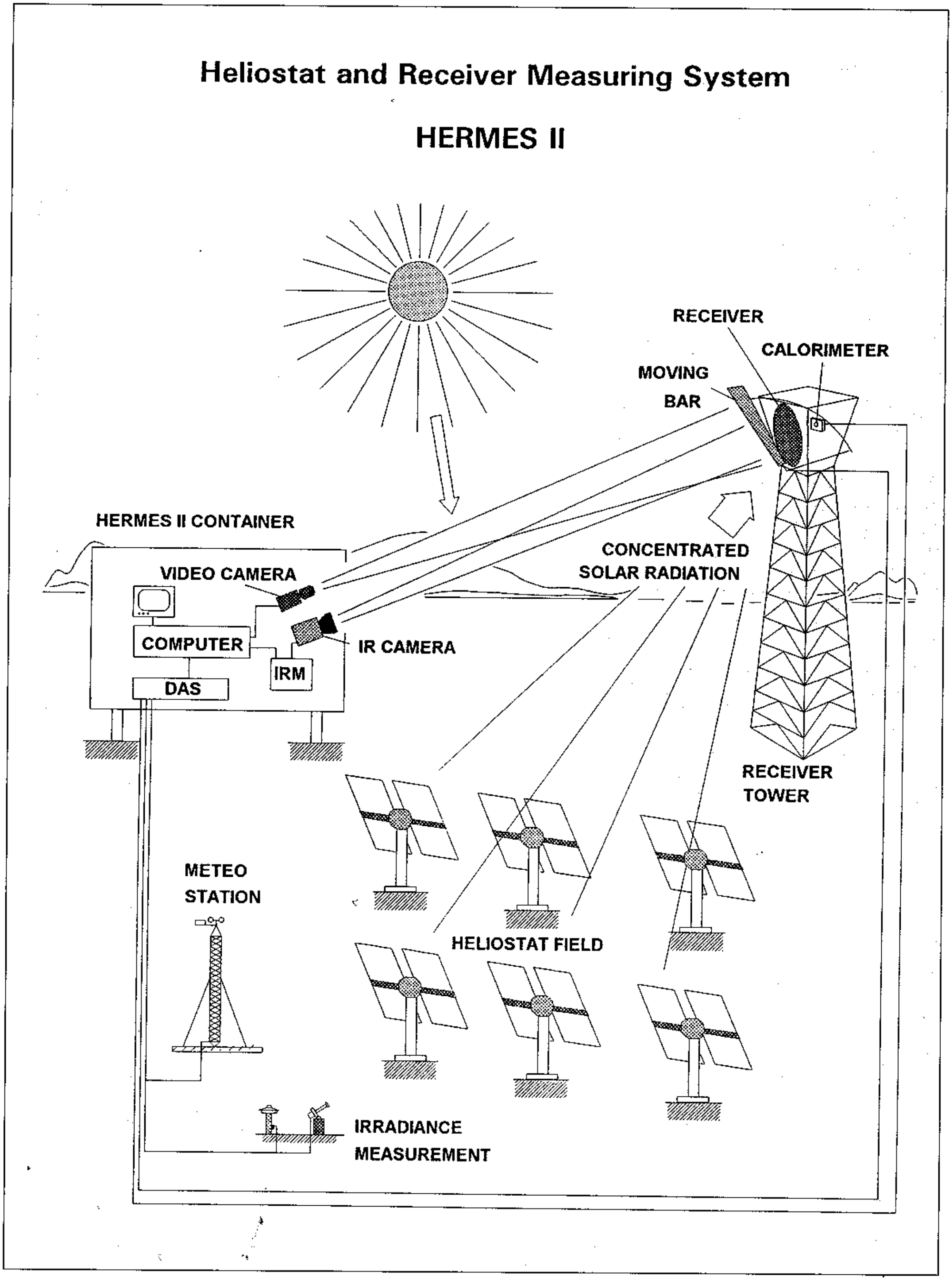
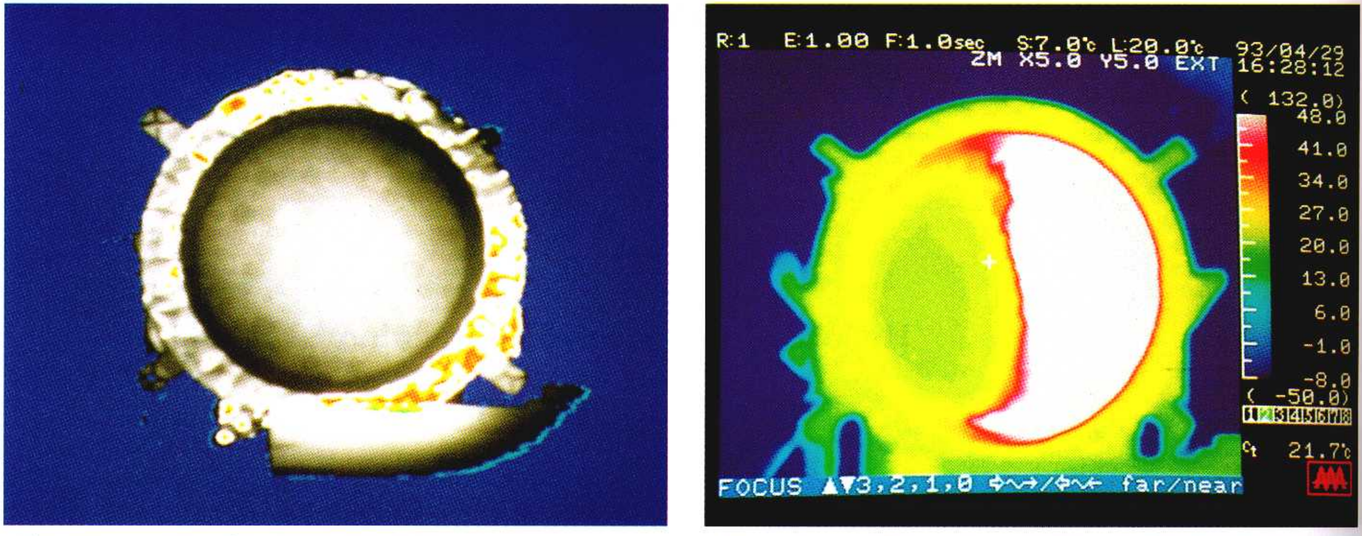
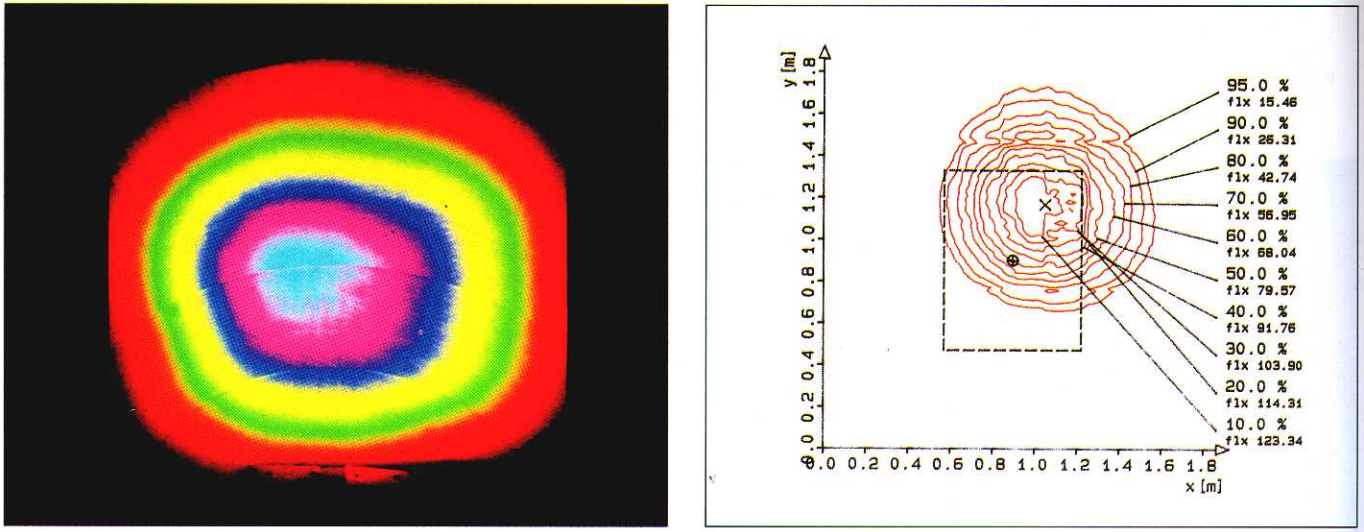


Figure 4-7. Schematic of the Hermes II System (Source: DLR)



Video camera picture of irradiated receiver front

Infrared camera picture of receiver front with colored temperature ranges



Radiant flux distribution on receiver front with colored flux density ranges

Equiflux lines of radiant flux distribution on receiver front

Figure 4-8. Typical output of the Hermes II System (Source: DLR)

5 Test Facilities

Previous chapters of this report described high-temperature solar thermal technology, including hardware concepts for receivers, storage, and solar detoxification, and application to material testing and chemical processes. To further assess R&D possibilities, this section describes test facilities currently available for solar thermal investigations.

The following existing test facilities are discussed in this section:

- In the Unites States:
  - National Solar Thermal Test Facility (NSTTF) at SNL in Albuquerque, New Mexico, the largest test facility site in the USA
  - High-Flux Solar Furnace (HFSF) at NREL in Golden, Colorado
- In Spain:
  - Plataforma Solar de Almería of CIEMAT near Tabernas in the province of Almería in the South of Spain, the largest test facility site in Europe, jointly operated by the Spanish CIEMAT and the German DLR
- In Germany:
  - Parabolic test bed concentrator (PAN) at DLR in Lampoldshausen near Heilbronn
  - High-flux solar furnace at DLR in Köln
- In Switzerland:
  - Facilities of the Paul Scherrer Institute (PSI) in Villigen near Zuerich
- In France:
  - High-flux solar furnace of CNRS at Odeillo in the French Pyrenees
- In Israel:
  - Facilities of the Weizmann Institute of Science (WIS) at Rehovot near Tel Aviv
  - Ben-Gurion National Solar Energy Research Center at Sde Boker in the Negev desert
- In Uzbekistan:
  - High-flux solar furnace of the Uzbek Academy of Sciences in Parkent near Tashkent.

Other solar test facilities not described here include plants located in the Crimea area of the Ukraine, in Saudi-Arabia near Riyadh (Solar Village), in Australia in Canberra/Sydney and in India north of Delhi.

Currently available facilities provide excellent opportunities for tests at the bench scale and prototype level. Solar power plants still require R&D work and demonstration, so the test facilities described here will play a key role in future solar R&D activities worldwide.

Figure 5-1. The 5.5-MW$_t$ central receiver test facility (CRTF) at SNL in Albuquerque, New Mexico, USA (Source: SNL)

National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories,
Albuquerque, New Mexico, USA

The NSTTF is operated by the Sandia National Laboratories (SNL) for the U.S. Department of Energy (DOE). The primary mission of the NSTTF is to support all R&D activities under the direction of DOE's Solar Thermal Division. However, the NSTTF is also permitted to support both foreign and non-solar thermal activities on a reimbursable basis. Typical experiments of this type include aerodynamic heat simulation, material studies, flux pulsing, heliostat qualification, advanced receiver tests, and other tests of solarspecific components (e.g. molten-salt pumps, valves, storage).

The NSTTF comprises a Central Receiver Test Facility (CRTF), a Distributed Receiver Test Facility (DRTF), and a 16-kW_t high-flux solar furnace.

All NSTTF facilities are supported by powerful data acquisition and control systems. Video-based beam characterization systems are used to calibrate flux densities and distributions and to characterize prototype heliostats and concentrators.

Central Receiver Test Facility (CRTF)

A north field of 222 heliostats (37 m^2) directs up to 5.5 MW_t of flux onto a test tower 61 m high (Figure 5-1). The test bays in the tower have been used to test air, salt, water/steam, and sodium receivers in sizes from 1 MW_t to 5 MW_t. Experimental operation of a 750-kW_e molten-salt electric system with storage was completed. A molten-salt film absorption receiver panel has been installed, and low-flux testing has been performed. A Swiss volumetric receiver and a small-scale central receiver photovoltaic array were also tested. A 50-MW-scale molten-salt pump and valve experiment was carried out; both test components remain available for evaluation of advanced components. The CRTF also serves as the experiment station for heliostats. Fourteen heliostats of different designs up to 200 m^2 reflective area have been installed for evaluation, including two large-area heliostats and four stretched-membrane heliostats.

Characteristics of the CRTF

- Collector Field
  - Field of 222 individually tracking heliostats
  - Reflective area = 6.1 m x 6.1 m (each)
  - Reflectivity = 80% (nominal)
  - Second surface silvered glass
  - Tracking accuracy = 0.7 mrad
- Major test locations on the tower:
  - Three test bays (36, 43, and 49 m above ground, respectively)
  - Tower top
- Peak flux = 2.6 MW/m^2; 90% of the peak within 0.7-m diameter
- Total power = 5.5 MW_t within 3-m diameter
- Tower lifting capacity = 100,000 kg.

Distributed Receiver Test Facility (DRTF)

The DRTF includes two test-bed 11-m-diameter parabolic dish concentrators. Figure 5-2 shows the 75-kW concentrator with a sodium pool boiler refluxing receiver. One of these dishes may also be operated as a solar furnace. In addition, the facility includes a 170-m^2 LaJet concentrator, a 7-m-diameter stretched-membrane dish manufactured by Solar Kinetics, and a 295-m^2 Power Kinetics, Inc. dish with a 50-kW_e steam engine. A Barber-Nichols organic Rankine cycle engine and a SNL-designed sodium pool boiler receiver were previously evaluated. An associated engine test facility supports ground-level testing of heat engines, such as the Stirling Thermal Motors STM 4-120 engine and bench-scale reflux receivers. A two-axis tracking line focus (trough) test bed is available for evaluating subsystems and components such as collectors, trackers, receivers, and flex hoses. One of four line-focus systems has been converted for evaluation of the solar detoxification of water.

Figure 5-2.
The 75-kW test bed concentrator (TBC) with sodium pool boiler refluxing receiver at SNL in Albuquerque, New Mexico, USA (Source: SNL)

Characteristics of the 75-kW$_t$ test bed concentrator (TBC)

- One-stage configuration: parabolic dish concentrator
- 11 m-diameter reflector
- 220 facets
  - Individually adjustable
  - Second surface silvered glass
  - Reflective area = 0.61 m x 0.71 m (nominal size)
  - Reflectivity = 95% (initial, maximum)
  - Average slope error = 1 mrad
- Focal length = 6.6 m
- Paraboloidal mounting structure f/d = 0.6
- Maximum mass at focus = 900 kg
- Rim angle = 45 degrees
- Tracking error = 1 mrad
- Slew rates
  - Azimuth = 200 °/h; ± 178 degrees of travel
  - Elevation = 200 °/h; 0-90 degrees of travel
- Peak flux = 15 MW/m^2
- Total power = 75 kW within 180 mm diameter.

16-kW High-Flux Solar Furnace

The 16-kW high-flux solar furnace (Figure 5-3) is used for solar receiver development, including volumetric and high-temperature thermochemical receiver design, flux-gauge calibration, and materials testing.

Characteristics of the 16-kW solar furnace

- Two-stage configuration of a non-imaging collector (one flat heliostat) and imaging parabolic concentrator (dish)
- Dish diameter = 6.7 m; focal length = 4.6 m
- 228 facets (on the dish)
  - second surface silvered glass
  - slump glass formed
- 12 facets (on the heliostat)
  - second surface silvered glass
  - reflector area = 50 m^2
- Peak flux = 2 MW/m^2 (currently); 90% within 150 mm aperture diameter
- Total power = 16 kW within 150 mm diameter
- Three-axis positioning test table, 4.4 MW/m^2 (if realigned); test samples located within 0.2 mm accuracy
- High-speed shutter.

Figure 5-3. The 16-kW solar furnace at SNL in Albuquerque, New Mexico, USA (Source: SNL)

High-Flux Solar Furnace (HFSF) at the National Renewable Energy Laboratory, Golden, Colorado, USA

The National Renewable Energy Laboratory (NREL) has developed this unique test facility for the U.S. Department of Energy (DOE) and operates it since December 1989 (Figure 5-4). The 10-kW HFSF, which is capable of generating extremely high-flux concentrations (principally up to 50,000 suns with a highly efficient secondary concentrator), has supported a number of research experiments since it became operational. Among the significant results was the demonstration of flux concentrations of 21,000 suns using a reflective nonimaging secondary concentrator designed and built by the University of Chicago. This facility is being used to conduct materials research, experiments for gas phase solar detoxification of chemicals and other industrial process experiments that can benefit from the use of a highly concentrated solar beam.

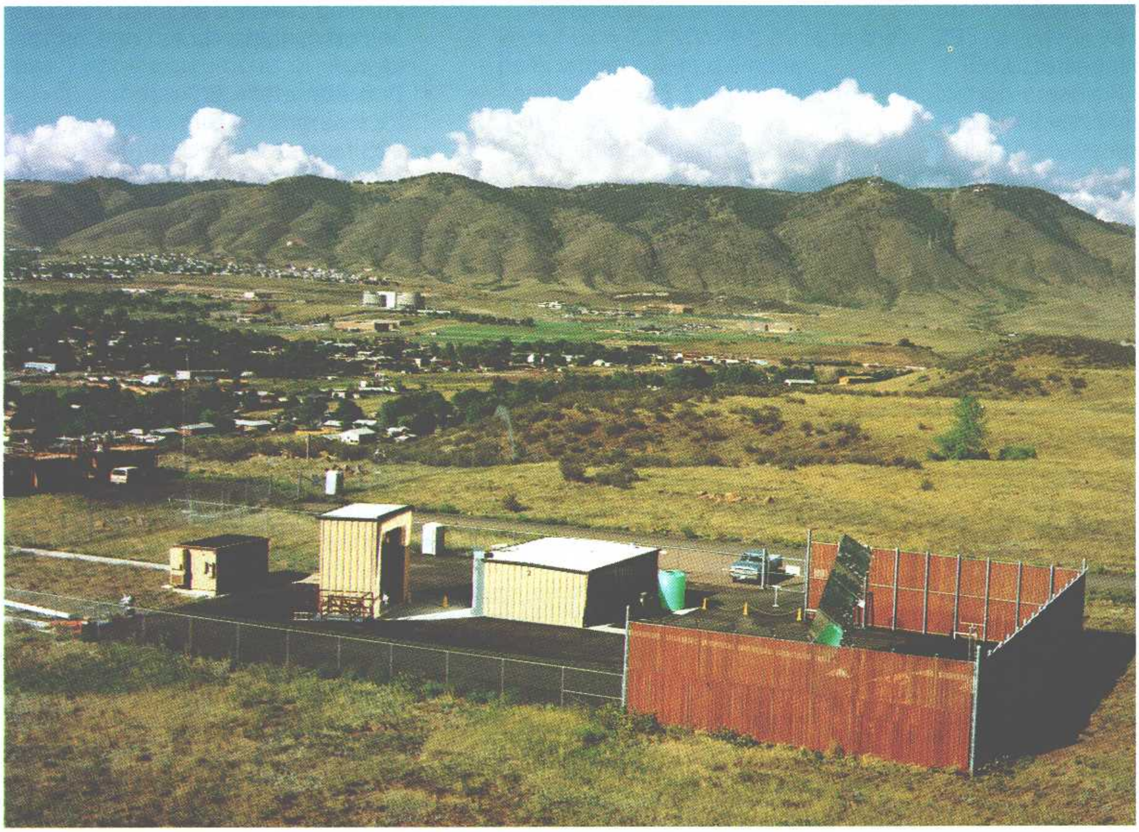


Figure 5-4. The 10-kW high-flux solar furnace (HFSF) at NREL in Golden, Colorado, USA (Source: NREL)

Characteristics of the HFSF

- Two-stage configuration:
  - Heliostat of approximately 32 m^2 with a flat reflective surface
  - Imaging primary concentrator
- Heliostat
  - 40 rectangular flat facets on 10 panels
  - 31.8 m^2 total area
  - Enhanced aluminum reflective surface
  - 0.5 mrad slope error
- Primary concentrator
  - 23 hexagonal glass facets with spherical curvature
  - 11.5 m^2 total area
  - Enhanced aluminum reflective surface
  - < 0.2 mrad slope error
  - 7 m focal length, f/D = 1.85
- Total power
  - 10 kW within 120 mm diameter
  - 95% power within 100 mm
- Off-axis design
  - Target located 30 ° off axis
  - Experiments placed at ground level
- Attenuator
  - Small, opposing plate design
  - Located 2 m in front of target
  - Flux/temperature control programmable
- Shutter/turning mirror
  - Fast acting shutter located 1 m in front of target
  - Turning mirror located 0.5 m in front of target to allow for horizontal experiment orientation
- Three-axis positioning table for mounting the experimental rig
  - 180 kg experiment weight
  - Position sequences can be programmed
  - 0.25 mm accuracy
- Data acquisition/control
  - 100 sensor inputs
  - Flexible configuration of inputs/outputs
  - PC-based
- Nonimaging secondary concentrator at focal region to increase concentration for special applications
- Performance:
  - Peak flux = 2500 suns (primary reflector alone)
  - 90% power within 100 mm-diameter aperture
  - Maximum system power = 9.4 kW at 1000 W/m^2 (normal direct insolation).

Plataforma Solar de Almería, Spain

The Plataforma Solar de Almería (PSA) is a solar test center that belongs to the Spanish Centro de Investigaciones Energéticas, Medioabientales y Tecnológicas (CIEMAT) of the Spanish Ministry of Industry and Energy and is jointly operated by CIEMAT and the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR, German Aerospace Research Establishment) of Germany. The PSA is the largest European solar test center and also participates in European Community scientific research support programs. The basic funds for the PSA are supplied equally by CIEMAT and by the DLR with funds from the German Ministry of Research and Technology (BMFT).

The PSA was initiated as a European Test Facility in the desert of Tabernas early in the 1980s, with the construction of two large experimental central receivers and parabolic trough plants that used concentrating solar technologies for electricity production. The first project was the SSPS (Small Solar Power Systems) plant of the International Energy Agency (IEA), which comprised a 500-kW$_e$ experimental central receiver power plant (CRS) with a sodium-tube receiver system and a 500-kW$_e$ experimental parabolic trough power plant (DCS) with oil as the working fluid. The second project was the 1-MW$_e$ CESA-1 (Central Electrosolar de Almería Uno) plant under the auspices of the Spanish Ministry of Industry and Energy. These two large projects were evaluated through 1985. Since 1986, both the SSPS and the CESA-1 plant have been operated as test beds for solar R&D work. The CESA-1 plant was also used as a test bed for the German-Spanish GAST Technology Program from 1985 to 1988.

In 1986, the PSA was converted into a research center directed toward the improvement of solar components and systems and the diversification of solar energy applications under a special Spanish-German cooperation agreement signed by CIEMAT and DLR.

Several small- to medium-scale solar experiments and technology programs have been or are being conducted at the PSA. These include the experiment of steam-reforming of methane ASTERIX, several volumetric receiver tests inclusive the 2.5 MW TSA-volumetric air receiver system test program and the internal salt film receiver tests (RAS), advanced heliostat characterization tests including the stretched membrane heliostat test program, solar detoxification experiments, solar chemical experiments, solar desalination tests, dish/Stirling qualification tests, solar drying, passive heating and cooling, two-axis photovoltaic tests, the HERMES space shuttle nose cone tests and various material tests.

The PSA offers engineering and test services for R&D work to European companies and institutions in electricity generation, industrial thermal processes, solar chemistry, materials testing, and education and publication of experience.

Figure 5-5. The Plataforma Solar de Almería, Spain (Source: PSA)

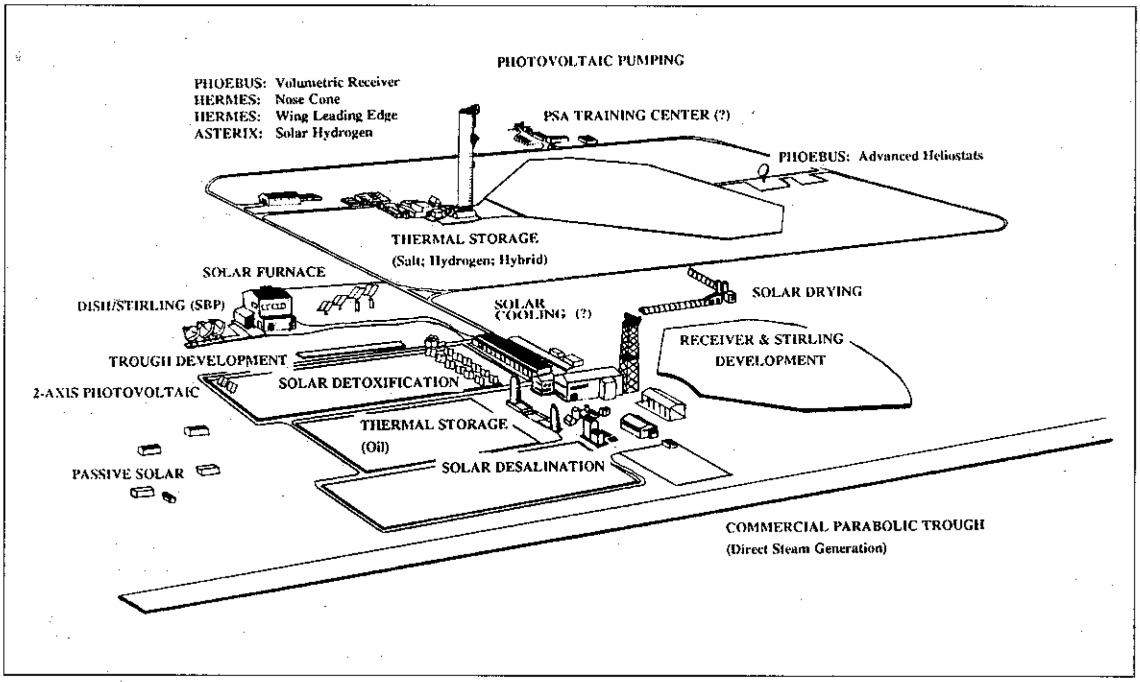


Figure 5-6. Artist's view of the Plataforma Solar de Almería, Spain (Source: PSA)

The main emphasis of future R&D work will be in the fields of:

- Direct steam generation in parabolic troughs
- Volumetric air receiver systems
- Stirling engines mounted on parabolic dishes
- Others: process heat applications, desalination, solar chemistry, materials testing.

Today, the major test installations available on the PSA (Figures 5-5 to 5-7) are: SSPS-CRS (central receiver system) SSPS-DCS (parabolic trough system) including thermal energy (oil) storage, CESA-1 (central receiver system) including thermal energy (salt) storage, high-flux solar furnace, and SBP dish/Stirling system (three units).

The following sections describe in more detail three installations that are important for solar flux treatment experiments: SSPS-CRS, CESA-1, and the PSA solar furnace.

Characteristics of the SSPS-CRS

- A heliostat field of 93 individually tracking heliostat units of 39.3 m² reflective area each (additional heliostats: approx. 20 second-generation heliostats (GAST) of 52-m² respectively 65 m² reflective area each)
- Heliostat unit:
  - Reflective area = 39.3 m²
  - Average reflectivity (clean mirrors) = 87%
  - Second surface silvered glass
  - Tracking accuracy = 1.2 mrad (error per axis)
  - Beam quality = 1.5 mrad (error width)
- Peak flux (at 950 W/m²) = approximately 2.5 MW/m²
  - 99% of power within diameter of approximately 2.5 m
  - 90% of power within diameter of approximately 1.8 m
- Total field power (at 950 W/m²) = 2.7 MW_t
- Tower weight capacity = approximately 20,000 kg
- Major test locations:
  - Two test platforms: on tower top at 43 m above ground level and at 24 m intermediate level
  - 600 kg crane on tower top
  - Elevator for personnel and equipment, 1000 kg capacity.

Characteristics of CESA-1
At present, the heliostat field is being equipped with advanced mirror facets; afterwards, the following performance figures can be reached:

- A heliostat field of 300 individually tracking heliostat units of 39.6 m² reflective area each
- Heliostat unit:
  - Reflective area = 39.6 m²
  - Average reflectivity (clean mirrors) = 90%
  - Second surface silvered glass
  - Tracking accuracy = 1.5 mrad (error per axis)
  - Beam quality = 3.0 mrad (error width)
- Peak power flux (at 950 W/m²) = approximately 3.3 MW/m²
  - 99% of power within diameter of approximately 4 m
  - 90% of power within diameter of approximately 2.8 m
- Maximum field power = 9 MW_t
- Tower weight capacity = approximately 100,000 kg on tower top
- Major test locations:
  - Test platforms and areas: 10 m-diameter platform on the roof at 80 m above ground level, area in front of tower below top, bay (4.5 m x 4.5 m effective) at 60 m above ground level, area (0.5 m x 0.5 m) at 45 m above ground level
  - 5,000 kg crane on tower top
  - Elevator for personnel and equipment inside tower, 250 kg capacity.

Characteristics of the PSA High-Flux Solar Furnace

Sunlight is reflected by four heliostats onto the primary concentrator, each illuminating a quarter of it resulting in 60-kW system power (Figure 5-7). Sunlight concentration is controlled by a louvered shutter. The experiment is mounted on a test table moveable on three axes. The concentrator, test table, and shutter are located inside the solar furnace building.

- Two-stage configuration of a non-imaging field of 4 heliostats (collector) and one imaging parabolic concentrator
- Collector:
  - A field of 4 second-generation (GAST) heliostats (each unit has a reflective area of 53.61 m², 16 nonconcentrating flat sandwich facets, and backsilvered glass)
  - 90% average reflectivity (clean condition)
  - Suntracking = computer-controlled
- Shutter:
  - Dimensions = 11.44 m x 11.20 m 30 slats (each with area 5.60 m x 0.93 m)
  - 15,800 positions between 0 ° (open) and 55 ° (closed), yielding angles accurate to 0.00346 ° and flux regulation accuracy of $8.01 \cdot 10^{-5}$ and $4.94 \cdot 10^{-5}$, respectively
  - Minimum closing time = 5 seconds
- Concentrator (a former MDAC parabolic dish):
  - Dimensions = 11.01 m x 10.41 m
  - 89 sandwich facets (0.91 m x 1.21 m); the different curvature radii are fixed to a partial surface of a segmented cylinder with individual segments displaced perpendicularly with respect to the cylinder axis
  - Total reflecting surface area = 98.51 m²
  - Reflectivity = 92%
  - Focal length = 7.45 m
  - Focal height = 6.09 m
  - Estimated focus size = 120 mm
  - Estimated black body temperature = 3150 K
- Test table:
  - Dimensions = 0.7 m x 0.6 m
  - Motion by three axes with speed control
  - Maximum velocity = 200 mm/s
  - Axes displacement paths x = 0.92 m, y = 0.66 m (along the optical axis), z = 0.50 m.

The parabolic trough collectors of the former IEA-SSPS project (Acurex/MAN) are used partly for solar experiments, e.g. for solar photocatalytic water detoxification processes, for sea-water desalination tests and for small scale solar chemistry experiments (compare Chapter 2.2. and 2.3). The situation of these facilities, which are called Distributed Collector System (DCS), can be seen in Figure 5-6. One type of these facilities has two-axis solar tracking. The other type follows the sun along its elevation axis only. A thermal oil energy storage system is part of the DCS as well as a steam generator and a steam turbine-generator (500 kW_e).

Other test facilities concern the dish/Stirling development using three SBP stretched-membrane dishes (compare Chapter 2.1.2 and 3.3), the development of low-cost heliostats (stretched membrane type) and direct steam production using advanced parabolic troughs (future R & D-project). Additionally, test facilities for research of solar convection drying of food products and of bioclimatic architecture are on the PSA site. Finally, the training and education plays an important role in the PSA activities.

Figure 5-7.
The 60-kW PSA high-flux solar furnace, primary concentrator, and focal experimental zone in Almeria, Spain (Source: CIEMAT)

Figure 5-8. DLR's 150-kW parabolic dish concentrator PAN in Lampoldshausen, Germany (Source: SBP)

Parabolic Test Bed Concentrator (PAN at DLR, Lampoldshausen, Germany)

The Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR, German Aerospace Research Establishment) installed a parabolic test bed concentrator (design of SBP) in Lampoldshausen near Heilbronn, to test solar-specific components in the power range of 150 kW (Figure 5-8). The PAN consists of a 17-m-diameter dish collector (stretched-membrane parabolic dish), which concentrates the sun's radiation above 1000 suns. It is equipped with a modern data acquisition system (the HERMES I measurement and beam characterization system of DLR) and a powerful computer system for data manipulation and evaluation.

The SBP stretched-membrane reflector is mounted on rails to track the sun. A supporting structure has been placed in the focal plane of the reflector to enable mounting of different experimental objects, such as electric conversion units, new receiver designs, and chemical reactors. In particular, a solid water-cooled Lambertian target was mounted to measure the flux distribution at different positions.

Characteristics of PAN

- One-stage configuration: parabolic dish concentrator
- Concentrator
  - Diameter = 17 m
  - Mass = 8000 kg
  - Area = 227 m^2
  - Usable mirror area = 95%
  - Reflectivity (clean) = 92%
  - Concentration ratio = > 1000 (maximum measured = 1500)
  - Focal length (actual) = 13.8 m
- Operational Characteristics
  - Permissible wind velocity while moving concentrator = 80 km/h
  - Permissible wind velocity in survival position = 160 km/h
  - Maximum permissible weight of experiment for test bed = 2500 kg
  - Tracking (azimuth/elevation) coarse sensor/fine sensor = ± 0.2 °/± 0.04 °
  - Current drives consumption = 2.5 kWh/day
- Performance
  - Power reflected on target = 152 kW measured at 800 W/m^2
  - Peak flux = 1.2 MW/m^2 at 800 W/m^2 or 1500 suns
  - 90% power within 640 mm – diameter aperture
  - Maximum system power = 180 kW at 950 W/m^2.

High-Flux Solar Furnace at DLR in Köln-Porz, Germany

The 20-kW high-flux solar furnace at the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR, German Aerospace Research Establishment) in Köln (Figure 5-9) was erected by DLR under sponsorship of the country Northrhine Westfalia (Germany). This furnace shall serve solar experiments, particularly in the field of solar chemistry and material-research. The envisaged experiments will concern e.g. the production of chemicals, the detoxification of waste materials, the thermo-chemical storage of energy, the substitution of fossil energy, the production of special materials, the surface treatment of materials. Reflective nonimaging secondary concentrators will also be used in order to increase the flux concentration.

In addition, a low-concentrating test facility using a dual-axis tracking parabolic trough module (a modified MAN Helioman module, for solar photo chemical synthesis of fine chemicals and a 1-kW_t highly concentrating parabolic dish (peak flux up to 15 MW/m^2) for materials testing are available at DLR in Köln (see background of Figure 5-9 and Chapter 2.3.2.4).

Characteristics of the DLR solar furnace

- Two-stage configuration
  - Heliostat of 52 m^2 with a flat reflective surface (a modified GAST heliostat)
  - Imaging primary concentrator
- Heliostat
  - Dimensions:
    width = 8.2 m
    height = 7.4 m
  - 52 m^2 total area
  - 32 rectangular flat facets of back-silvered glass mirrors
  - TiO_2 front surface coating
  - Reflectivity = 87%
- Primary concentrator
  - Dimensions:
    width = 7.3 m
    height = 6.3 m
  - 39 m^2 total area
  - 147 hexagonal glass facets with spherical curvature and front-aluminized reflective surface, SiO_x front surface coating
  - Reflectivity = 89%
  - Average target range:
    7.3 m, $f/D \approx 1.1$
- Off-axis design
  - Target located off-axis to the primary concentrator/heliostat
  - Experiment placed at ground level inside the building of the solar furnace
- Shutter
  - Located 1.05 m in front of focus
  - Fast acting: closing time 0.8 s
- Turning mirror
  - Located in front of target to allow for horizontal experiment orientation, size = 0.75 m x 1 m
- Three-axis positioning table for mounting the experimental rig
- Data acquisition by PC-based system
- Flux measurement by video camera and PC-based system; IR camera available
- Heliostat control by PC-based controller
- Performance
  - Peak flux: insolation 4000 kW/m^2 (at 850 W/m^2 normal direct insolation) or 4700 suns
  - Maximum system power:
    20 kW at 850 W/m^2,
    90 % power within 130 mm-diameter aperture
  - Transmission of UV-spectrum:
    59 - 70 %
  - Energetic flux densities controllable from 40 kW/m^2 up to 4 MW/m^2
  - Expected annual operation hours up to 500 h/ year.

The heliostat is planned to be modified later (63-m^2 reflective surface, front-aluminized glass mirrors).

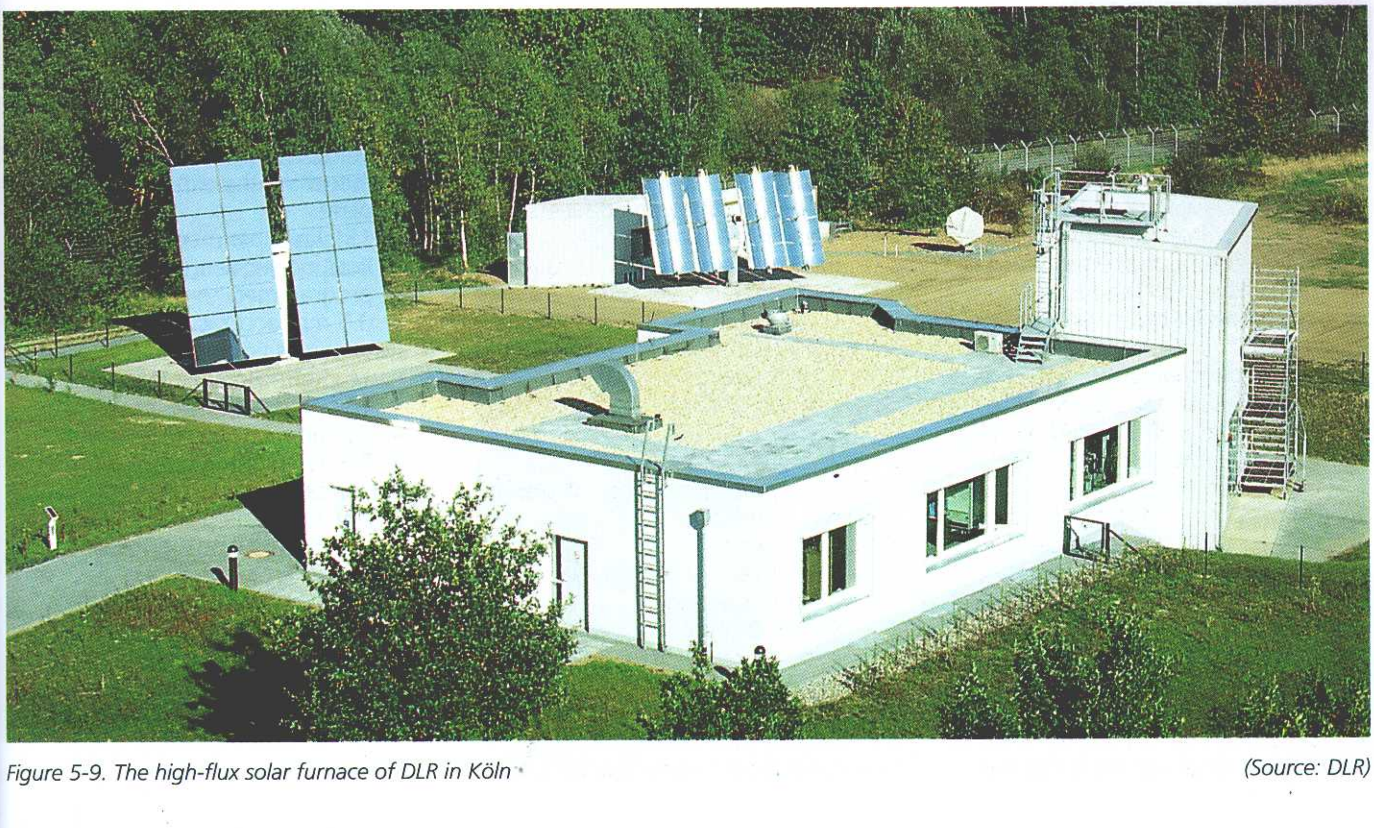


Figure 5-9. The high-flux solar furnace of DLR in Köln

(Source: DLR)

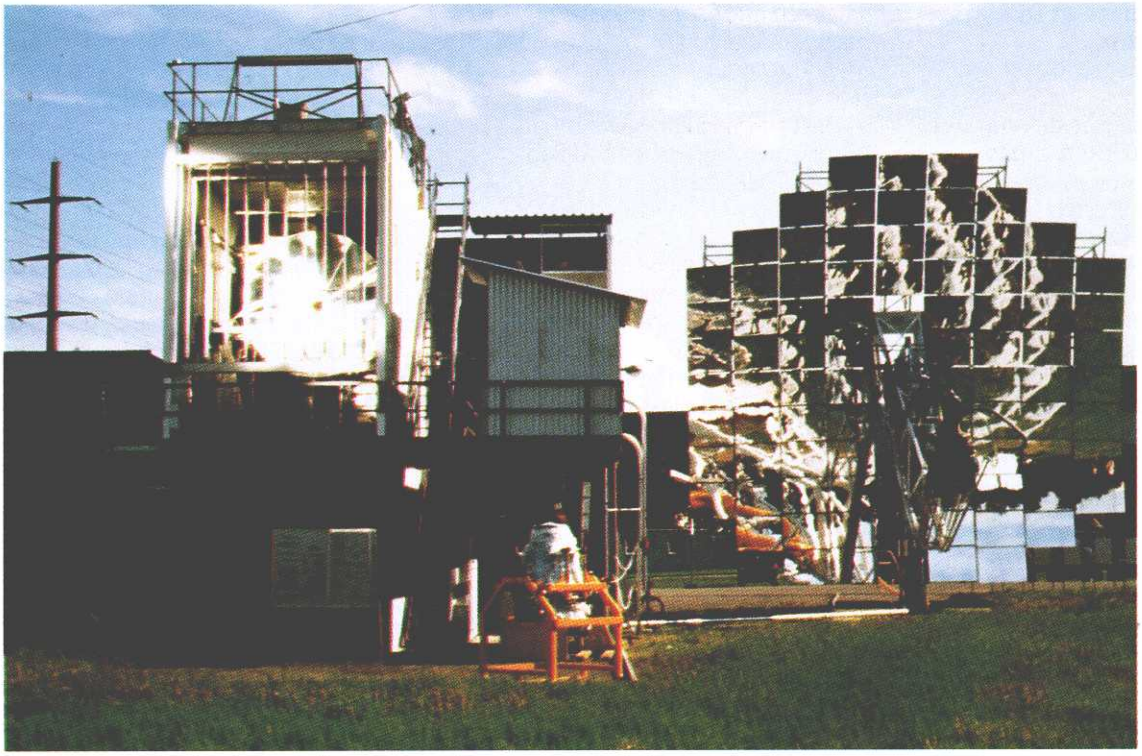


Figure 5-10. The 16-kW high-flux solar furnace and parabolic test bed concentrator of PSI in Villigen, Switzerland (Source: PSI)

Solar Research Facilities of the Paul Scherrer Institute, Villigen, Switzerland

The present R&D solar facilities at the Paul Scherrer Institute (PSI), operated since 1991, consist of a two-stage high-flux solar furnace and a parabolic dish concentrator. Both facilities are mainly used for experiments in the field of high-temperature solar chemistry for the conversion and storage of concentrated solar radiation. The main goal of PSI's solar chemistry research program is the water-splitting in thermochemical processes converting high-temperature solar energy. The solar experiments in the test facilities include the development and testing of direct absorption particle receiver/reactors, kinetic studies under solar high-flux conditions, as well as development of new methodologies, e.g. for temperature measurement in solar reactors.

PSI high-flux solar furnace

The 16-kW PSI high-flux solar furnace (Figure 5-10) is capable of generating flux concentrations of about 6000 suns. The furnace was operated for the first time in 1989 before it was moved to its present location in 1991. Since then it has supported a number of research experiments. Beside experiments in solar chemistry, the facility may serve for e.g. materials research or receiver/absorber development.

Characteristics of the PSI solar furnace

- Two-stage configuration:
  - Prefocussing heliostat of approximately 52 m² with a focal length of 100 m
  - Primary parabolic concentrator
- Heliostat
  - 48 rectangular curved facets on 8 adjustable panels
  - 51.8 m² total area
  - Back-coated silver reflective surface
- Primary concentrator
  - 12 parabolic aluminum cast segments, surface coated
  - 5.7 m² total area
  - 2.7 m diameter
  - 1.82 m focal length
  - 45 degree rim angle
- Total power
  - approximately 8 kW within 80 mm diameter
  - approximately 50% power within 80 mm
- On-axis design
  - Primary parabolic concentrator located on the optical axis of the heliostat
  - Distance heliostat to primary concentrator 73 m
  - Experiments placed on the optical axis
- Attenuator/shutter
  - Located 4.5 m in front of the primary concentrator
  - Vertical venetian blind design (10 blinds)
  - Flux/temperature control programmable
- Positioning table
  - Three-axis positioning table for mounting the experimental base plate
  - 150 kg experiment weight
  - Position sequences can be programmed
  - 0.5 mm accuracy
- Data acquisition
  - 16 thermo-couple inputs
  - 16 analog inputs/outputs
  - additional 32 flexible inputs
  - PC-based
- Flux measurement
  - by CCD camera and PC-based system
- Heliostat control
  - Velocity controlled heliostat
  - Accuracy < 1 mrad
  - PC-based controller
- Nonimaging secondary concentrator at focal region to increase concentration for special applications

- Performance
  - Peak flux = 6000 suns
  - 90% power within 140 mm-diameter aperture
  - Maximum system power = 16 kW at 850 W/m² (normal direct insolation).

PSI Parabolic Dish Concentrator

The 60-kW parabolic dish concentrator (a former MDAC dish) with a present peak flux of about 5000 suns is operated at PSI since late 1991 (Figure 5-11). The concentrator was modified such that its focal area can be used for high-flux solar chemical experiments. The dish concentrator follows the sun by a dual-axis tracking mode.

Characteristics of the PSI parabolic Dish

- One-stage configuration:
  - Parabolic dish of approximately 87 m² with a focal length of 7.5 m
- Dish
  - 82 rectangular curved facets on adjustable panels
  - 87 m² total area
  - Back-coated silver reflective surface
  - 7.5 m focal length
  - 11 m diameter
  - 38.6 degree rim angle
- Total power
  - 62.5 kW within 200 mm diameter
- Positioning table
  - Two-axis positioning table for mounting the experimental reactors
  - 450 kg experiment weight
  - Position sequences can be programmed
  - 1 mm accuracy
- Data acquisition
  - 16 thermo-couple inputs
  - 16 analog inputs/outputs
  - PC-based
- Flux measurement
  - By CCD camera and PC-based system
- Dish control
  - Velocity controlled dish
  - Accuracy < 1 mrad
  - PC-based controller
    Slew rates:
    Azimuth = 18 °/min.;
    ± 180 degrees of travel;
    Elevation = 18 °/min.;
    0-90 degrees of travel
- Nonimaging secondary concentrator at focal region to increase concentration for special applications
- Powder conveying system for particle clouds
- Performance
  - Peak flux = 5000 suns
  - 90% power within 150 mm diameter aperture
  - Maximum system power = 62 kW at 805 W/m² (normal direct insolation).

Figure 5-11. The 60-kW parabolic test bed concentrator of PSI in Villigen, Switzerland (Source: PSI)

High-Flux Solar Furnace of CNRS, Odeillo, France

The 1-MW high-flux solar furnace of the Centre National de la Recherche Scientifique (CNRS), Institut de Science et de Génie des Matériaux et Procédés, at Odeillo, France, produces very high temperatures up to 3000 °C (Figure 5-12). Experiments at this facility primarily concern the evaluation of thermal properties and behavior of materials at high temperatures. High-temperature materials testing (metals, ceramics) is performed at this facility, for example along with high-temperature properties determination (emittance, conductivity, diffusivity) in air, controlled atmosphere, or vacuum.

Characteristics of the Odeillo solar furnace

- Two-stage configuration of a non-imaging concentrator (heliostat field) and one imaging parabolic concentrator
- Heliostat unit
  - Faceted reflector = 180 square flat facets (0.5 x 0.5 m)
  - Total dimensions of reflective area = 45 m² (6 m x 7.5 m)
  - Back-silvered glass, 7 mm thick
  - Reflectivity (clean) = 80%
  - Hydraulic actuators
  - Closed loop tracking (sun ray sensors)
- Heliostat field
  - Field design = 8 hillsided terraces
  - 63 heliostat units
  - Total reflective area = 2835 m²
  - Two heliostat rows per terrace
- Parabolic concentrator
  - Truncated paraboloid
  - Intercepting area = 1850 m²
  - Total dimensions = 45 m high, 54 m wide
  - Faceted reflector = 9130 facets of 0.485 m x 0.485 m (average dimension)
  - Back-silvered tempered glass, 4 mm thick, mechanical bending
  - Reflectivity (clean) = 87%
  - Focal length = 18 m
- Focal building comprising the focal room for experiments and the heliostat field control room
  - Various chambers for vacuum or controlled atmospheric experiments
  - 3-D computer-controlled automatic holder
  - 64-channel high-speed data acquisition system.

Figure 5-12. The 1-MW high-flux solar furnace at Odeillo, France (Source: CNRS)

Solar Research Facilities of the Weizmann Institute of Science, Rehovot, Israel

The Solar Research Facilities Unit (SRFU) at the Weizmann Institute of Science (WIS) include the central receiver research facility and a high-flux solar furnace.

WIS Central Receiver Research Facility

The central receiver research facility has been in full operation since 1988 and provides a total power of up to 3 MW_t at equinox noon (Figure 5-13).

The top of the tower, 53 m above ground level, has a rectangular cross section 10 m (eastwest) by 15 m (northsouth). Tests are conducted in four main test bays and on the roof of tower. The tower is fully equipped with a lifting capacity of 20,000 kg of hardware equipment from the ground to the test bays. A bridge crane on the three test levels moves the equipment into experimental position. The tower's north face is covered with a passive thermal protection against concentrated sunlight.

Characteristics of WIS Central Receiver Research Facility

- Heliostat field of 64 individually tracking heliostats
- Heliostat unit:
  - Reflective area = 54.25 m^2 (20 facets)
  - Reflectivity of clean mirror = 91%
  - Facet made of two layers of glass, back-silvered mirror
  - Tracking accuracy = 0.45 mrad (error per axis)
  - Beam quality = 1.2 mrad (at the source, half angle)
  - On-axis canting
- Total field power on clear day = 3 MW_t (March 21, noon)
- Tower height = 53 m
- Two elevators and one lifting platform, 20,000 kg capacity
- Test Locations:
  - 5 experimental platforms and areas (heights to center of the targets):
    - Roof level (55.5 m): chemical reformer, two areas in parallel
    - Top level (49.5 m): solar pumped lasers
    - Second level (39 m): solar gas turbine experiment
    - Third level (31 m): high-temperature receivers
    - Lower level (25 m): solar gasification of solids.

Figure 5-13. The 3-MW_t central receiver research facility of the Weizmann Institute of Science in Rehovot, Israel (Source: WIS)

The heliostat field control system is capable of focusing solar radiation onto five possible targets located at the five different test levels simultaneously and independently. The assignment of specific heliostats to each of the active targets is commanded by the operator through the master control console. It is possible to have automatic power control in each experiment from the experiment's computer by automatic moving of heliostats that belong to the allocated group focused to the target. The facility is equipped with a heat rejection subsystem, feed water supply, air supply subsystem, and other essential complementary services.

The major research tasks conducted at the central receiver research facility are development of solar-pumped lasers, development of a solar thermochemical pipeline (tests using a 450-kW$_t$ capacity loop for a methanator (methane reforming) plant), and development of a high-temperature solar Brayton cycle (solar air turbine) for generating electricity (tests using a 200-kW$_e$ system).

WIS High-Flux Solar Furnace

The 16-kW WIS high-flux solar furnace, used to perform small-scale solar experiments, began operating in May 1986 (Figure 5-14). The furnace is capable of focusing 16 kW into a 100-mm-diameter area in the focal plane, with a concentration ratio of about 7,000 on a 40-mm-diameter region. The dish is located inside a building; double doors on the north face enable attenuation of the solar energy arriving at the dish from a 96 m^2 flat heliostat.

Characteristics of WIS High-Flux Solar Furnace

- Two-stage configuration of a non-imaging collector (one heliostat) and one imaging parabolic concentrator (dish)
- Heliostat:
  - 96 m^2, flat mirrors, 2 D.C. motors computer controlled
  - reflectivity of clean surface = 93%
- Concentrator:
  - Parabolic dish, 7.3 m diameter inside a house with door at the north side
  - 590 trapezoidal segments (facets) each one is spherical, back-surface mirrors, rim angle = 65 °, reflectivity = 88%
  - The facets are arranged in 13 concentric rings; the inner ring has focal length of 350 mm, the outer one 400 mm
  - The optical axis is 4.4 m above ground
  - Total maximum power is 20 kW, actual power is 16 kW into 0.1 m diameter. Average concentration is 7,000 into 0.04 m diameter; maximum concentration at the centroid reaches about 11,000 at 930 W/m^2
- Test table:
  - 0.8 m x 0.8 m platform
  - Coarse movement by hydraulic piston
  - Fine movement by three-axis positioning table with small stepping motors.

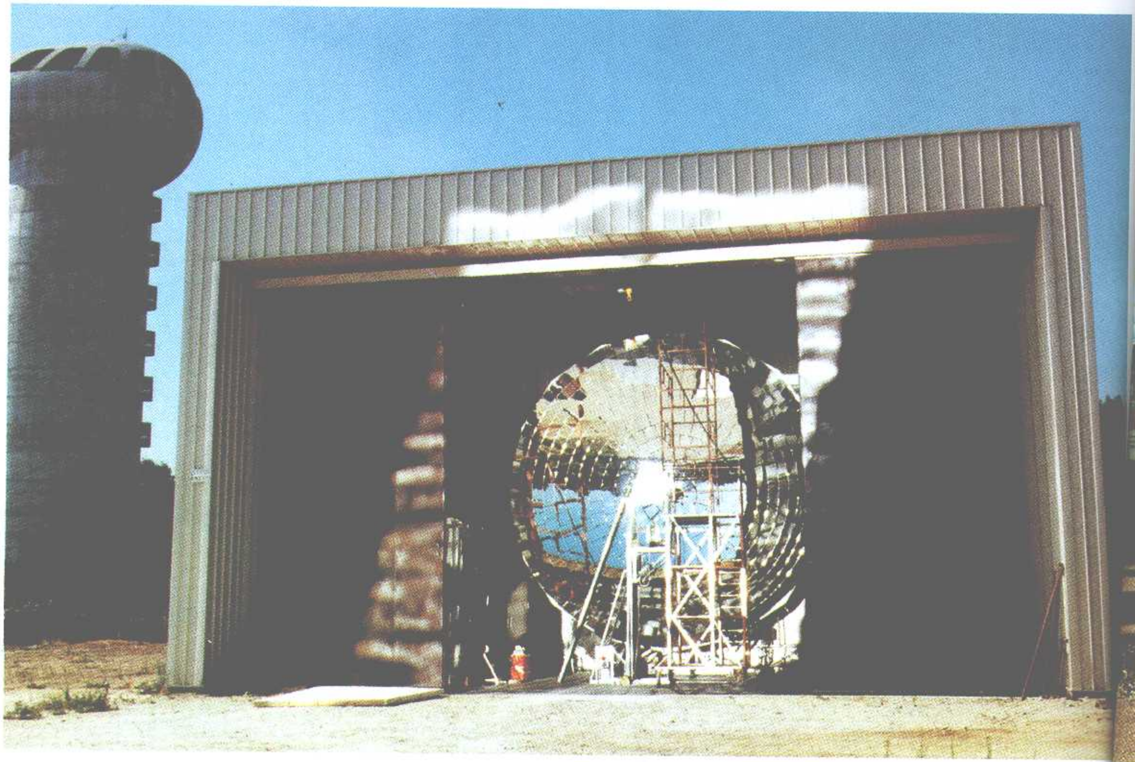


Figure 5-14.
The 16-kW high-flux solar furnace of the Weizmann Institute of Science in Rehovot, Israel
(Source: WIS)

Ben-Gurion National Solar Energy Research Center, Sde Boker, Israel

In November 1985, the Ministry of Energy and Infrastructure broke ground at Sde Boker for the Ben-Gurion National Solar Energy Research Center. The test center opened in February 1987 and is in charge of the Ben Gurion University since 1991. The test site is located within the Negev desert (30.8 ° northern latitude). This desert makes up more than half of Israel's land area and is believed to be the best site in Israel for solar energy/ electricity generating facilities. Figure 5-15 shows a view of parabolic trough test facilities.

The program was established to advance and assess promising alternative energy technologies, particularly those involving solar electric power generation. The Ministry of Energy, which constructed and owns the test center, provides operation, maintenance, and system performance evaluation services for participant-owned installations, and also provides a grant of up to 30% of the installed cost of each qualified system.

In 1991, a year of transition for the Sde Boker test station, the Jacob Blaustein Institute for Desert Research of the Ben-Gurion University of the Negev replaced Petroleum Services Limited as the operator. The long-term objective of this change is to emphasize research rather than testing of commercial solar systems.

Main projects at the research center are:

- PAZ Oil Company – photovoltaic installation (189 Solarex modules, 8.6 kW_{net} to grid)
- LUZ Israel – thermal installation (four parabolic trough collector assemblies of the LS-2 type, 960-m^2 aperture area, 560 $kW_{t)}$ for fundamental experiments and demonstration of the technology
- PAZ Oil Company – thermal installation (15 parabolic trough collectors of the Pimat CS-112 type, 750-m^2 aperture area, 220 kW_t)
- PAZ Oil Company and PAZ-GAL Energy Company – absorption refrigeration system (absorption heat-pump system using organic working fluid)
- Israel Electric Corporation – photovoltaic installation (75 Siemens SM 55 modules, 3.3 kW_{net} to grid)
- LUZ Israel – direct steam generation facility (20 parabolic trough collector assemblies of the LS-3 type, 8 ° tilted versus the horizontal, 2760 m^2 aperture area, 2107 kW_t); this project was stopped by financial problems of LUZ. A Belgian Company, Belgo Instruments International S.A., has aquired part of LUZ Israel and plans to resume the construction of the demonstration facility at the research center, and to examine different alternatives of direct steam generation, including its own technology.

The major site features are general services and infrastructure, a meteorological station, data acquisition systems, a computerized processing system, and a visitor center.

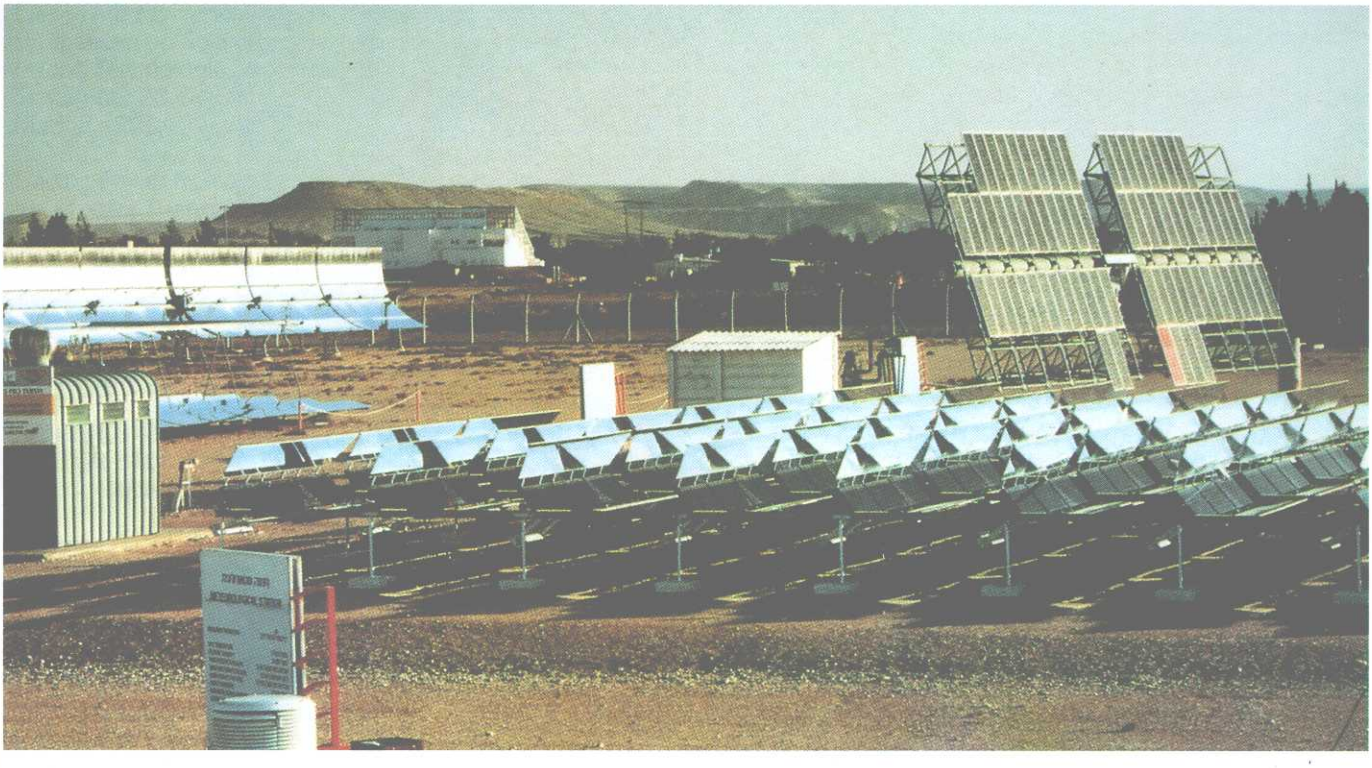


Figure 5-15.
The Sde Boker test station, Israel
(Source: MEI)

High-Flux Solar Furnace of the Uzbek Academy of Sciences, Parkent, Uzbekistan

A 1 MW high-flux solar furnace has been operated since October 1987 by the Scientific Association "Physics Sun" of the Uzbek Academy of Sciences (UAS) in Parkent near Tashkent (Figure 5-16). One of its main goals is to support fundamental research on the physical and chemical processes of heat treating of different objects with high-flux solar radiation. The research comprises a wide range of experiments, from the study of interaction mechanisms of photons and ion components of solid material to the synthesis of pure ceramic materials and multicomponent systems with definite properties.

The solar furnace is a two-stage mirror system with a horizontal optical axis comprising a field of 62 heliostats positioned on eight terraces and a primary concentrator mounted on a fixed steel structure. A tower placed at the focal region contains the test room with instrumentation and controls. The concept of this solar furnace is similar to that of the Odeillo solar furnace.

Characteristics of the UAS solar furnace:

- Two-stage configuration:
  - Nonimaging collector (62 flat heliostats)
  - Imaging concentrator (paraboloid) of 2000 m^2
- Collector:
  - 62 heliostat units in field
  - Eight terraces
  - Heliostat unit: reflective area 6.5 m x 7.5 m (48.8 m^2), 195 square polished glass facets of 0.5 m x 0.5 m, back-aluminized glass, thickness 6 mm
  - Heliostat mounting: azimuthal
  - Heliostat drives and controls: electromechanical, automatic tracking control, tracking sensors
- Concentrator:
  - Rigid steel structure
  - On-axis truncated parabolic mirror
  - Reflective area = 2000 m^2
  - Concentrator height = 41 m
  - Concentrator width = 54 m
  - Focal length = 18 m
  - Focus height above ground = 21.6 m
  - 214 mirror/steel structure elements (each element: 4.5 m x 2.25 m, 50 mirror facets, 0.45 m side length, back-aluminized glass, thickness 5 mm, spherical bending by mechanical means)
- Tower:
  - Frame-space design, 5 m x 24 m cross section
  - Height = 26 m
  - Window for experimental room = 6 m x 4 m
  - Window closure by two automatically water-cooled folds
- Total peak power = 1 MW
- Maximum permissible mass of experiment = up to 10,000 kg
- Solar radiation spectra E = 0.4-5.0 eV
- Solar concentration I = 1.7 x 10^3/cm^2.

Figure 5-16. The 1 MW high-flux solar furnace of the Uzbek Academy of Sciences in Parkent, Uzbekistan (Source: DLR)

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Chapter 2

Section 2.1

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Abbreviations and Acronyms

Acurex	Acurex Corp., Mountain View (USA)
APS	Arizona Public Service, Phoenix (USA)
ASES	American Solar Energy Society
ASINEL	Asociación de Investigación Industrial Eléctrica, Madrid (Spain)
ASME	American Society of Engineers (USA)
ASTERIX	advanced steam reforming in heat exchange
ATS	Advanced Thermal Systems, Englewood (USA)
bar	100,000 Newtons/m^2
BCS	beam characterization system
Bechtel	Bechtel National, Inc., San Francisco (USA)
BMFT	German Ministry of Research and Technology, Bonn (Germany)
BWK	Brennstoff Wärme Kraft, Journal of German Society of Engineers (VDI)
CAESAR	catalytic enhanced solar absorption receiver
CCD	charged coupled device
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Technológicas, Ministerio de Industría y Energía, Madrid (Spain)
CNRS	Centre Nacional de la Recherche Scientifique, Institut de Science et de Génie des Matériaux et Procédés, Odeillo (France)
CO_2	carbon dioxide
CPG	Cummins Power Generation, Inc., Columbus (USA)
CRRF	Central Receiver Research Facility, WIS (Israel)
CRS	central receiver system
CRTF	Central Receiver Test Facility, SNL (USA)
CVD	chemical vapor deposition
DCS	distributed collector system
DGS	Deutsche Gesellschaft für Sonnenenergie (International Solar Energy Society – German Section)
DIDIER	Didier-Werke AG, Wiesbaden (Germany)
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V. (German Aerospace Research Establishment), Köln (Germany)
DOE	U.S. Department of Energy, Washington (USA)
Dornier	Dornier System, Friedrichshafen (Germany)
DRTF	Distributed Receiver Test Facility, SNL (USA)
EPRI	Electric Power Research Institute, Palo Alto (USA)
f/D	focal length-to-diameter
FDE	Fichtner Development Engineering, Stuttgart (Germany)
Flagsol	Flachglas Solartechnik GmbH, Köln (Germany)
GA	General Atomic Company (USA)
GAST	Gas-cooled Solar Tower project/technology program
GDFI	General Organization for Industrialization, Cairo (Egypt)
GEW	Gas-, Elektrizitäts- und Wasserwerke, Köln (Germany)
GJ	gigajoule
HERMES I and II	Heliostat and Receiver Measuring System I and II
HERMES	Name of space shuttle project
HFSF	High Flux Solar Furnace, NREL (USA)
HTC-Solar	HTC-Solar, Lörrach (Germany)
IEA	International Energy Agency, Paris (France)
IECES	Intersociety Energy Conversion Engineering Conference
INITEC	Empresa Nacional de Ingeniería y Technología, S.A., Madrid (Spain)
INTERATOM	Interatom GmbH, subsidiary of Siemens AG, Bergisch Gladbach (Germany)
ISES	International Solar Energy Symposium
IST	Industrial Solar Technologies, Inc., Denver (USA)
JPL	Jet Propulsion Laboratory, Pasadena (USA)
Jupasa	Jupasa, Toledo (Spain)
KFA	Kernforschungsanlage Jülich GmbH, Jülich (Germany)
kg	kilogram
kW	kilo Watt
kW_e	kilo Watt, electric
kWh	kilo Watt-hour
KWU	Kraftwerk Union, subsidiary of Siemens AG, Erlangen (Germany)
LaJet	LaJet S.A., Bulle (Switzerland)
LANSIR	large-aperture, near-specular imaging reflectometer
LCS	L&C Steinmüller GmbH, Gummersbach (Germany)
LEC	levelized energy cost
LUZ	LUZ International Ltd., Los Angeles (USA)
MAN	MAN Technologie AG, München (Germany)
MBB	Messerschmitt-Bölkow-Blohm GmbH, München (Germany)
MDAC	McDonnel Douglas Astronautics Co., Huntington Beach (USA)
MEI	Ministry of Energy and Infrastructure, Jerusalem (Israel)
MPa	Mega Pascal
MW	Mega Watt
MW_e	Mega Watt, electric
MWh_t	Mega Watt-hour, thermal
MW_t	Mega Watt, thermal
NEDO	New Energy Development Organization (Japan)
nm	nanometer = 10^{-9} meter
Nm^3	Norm cubic meter
NREL	National Renewable Energy Laboratory (formerly SERI), Golden (USA)
NSTTF	National Solar Thermal Test Facility, SNL (USA)
PAN	parabolic test bed concentrator, DLR (Germany)
PC	personal computer
PCB	polychlorinated biphenyl
PG&E	Pacific Gas and Electric Company, San Ramon (USA)
PHOEBUS	PHOEBUS Consortium (Germany) including US PHOEBUS Associates (USA)
PNL	Pacific Northwest Laboratory, Richland (USA)

ppb	parts per billion
ppm	parts per million
PSA	Plataforma Solar de Almería, Tabernas/Almería (Spain)
PSI	Paul Scherrer Institut, Villigen (Switzerland)
Pujol	Pujol Muntala, Manresa (Spain)
RAS	internal salt film receiver
R&D	research and development
rms	root-mean-square
RTCVD	rapid thermal chemical vapor deposition
RWTH	Rheinisch-Westfälische Technische Hochschule (Technical University), Aachen (Germany)
SAIC	Science Applications International Corporation, San Diego (USA)
Sanders	Sanders Associates, Inc., Nashua (USA)
SBP	Schlaich, Bergermann & Partner, Beratende Ingenieure (civil engineering consultants), Stuttgart (Germany)
SCR	solar chemical reactor
SERI	Solar Energy Research Institute (today NREL), Golden (USA)
SHOT	scanning Hartmann optical test
SHS	self-heating synthesis
Siemens	Siemens AG, Berlin and München (Germany)
Siempelkamp	Siempelkamp, Krefeld (Germany)
SKI	Solar Kinectics, Inc., Dallas (USA)
SNL	Sandia National Laboratories, Albuquerque (USA)
SolarPACES	solar power and chemical energy systems (IEA-project)
SOLO	Solo-Kleinmotoren GmbH, Maichingen (Germany)
SOTEL	Consortium Solar Thermal Electricity, Baden (CH)
Sovelectro	Foreign Trade Organisation, Moscow (Russia)
SPECO	Solar Power Engineering Company, Morrison (USA)
SPS	Stirling Power Systems, Michigan (USA)
SRFU	Solar Research Facility Unit
SSPS	Small Solar Power System (former IEA-project)
STEP	Solar Total Energy Project
STM	Stirling Thermal Motors, Ann Arbor (USA)
SULZER	Gebrüder SULZER AG (SULZER Brothers Ltd.), Winterthur (CH)
TBC	test bed concentrator
Thermacore	Thermacore, Inc., Lancaster (USA)
TSA	Technology Program Solar Air Receiver
UAS	Uzbek Academy of Sciences, Tashkent (Uzbekistan)
USAB	United Stirling AG, Malmö (Sweden)
UV	ultraviolet frequency of light
WIS	Weizmann Institute of Science, Rehovot (Israel)
ZSW	Zentrum für Sonnenenergie- und Wasserstoff-Forschung (Center for Solar Energy- and Hydrogen-Research), Stuttgart and Ulm (Germany)
µm	mikrometer = 10^{-6} meter

Key Words

solar concentrating systems
solar thermal energy
solar chemistry
solar process heat
central receiver system
parabolic dish system
parabolic trough system

The Book:

This book presents numerous important applications and technologies of solar concentrating systems. The intention is not to provide a detailed technical discussion of all solar energy applications and technologies, but rather to introduce the reader to possibilities for applying concentrated solar energy to a number of interesting industrial processes.

By presenting instructive pictures, diagrams and schematics, the different solar systems are described:

- for the generation of power and process heat (central receiver systems, parabolic trough and parabolic dish systems)
- for the application to solar chemistry processes
- for detoxification and for material treatment.

Additionally, important solar test centers and facilities all over the world are described.

The status and the future prospects of the solar concentrating systems are presented using numerous illustrations. Also, important references are given.

The brochure is result of an international cooperation of the German Aerospace Research Establishment (DLR) at Cologne/Germany and of the National-Renewable Energy Laboratory (NREL) at Golden/Co., USA. Numerous experts from Europe and USA contributed to the brochure and acted as reviewers. Financing support was given by the German Ministry of Research and Technology (BMFT) and the American Department of Energy (DOE).

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