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High-Temperature Solar Options for Electric Utilities and Users of Process Heat

(Submitted to *Solar Age Magazine*)

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HIGH-TEMPERATURE SOLAR OPTIONS FOR ELECTRIC UTILITIES AND USERS OF PROCESS HEAT

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ABSTRACT

Only in the last ten years has there been a significant effort to apply modern technology to the use of solar energy. One of the more promising approaches now receiving world-wide attention is the central receiver concept, in which a field of individually aimed mirrors, or heliostats, focuses the sun's energy onto a tower-mounted receiver where the concentrated flux heats a fluid used to power a turbine or to heat an industrial process. Energy concentrations greater than 1000 suns, leading to high efficiencies, are easily attained. Feasibility has been demonstrated, and if present cost trends continue, solar energy costs may soon be competitive with those of fossil fuels--including coal. Land use would be modest. If present progress continues over the next five years, the concept will become a practical energy option.

CONTENTS

ILLUSTRATIONS

HIGH-TEMPERATURE SOLAR OPTIONS FOR ELECTRIC UTILITIES AND USERS OF PROCESS HEAT

Introduction

Although man has always been dependent on solar energy, it has only been in the last ten years that he has devoted significant effort to applying modern technology to collect and convert the sun's energy into more usable forms. As recently as 1973 the total U.S. budget for solar energy research was only $4 million, but in 1980 it has grown to over $600 million.

One of the more promising methods for collecting solar energy involves the central receiver concept, in which a field of individually controlled mirrors, or heliostats, reflects the sun's energy onto a receiver mounted on a tower (Figure 1). At the receiver, highly concentrated solar flux heats a circulating fluid that is used to power a conventional steam or gas turbine or to operate an industrial process. This same hot fluid may also be stored for later use. The central receiver concept was first proposed in 1956 in a paper, "High Power Solar Installation," by V. A. Baum, R. R. Aparisi, and B. A. Garf, members of the Energetechneskii Institute, Russian Academy of Sciences. Within the United States, research on the concept was sponsored starting in 1972 by the National Science Foundation and since then has been expanded into a major research and development program under the Department of Energy, Division of Solar Thermal Energy Systems.

The concept has many advantages. For one, high temperatures can be achieved, since energy concentrations in excess of 1000 suns are easily

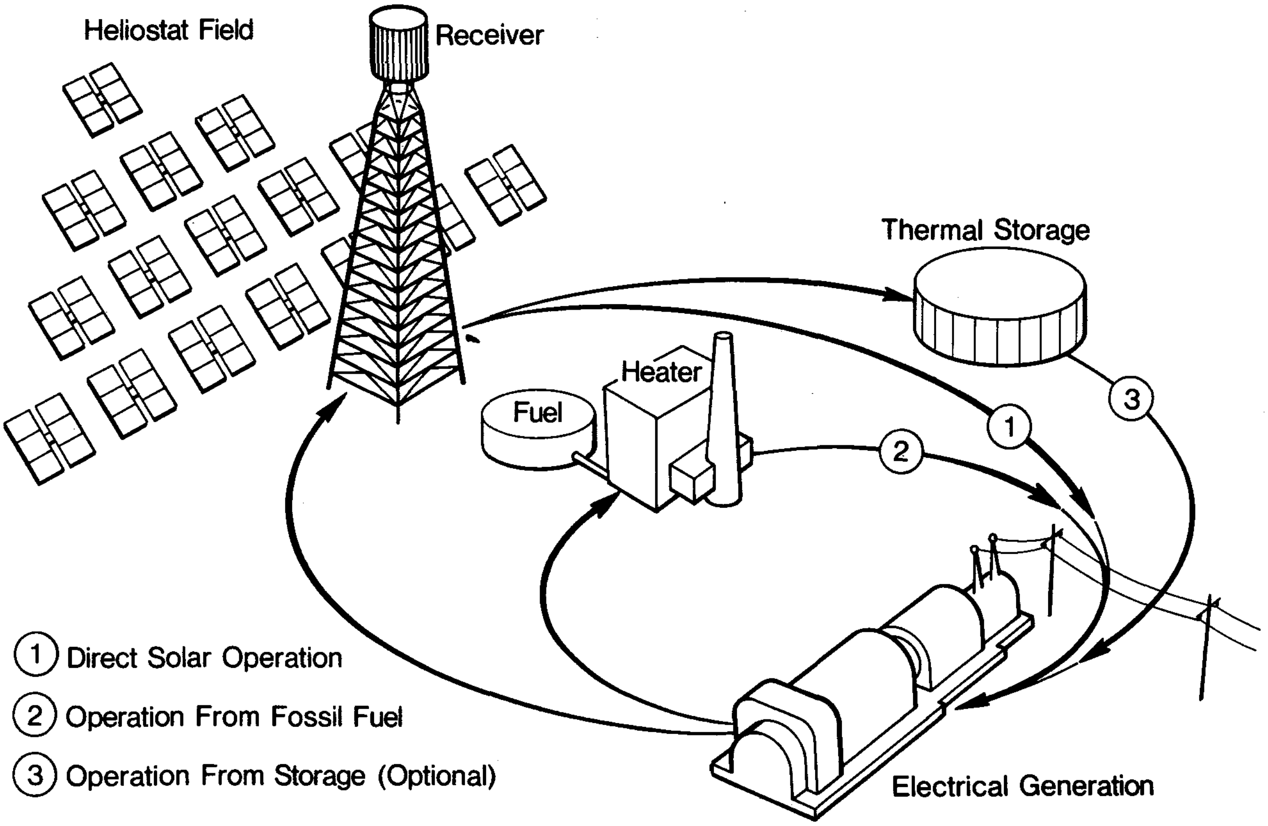


Figure 1. Solar Central Receiver Concept, a Hybrid System Combining a Central Receiver and Heliostat Field with Fossil-Fueled Power Plant

possible. This capability leads to high efficiencies when one converts the thermal energy to mechanical or chemical energy and also makes it possible to generate electricity efficiently. Recent studies project that the concept may soon be economically competitive with fossil energy sources--even with coal--for both high- and moderate- temperature applications. This rather startling trend is due to two factors: (1) improved cost-to-performance ratio of the central receiver concept as a result of the vigorous research and development program which has been carried on and (2) the rapid escalation in the price of fossil fuel alternatives.

Using only modest amounts of land, this concept could contribute substantially to the U.S. energy supplies. A 100-MW_e plant operating, for example, during 25 percent of the annual hours will require about 600 to 700 acres. In fact, if 10 percent of the total present U.S. electrical generating capacity of 600 000 MW were to be satisfied by central receiver systems, a total land area equal to only about 0.2 percent of the state of Nevada would be required.

Central Receiver Test Facility Fully Operational

Operated by Sandia National Laboratories, the Central Receiver Test Facility (CRTF), Figure 2, has been fully operational since October 1978. The CRTF, located in Albuquerque, New Mexico, has 222 heliostats, each with an area of 37 square meters. More than five megawatts of solar energy can be delivered at concentrations of more than 1000 suns to receiver experiments located on a tower 65 meters tall. The first test, a 1-MW_t receiver experiment developed by Boeing under funding by the Electric Power Research Institute, was successfully completed in 1979. Testing on a larger receiver experiment designed by McDonnell Douglas was completed early in 1980. The McDonnell Douglas experiment measured the performance of a single panel of a receiver to be built as a part of a pilot plant.

Barstow Pilot Plant

A key element in the central receiver program is a 10-MW_e pilot plant (Figure 3) being built at Barstow, California, to establish the technical feasibility of a steam/electrical generating plant and to provide development, production, and operating data. Funded jointly by the government and by utility companies, the plant will be operated by the Southern California Edison Company in their commercial grid network. The Los Angeles Department of Water and Power and the California Energy Commission are participating in

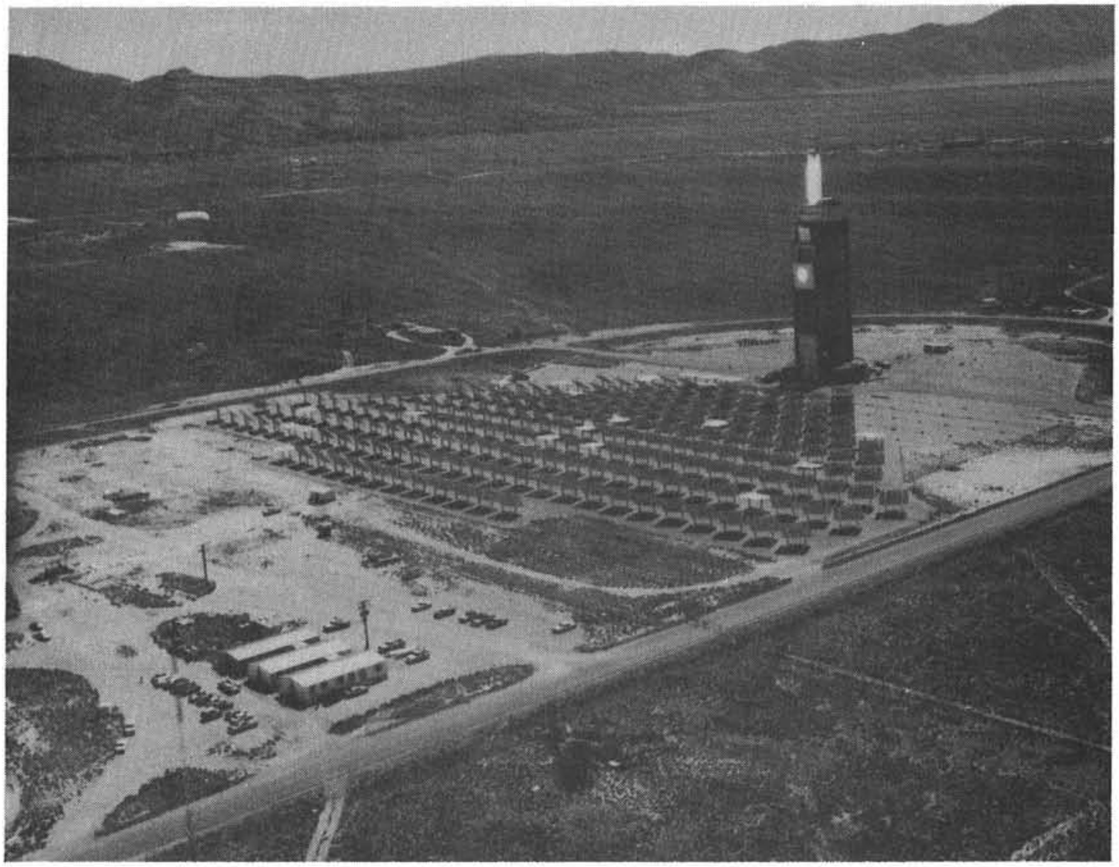


Figure 2. The Central Receiver Test Facility, Operated by Sandia National Laboratories in Albuquerque, New Mexico

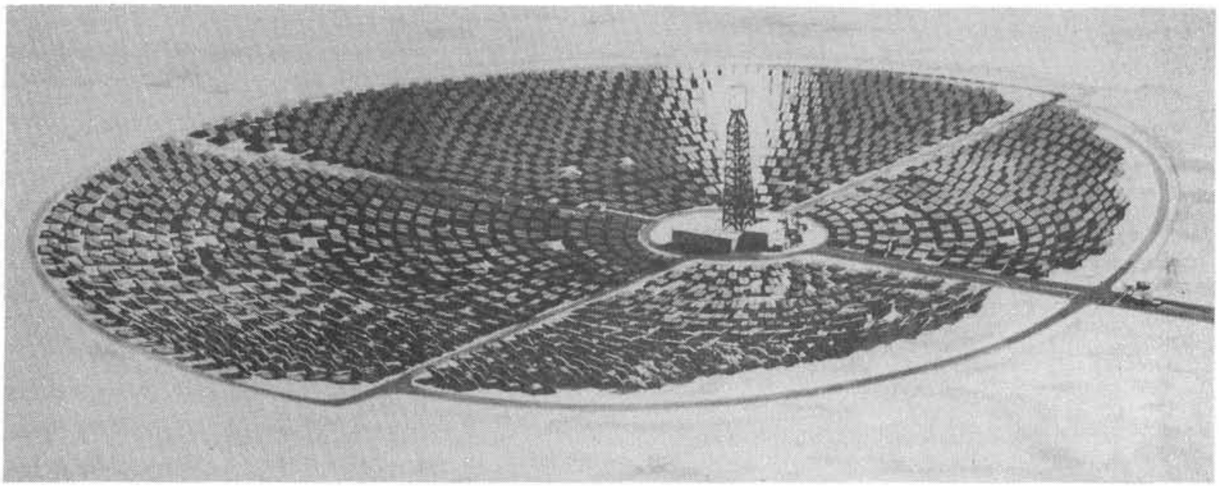


Figure 3. Artist's Conception of the 10-MW_e Pilot Plant under Construction in Barstow, California

the engineering management, construction, and technology transfer activities of the project. With initial operation scheduled for late 1981, the plant will use 1800 forty square meter heliostats designed and constructed by Martin Marietta. McDonnell Douglas is responsible for the design integration of the project.

Projects in Other Countries

Many countries outside of the United States have shown interest in the central receiver systems. The International Energy Agency is building a 0.5-MW_e central receiver plant in Almeria, Spain, to begin operating in mid-1981. The project is jointly funded by Germany, Sweden, Spain, Greece, Belgium, Austria, Switzerland, Italy, and the United States. The Spanish government is building a 1-MW_e plant at Almeria, Spain, with U.S. technical assistance, and the European Economic Committee is building a 1-MW_e plant in Sicily, both to be operational in 1981. The French, too, are constructing a 2-MW_e plant, Themis 1, at Targasonne, France, to be in operation the same year. Japan has a small (150-kW_t) experimental central receiver system operating and is building a 1-MW_e plant at Nio on the island of Shikoku to be operational in 1981. The Soviet Union has indicated, that it is planning a 1-MW_e plant in the Crimea; however, the current status of this project is not known. Thus in at least six major projects, operational data will be developed in the 1981-1982 time frame. In addition, the United States has in the planning stage several central receiver projects, which if authorized, will provide additional design and operating data.

Central Receiver Testing

Extensive receiver operating experience has also been gained during the last five years through the major receiver subsystems tests listed in Table I.

TABLE I

U.S. RECEIVER EXPERIMENTS

Fluid	Receiver Configuration	MW_t Capacity	Test Type	Test Facility	Date	Report No.	Design Organization
Water/Steam	Cavity	1	Radiant	Sandia	1976	SAN-1068-1	Martin Marietta
Water/Steam	Cavity	5	Radiant	Sandia	1977	SAN-1110-77-2	Martin Marietta
Water/Steam	Cavity	5	Radiant	Northern States Power	1977	TID-29434	Honeywell
Water/Steam	External	5	Radiant	Rockwell	1977	SAN-1108-8	McDonnell Douglas
Water/Steam	External	0.2	Radiant	Sandia	1979	SAND80-8020	Sandia
Water/Steam	External	1	Solar	CNRS	1976	SAN-1068-1	Martin Marietta
Water/Steam	Cavity	0.3	Solar	ACTF	1978-79	*	Ansaldo
Water/Steam	Cavity	3	Solar	CRTF	1979-80	SAND79-8179	McDonnell Douglas
Air	Cavity	1	Solar	CRTF	1979	Not published	Boeing
Air	Cavity	0.02	Solar	White Sands	1976	COO0-2823-2	Sanders
Air	Cavity	0.25	Solar	ACTF	1978	DOE/ET/21011-1	Sanders
Air	Cavity	1	Solar	CRTF	1980	Not published	Black & Veatch
Sodium	External	3	Solar	CRTF	1981	Not published	General Electric
Molten Salt	Cavity/External	3	Solar	CRTF	1980	Not published	Martin Marietta

*Paper presented at the 1978 meeting of the American Section of the International Solar Energy Society, "U.S. Department of Energy Advanced Components Test Facility," by R. F. Altman, C. T. Brown, and H. L. Teague

Two types of tests have been conducted, solar and radiant. Under the U.S. program, more than 900 hours of solar tests have been performed with fields of mirrors collecting the sunlight. Testing was done at the Central Receiver Test Facility in Albuquerque, New Mexico; the Advanced Component Test Facility (ACTF) in Atlanta, Georgia; the White Sands solar furnace, White Sands, New Mexico; and the Centre National de la Recherche Scientifique solar facility, Odeillo, France. The second type of test uses electrical radiant heat lamps to simulate the concentrated solar energy. More than 800 hours of radiant tests have been performed at several locations in the U.S. (Table I).

Receiver System Designs

A key factor in central receiver system design is the heat transport fluid used in the receiver. Characteristics of fluids which influence the selection include the maximum operating temperature, thermal properties, safety, and ease of handling. Under active development are receivers using, water/steam, sodium, molten salt, air (gas), and heat-transfer oil (Figure 4).

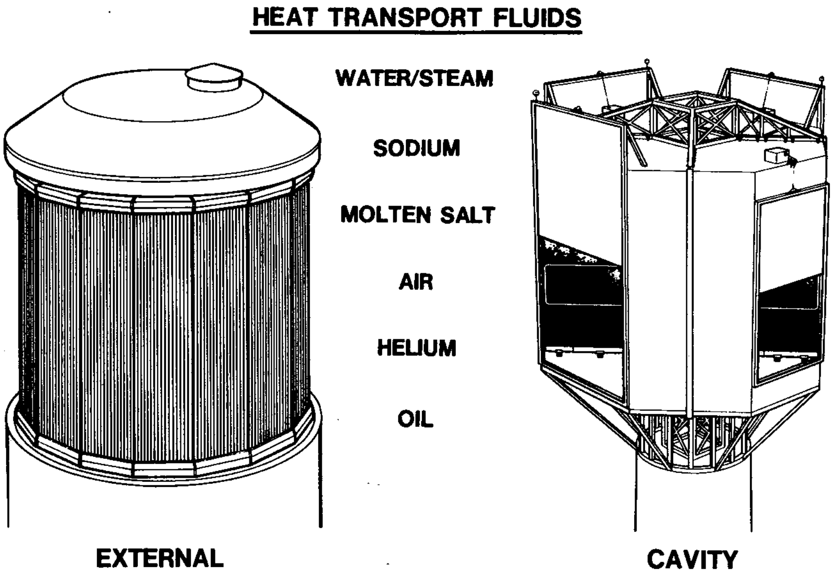


Figure 4. Solar Central Receiver Designs of the External and Cavity Configurations

Water/Steam Systems--The advantages of water/steam as a heat transport fluid are its familiarity to both industrial and utility users, ready availability, extensive industrial design and operating experience, and high energy density when a phase change is used. Also, pumping and transport equipment is commercially available. Disadvantages include possible corrosion problems, stringent purity requirements, and difficulty of matching thermal characteristics to low-cost thermal energy storage systems. Water/steam receivers are well suited to electrical generating applications where limited thermal storage is desired or where a solar energy capability is being added to an existing power plant. Water/steam receivers also are applicable to industrial processes where saturated or superheated steam is desired.

Water/steam receiver configurations have been tested by three contractors, (Honeywell (Figure 5), Martin Marietta, (Figure 6), and McDonnell Douglas), at power levels of 1-5 MW_t using radiant heat lamps. Figure 7 shows a 1-MW_t receiver that was tested at the CNRS solar facility in Odeillo, France. As previously mentioned, a 3-MW_t receiver designed by McDonnell Douglas has recently been solar-tested at the CRTF to acquire thermalhydraulic performance and control data. In addition, a radiant heat test of a receiver panel 0.15 meter wide by 17 meters long (Figure 8) was done at Sandia to understand the boiling phenomena which take place in a water/steam receiver. Water/steam has been selected as the heat transport fluid for Barstow; the European Economic Community project; CESA-1, the Spanish project; and the Japanese project. Using existing water/steam receiver design information as a basis, three companies, Babcock & Wilcox, Combustion Engineering, and Martin Marietta, have extended the knowledge of water/steam receivers by completing conceptual designs of receivers and doing limited testing of tubing options. In fact, water/steam receivers are becoming state-of-the-art. Conceptual designs of

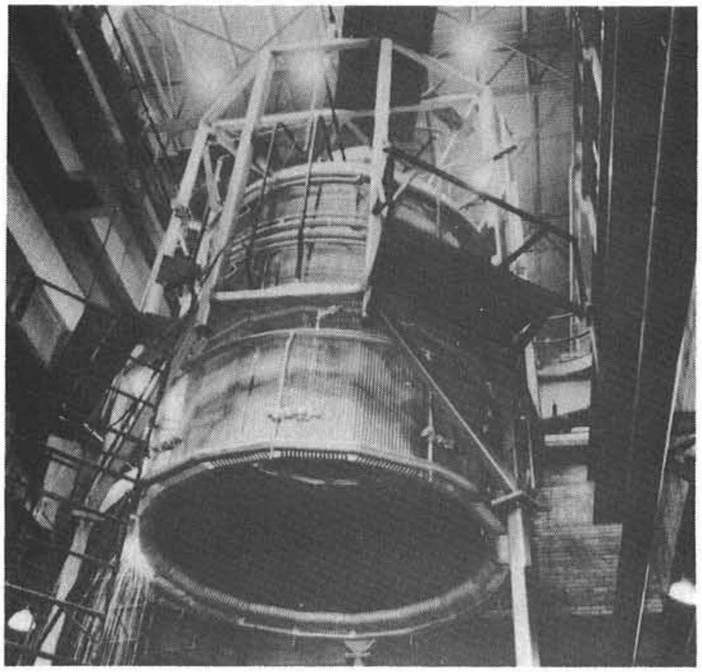


Figure 5. Honeywell Water/Steam Receiver, Radiant-Tested at Power Levels of 3 MW_t

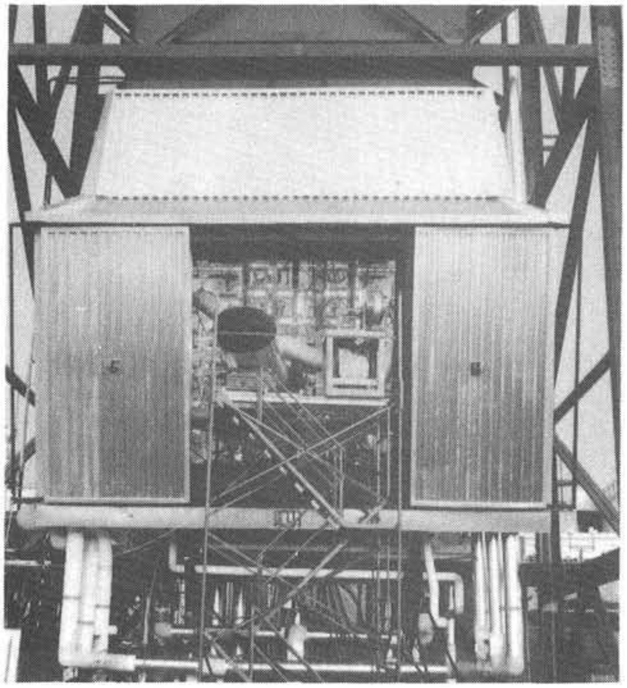


Figure 6. A 5-MW Receiver Radiant Test Conducted at Sandia National Laboratories in Albuquerque

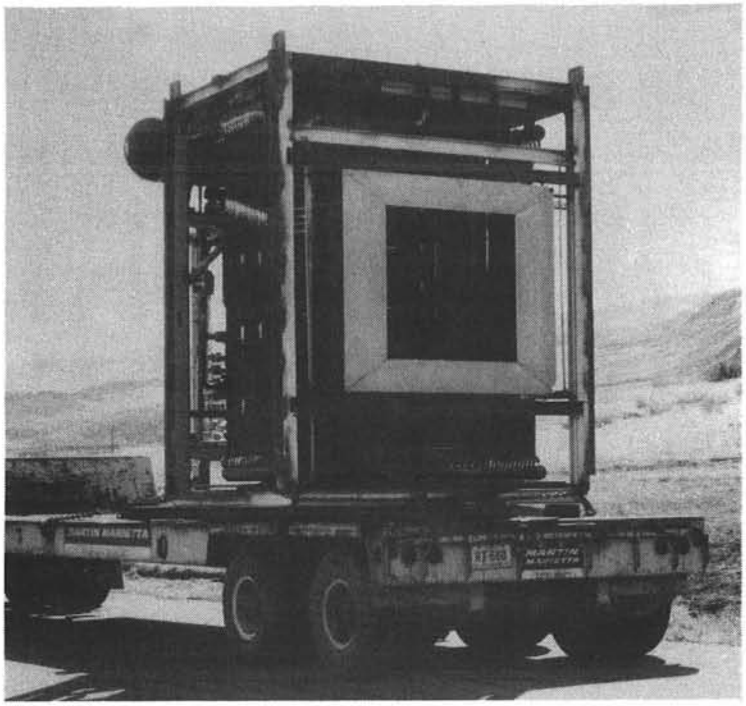


Figure 7. 1-MW_{th} Solar Cavity Receiver Tested at the CNRS Solar Facility in Odeillo, France

large-scale electrical generating plants using water/steam receivers have been done by five firms. Component-level testing has been completed and system operation will soon be demonstrated by several projects.

Sodium Systems--Solar receivers using sodium as the heat transport fluid have been under development in the U. S. for more than four years. Conceptual receiver designs for large-scale plants (100-300 MW_e) have been developed by General Electric and the Energy Systems Group (ESG). Sodium has become familiar to many users through the nuclear reactor program, and extensive design information and materials data exist. Also, many of the system components such as pumps and heat exchangers have been developed and may be purchased.

Sodium has several desirable characteristics including excellent heat transfer and ready availability. Because of its excellent thermal properties, sodium can operate at solar fluxes up to 3 MW/m^2, although current designs

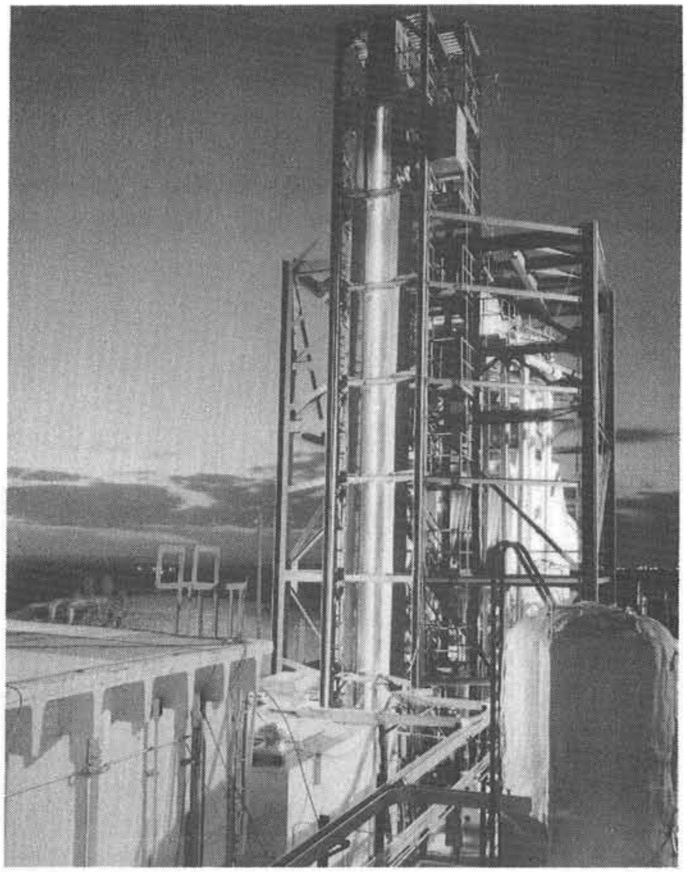


Figure 8. A Radiant Heat Test of a Receiver Panel to Examine Boiling Phenomena in a Water/Steam System

operate at about 1 MW/m^2. The first sodium receiver tests will be started by General Electric in late CY80 (Figure 9), and the receivers are expected to become state-of-the-art within the next few years. Sodium has been selected as the heat transport fluid for the IEA central receiver project in Spain.

Sodium receivers are well suited to either electrical generation or industrial heat applications using energy at temperatures up to 600°C. Long-term thermal energy storage in sodium is, however, relatively expensive ($80-100/KW hr versus $10-30 for molten salt); so another storage fluid must be coupled to a sodium receiver if extended thermal storage is desired.

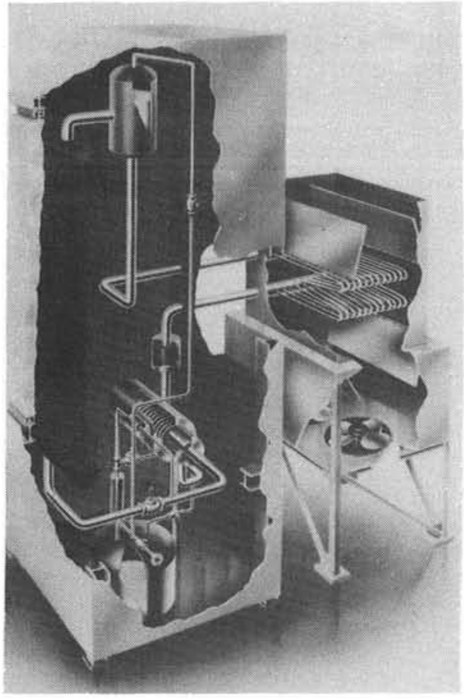


Figure 9. General Electric Solar Test Receiver Using Sodium As the Heat Transport Fluid, to Be Tested at the CRTF at the End of 1980

Molten Salt Systems--Molten salt receivers have also been under development in the U.S. for more than four years. The salts under primary consideration are mixtures of potassium and sodium nitrates, although many other salts can be used. Conceptual receiver designs have been done by Martin Marietta for 100-300-MW_e systems and by McDonnell Douglas for a small system (~1 MW_e), and a test of a 3-MW_t experimental receiver will be done by Martin Marietta at the CRTF in late 1980 (Figure 10). Molten salt has been selected as the heat transport fluid for the French project, Themis-1, and as the storage fluid for both CESA-1, the Spanish project, and the European Economic Community project. Many of the components, such as pumps and heat exchangers, are commercially available for these systems, but research comparable to that for sodium has not been done. Molten salt systems are in commercial use, most of them operating at 450°C or less. Though the state of design and material information is less well developed than for either water/steam or sodium, this gap in knowledge is being filled by DOE-sponsored research at a pace which will see the necessary information developed within a few years.

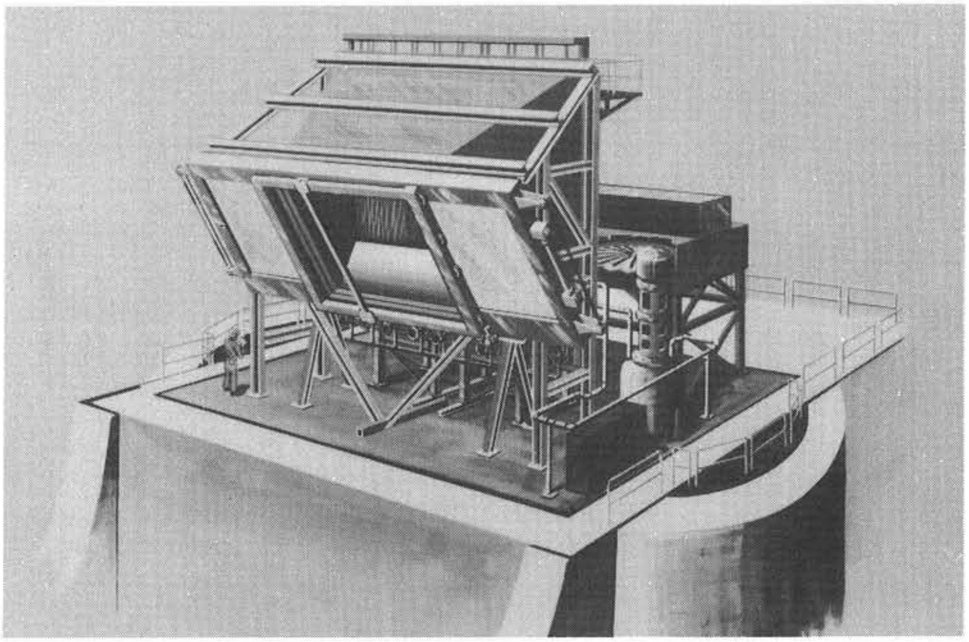


Figure 10. Martin Marietta Molten Salt Solar Receiver Cavity Configuration, to Be Tested at the CRTF in Late 1980

Molten salt has a substantial advantage over other fluids because it can be economically used for thermal storage (\$10-30/MW_t hr). Thus the receiver fluid can itself be stored without the expense or loss of availability which result from using intermediate heat exchangers. Molten salt receiver systems have broad application to electrical generation and industrial process heating, both with and without thermal storage.

Gas Systems--Receivers using a gas such as air or helium have been under active development in the U.S. for more than five years. An advantage of using a gas is that the receiver working fluid can be used directly in a Brayton cycle turbine or it can be coupled without intermediate heat exchangers to an industrial process such as gypsum board drying or ammonia production. If metal pipes are used to contain and transport the working fluid, outlet fluid temperatures up to 815°C can be achieved, while receivers constructed of ceramic materials can supply hot gases above 1000°C. Air as a heat transport fluid has the advantages of low cost, ready availability, and familiarity to users. However, air has a lower conductivity and heat capacity than sodium, salt, or water/steam and thus requires larger-sized pipe, since substantially more mass must be transported. Gas receivers are designed to operate at lower incident fluxes (typically 0.1-0.2 MW/m^2 versus about 1.0 MW/m^2 for sodium or salt); therefore, receivers tend to be larger and heavier than those using other fluids.

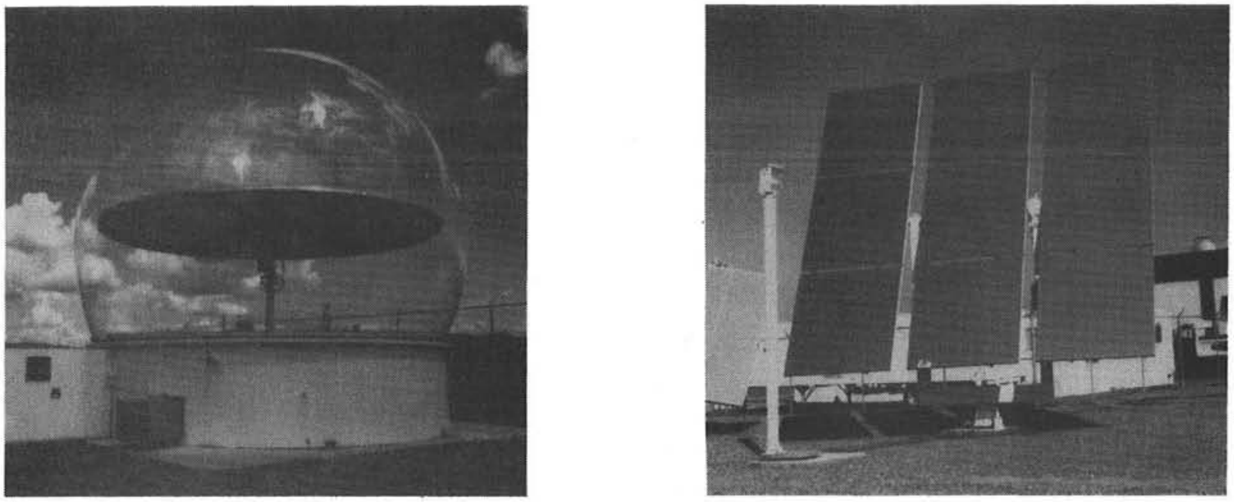
Boeing, under DOE funding, has developed conceptual designs for 100-300-MW_e generating plants and, under Electric Power Research Institute funding, has built and tested a 1-MW_t receiver using air. Dynatherm, Cockysville, Maryland, has done a conceptual design of an air receiver using metallic heat pipes to enhance the rate of heat transfer. Recently, they have been working as part of an industrial team headed by Bechtel Corporation to further refine their design and incorporate it into a 300-MW combined cycle electrical generating plant. Sanders Associates, Inc., Nashua, New Hampshire, has designed a receiver in which the concentrated solar energy is absorbed in a ceramic honeycomb structure and transferred to air. A 50-KW_t experiment was tested at the solar furnace at White Sands, New Mexico, and a larger version (250 KW_t) was tested at the Advanced Component Test Facility in Atlanta, Georgia. Black and Veatch, under EPRI funding, is designing a 1-MW_t experiment to be tested at the CRTF in 1981. Lincoln Laboratories at MIT has been working on the design of a small high-temperature air receiver using ceramic domes to form the wall of a cavity.

Heat-Transfer Oil Systems--Northrup, Inc., has recently designed a receiver using heat-transfer oil. It can operate at temperatures up to 320°C and is a low-cost system because conventional carbon steel can be used. This receiver is especially well suited to moderate-temperature applications which use heat transfer oil in the process, thus eliminating the need for intermediate heat exchangers.

In summary, by mid 1981, engineering feasibility tests of receivers using water/steam, air, molten salt, and sodium heat transport fluids will be completed and central receiver system designers will then be able to match applications requirements to receiver fluid characteristics.

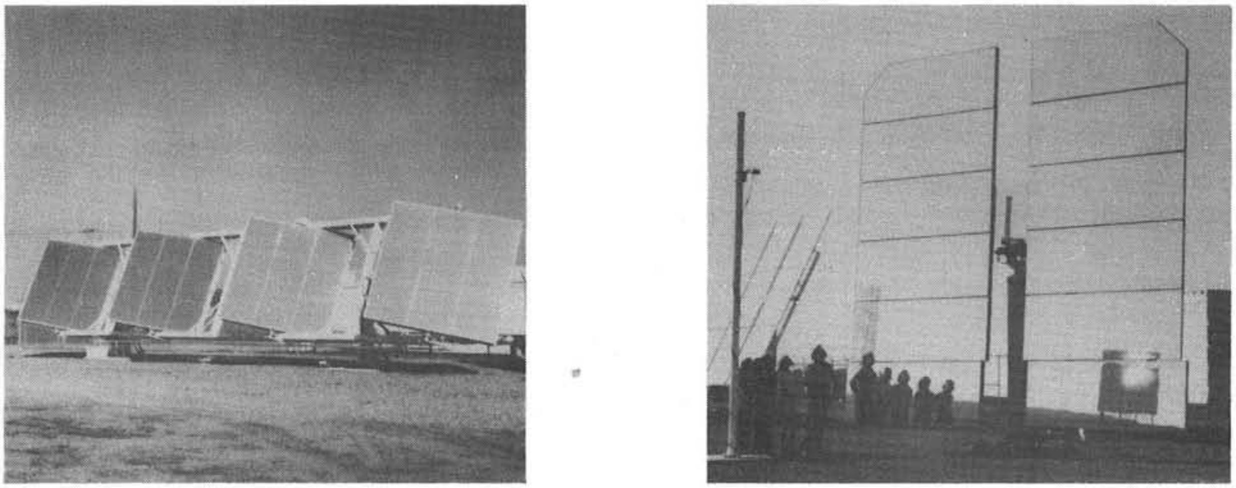
Heliostats

The U.S. central receiver program established a rather ambitious cost goal of $65 per square meter of reflective surface very early in the program (1975). Heliostats were, and still are, projected to comprise one-third to two-thirds of the plant cost. Starting in 1975, four contractors began to build and test first-generation heliostats (Figure 11). Two basic approaches have been used to achieve low manufacturing cost together with the desired performance. The first approach is to mount silver-plated glass mirrors on steel structures. The mirrors are usually structurally reinforced with honeycomb or plastic foam backing. The second approach is to use light-weight plastic reflectors mounted inside air-supported domes of clear plastic which protect the mirrors from wind loads and greatly reduce structural weight. A



Boeing

Martin Marietta



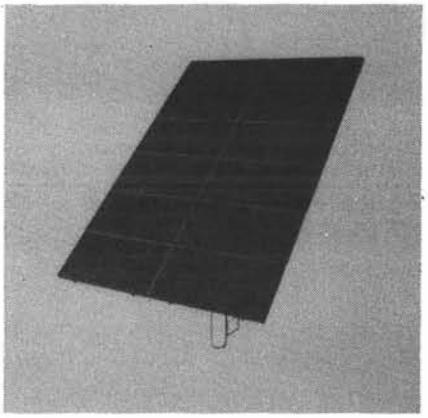
Honeywell

McDonnell Douglas

Figure 11. Four First-Generation Heliostats Undergoing Tests at Sandia National Laboratories in Livermore, California

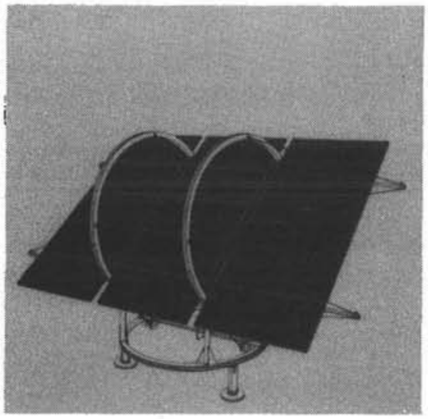
well-designed glass-steel heliostat weighs 37 kg/m^2 of reflective surface, while a plastic heliostat-dome combination only weighs 4 kg/m^2. Testing of these first-generation glass/steel heliostats was completed by Minneapolis Honeywell, McDonnell Douglas, and Martin Marietta in 1977, while at the same time, Boeing built and tested several plastic heliostats. All of the heliostats performed adequately, but since the single supporting pedestal design of McDonnell Douglas appeared to have cost advantages, this type of design was selected for use in the Barstow, California, pilot plant. The Boeing heliostat, while it also performed well, had the disadvantages of lower optical performance (20 percent of the energy is lost in receiving and transmitting the sunlight through the dome) and the use of relatively costly plastics. In 1978 Boeing, General Electric, McDonnell Douglas, and Solaramics were funded to develop conceptual designs and manufacturing plans for heliostats. In mid 1979, Boeing, Martin Marietta, McDonnell Douglas, Northrup, and Westinghouse were awarded contracts to design and build heliostats which have been termed "second-generation" (Figure 12). By early 1981 these designs, all of which use the glass-steel approach, will be tested, and measured performance data will be available. To lower heliostat cost and improve performance, numerous special studies have been conducted. These include further exploration of the plastic dome approach and studies of low-cost mirror module fabrication, reduction of dust buildup, improved alignment techniques, cable drive systems, mirror cleaning techniques, and portable reflectance measuring equipment.

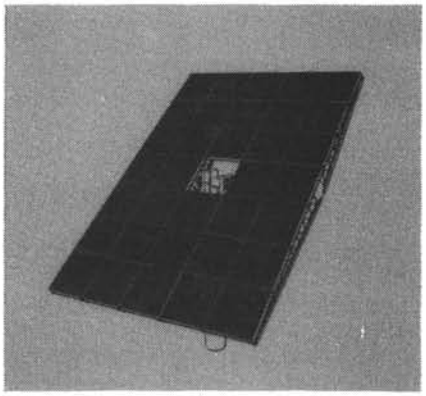
With the completion of second-generation testing, the U.S. program will have demonstrated the performance of heliostats through experimental evaluation of over 30 prototypes and several years of successful operation of 222 heliostats at the CRTF. By the end of 1981, over 1800 heliostats will be in operation at the Barstow plant. Engineering feasibility has been clearly demonstrated for heliostats; however, what they will cost when produced in large quantities remains uncertain, since achieving low manufacturing cost depends on implementing mass production techniques. More than 15 heliostat manufacturing studies have been completed by heliostat designers and by



Boeing

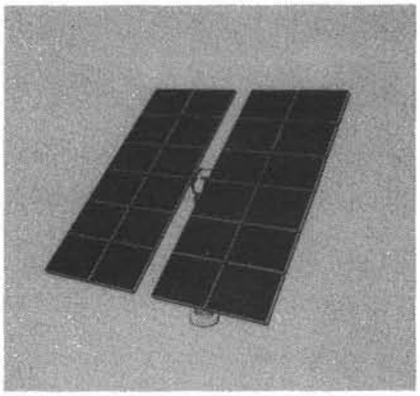
Westinghouse





Northrup

Martin Marietta



McDonnell Douglas

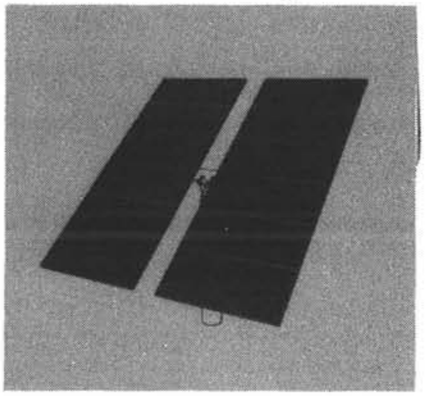


Figure 12. Prototype Second-Generation Heliostat Designs Using the Glass-Steel Approach

commercial and government organizations; and while nearly all indicate that glass-steel heliostats can be manufactured for less than \$125/m^2, several project costs of less than \$65/m^2. Plastic enclosed heliostats are projected to cost \$25/m^2. Achievement of costs in the \$100/m^2 region will allow the central receiver concept to provide energy which in the future is projected to be economically competitive with fossil fuels for many applications, provided the capital and fuel cost escalation rates remain what they have been. Ultimately, however, the accuracy of such cost projections can only be verified by building and installing heliostats in modest quantities--perhaps 20,000--but this effort will require the construction of one or more heliostat manufacturing plants capable of mass production and the investment of a substantial sum in labor and material--perhaps a quarter of a billion dollars. Without an assured market for heliostats, it is highly unlikely that private industry will risk an investment this large. Therefore, government subsidy or incentives are expected to be necessary, and various approaches to solving this problem are being explored by industry and the Department of Energy.

Thermal Energy Storage

Solar central receiver plants operated only during daylight hours in sunny locations will deliver energy for about 25 percent of the total hours of the year. Storing collected thermal energy, however, can increase the duration of operation to 90 percent or more of the time. The energy may be stored as either sensible or latent heat in a solid, liquid, or gas. Desirable characteristics for storage media are low cost, high specific heat, low specific volume, adequate thermal stability, and good heat transfer. Storage of energy in mechanical or electical form has been examined for central receiver systems, but generally seems to be less cost-effective than storage as thermal energy.

If the heat transport fluid in the receiver is also used as the storage fluid, costly intermediate heat exchangers can be eliminated. For example, sodium can effectively store energy for sodium receivers, and it costs about $0.90 per kg. A mixture of molten potassium nitrate and sodium nitrate salts, a good choice for molten salt receivers, costs only about $.30-.40 per kg. An experiment to demonstrate the storage of molten nitrate salts will be started in 1981. Since storing energy in pressurized water, steam, or air is very costly, storage for water/steam or air receivers is generally accomplished in another medium. For example, McDonnell Douglas has tested a system using a mixture of heat-transfer oil and rock, and this system will be used for the Barstow pilot plant. A two-stage molten salt and heat-transfer oil system for water steam receivers was successfully tested by Martin Marietta at the Georgia Power and Light Co., Atlanta, Georgia, in 1977. For air receivers, storage as sensible heat in alumina brick has been proposed.

Repowering

In 1978 the Public Service Company of New Mexico completed a conceptual design study of adding a central receiver capability to an existing electrical generating plant in Albuquerque, New Mexico. The concept has been termed "repowering." Recently the U.S. Department of Energy has funded 12 site-specific conceptual designs for adding such central receiver capabilities to existing industrial process plants and electrical generating plants, and teams of industrial firms are developing solar plant designs tailored to meet the site and interface requirements for each application. A thirteenth privately funded repowering study is underway. These studies have stimulated interest and enthusiasm on the part of the energy-using organizations. These conceptual design studies are to be followed by a Program Opportunity Notice soliciting bids on the design and construction of one or more repowering projects that would be jointly funded by private industry and the U.S. government.

Costs

The engineering feasibility of several solar central receiver technologies is being demonstrated; but although this is a necessary condition, it is by no means sufficient. Economic criteria, too, must be satisfied, and both technical and cost data must be available to potential users so that they can arrive at their own decisions on whether to implement the technology. In the U. S. program, emphasis has been on developing conceptual designs for large, commercial scale plants which can deliver up to 300 megawatts of electricity or up to 1500 megawatts of thermal energy. Costs have been estimated for all of the elements of these plants, and a typical cost breakdown is shown in Figure 13. It should be noted that the capital cost is a function of the capacity factor; i.e., the number of hours of operation per year. If the plant is to operate more than 25 percent of the time, energy storage and additional heliostats to charge that storage must be added.

Levelized busbar energy cost as a function of capacity factor is shown in Figure 14 for an electrical generation application. The cost of energy is lower at higher capacity factors because there is better utilization of the fixed-cost portion of the plant; e. g., the turbine generator and power-conditioning equipment. Construction cost uncertainties are typical of any major construction project, and the current rapid escalation of raw and finished material prices and labor rates, together with the cost of capital, are affecting the cost of all major projects. For solar central receiver plants, moreover, additional factors must be considered. Heliostats, which account for one-third or more of the total cost, have not yet been built in

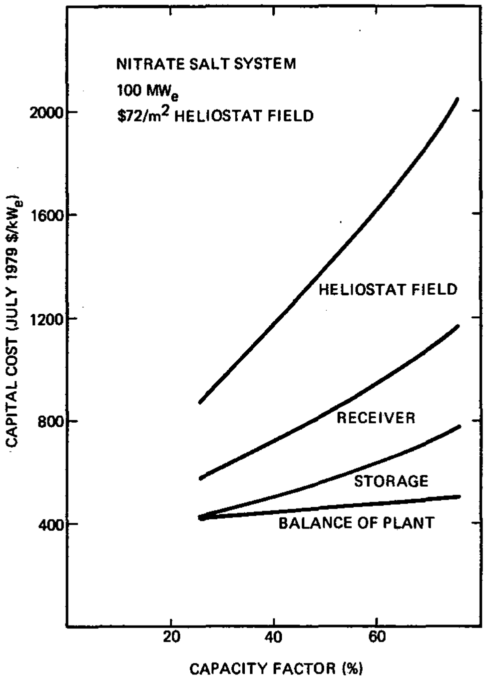


Figure 13. System Capital Cost Breakdown

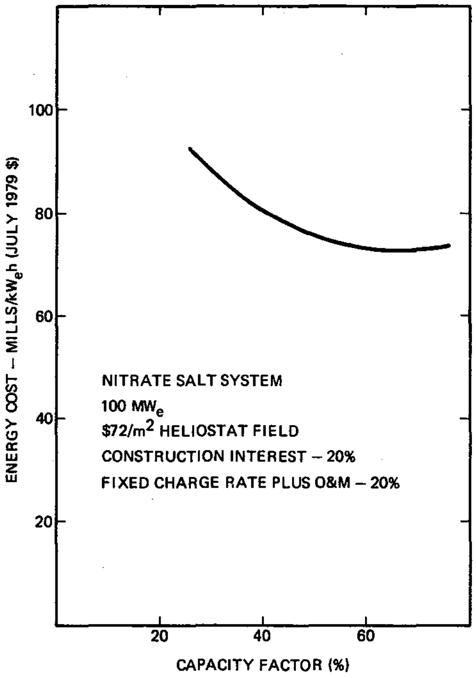


Figure 14. Levelized Busbar Energy Cost

large quantities (as has been discussed previously) and a single plant may require more than 10 000 of these. Another factor is that large central receiver plants have not yet been built. The Barstow plant is thus a major stepping stone, but even larger demonstration plants must be built and operated.

The Future

Engineering feasibility of several central receiver technology options will be completed within two years. Additional system-level demonstrations are needed, and the development of an industrial capability for mass producing heliostats is crucial. Since 1974, the central receiver concept has progressed from an engineering curiosity to a potentially viable alternative to fossil fuel. If the present rate of progress continues for the next five years, the concept will take its place as a practical energy option.

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