Chapter VIII

COLLECTORS

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Chapter VIII

Collectors

BACKGROUND

This chapter reviews the diverse assortment of techniques which can be used to collect sunlight on receiving surfaces. Technologies for converting the energy collected into mechanical or electrical energy are examined in chapters IX and X.

Solar collectors are the only components of solar energy systems which are unique; all other parts of the systems—heat engines, storage devices, and the like—have a history of use in other applications. Collectors can, however, be relatively simple devices and have much in common with other types of heat exchangers. A variety of design approaches are possible using well-established technology. The major problem is reducing the cost of the devices with innovative designs or mass production techniques. Low-cost collectors are critically important to the future of solar energy since collector costs dominate the cost of solar energy in almost all systems.

Evaluating collectors at this stage in the history of the technology is an extremely treacherous undertaking. The field is changing at a bewildering rate and it is much too early to be dogmatic about the outcome. Since collector designs can be perfected without the need for sophisticated development laboratories, a large number of inventors have entered the field and an incredible variety of approaches have been proposed. Concepts have come from home inventors, university laboratories, and small manufacturing concerns, as well as large Government and corporate development laboratories. Many of these new ideas will never reach the marketplace and many that do will not survive the intense competition which is beginning to take place. There are presently about 200 independent organizations in the United States with a collector on the market.

Many interesting designs have never been produced commercially and many of the designs which have reached the market have been available for such a short time that their long-term performance cannot be accurately evaluated. In particular, few systems have been tested extensively in adverse weather conditions. Moreover, many contemporary collector manufacturers are small firms which are unable to make reliable estimates of a selling price which can sustain the overhead and marketing costs of their concerns—several companies have failed in the past year. As a result, the claims made by many manufacturers of inexpensive devices must at this point be treated with great caution.

Uncertainty about the reliability and performance of collectors may be alleviated to a considerable extent when consensus standards are developed by the industry **for testing collectors and when testing laboratories are certified** for conducting the needed tests. (This uncertainty about system quality is a major problem for consumers and is discussed more extensively in chapter III, *Policy Analysis.]*

In almost all cases, forecasts of the future price of collectors are based on estimates of potential mass production and are not based on a detailed analysis of specific manufacturing processes, In fact, the price of many of the products now on *the* market is unlikely to fall dramatically with mass production–the cost of materials already represents a significant fraction of the total cost of some devices. Significant price reductions are more likely to result from the development of innovative designs.

In spite of the uncertainties, collector production is increasing rapidly. Manufacturers reported production of 426,000 m^2 of collectors during the first half of 1977 (4.5 million square feet), of which about 250,000 m^2 were low-temperature devices designed primarily for heating swimming pools. Sales have been increasing by more than so percent every 6 months. Collector sales were expected to amount to over $100 miIlion during 1977.

MAJOR DESIGN CONSIDERATIONS

The enormous variety makes the selection of an optimum collector design a complex decision. The choice can only be made by analyzing the space available for collectors on building roofs or in landscaping around buildings, the local climate (including the availability of direct and indirect sunlight), and the compatibility of the collector output with storage equipment, engines, and other elements of the solar energy system. Clearly, no single design will be optimum for all applications in all climates. The following discussion reviews some of the major **variables which must be considered in selecting a collector.**

TRACKING VERSUS NONTRACKING SYSTEMS

The vast majority of the collectors now on the market do not follow or "track" the Sun or concentrate sunlight with an optical system, but are "flat-plate" systems rigidly fixed to rooftops or frames in fields. This kind of collector has the advantage of simplicity and reliability, and can be integrated into building designs with relative ease.

If sufficient land is available and large quantities of low-temperature (500 to 90° C) thermal energy are required, shallow pond collectors, which use the earth for much of their support, will almost certainly provide the lowest cost solar energy. Nonfocusing collectors are also uniquely able to make use of diffuse sunlight reflected from the atmosphere and the ground. (Some diffuse solar energy can be collected by concentrators which magnify the Sun's intensity only 2 to 3 times,) Flat-plate collectors are not able to provide temperatures high enough to operate most kinds of heat engines, however, and cannot be used to provide high-temperature process heat. (A heat engine which can operate from the temperatures produced by flat-plate devices is discussed in chapter IX, *Energy Conversion With Heat Engines.*)

Some types of flat-plate collectors may cost more per unit of aperture than tracking devices. This is because flat-plate units require a considerable amount of material for each unit of collector area —the entire area must be covered by an absorber surface, insulation, and one or two layers of glass or plastic. The large heated area also means that thermal losses for flat-plate devices are generally larger than those of systems which concentrate sunlight, even though the concentrating systems typically operate at higher temperatures,

Systems which track the Sun and concentrate sunlight are able to produce the high temperatures needed to operate efficient heat engines or can be used to reduce the area of photovoltaic cells needed for electricity production. Their use with solar cells is important if the cost per unit area of the tracking collector is significantly cheaper than the unit area cell costs, and if the tracking device allows the use of a high-efficiency cell. This is discussed in greater detail in later sections.

Although most concentrating collectors now on the market cost considerably more than flat-plate devices, it may eventually be possible to build concentrating devices which cost no more (perhaps less) than standard flat-plate systems since most of the area of concentrating collectors is covered only with a thin layer of reflective surface or

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[1] Stoll, R. (DOE) *Solar Collector Manufacturing Activity,* November 1977

lens material. The inability to utilize diffuse sunlight is compensated for, to a large extent, by the fact that tracking devices can maintain a better angle to the Sun than stationary systems.

Systems have been proposed which concentrate sunlight without tracking — examples are simple stationary reflectors placed between tilted flat-plate collectors and the "compound parabolic concentrator" under development at the Argonne National Laboratory; and systems have been proposed in which flat-plate collectors track the Sun without concentrating sunlight. **In most** cases, however, tracking and concentration are used together.

Tracking collectors can be conveniently divided into two general categories depending on whether they track the Sun by tilting around one or two axes. The one-axis tracking systems are typically shaped like long troughs which swing about the trough's long axis. These troughs cannot keep the receiver aperture perpendicular to the Sun's direction, but provide better Sun angles than a fixed device. One-axis systems typically are used to magnify the Sun less than 50 times and are not used to provide temperatures above **3500 C (660 °F); some simple,** inexpensive systems are designed to produce fluids at650 to 1200C(1500 to 2500 F).

The advantages of concentrating collectors are counterbalanced by the added costs of maintaining the optical surfaces and moving components, and by the cost of the tracking unit itself. The tracking systems need not be very expensive since a single tracker can be used to drive a large array of collectors and wear on the moving parts will be minimal since a collector will rotate only 11,000 times in 30 years. Maintenance of the optical surfaces is likely to be the largest problem. Optical losses can be a dominant factor in the overall efficiency of concentrating collectors (the relatively poor optical efficiency of some concentrating collectors tends to offset their relatively good thermal efficiency), and these losses can be significantly increased if dirt or scratches accumulate on mirror or lens surfaces.

Dirt can scatter light and therefore interferes with the ability of the optical devices to focus light even when the amount of light absorbed by the dust is not important. Recent experience at Sandia Laboratories has indicated that the specular reflectivity of tracking mirrors can be reduced by as much as 15 percent in poor locations if the mirrors are not washed during a year. The effect is very sensitive to the location of the collectors since precipitation can reduce dust accumulation but no data is available on this problem in most locations. Table VII I-l indicates the degradation in the performance of flat-plate photovoltaic collectors. It can be seen that the effect of dirt depends strongly on the cover material and the operating environment. The degradation of performance apparently is quite rapid during the first 3 months, but levels off quickly. Performance at 9 months is not much worse than performance at 3 months.[2] A relatively simple hose-down once or twice a year may be sufficient for most cleaning requirements. ' Larger collector arrays may require specially designed equipment to facilitate cleaning collectors.

The timing of cleaning cycles will depend on a detailed comparison of the cost of alternative cleaning schedules and the cost of energy lost because of the dirt which can accumulate as a result of each schedule. Unfortunately, most types of tracking devices have not operated long enough to allow the collection of adequate information about the degradation of performance over time. Cleaning is, of course, also important for flat-plate collectors, but tends not to be as critical a factor in their performance since a significant fraction of the light scattered by dirt can still be captured by a flat-plate absorber.

Wind loads present a particularly serious problem for tracking collectors since they can act like sails and much of the cost of tracking devices results from the need to

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[2] A. F. Forestieri, NASA Lewis Research Center, private communication, November 1977

[3] Rosco Champion (Sandia Laboratories), private communication, February 1977

Table VIII-1.— Degradation in the Performance of Flat-Plate Photovoitaic Arrays Located in Cleveland, Ohio, September-December 1975

	Heavy industrial environment		Suburban environment	
	81 days	250 days	74 days	250 days
Arrays not cleaned				
Cells encapsulated in glass	-5.7		+ 1.8	
Cells encapsulated in silicone rubber (average of three products tested)	-32	~-30	-9	
Performance after arrays scrubbed with a detergent solution				
Cells encapsulated in glass.	+ 1.8		0	
Cells encapsulated in silicone rubber (average of three products tested)	-7	~ -12	-2	-6 to -10

NOTE: Measurement error was - ±2%, so + 1.8% means only that no measurable degradation had occurred

SOURCE Forestieri, A F "Results of Outdoor Real Time and Accelerated Testing" presented at ERDA National Photovoltaic Program Review, Silicon Technology Program Branch, San Diego, Calif, Jan 18, 1977 (p 230)
Forestieri, A F private communication, November 1977

build massive supporting structures capable of withstanding high winds. A clever technique for reducing such costs would be a welcome innovation.

Another potential problem with tracking systems is the difficulty of integrating the devices aesthetically into the architecture of a building; many of the experimental tracking systems are far from attractive. The architectural problem of integrating tracking systems gracefully into a building, however, has not been adequately examined.

Finally, it can be difficult to design reliable couplings to carry very hot fluids from a moving receiver. Several approaches are possible. For temperatures below boiling, a flexible radiator hose may be adequate, although occasional replacements may be necessary. For temperatures of 4000 to 6000 F, rubberized braided-steel hose can be used. For higher temperatures, stainless steel accordian bellows can be used. These are commonly used to allow for expansion and contraction in industrial pipes which must carry very hot or very cold fluids or steam. The reliability of each approach can only be established with careful testing.

INSTALLATION

The cost of installing collectors is an important and often overlooked component of the cost of a solar system. The relatively straightforward plumbing, carpentry, and electrical work associated with installing collectors can represent more than half of the installed cost of a collector system. These costs tend to be significantly higher in the case of devices retrofitted onto existing structures.

It may be possible to integrate collectors into the walls or roofs of new buildings in a way that can lead to some savings in building materials and insulation. Plumbing and wiring costs can be minimized with careful building designs. Some additional construction costs may be incurred if heavy collectors or collectors subject to high wind loads must be supported by the building.

Collector systems **which are not attached to buildings incur the additional cost of land-grading, concrete foundations, and the cost of purchasing needed land. In many cases, the land cost can be eliminated by mounting collectors over parking lots or other areas where the** collectors will not interfere with use.

The problem of installation costs has not received the attention which this issue merits.

WORKING FLUID

A variety of fluids can be used to convey the energy from a solar collector to the site where the energy is needed or into storage. At low temperatures, the prime candidates are air, water and mixtures of water, and antifreeze. (Pure water cannot be used in colder climates unless the system is designed to drain completely during cold, sunless periods or the collector is made from flexible plastics or other materials which are not damaged by expansion.)

Air collectors have the advantage of avoiding the problem of freezing altogether, and are not affected by the corrosion which can result from untreated water. Air can be heated to temperatures above boiling without producing excessive pressures, and leaks in air collectors do not lead to building damage. Air collector heating systems can use inexpensive rock beds for heat storage, thus eliminating the inefficiencies, temperature drops, and costs associated with heat exchangers. However, the relatively low density and specific heat of air (compared to water) means that the collectors, storage, and heat transfer systems must be considerably bulkier than the liquid systems.

Water can also be used as the working fluid in high-temperature systems, but pressurized systems can be expensive, especially if steam must pass through rotating joints or be transported over long distances. A variety of heat transfer fluids have been developed for chemical processing which can be used to transport heat from solar collectors, although there are disadvantages associated with their use. These fluids can be costly, some are flammable, and others degrade with continued thermal cycling. The use of helium gas has been proposed for use in the receivers of very high-temperature collector systems.

If an efficient and inexpensive chemical process can be developed which either converts light directly into chemical energy (photochemical reactions) or which uses thermal energy to drive a chemical reaction (thermochemical reactions), it may be possible to pump the appropriate chemicals directly into collectors to produce a higher energy material which can be stored for later use.

SURVIVAL IN ADVERSE CONDITIONS

A collector system should be able to withstand strong wind and hail, and should be able to operate after snowstorms. Some tracking collectors are designed to protect themselves from inclement weather by turning the vulnerable surfaces down toward the building or the ground.

Another factor which must be considered is the collector's ability to survive a failure of the pump control systems or plumbing which prevents the working fluid from carrying heat away from the collectors. If fluid flow stops, the temperature of even simple collectors can reach 1000 to 1500 C (the so-called “stagnation temperature” of the collector). These temperatures can melt critical components of poorly designed systems or cause expensive damage in other ways. The collector performance and certification tests designed by the National Bureau of Standards will include a test of the performance of the collector after it has operated without cooling fluids for some length of time.

SURVEY OF COLLECTOR DESIGNS

The following section examines a representative set of solar collectors. Some of these devices are on the market and some remain in the laboratory, but an attempt has been made to represent each generic category. The selection of particular collectors as examples does not imply any judgment about their performance relative to other devices, nor is the survey intended to provide a comprehensive listing of all available designs. Extensive catalogs of solar collectors have been published by the Energy Research and Development Administration (ERDA),[4] the House Subcommittee on Energy Research, Development, and Demonstration,[5] and the Solar Energy Industries Association.[6]

"PASSIVE" SYSTEMS

The heating and cooling requirements of buildings can be reduced if care is taken in the design of the building and the choice of a building site. With imaginative planning, most of the options should not add substantially to the cost or detract from the appearance of structures. At some added cost, new **buildings can be designed with more elaborate structural features (such as large south-facing windows and thick walls) which can further reduce heating and cooling requirements.** These features are all commonly categorized as "passive solar" collection systems since they typically have no moving parts.

Passive systems are extremely attractive because of their simplicity, very low initial cost, and freedom from maintenance costs.

Many of the more sophisticated passive solar designs are only applicable to new construction since they affect the basic design of the building; many simple changes, such as the addition of awnings, shutters, and lean-to greenhouses can be retrofit on existing structures. Temperature control can also be difficult with some systems.

Siting

A wise decision about building placement should take into account local topography, sun angles, trees and other vegetation, ground water, precipitation patterns, and other aspects of the local climate and geography. There cannot be a simple, all-inclusive formula for resolving these issues because each decision must be made on the basis of specific site conditions. Table VIII-2 indicates some of the basic elements of building siting decisions for four different climatic regions, and figure VIII-1 gives an example of an efficient siting plan developed by the AIA Research Corporation. The following features were used in developing the plan:[7]

- The use of windbreak planting;
- The orientation of road alinement with planting on either side to channel summer breezes;
- The location of units in a configuration suggested by the topography;
- The use of the garage to buffer the dwelling from northwest winter winds;
- The use of berms to shelter outdoor living terraces; and
- The use and location of deciduous trees to block or filter afternoon sunlight in the summer.

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[4] *Catalog on Solar Energy Heating and Cooling Products.* ERDA-75 ERDA Technical Information Center, Oak Ridge, October 1975

[5] *Survey of Solar Energy Products and Services – May 1975.* Prepared for the Subcommittee on Energy Research, Development, and Demonstration, U.S. House of Representatives, by the Congressional Research Service, Library of Congress, June 1975 For sale by U S Government Printing Office, $4.60

[6] *Solar Industry Index.* Solar Energy Industries Association, January 1977 $8.00 prepaid

[7] The American Institute of Architects Research Corporation, *Solar Dwelling* Design Concepts, prepared for the U S Department of Housing and Urban Development, Office of Policy Development and Research, May 1976

Table VI II-2.—Site Orientation Chart

Type of climate	cool	Temperate	Hot humid	Hot arid
Adaptations	Maximize warming effects of solar radiation. Reduce impact of winter wind Avoid local climatlc cold pockets	Maximize warming effects of Sun in winter. Maximize shade in summer. Reduce impact of winter wind but allow air circulatlon in summer	Maximize shade Maximize wind	Maximize shade late morning and all afternoon. Maximize humidity, Maximize air movement in summer
Position on slope	Low for wind shelter	Middle-upper for solar radiation exposure	High for wind	Low for cool alr flow
Orientation on slope	South to southeast	South to southeast	South	East-southeast for p.m shade
Relation to water	Near large body of water	Close *to* water, but avoid coastal fog	Near any water	On lee side of water
Preferred winds	Sheltered from north and west	Avoid continental cold winds	Sheltered from north	Exposed to prevaillng winds
Clustering	Around Sun pockets	Around a common, sunny terrace	Open to wind	Along E-W axis, for shade and wind
Building orientation •	Southeast	South to southeast	South, toward prevailing wind	South
Tree forms	Deciduous trees near building; evergreens for windbreaks	Deciduous trees nearby on west; no evergreens near on south	High canopy trees; use deciduous trees near building	Trees overhanging roof if possible
Road orientation	Crosswise to winter wind	Crosswise to winter wind	Broad channel; E-W axis	Narrow; E-W axis
Materials coloration	Medium to dark	Medium	Light, especially for roof	Light on exposed surfaces, dark to avoid reflect ion

*Must be evaluated in terms of impact on solar collector, size, efficiency, and tilt.

SOURCE Solar Dwelling Design Concepts op cit p 72

In warmer climates, a building should be placed at the highest part of the terrain to take advantage of cooling winds (a form of solar energy); in colder climates, it should be located, ideally, in the cup of a hill, allowing sunlight to reach the building while protecting it from chilling winds.

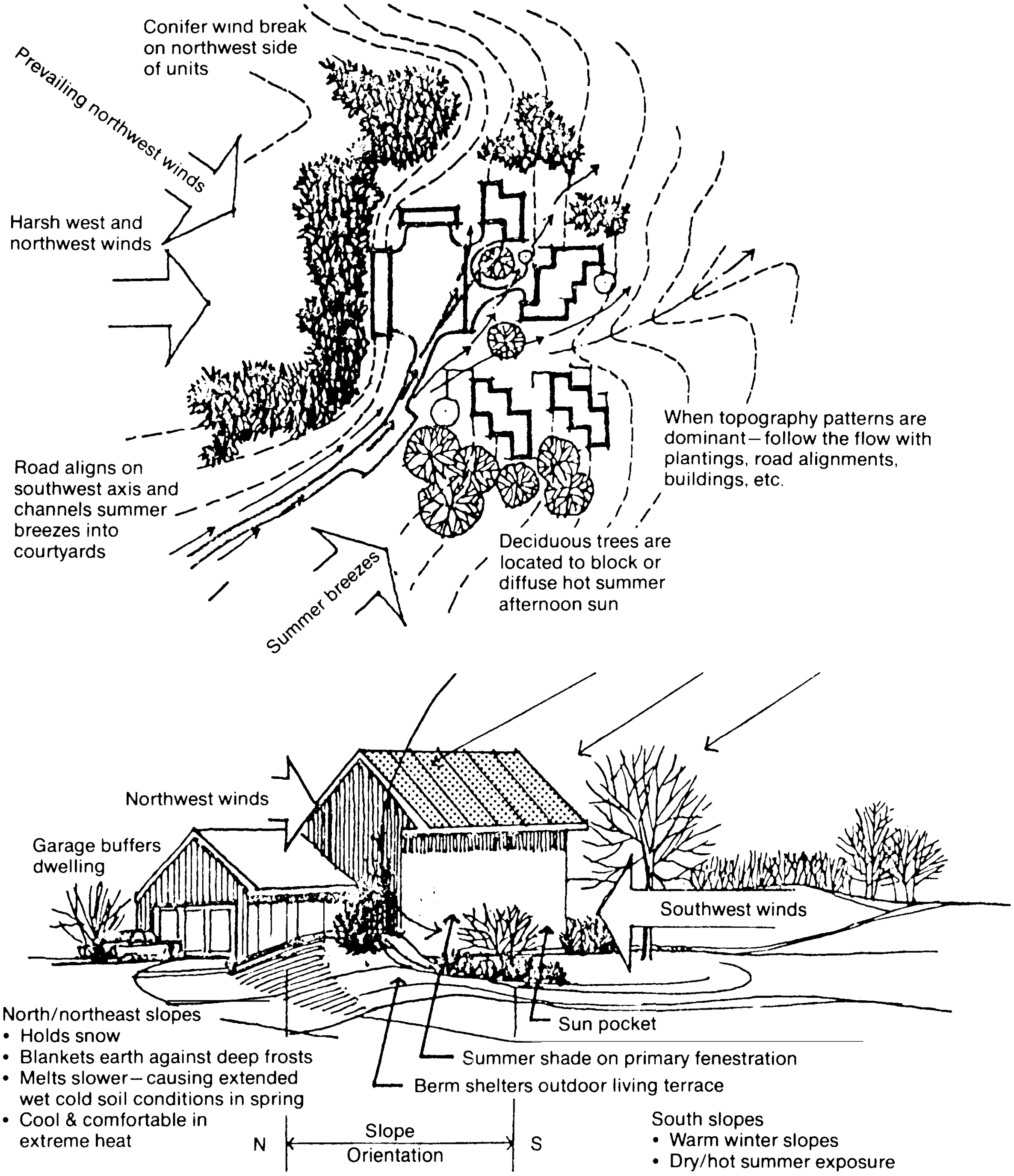
When the terrain and local building codes permit, siting at least part of the building underground or at ground level provides excellent *insulation.* Trees are also an important factor in site selection, acting both as a windbreaker and a lightbreaker. Deciduous trees shade the south side of the house for much of the year, allowing sun light to penetrate during the colder months. The same shading principle is true of such plants as ivy on the walls of the house,

Basic Architectural Considerations

A considerable amount of passive solar heating and cooling can be achieved simply by carefully designing the shape of a house, and the placement of windows and thermal masses in the building (e. g., thick masonry walls). Many older buildings incorporated these features in their designs. (The art of taking such factors into consideration **in designing a house seems** to have been neglected when inexpensive heating fuels became available.)

The size and location of windows is a major factor in determining the temperature of a house. Large, south-facing windows can collect a surprising amount of solar heat, which is transferred to walls and floors.

Figure VII I-I .—A Sample Site Plan Illustrating Techniques for Minimizing Heating and Cooling Requirements



SOURCE The AIA Research Corporation, "Solar Dwelling Design Concepts"

Small, northern windows minimize heat loss. The use of natural shading and orientation to breezes provides improved cooling through windows.

The basic shape of a structure is also important. Long ranch-style homes, for example, require much more heating per unit of floor space than cube-shaped, two-story homes, Roof overhangs should shade windows during the summer when the Sun is high in the sky and allow sunlight to enter when the Sun is lower in the sky during the winter months. Dense interior materials with a high heat-retaining capacity, such as masonry, concrete, or stone, can be used to absorb surplus heat from sunlight during the day, and return this heat to the room after dark.

Passive heating and cooling of buildings can be enhanced by taking advantage of the heat gained in southern walls and roofs, natural convection, and the heat-storage capabilities inherent in windows and walls. A number of recent publications have reviewed these designs.[8][9][10]

The simplest systems consist only of a window with insulated shutters. The shutters are opened to permit sunlight to enter and heat the house during winter days, and are closed at night to prevent heat from escaping. The shutters are closed during summer days because white or silver surfaces on their outer surface reflect the Sun's heat. During summer nights, the units open to cool the building. Several innovative techniques have been developed for controlling shutters and covers of this kind. Buildings have been designed which incorporate greenhouses into the southern wall. Designers of one such system, located on prince Edward **Island, Canada, claim that** their building re**mained at a comfortable** temperature throughout the severe winter of 1976-77 without using backup heating systems.[12]

Two slightly more elaborate techniques involve the use of "thermosyphoning" and thermal masses. The "thermosyphoning" systems use natural or forced convection to heat building air in walls, ceilings, or window surfaces heated by the Sun.[13] A variety of techniques have used solar radiation for heating a mass with large heat capacity via sunlight, and using direct radiant heating from these masses after the Sun sets. The thermal mass can be nothing more than a dark wall or floor made of thick masonry, stone, or adobe, or a water tank integrated into the wall or floor. The system designed by Steve Baer of the Zomeworks Corporation uses cylinders of water to provide the thermal mass.[15]

A system which has become known as the "Trombe-wall" collector (after Felix Trombe, a French designer who has designed several such structures since 1967) is illustrated in figure VII I-2. Figure VII I-3 shows a house in Maryland which includes a Trombe wall, The owners estimate that the passive solar system added approximately $2,500 to their construction costs. The device is expected to provide about 50 percent of the building's heat requirements.

The Trombe wall is essentially a vertical hot air collector which uses a thick wall both for a receiver and a storage system. The air can circulate with natural convection or with a fan. In most climates, the performance of the system is improved if adjustable vents are installed over the open-

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[8] B Anderson, (Total Environmental Action), *The Solar Home Book,* Cheshire Books, Church H Ill, Harrisville, N H 1976

[9] Leek le, et al , *Other Homes and Garbage Designs for Self-Sufficient Living,* Sierra C lub Books, 1975

[10]$ Alamos Scientific Laboratory *Passive Solar Heating and Cooling Conference and Workshop Proceedings,* LA-6637-C, May 18-19, 1976

[11] Bruce Anderson, *Solar Energy Fundamentals in Building Design.*

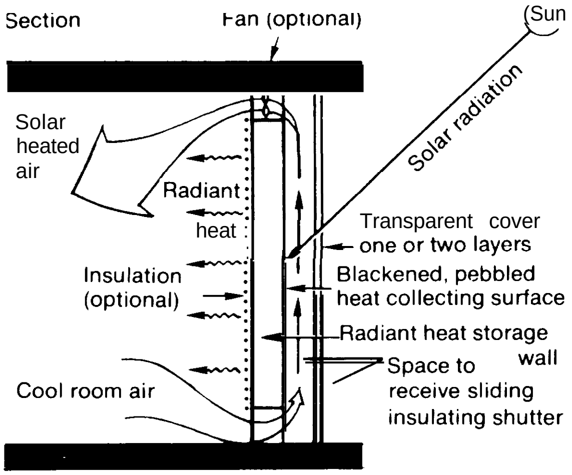
[12] J Todd, et al , *The Journal of the New* 4/chemists, New Alchemy, Woods Hole, Mass , spring 1975

[13] T Price, "Low-Tee h no logy Solar Homes that Work with Nature," *Popular* Science, Times Mirror Magazines, I nc , December 1976, pp 95-98, 143

[14] S Baer, *Sunspots,* The Zomeworks Corporation (1975)

[15] M J H arisen, "The Benedictine Monastery, " *Solar Age,* October 1977, p 24

Figure VIII-2.—The Operation of the Trombe-Wall Collector/Storage System



SOURCE: Trombe, F. et al., Concrete Walls to Collect and Hold Heat, *Solar Age*, August 1977, p. 13.

ings which connect the collector airspace with the interior of the house.[16]

The response of walls of various thickness is illustrated in figure VI I I-4, The ability of the thermal mass to average the external temperatures is clearly illustrated. Analysis of the many varients of this system which are possible have just begun, and an analysis of the economics of the systems is difficult because of the scarcity of consistent cost information and the small number of systems which have been adequately instrumented.

The "Skytherm" house in Atascadero, Cal if., uses water beds covered by removable insulating panels on the roof of a building. During the winter, the panels are automatically removed during the day, allowing the water to be heated and replaced at night. Heat is provided to the living areas by direct radiation through a metal ceiling

Figure VII I-3.—A House Using a Trombe-Wall Collector Located in Eastern Maryland

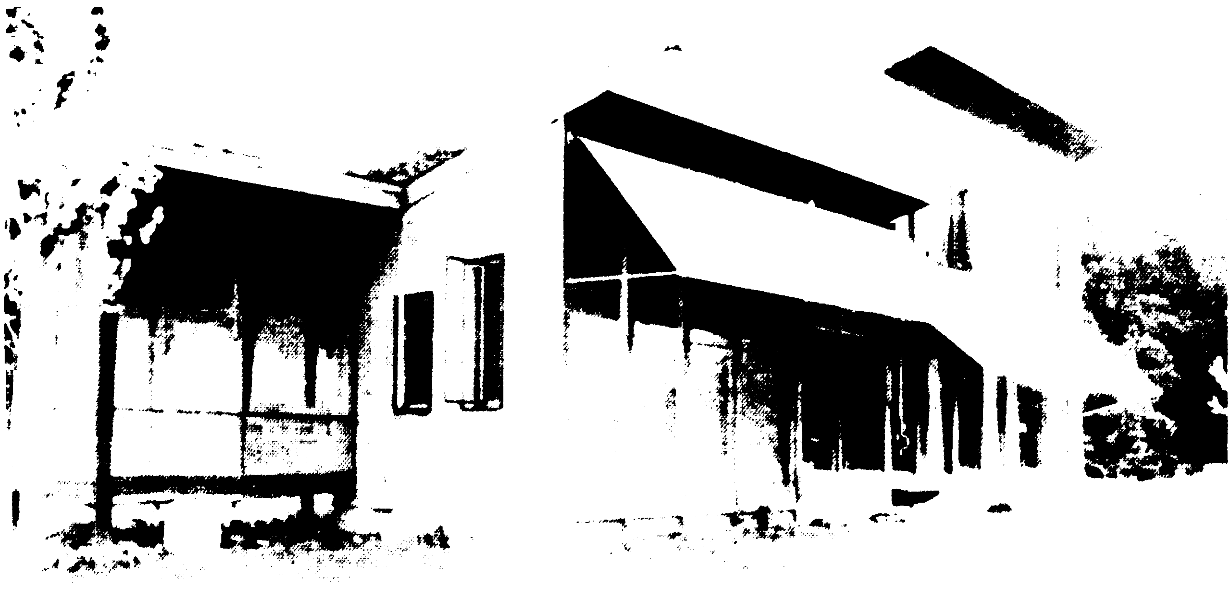


PHOTO Courtesy of Andrew M Shapiro, "The Crosley's House—With Calculations and Results," *Solar Age*, November 1977, p 31

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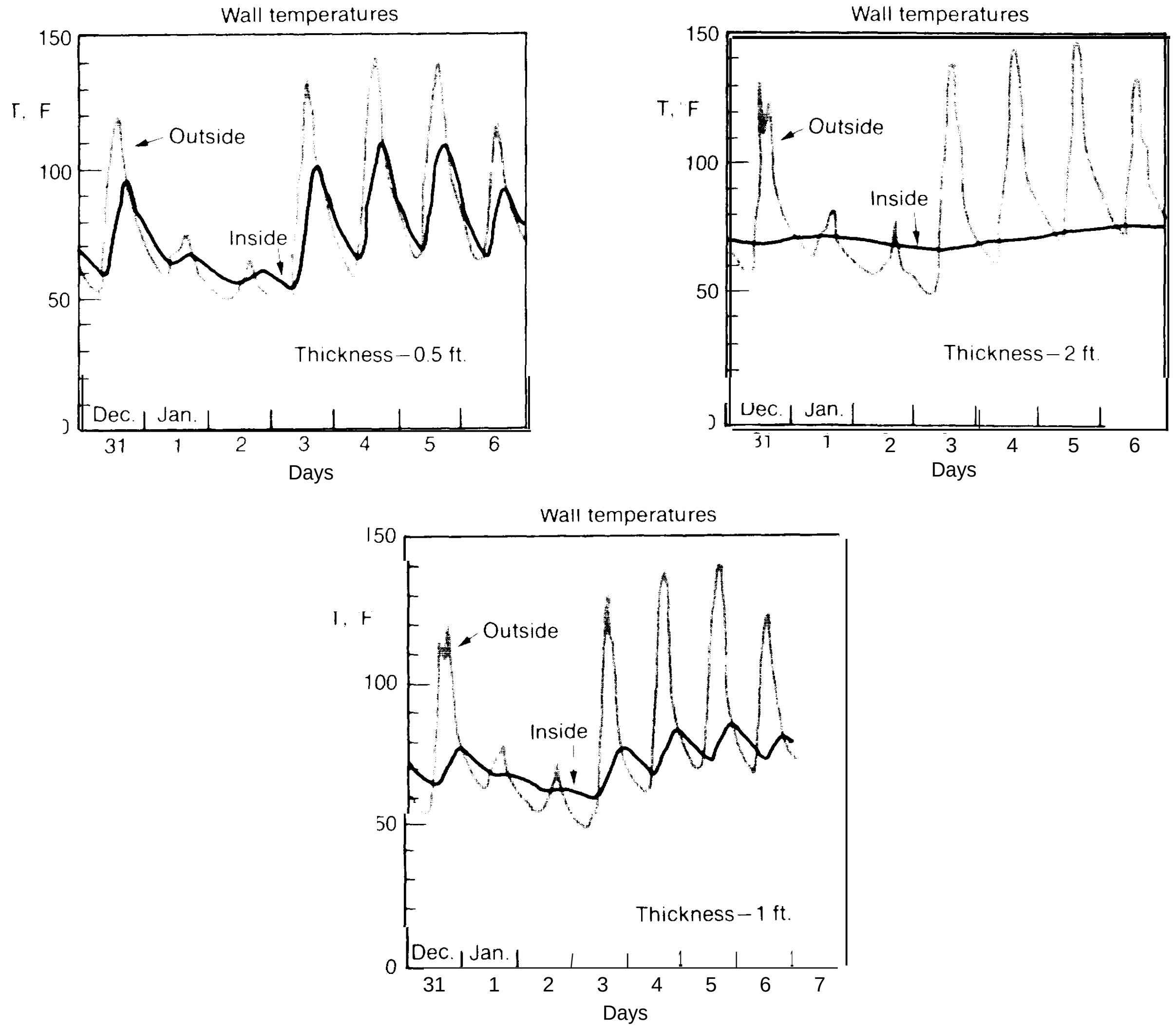
[16] J D Balcomb, et al , "Thermal Storage Walls for Passive Solar Heating Evaluated, " *Solar Age*, August 1977, p 22

Figure VIII-4.—The Temperature Averaging Effects of Masonry Walls of Various Thickness



SOURCE Balcomb, et al Simulation Analysis of Passive Solar Heated Buildings -- Preliminary results *Solar Energy*, vol 19 (1977) page 281

separating the interior of the house from the water beds. In dry climates with cool summer nights, the system can also provide cooling. Heat is radiated from the water to the sky during the night when the insulating covers are removed, and the thermal mass is used to absorb building heat during the day when the insulating covers are in place.[17] **In some** recent measurements, this house was shown to maintain an inside temperature between 180 and 240 C (65 °and 750 F) during **a** 9-month period in which the average high temperature for the hottest month was 32° C (90 °F) and the average low temperature for the coldest month was -1°C (30 °F).[18]

STATIONARY FLAT-PLATE COLLECTORS

Flat-plate collectors have been used for several decades to provide hot water in

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[17] Harold Hay, private communication

[18] Philip W B Miles, "Thermal Evaluation of a House Using a Movable Insulation Heating and Cooling System," *Solar* Energy, Vol 18, (1 976)

Australia, Japan, and Israel. Large numbers of the devices were also sold in southern parts of the United States during the late 1920's and early 1930's, but sales declined rapidly as low-cost natural gas and oil became available. In recent years, however, there has been a great resurgence of interest in the systems, and a large number of designs are being marketed or prepared for marketing. A typical installation is shown in figure VI 11-5.

The cross section of a typical collector is shown in figure VI 11-6. The fluid is heated as it is passed over or through an absorbing surface. At some additional expense, this surface can be specially designed to maximize the amount of sunlight it absorbs and to minimize its radiation at the operating **temperature of the collector.** The absorptivity of the system is high for wavelengths where the Sun's intensity is greatest and low at wavelengths where the intensity of the radiation from the heated receiver surface is greatest, A number of such "selective surfaces" are now on the market but the development of a high-performance, low-cost selective surface would be a great boon to the collector industry.

The heated surfaces are insulated on the back and sides by standard types of insulation (e. g., fiberglass), and on the front by one or two layers of glass or plastic. These transparent or semitransparent covers can also be made selective. Several common materials are nearly transparent to visible light from the Sun but absorb the infrared radi-

Figure VIll-5.— Typical Home With Solar Water Heating Using Flat-Plate Collectors

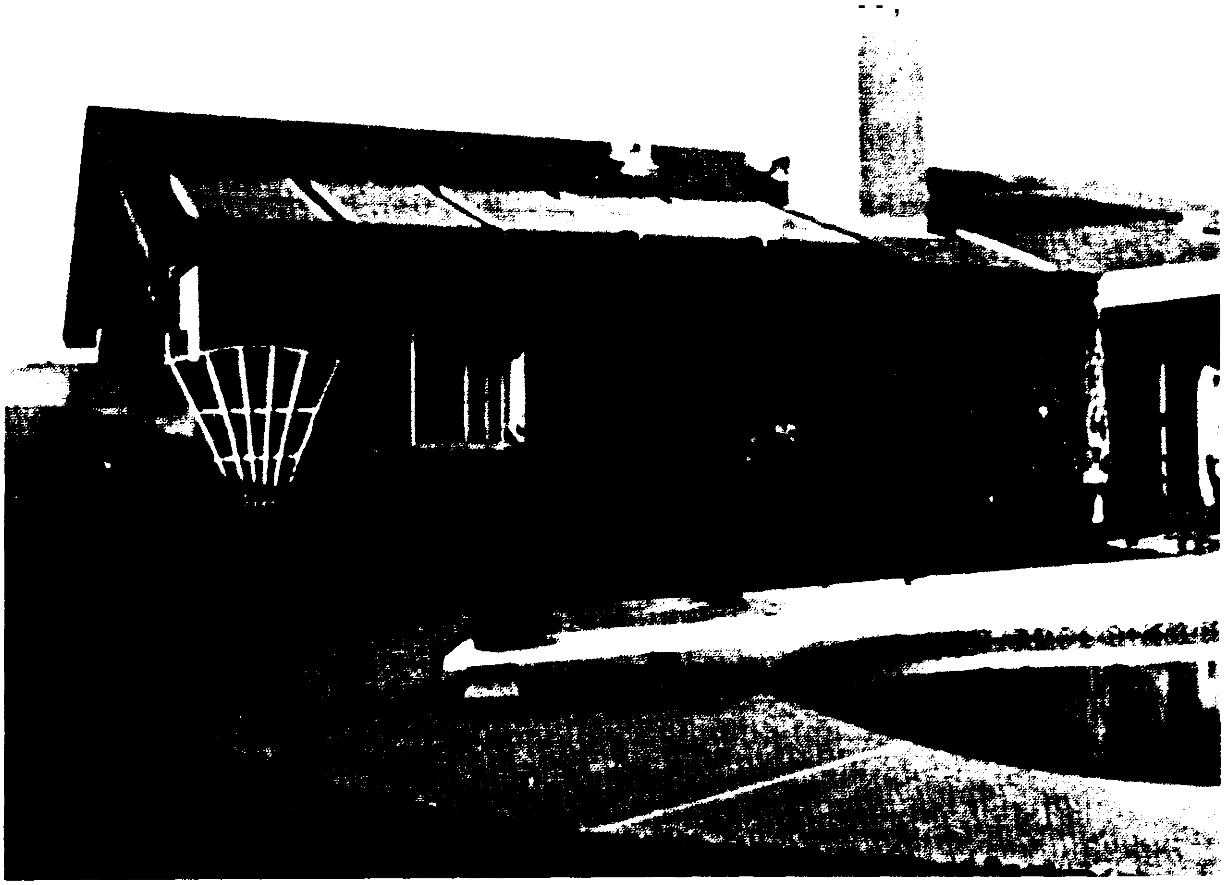
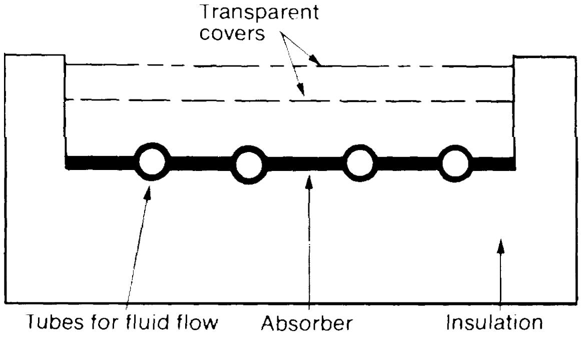


PHOTO Courtesy of American Heliothermal Corp

Figure VIII-6.— Cross-Section of a Typical Modular Flat-Plate Solar Collector



ated by the collectors. (All common glass possesses this property. This is the basis of the "greenhouse effect" which heats closed cars and rooms with southern windows.) Special "heat mirror coatings, " such as indium oxide, can be deposited on collector covers to further reduce losses Such coatings reflect the infrared radiated by the hot receiver, but permit most of the incident sunlight to pass into the collector.

Pond Collectors

Pond collectors can be used when sufficient level ground is available near a site where relatively low-temperature flu ids are required; the systems will probably be most useful when combined with long-term (6-month) thermal storage or when used for industrial-processing facilities since very little output is provided during winter months. Research on these devices has been conducted in Israel for many years. One of the first installations in the United States using such collectors was designed by the SOHIO oil company working with the Lawrence Livermore Laboratory to develop a pond system which could be used for processing uranium. Two types of solar pond collectors are shown in figure VIII-7a and VIII-7b.

The basic Livermore collector design consists of a reinforced concrete curb which forms the periphery of the pond. A layer of sand and a layer of foam-glass insulation are placed inside this curb and a watertight polyvinyl chloride (PVC) bag is placed on top of the rigid insulation. The upper cover of this bag consists of 12 mill (C).3 mm) clear PVC while the bottom layer is a 30 mill (0.8mm) black PVC. A single upper cover for the collector is provided by a flexible fiberglass material called Filon which is commonly used to construct greenhouses. The

Figure VIII-7a.— Pond Collector With a Rigid Cover

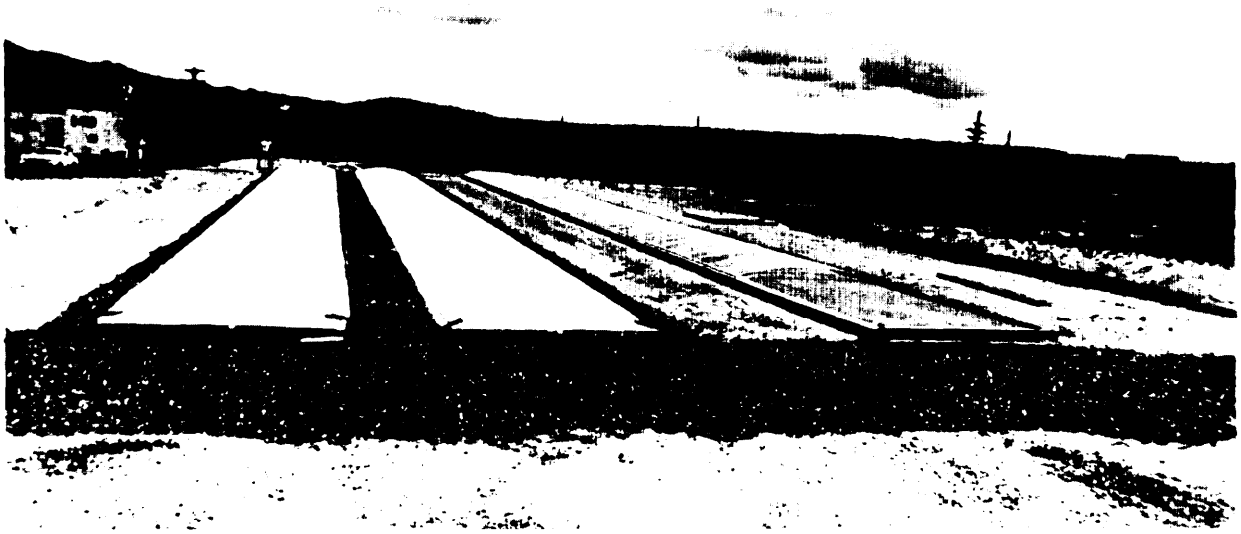
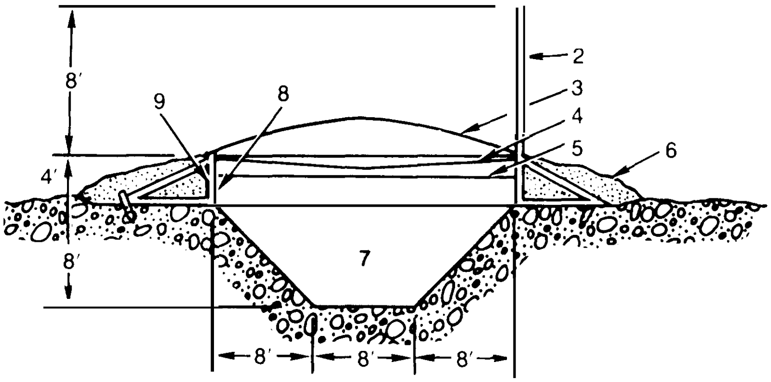


PHOTO Courtesy of University of Call fornia, Lawrence Livermore Laboratory and the U S Department of Energy

1. Polyvinylchloride Pool Liner
2. Solar Reflector (North Side)
3. Outer Glazing of Collector
4. Collector absorber Surface and Inner Glazing
5. Bead Insulation
6. Earth Berm
7. Pool Water
8. Pool Extension Wall
9. Support Structure



Source J Taylor Beard, Ibid

entire collector is inclined to provide a slope of 0.083 percent (1 inch in 100 feet) of collector length. One limitation of this design is that the thin PVC bag probably must be replaced every 5 years. It is estimated that this replacement will cost about $6/m^2$ of collector.[19]

A contracting firm in New Mexico has estimated that an 8,000 m^2 collector based on this design could be constructed for about $30/m^2.[20] (Smaller systems would, however, be considerably more expensive per unit area.) This collector is typically operated by filling the bag with water in the morning and draining the heated water in the evening, instead of flowing water continuously through the collector. It would be able to provide fluids at a temperature of about sO °to 600 C during the summer and about 300 to 350 C on sunny winter days, If a second cover is added to the collector (at a probable cost of less than $5/m^2) the devices should be able to provide fluids at about 900 C. PVC bags could not be used at these temperatures, however.

A **number of improvements to this basic design are being investigated.** The Teledyne-Brown Company has proposed replacing the concrete curbing with an extruded aluminum frame which could be assembled rapidly on simple footings. This design would also permit rapid replacement of the plastic film materials.[21] A number of plastic materials are being examined which would improve on the performance of the PVC systems used in the experimental systems. Polybutylene (which is used for "boil **in the bag" processed** foods) can be extruded into a thin (5 mill 0.1 mm) bag, saving material costs and permitting operation at higher temperatures. A du Pont plastic called Hypalon can be used to provide a back absorbing surface for the collector which would probably last 10 to 20 years.

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[19] Alan Casamajor, Lawrence Livermore Laboratory, private communication, November 1977

[20] Ibid

[21] Dr Gerald Guinn, Teledyne-Brown Company, private communication, November 1977.

Two systems **which use a pond collector combined with a thermal storage pond have been built and are currently being tested in Virginia[22][23] (figure** VIII-7). In one design, the storage system is simply a trough in the ground lined with a plastic swimming pool liner, The trough is filled with water and covered with a foot of styrofoam beads to provide insulation. The thermal losses from such a pond should be acceptable, even without insulation under the pond. The collector is a modified Thomason trickle collector placed over the floating beads. The top cover is a flexible plastic (Monsanto 602) supported by air pressure from a small blower. The pond uses a reflector along the north side to enhance its performance.

A similar, but somewhat larger pond collector/storage system (1,340 ft^2, 80,000 gallons) has been built to heat a well-insulated 5,000 ft^2 home in Stanardsville, Va.[24] This system, which cost $6,000, is expected to provide all of the heating needs of the house. A unique radiant heating system is used which permits the use of water only 50 to 100 F warmer than the room temperature for heating purposes.

Pond *collectors* provide a smaller fraction of their output during winter months than tilted collectors since the winter Sun is low in the sky. For conditions typical of many solar heating systems, the output occurring during the coldest 6 months of the year is only 5 to 16 percent of the total annual output. (See table VIII-13 at the end of this chapter.) As a result, the attractiveness of ponds used for heating would be greatly increased if a low-cost technique for storing energy generated by the pond during the summer is developed. It is possible to build the collector on top of a pond.

Flat-Plate Collectors Assembled Onsite

Thomason.–One of the oldest and simplest solar liquid collector designs used for heating buildings is the "Solaris " system designed by Harry E. Thomason. The first system was installed in a suburb of Washington, D. C., in 1959. In this system, water is pumped to the roof ridge and trickled down channels of a black-painted, corrugated-aluminum absorber. The heated water is collected in a gutter at the cave. A single glass cover is used. The system can only produce fluids with temperatures in the range of 300 to 500 C. Special ductwork is required in the houses employing the system, since relatively large amounts of air must be moved through the house; the air used to heat the house is cooler than air typically used in forced-air heating systems. Systems are sold with a 5-year guarantee. The performance of the system has been a subject of continuous controversy.

Calmac.–Another low-priced collector is the Calmac Sunmat. The absorber consists of a 4-foot-wide mat of black synthetic rubber tubes. At the building site, the mat is spread on 1-inch-thick fiberglass insulation board and glazed over with translucent plastic/fiberglass sheets. The Sunmat's nonmetallic materials have been tested up to 180° C, and the price of materials for double-glazed systems is \$35 to \$44/m^2. Assembling the system will, of course, add significantly to system costs, but the assembly is simple enough that unskilled workers or homeowners could do it. The life expectancy of the system remains to be established.

Factory-Assembled Modular Collectors

PPG.-Glass has been used longer than plastic as a flat-plate cover material, and PPG built its Baseline Solar Collector around standard, hermetically sealed, double-pane window units. PPG's collector consists of a flat, black, aluminum roll-bond absorber backed by 6 cm of fiberglass insulation. Panels are 193 by 87 by 9.5 cm (76-3/16 by 34-3/16 by 3-3/4 in) and weigh 50 kg (110 lbs) empty. They are available only

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[22] J Taylor Beard, F A Iachetta, L V Lilleleht, and J W Dickey, *Annual Collection and* Storage *of Solar Energy* for *the Heating of Buildings, Annual Progress Report,* May 1976-July 1977 to ERDA under Contract No E-(40-1)-5136, Publication ORO/5136-77

[23] John W Dickey, "Total Solar Heat-Totally Non-polluting, " presented at Eleventh Advanced Seminar, Society for Clinical Ecology, San Francisco, Calif, Oct 31, 1977

[24] John W Dickey, Ibid

through distributors and contractors. PPG recommends that the collectors be used in a closed system with treated water to prevent corrosion. Collectors are sold with a 2-year warranty which excludes glass breakage. (Although the insulation is optional, that option has been assumed in the cost shown in the summary table at the end of this chapter. Other options include copper roll-bond absorbers, selective surface, and singlecover glass.)

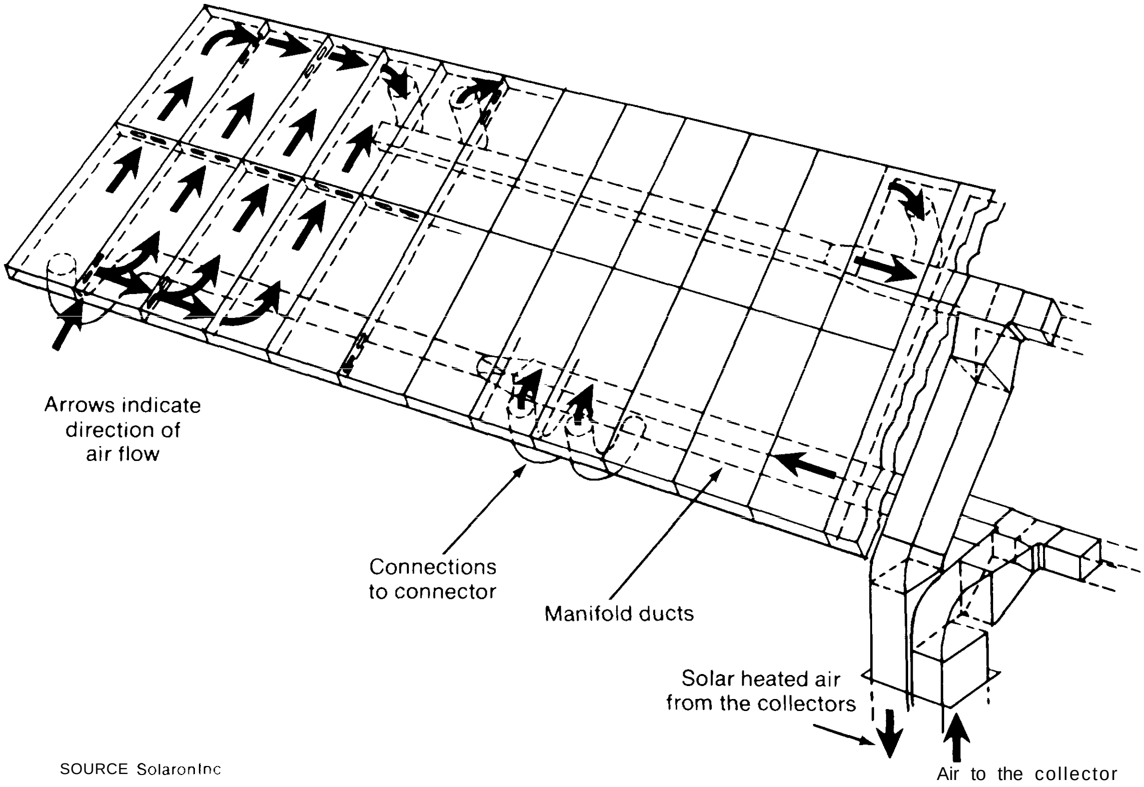
Sunworks.–Sunworks sells a selective-surface collector with a single glass cover for $84 to $114/m2. This design can achieve efficiencies comparable to those of double-cover systems which do not use selective surfaces. The absorber is copper tubing soldered to a copper sheet and treated to produce a selective surface. Because it is copper, a tapwater, flow-through system can be used. Panels measure 91 by 213 by 10 cm (4 ft by 7 ft by 4 in), and weigh 50 kg (110 lbs) empty. A 5-year **warranty is offered, excluding** cover-glass breakage.

Honeywell/Lennox.–Where output temperatures of 950 C and higher are required, higher efficiency can be achieved if a selective-surfaced absorber is combined with two covers. Lennox Industries markets a collector of this type under license from Honeywell for around $145/m2 wholesale. Two sheets of antireflection-etc heal, low-iron glass, and a black-chrome selective coating on the steel absorber are key features of the high-performance Honeywell LSC-18-I Solar Collector. Copper tubing, bonded to the steel plate, provides the resistance of copper to fluid corrosion without the expense of an all-copper system.

Panel dimensions are 183 by 91 by 16.5 cm (6 ft by 3 ft by 6-1/2 in) and dry weight is 68 kg(150 lbs).

Solaron.-The Solaron collector is an air-heating device designed by George Lof, who has been **designing solar collectors** for nearly 30 years. The device (shown in figure VI 11-8) has a steel frame insulated with 3.75

Figure VII I-8.—Typical Air Collector Installation



SOURCE SolaronInc

in (9.5 cm) fiberglass and has two 0.125 in (0.32 cm) low-iron, tempered-glass covers. The absorber is a 28-gauge steel plate with a high-absorbance ceramic enamel coating. The collector is about 65-percent efficient when the temperature of the air leaving the collector is 490 C above the ambient air temperature. 25 The company has attempted to make the collector easy to install by designing units so that they can be butted together and bolted in place without additional fittings between collectors, The wholesale price of the device is currently $1 18/m2. 2

TUBULAR SOLAR COLLECTORS

Another type of stationary collector beginning to reach the market has a tubular rather than flat-plate configuration. The heat-transfer fluid is circulated through a glass or metal tube which is enclosed in a larger glass tube The space between the inner and outer tubes is dead air or a vacuum, If a vacuum is combined with a selective surface, thermal losses are much smaller than with the conventional f tat-plate design. The tubular concept also eliminates insulation in back of the absorber. Such a collector can be lighter than the conventional double-glazed, flat-plate type,

The outer glass envelope is produced by the same machines which make fluorescent-lighting tubes. Indeed, three of the four manufacturers of tubular collectors are also major makers of tubular lamps. The fourth, KTA, is a small business which buys its tubing from a large fluorescent light tube manufacturer.

Each manufacturer boosts its collector's performance differently (figure VI 11-9). Philips of the Netherlands and KTA silver the bottom half of the glass tube. Owens-1 Illinois spaces the tubes and places a flat, white reflector behind them. General Electric also spaces the tubes, but puts a reflective trough behind them. KTA does not evacuate the outer-glass tube, but covers the array of tubes with a plexiglass cover which serves both to reduce heat losses and protect the tubes. Owens-1 Ilinois, KTA, and General Electric apply a selective surface to the absorber while Philips applies a selective heat mirror of indium oxide to the outer-glass tube.

CONCENTRATING COLLECTORS

Nontracking Concentrating Systems

Boosted Flat Plates.–The simplest concentrator is the boosted flat-plate collector. One or more flat mirrors are mounted so that they reflect light onto a flat-plate collector most of the time. The rows of collectors run east to west and the mirrors are between the rows, In winter, when the Sun is low in the sky, the light comes straight into the collectors, missing the mirrors. **In** summer, when higher temperatures are needed to operate absorption air-conditioning, the Sun is higher in the sky and strikes both the collector and the mirrors — thus increasing the concentration of light on the collector.

Several varients on this basic approach have been proposed, Some of the tubular collectors, shown in figure VIII-10, for example, use a stationary or cusp-shaped mirror to achieve a low level of concentration. A system proposed by K. Celchuck of JPL uses a shaped-mirror unit mounted between stationary flat plates, The mirror unit is manually I if ted and rotated twice a year to ensure maximum performance during the summer **and winter seasons**

Several recent theoretical and experimental studies of the performance of simple mirror booster systems have indicated that the output Of flat-plate collectors can be enhanced by factors of 1.45 to 1.6.2728

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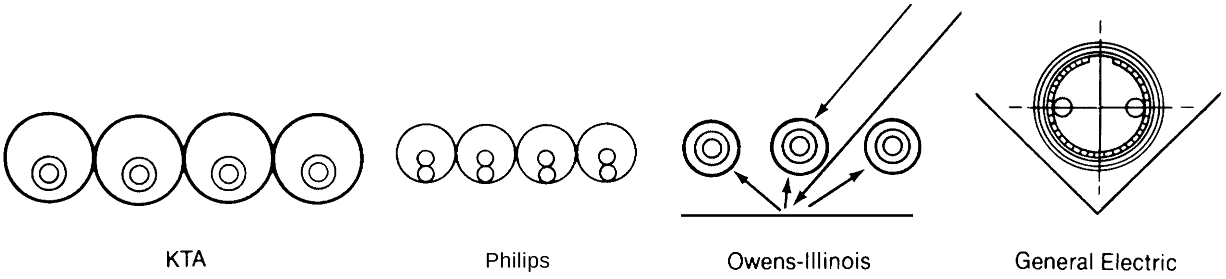
[2] 'The Solaron Corporation, 485001 ive Street, Commerce City, Colo 80022, "Technical Data, Seires 2000 Air Type Solar Collector"

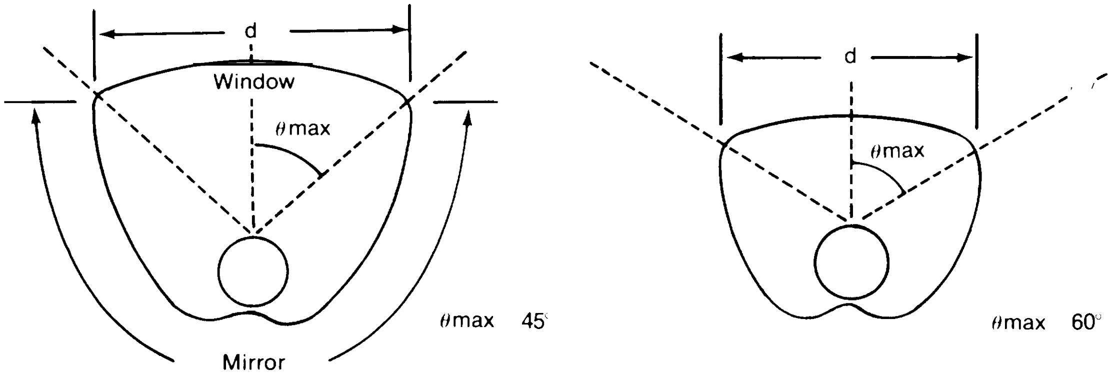
"George Lof, Solaron Corporation, private communication, November 1977

[27] A M Clausing and A L Edgecombe, "Solar Collector Cost Reduction with Reflector Enhancement, " ISES 1977 meeting, p 37-25

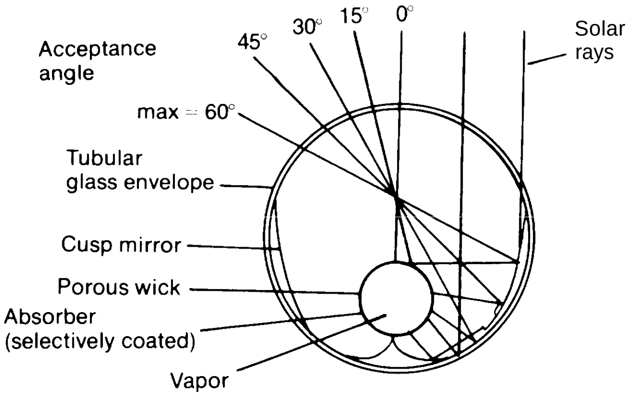
[28] R L. Reid, et al , "Measurements on the Effect of Planar Reflectors on the Flux Received by Flat-Plate Collectors," ISES 1977 conference, p 37-12

Figure VIII-9.—Various Tubular Collector Designs





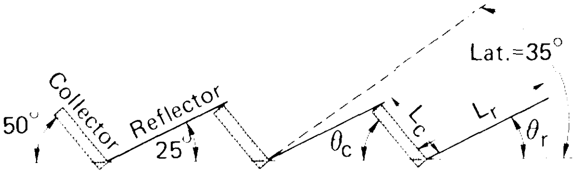
Proposed optimum cusp designs (J. D, Garrison)



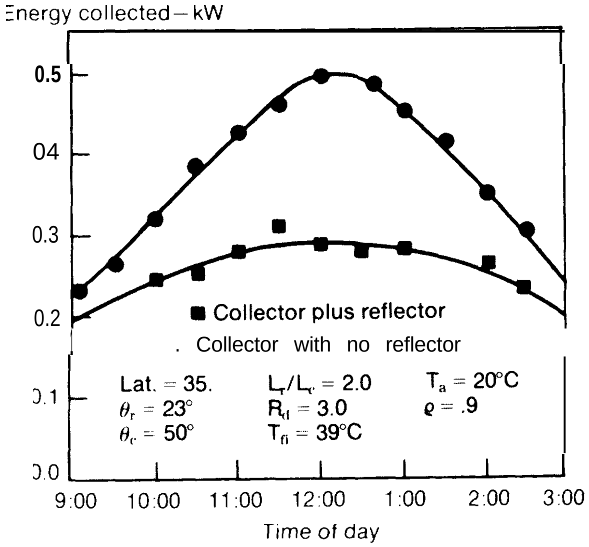
Corning Glass

SOURCES Manufacturers data
Garrison, J D 'Optimization of a Fixed Solar Thermal Energy Collector, ” Proceedings of the 1977 Annual Meeting of the American Section of the International Solar Energy Society, Orlando Florida. June 6-10 1977, p 36-15
Ortabasi, U and W M Buehl, ‘<An Internal Cusp Reflector for an Evacuated Tubular Heat Pipe Solar Thermal Collector, 1977 ISES meeting, p 36-30

Figure VIII-10.— Flat-Plate Collectors With Stationary Boosters



Prepared by OTA from data below



Actual enhancement due to reflector is 1.56. Theoretical enhancement is 1.61.

SOURCE: Hill, John M. and Edward H. Perry "Enhancement of Flat Plate Solar Collector Performance Through the Use of Planar Reflectors" Proceedings of the 1977 Annual Meeting of the American Section of the International Solar Energy Society page 37-19

Total-Internal Reflection Concentrator.–A concentrator system using a plastic doped with fluorescent dies has recently been suggested which may be able to achieve con**centrations on the order of 100 x with no tracking.**[29] [30] The dye molecule reradiates light that it absorbs at a random angle. The reradiated light striking the **receiving** surface at an angle greater than the angle of total internal reflection continues to be reflected until it reaches the edge of the sheet covered with the receiver. (The frequency of the reradiated light can be selected to optimize photovoltaic cell performance.) If the dye has zero absorptivity at the reradiated frequencies, collection efficiencies as high as 60 to 75 percent are theoretically possible using plexiglass cells 1 to 2 meters on a side,31

Compound Parabolic Collectors.-The Compound Parabolic Concentrator (C PC) collector (also called the “Winston” or “Baranov” collector) consists of a stationary reflective trough with a receiver at the bottom Each wall is a section of a parabola, and the system is designed so that all of the light received from a relatively large region of the sky will reach the receiver surface (see figure VI 11-11). Sunlight received from a solar disk which is not on the main axis of the collector, however, produces a very irregular image on the receiver and some care must be taken to ensure that this lack of uniform illumination does not create damage to the receiver. Systems with concentration ratios of 9 to 10 can be designed which are able to collect energy from the Sun’s disk for at least 7 hours each day with only 10 position adjustments per year.[32] If the system is not seasonally adjusted, useful output will be available for less than 7 hours. (A two-dimensional concentrating system has also been designed, but this system must be moved at 15-minute intervals about one axis to follow the Sun during the day.) The mirror shape developed for this design can also be used at the focus of other concentrating systems to reduce the requirements for high-tracking precision.

The CPC cuts costs by eliminating the need for elaborate tracking systems, but it uses more mirror area than a trough or dish of the same aperture because of the steep angles of its reflective sides. The CPC also uses more receiver pipes because of its lower concentration ratio. Moreover, multiple reflections inside the collector can attenuate the sunlight before it reaches the receiver, These factors considerably increase the cost of the CPC design. *inexpensive* techniques have been proposed for producing the required shape by extrusion or other shaping processes. Material costs of \$5 to \$20/m^2 appear possible for collectors

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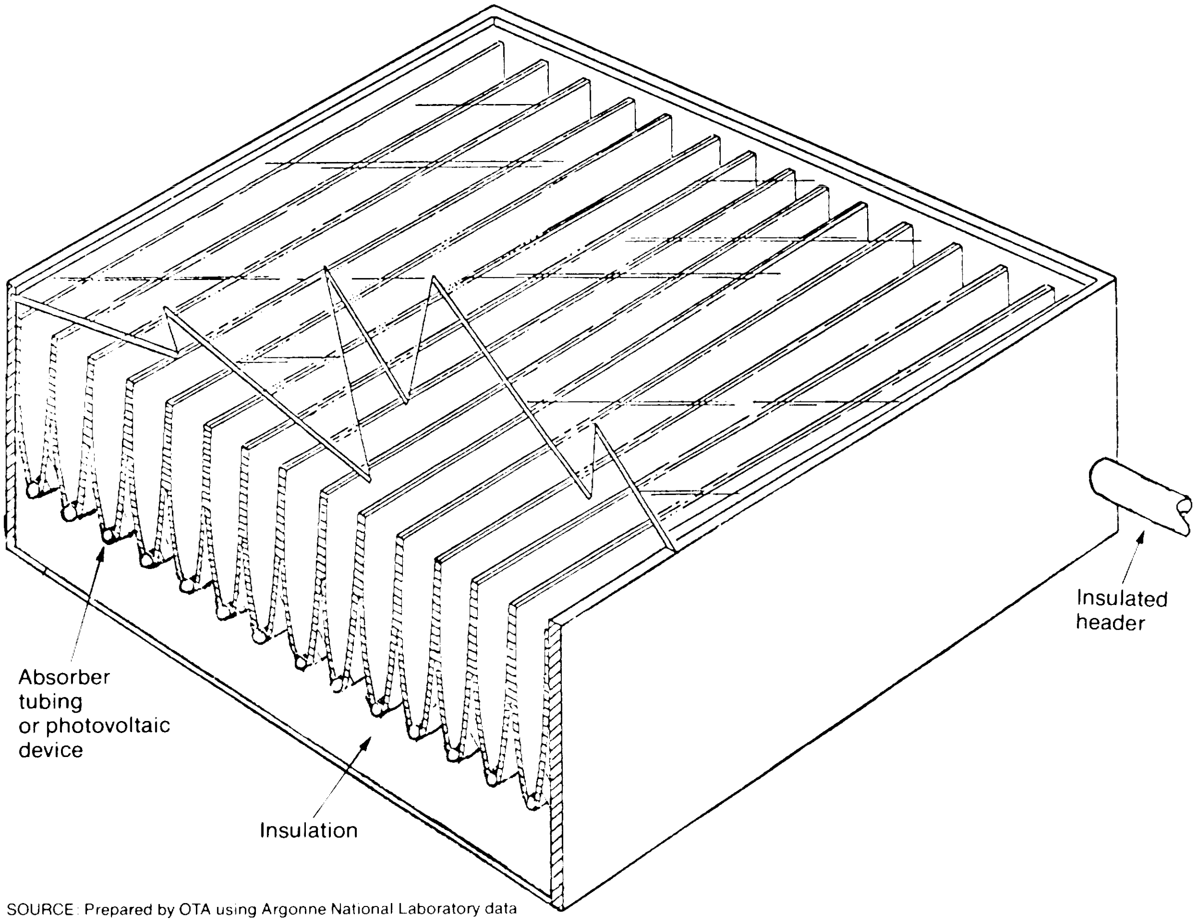
[29] W H Weber and J Lambe, Appl Opt 16, 2299 (1 976)

[30] A Goetzberger and W Breubel, Appl Phys 14, 121 (1977)

[31] A Goetzberger, op cit

“Argonne, op cit

Figure VIII-11.—One-Axis Compound Parabolic Collector



SOURCE: Prepared by OTA using Argonne National Laboratory data

used with photovoltaic systems. Fabricating costs are difficult to estimate at this point.

Active Tracking and Concentrating Systems

Techniques used to track the Sun fall into three broad categories:

1. Systems in which the concentrator and the receiver both rotate (focusing can be by means of a curved or segmented mirror or a Fresnel lens);
2. Systems in which the concentrating mirrors remain stationary and the receiver shifts to follow a moving focal point or line; and
3. Heliostat systems in which the mirrors rotate to focus light onto a stationary receiver.

ONE-AXIS TRACKING

One-axis tracking collectors concentrate the Sun's energy onto a linear receiver. They typically are capable of producing temperatures in the range of 1500 to 3000 C, and there are many different ingenious designs. One-axis trackers can either follow the Sun from east to west each day, or they can face due south and tilt up-and-down to follow the Sun. The terminology can be confusing because the axis of the east-to-west tracker runs in a north-to-south line, and the axis of the south-facing collector runs in an east-to-west line, Solar technologists usually refer to these collectors according to their axis orientations. Thus, for example, a parabolic trough concentrator which follows the Sun from east to west is called a "north-south

Figure VIII-12. —Albuquerque-Western Tracking Collectors Installed on Modular Home

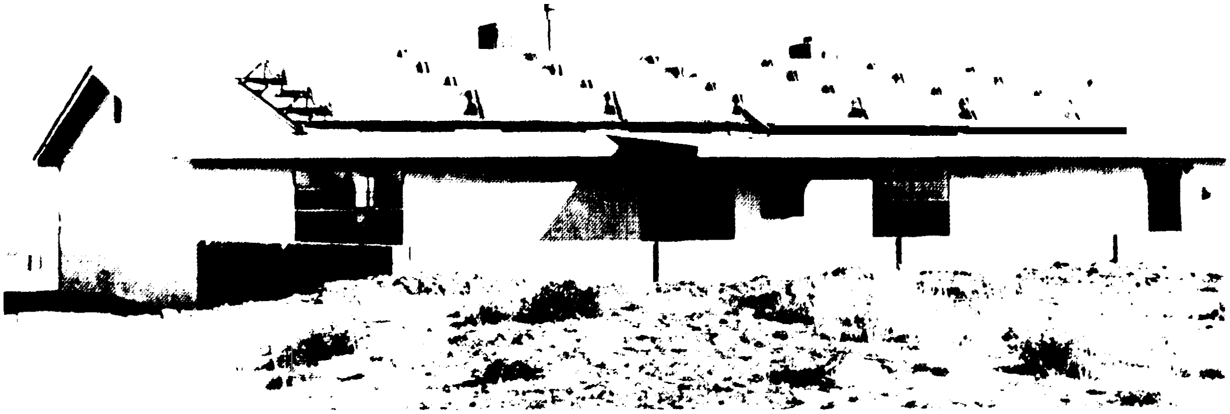


PHOTO Courtesy of Albuquerque Western Solar Industries

trough, " The "north-to-south" polar-mount collectors collect more energy than north-south or east-west troughs with horizontal axes

Collector and Receiver—Both *Tracking*

Parabolic Troughs.–Albuquerque- *Western:* Albuquerque-Western Industries, a modular housebuilder, is now producing parabolic trough solar collectors as well as complete solar heating and water heating systems. The company has installed systems on new modular houses (figure VIII-**12) and on existing conventional residences.** The collectors (including tracker) sell for $48 to $51 per square meter of aperture. This makes them less expensive than most flat-plate collectors Each trough is 51 cm wide and 2.44 m long (20 in by 8 ft) with a clear Tedlar plastic front window and a 3.2 cm (1 ,25 in) flat-black copper absorber tube inside The reflector is aluminized Mylar. The present unpressurized system is designed to produce hot water at up to 880°C , Albuquerque-Western Industries is working on an improved but more expensive collector which will produce 1500 C, enough to run absorption air-conditioning or to store more heat for winter heating, The Mylar reflector may have a relatively short life, and a new material may need to be developed; but they are designed for easy replacement on-site.

Sandia: As **part of its total energy** program, Sandia Laboratories in Albuquerque has built some high-performance parabolic troughs for use at 2300 to 3150 C. Sandia's units, like most other linear-focus collectors, may be mounted with the axis oriented either east-west or north-south. The receiver is a selectively coated pipe inside an evacuated glass tube. The cost of the system in commercial production has not been established.

Acurex: Acurex Corporation is commercially producing two models of parabolic troughs. One is a high-performance parabolic trough similar to the Sandia design (figure **VIII-13). The trough is formed by clamping** polished aluminum reflective sheets to parabolic ribs. The sheets are easily replaceable and the units collapse for compact shipping. Black chrome selective coating is used on the 3,35 cm (1.3 in) diameter stainless steel absorber pipe which is inside a 5.08 cm (2 in) diameter glass tube (not evacuated). The absorber tube is specially designed to increase heat transfer to the fluid. Each trough is 3.05 meters long and 1.83 meters wide (10 by 6 ft), and eight troughs (end-to-end) can be driven by each

Figure VIII-13.—Acurex Parabolic Trough

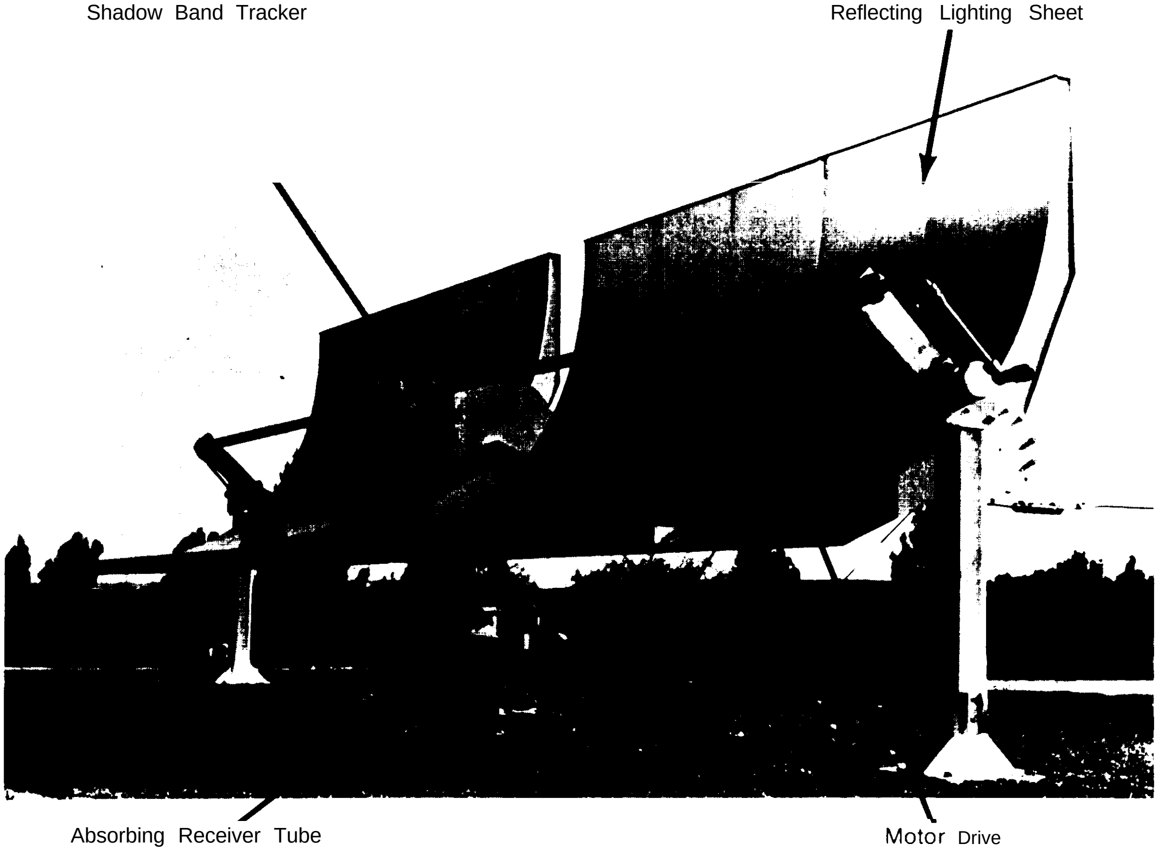


PHOTO Courtesy of Acurex Corporation, 1977

tracker unit. The receiver pipes of the eight collectors attach directly to one another, eliminating much interconnect piping and reflector end losses. The other trough design is basically similar but is designed for use at lower temperatures (less than 1800 C). It is only 4 feet wide and the absorber tube is uncovered. In a recent contract, Acurex sold 625 m^2 of its collectors to New Mexico State University for $156/m2.

Solartec: Solartec Corporation is producing a 44X concentration parabolic trough which heats pressurized water or other fluids to over 200° C. Each 1.22 by 3.05 m (4 by 10 ft) trough has an aperture of 3,4 m^2 and weighs 25 kg. The 2.54 cm (1 in) hard copper absorber pipe has a selective coating. A smaller pipe within the absorber pipe improves fluid heat transfer by increasing the flow velocity, The mirror is presently coated, anodized, polished sheet aluminum, but other material may be used in the future to achieve better reflectivity. There is a 2-, 5-, and 10-year limited warranty on moving parts, reflectors, absorbers, and framework, respectively.

Beam Engineering: Beam Engineering makes a sheet aluminum parabolic trough very similar to the Albuquerque-Western trough, except that each Beam trough is smaller and has its own tracker (figure VI 11-14). Costs are considerably higher but Beam feels that large orders and the use of fewer trackers could lower prices significantly. Each collector is 1.83 m long and 0.51 m wide (6 ft by **20** in) with a replaceable clear Tedlar front window and a 5.08 cm (2 in) black-copper absorber tube.

Linear Fresnel Lens.–A linear Fresnel lens of extruded acrylic plastic forms the focusing

Figure VIII-14.— Beam Engineering Parabolic Trough on a Polar Mount

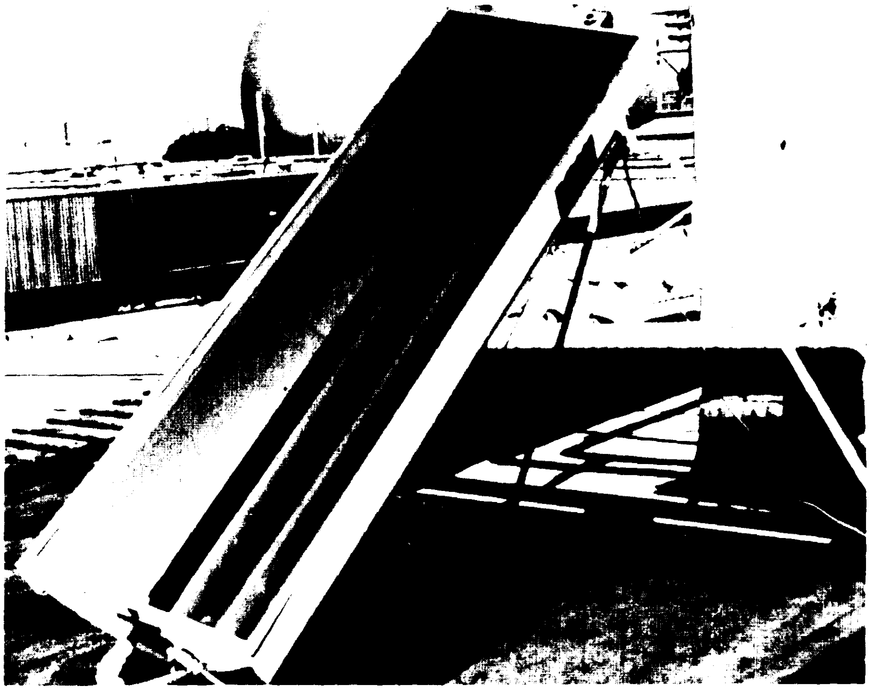


PHOTO Courtesy of Beam Englneenng

element of the Northrup concentrating solar collector shown in figure VII 1-15. Northrup Inc., a Texas Company whose principal business has been manufacturing heating and cooling products, has invested nearly $250,000 developing this unit. Several large DOE-assisted demonstration projects are using Northrup collectors. Each unit is 3.05 m long with a 30.5 cm wide aperture (10 ft by 12 in). The recommended mounting is with the axis parallel to the Earth's axis ("polar mount") and with a center-to-center spacing of 60 to 75 cm between adjacent units. One tracker drives 24 units. Northrup offers a limited warranty on all parts and workmanship of 18 months from shipment or 12 months from installation, whichever occurs first. Currently, the collectors are much more expensive than flat-plate devices capable of producing energy at equivalent rates,

Northrup is also working on a higher performance linear Fresnel collector with a greater concentration ratio and a more efficient absorber. This advanced unit will produce the higher temperatures necessary for efficient absorption air-conditioning and heat engine operation.

McDonnell-Douglas Company has developed several prototype high-performance linear Fresnel collectors under contract to the DOE/Sandia Solar Total Energy Program. Using Therminol heat-transfer fluid, the units have produced 3150 C steam. The 3.8-cm- (1 'A-in) wide absorber tube is coated with a black-chrome selective surface and placed in a glass tube to cut heat loss (figure VIII-16). The collector design is still being developed. The lenses used are manufactured by Swedlow, Inc.[33] The lenses used in the prototype were cast in one 94 by 233 cm (37 by 92 in) piece and produced a concentration ratio of 21:1 Swedlow believes that *40:1* is about the maximum practical limit

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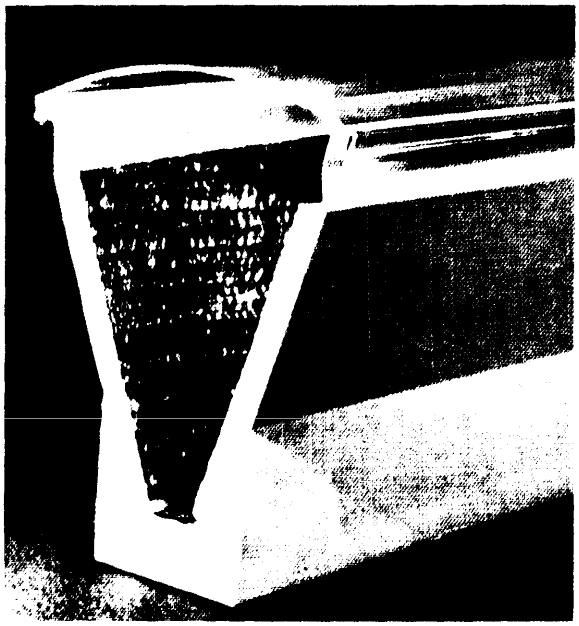
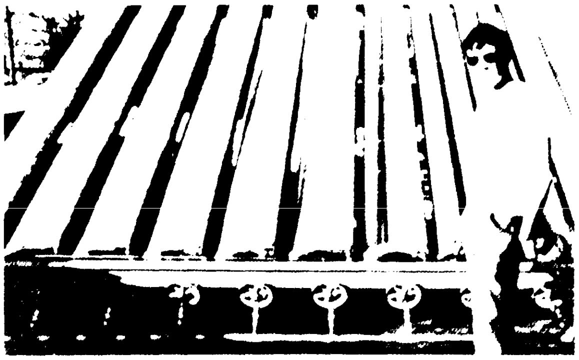
[33] W R Lee (Swedlow, Inc , Staff Assistant, Marketing Vice President), private communication, Nov 17, 1976

Figure VIII-15.—(a) The Linear Fresnel Lens and the Absorber Tube are Both Visible in This Cross-Sectional End-View of the Northrup Concentrating Collector



(b) Array of Northrup Collectors is Mounted for Polar Tracking



PHOTOS Courtesy of Northrup, **Inc**

Figure VIII-16.— Receiver Pipe Inside McDonnell Douglas Prototype Linear Fresnel Lens Concentrator

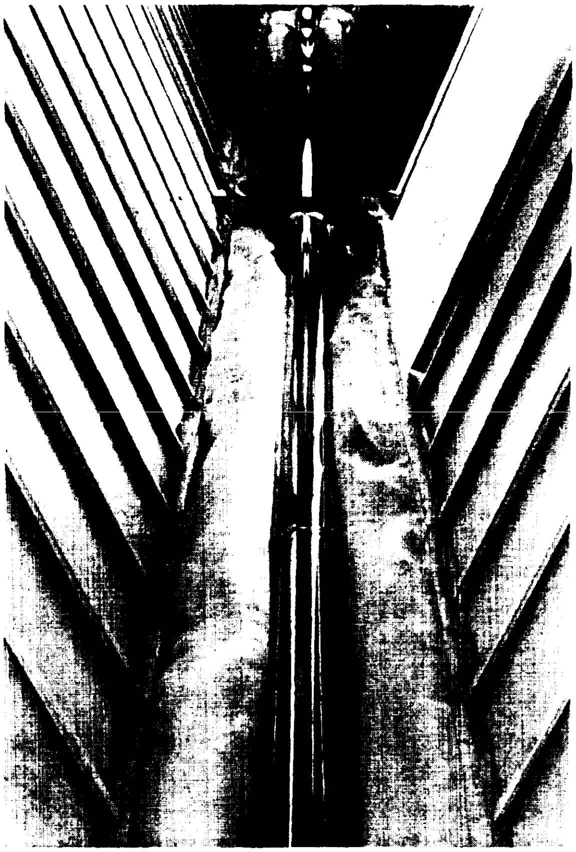


PHOTO: Courtesy of McDonnell Douglas Astronautics Co

for linear Fresnel lens concentration. More information on the Swedlow cast-acrylic Fresnel lens is presented in the discussion of two-axis, full-tracking systems.

Tracking Receiver—Stationary Mirrors

These designs give the benefits of concentration while keeping most of the collector area stationary. But since the aperture does not follow the Sun, early morning and late afternoon performance suffers.

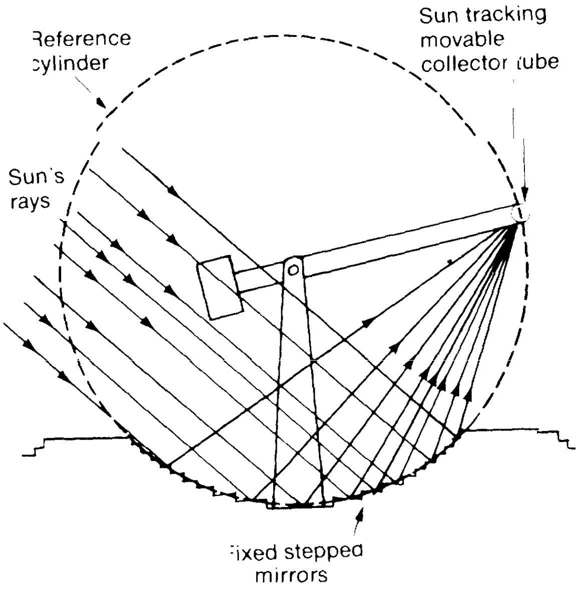
General **Atomic.–General Atomic Company has patented a design** for a trough consisting of reflective strips which can be rigidly fixed while still maintaining sharp focus (figure VIII-17). The design is sometimes called the Russell collector after one of its inventors. The troughs are oriented east to west and a glass mirror is bonded to a concrete form. The focal line moves in a circular arc as the Sun changes position, and the absorber pipe moves to follow it. The pipe is a high-performance design and may incorporate a secondary reflector to raise the overall concentration ratio to 60:1.

General Atomic hopes that this design can eventually be built to sell for less than \$65/m^2 installed after a large production industry is established but, of course, this cost has not been verified. The design is well

Suited to casting in concrete. Sandia has ordered a 7-ft-wide by 400-ft-long prototype from General Atomic being tested in connection with its solar total energy system.[34]

Scientific-Atlanta. Scientific-Atlanta, Inc., is a General Atomic licensee and is producing 2.44 x 3.05 m (8 by 10 ft) collectors (figure VIII-18). Rather than embedding mirrors in concrete, Scientific-Atlanta uses steel sheet-metal ribs on which the low-iron, back-silvered glass mirrors are fixed. The collectors bolt end-to-end to reduce optical end-losses and interconnection pipe expense The receiver is a high-performance, tubular-evacuated collector manufactured by Corning Glass Works. Scientific-Atlanta installed a 50 m^2 prototype at the Georgia Institute of Technology in 1975.

igure VIII-17.—General Atomic Distributed Collector Concept



SOURCE Nontechnical Summary of Distributed Collector Concepts ATR-76(7523-07)-1 (I) ERDA

Figure VIII-18.— Russell Collector by Scientific-Atlanta, Inc., Installed at Georgia Institute of Technology

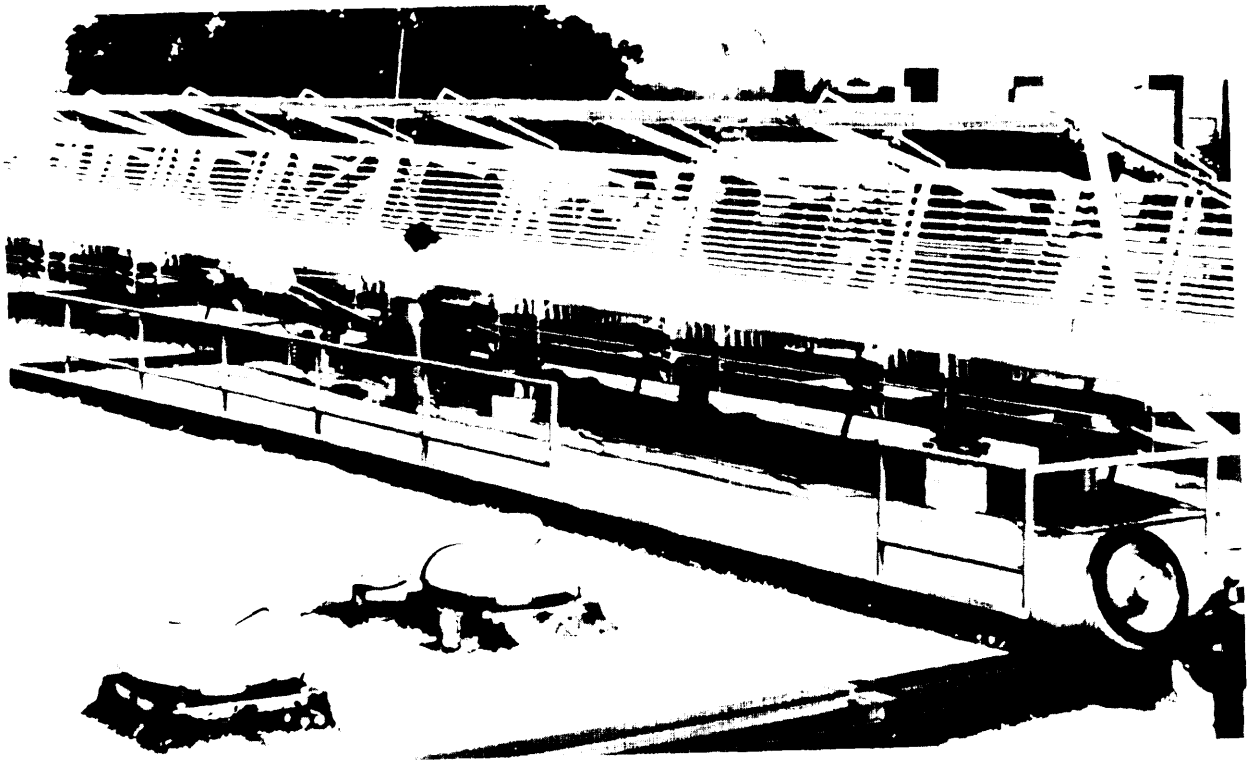


PHOTO John **Furber**

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[34] J Russel (General Atomic Co.), private communication, March 1977

AAI.-AAI is also **developing a fixed trough with a tracking receiver.** The trough has a circular cross section and the concentration ratio is 8:1. It is not designed to produce the very high temperatures of the General Atomic design. The effective cost of the system would be considerably less if the trough could be used as a part of a building roof. The axis is oriented east to west and a wide range of trough sizes is possible. The receiver is similar in construction to a long, narrow, flat-plate collector mounted upside down on long arms above the reflecting trough. The reflecting surface is glass mirror.

Linear Heliostats/Stationary Receiver

The linear-segmented reflector concept was originally suggested by Professor F. Francia and tested in 1963 at the Universite de Provence in Marseilles. ” The design has attracted the interest of several U. S. manufacturers. The basic approach is illustrated in figure VII 1-19. The receiver is fixed and the light is focused on it by an array of long, narrow mirrors which follow the Sun. The design has several advantages: the receiver pipe carrying heated liquids does not move; the moving mirrors are all relatively small; and al I mirrors are driven by a single tracker.

SunTech Systems (a subsidiary of Sheldahl) is producing a concentrator consisting of 10 long, narrow reflectors which direct the Sun onto a single stationary receiver pipe. Each reflector is 6.1 x 0.30 m (20 by 1 ft) and is slightly curved to concentrate the Sun by four times onto the absorber. This gives an overall concentration ratio of 40X. Two of these modules are placed end-to-end and driven **by a single tracker.**

This unit can withstand very high winds, and the slats are automatically turned upside down when the Sun isn't shining to prevent frost formation or snow accumulation. Sheldahl received a $176,156 ERDA contract in 1976 to develop the design. A prototype has been installed at Sandia.

Itek is doing research on a similar linear-segmented reflector. However, Itek's receiv-

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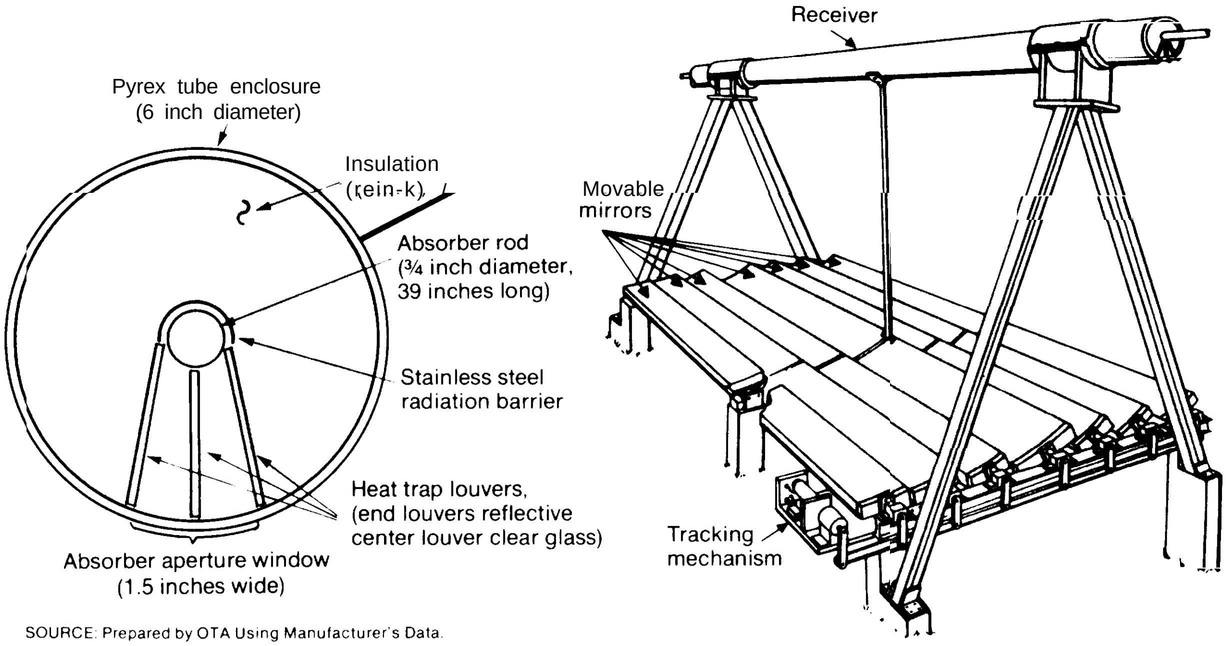
“Arrow & Francia, *Journal of Solar Energy,* Vol 11, 1, 1967.

Figure VIII-19.– ITEK Distributed Collector Concept With Inset Showing the High” Performance Receiver Design



SOURCE: Prepared by OTA Using Manufacturer's Data.

er is designed for high performance at even higher temperatures. AAI is also interested in this concept and has built a prototype.

TWO-AXIS TRACKING

Solar collectors capable of producing temperatures above about 3000 C must be able to track the Sun by rotating about two independent axes. The most common systems are the equatorial and the azimuth mount. The equatorial mount is advantageous because all tracking during the day follows one axis (parallel to the Earth's axis of rotation). The change in the Sun's elevation is only a maximum quarter-of-a-degree per day and can be compensated for by a simple adjustment of the declination axis every few days. All other tracking systems require active tracking along both axes during the day. The azimuth mount is often used because of its mechanical simplicity; this mount, for example, is used for most radar dishes and for naval artillery. The azimuth axis is vertical and the altitude or elevation axis follows the Sun's movement from horizontal to vertical.

Two-dimensional concentrators fall into three classes:

1. Systems which focus light on a small-point receiver which moves with the optical system.
2. Heliostat systems, where a large field of individual mirrors focus on a central receiving tower
3. Stationary concentrators with tracking receivers.

Collector and Receiver Both **Tracking**

Most early two-axis tracking systems used a single large reflecting dish which looked much like a radar antenna. These systems may prove to be the most attractive in applications where there is an incentive to focus large amounts of energy on a single point (e g., where a small heat engine or sophisticated photovoltaic device is employed). In many applications, however, it is possible to use a number of smaller concentrating units focusing light on a series of relatively small **receivers.** These small units typically are ganged together into a single tracking unit. Determining the optimum size of the individual concentrator device will require a substantial amount of engineering analysis for each application,

Ganged Concentrators.–Both mirrors and Fresnel lenses can be used in a ganged concentrator. Mirrors have the advantage of being less expensive per unit of aperture and do not experience chromatic aberation if used to produce high-concentration ratios. (Mirrors will probably be preferred in systems with concentration ratios greater than 500 **x).**[3]' **37** The Varian Corporation has built a two-axis tracking device using an array of 7 rows of 17 parabolic mirrors each 25 cm (10 in) square, mounted on a single tracking platform (see figure VI 11-20). Each mirror provides a concentration of 1,000 **x .**[38]

MIT and the National Patent Development Corporation are doing research on a modular, mirror-concentrater/photovoltaic system in which the separate, round, parabolic mirrors are connected to a common tracking system (see figure VI 11-21). A small secondary mirror in front of each of the main mirrors reflects light back through a hole in each main mirror onto a solar cell. This reduces any shadows from the cell and cooling water pipes. A concentration ratio of 300-500:1 is felt to be optimum. The system is designed to produce both electricity from the photovoltaic cells and thermal energy from the liquids used to cool the cells. The company hopes to be able to sell a complete system of unspecified size for less than $5,000— a system which will last at least 10 years with minimal maintenance,

Fresnel lenses have the advantage of being somewhat less *sensitive* to tracking er-

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[36] L W James (Varian), private communication, May 6,1976

“W R Lee (Swedlow, Inc), private communication, Nov 17, 1976

[38] L W James (Varian Associates, Baton Rouge, La), phone conversation, April 1976

[39] Washington Post, June 5,1976, p Al

Figure VIII-20.—The Varian Two-Axis Concentrator Using GaAs Photovoltaic Devices

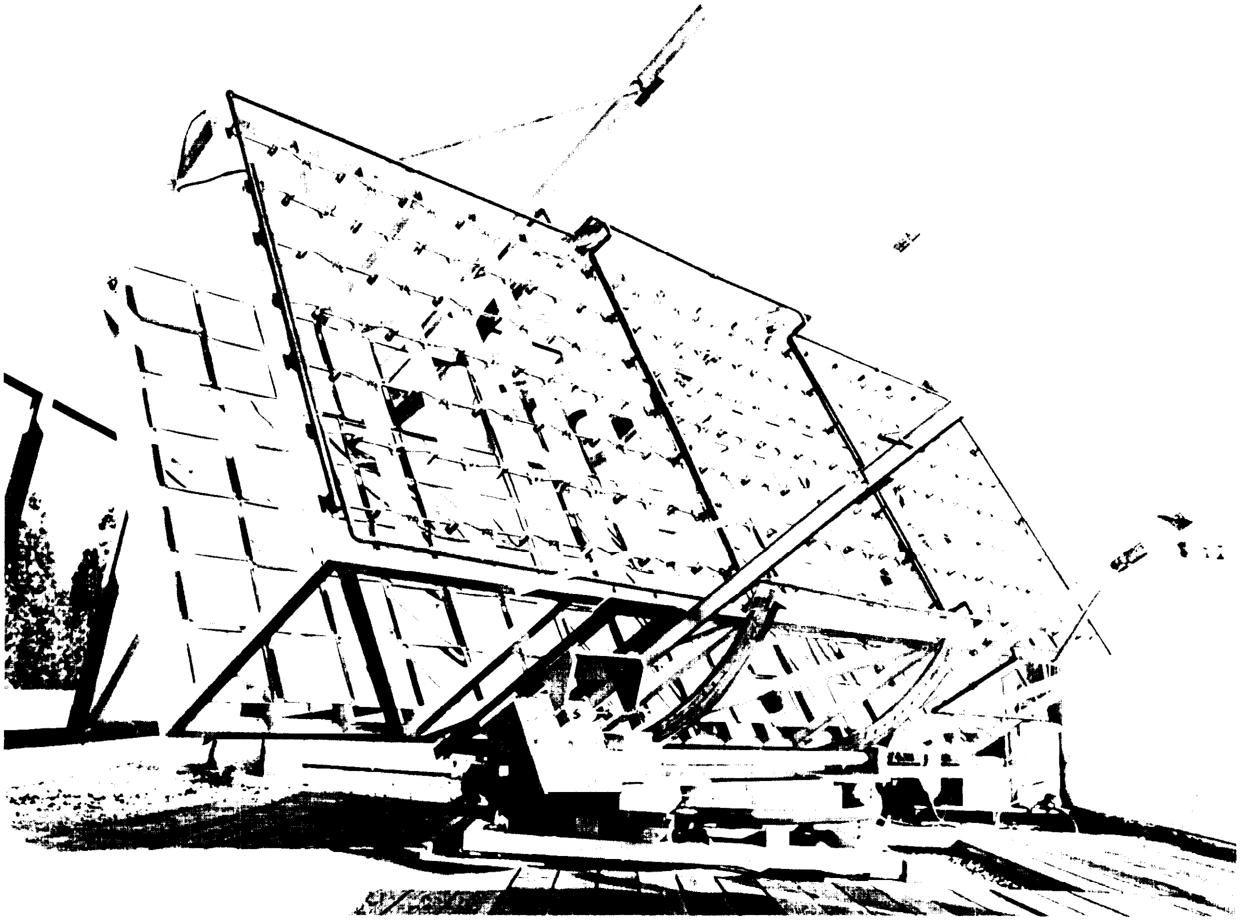

PHOTO Courtesy of The Varlan Corporation, 1977

rors than mirror systems, and they can be designed to provide a uniform intensity across the receiver surface. The lenses can be made from durable plastic materials and it may be possible to manufacture them very inexpensively in mass production facilities. The special designs required for solar applications would not add to the cost of manufacturing the systems. [40] [41]

The best material for Fresnels will probably prove to be some kind of acrylic plastic even though this material is considerably more expensive than glass. It is very difficult to cast glass with the accuracy and sharpness that is possible with acrylic, which is not as viscous as glass when it is cast, Acrylics can be made which can withstand outdoor climates for over 20 years."[42] [43] [44] Swed-

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[40] W R Lee (Swedlow, Inc), private communication, Nov 17, 1976.

[41] L. W James, et al (Varian), "Performance of a 1-kW Terrestrial Array of AlGaAs/GaAs Concentrator Solar Cells, " 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, La , Nov 15-18, 1976

[42] R P Falconer (Lectric Lites Co , V Pres), private communication, Oct 15, 1976

[43] W R. Lee (Swedlow, I nc), private communication, Nov 30, 1976.

[44] L G Rainhart and W. P Schimmel, Jr (Sandia Labs), "Effect of Outdoor Aging of Acrylic Sheet, " SAND 74-0241

Figure VIII-21.—An MIT Design for a Small Two-Axis Tracking Unit

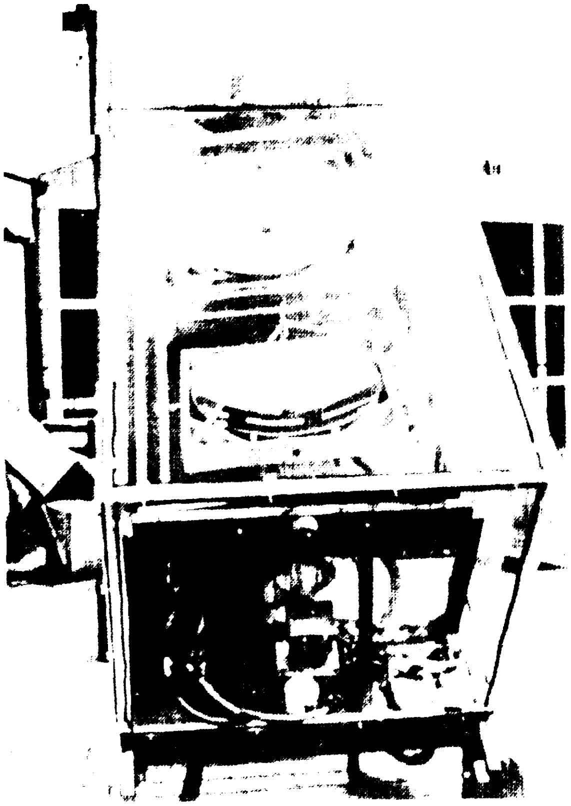

PHOTO: Courtesy of MIT, "Reports on Research," May 1976, Vol. 3, No. 8, p. 1

low, Inc., has estimated the price at which they could sell cast-acrylic Fresnel lenses at various production levels. These estimates appear in figure VIII-22. Swedlow has invested about $200,000 in solar lens research at this writing, and the firm estimates that a large-scale production line could be operating in 22 months if a decision is made to initiate manufacture. [45]

Sandia Laboratories, Albuquerque, has built a 1 kWe photovoltaic test bed using pressed-acrylic Fresnel lenses supplied by Fresnel Optics, Inc., of Rochester, N.Y. This collector consists of a checkerboard of **square Fresnel lenses mounted on the top surface of a flat box (figure VIII-23.)**

A collector using Fresnel lenses in a design similar to the MIT device discussed previously has been designed for use on an experimental basis by the RCA Corporation (see figure VIII-24). This kind of design has a relatively low profile and can be integrated into a house or building more easily than any other type of two-axis tracking system.

Large Paraboloid.-Large tracking parabolic dishes are commercially available but current commercial designs are much too expensive for any practical solar **energy system application.**

The Jet Propulsion Laboratory (JPL) of the California Institute of Technology has developed a conceptual design for a high-efficiency, low-cost paraboloidal solar powerplant (figure VIII-25). The reflecting surface is made of commercially available silvered mirrors which are curved slightly by glueing them to concave pieces of foam glass. These curved pieces are then mounted on a metal framework and all are aimed at a single focal point, The entire framework tracks the Sun.

The tracking paraboloid system is well suited for applications using a Stirling or Brayton engine and electric generator. JPL has estimated that it may be possible to mass produce and install these collectors for less than $120/m^2.[46] The mirror and foam glass surface cost about $20/m^2. This is admittedly optimistic since precision tracking radar dishes now cost about $322/m^2,[47] but the solar devices could be produced in much greater quantities and would not need to be as precisely constructed or as reliable,

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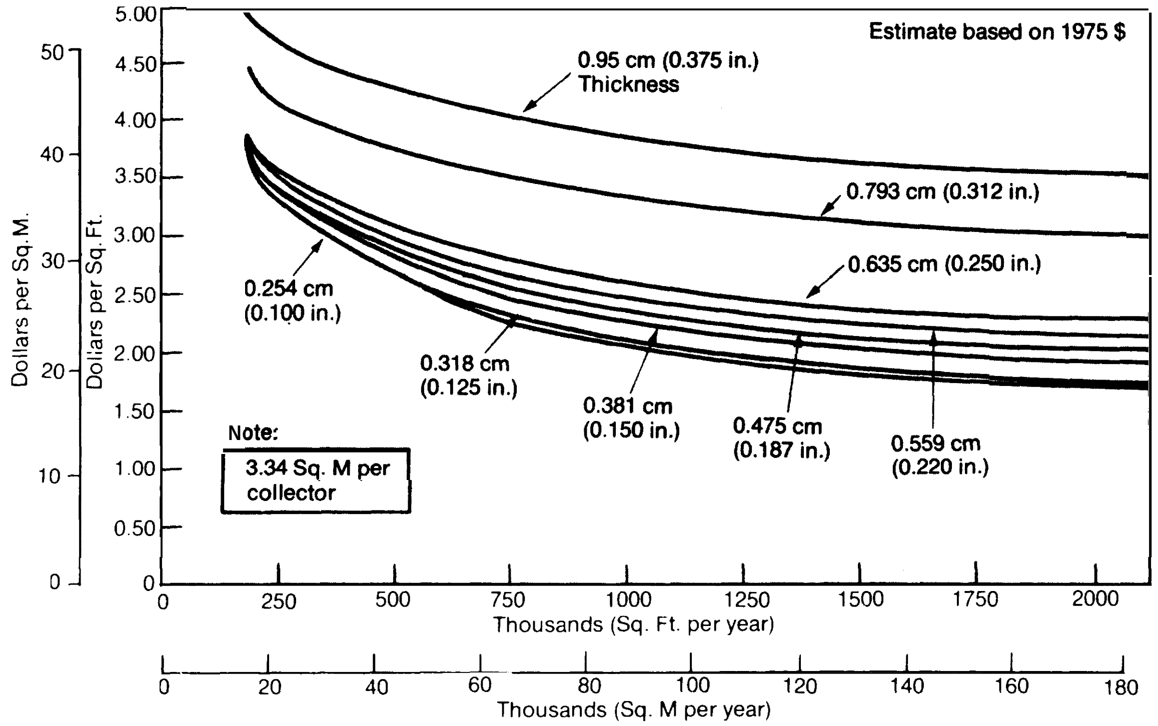
[45] W. R. Lee (Swedlow, Inc.), private communication, Oct. 14, 1976.

[46] M. K. Selchuk, et al., *Solar Stirling Power Generation: Systems Analysis and Preliminary Tests*, Proceedings of the 1977 Annual Meeting of the American Section of the International Solar Energy Society, Orlando, Fla., June 6-10, 1977, p. 20-8.

[47] Selchuk, op. cit., p. 20-9.

Figure VIII-22.—Sales Price of Cast-Acrylic Fresnel Lens Versus Production Volume



SOURCE *Unsolicited Technical* **Proposal** *for Cast-Acrylic Fresnel Lenses for Solar-Cell Energy Generator?,* Swedlow Report No 873, September 30 1976 Swedlow Inc Garden **Grove** CA pp 5-3

The **Carousel Collector. -Another approach to two-axis tracking is illustrated** in figure VI 1 I-26. **In this approach, a number of one-axis tracking parabolic troughs are mounted together in a platform which rotates to** follow the Sun. The system illustrated is mounted on tracks, but it is also possible to simply float the platform on a pond of water. ” A simpler one-axis tracking system can be manufactured along the same lines by rigidly mounting the trough **concentrators on the rotating platform.**

Heliostat/Central Receiver

The heliostat/central receiver arrangement can be scaled up to very large sizes, although small systems may also be useful. Such a system has an advantage over most distributed collector field concepts in that the energy is transmitted to the central **receiver as light rather than through an expensive piping network as heat.**

Francia Solar Heliostat Tower.–Professor Francia of the University of Genoa has had a 100 kW_t solar steam-generating station operation near Genoa (S. Ilario), Italy, since 1967 (figure VI 11-27). All of the mirrors in the field are linked together and driven by a single pendulum clock. A joint venture of ANSALDO, S.A., a large Italian industrial organization, and Messerschmidt of Germany is now selling solar steam-generating systems of Francia's design. The Georgia Institute of Technology in Atlanta bought a 400 kW_t test facility of this design from ANSALDO. It began operating on the Georgia Tech campus in 1977.[49] In addition to the innovative linked-mirror field, the Francia design appears to have an unusually

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[48] Solar Energy Digest (9)1 (1 977)

4'S H Bomar (Georgia Institute of Technology), private communication, Nov 13, 1976

Figure VIII-23.—1kW$_e$ Focusing Photovoltaic Test Bed at Sandia Laboratories, Albuquerque”
1-square Foot Fresnel Lenses Focus on 2-in.-Diameter Solar Cells

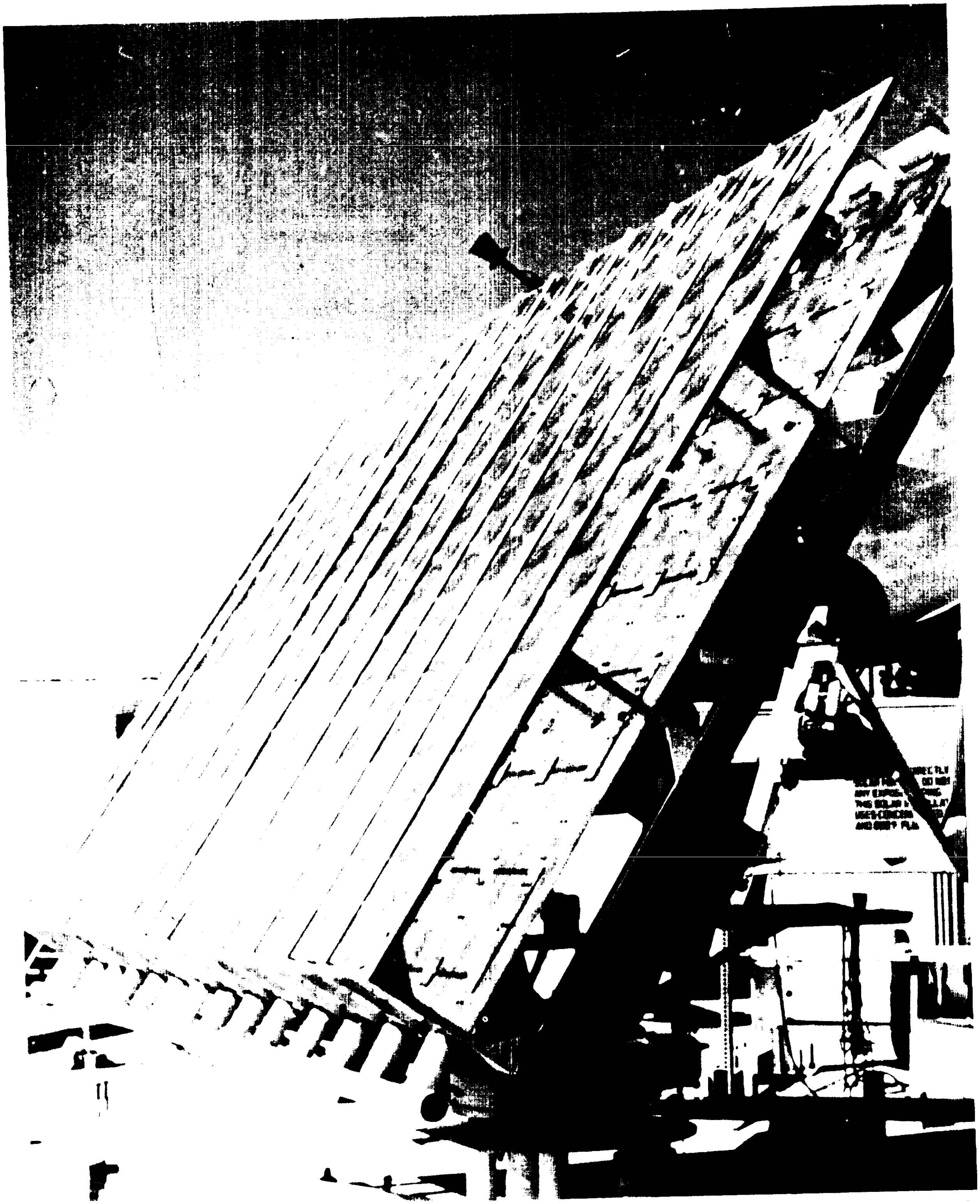


PHOTO Courtesy of Sandia Laboratories

Figure VIII-24.— RCA'S 300W_e Photovoltaic Concentrator

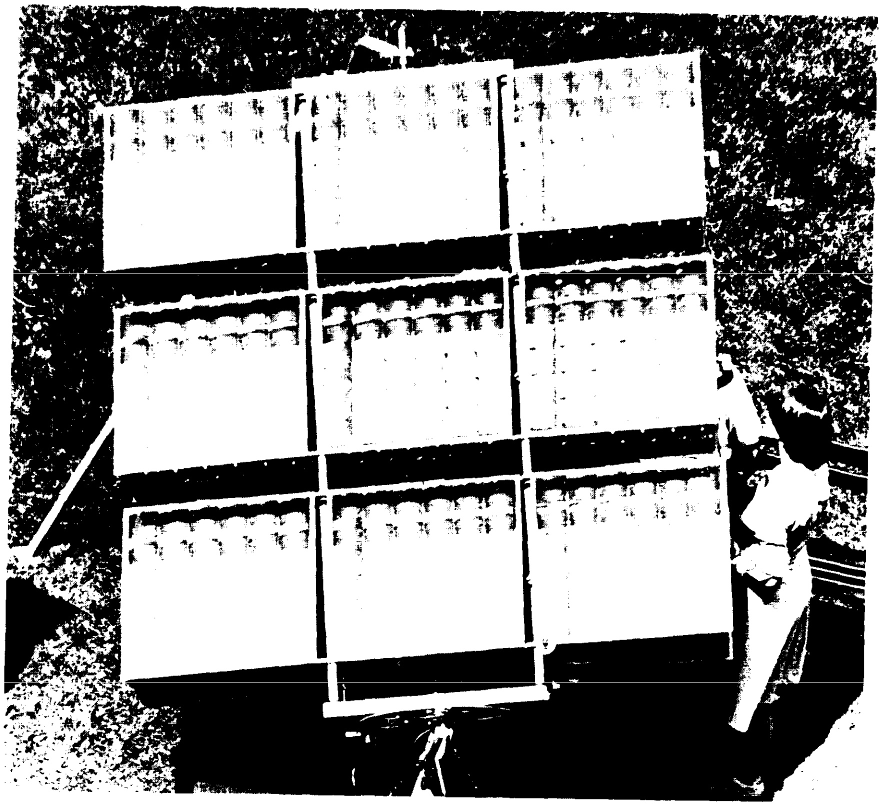
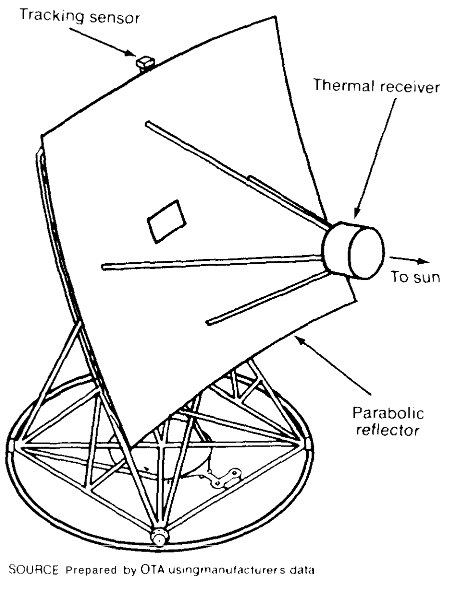


PHOTO Courtesy of RCA

Figure VI II-25 .—JPL Paraboloid Design With Stirling Engine at Collector Focus



SOURCE Prepared by OTA using manufacturers data

SOURCE Prepared by OTA using JPL Information

high thermal efficiency, Professor Francia has reported a net collection efficiency of 73 percent.[50] Analysis at Georgia Tech indicates that even better results can be obtained by using molten salt or liquid metal instead of steam in this type of receiver.[51]

Francia's design has been used by Mitsubishi Heavy Industries, Ltd., of Hiroshima to build the 7 kW_t test facility (shown in figure VI 11-28). Mitsubishi changed the heliostat design slightly. to allow the field to move its focus from one receiver tower to another. This improvement has been incor-

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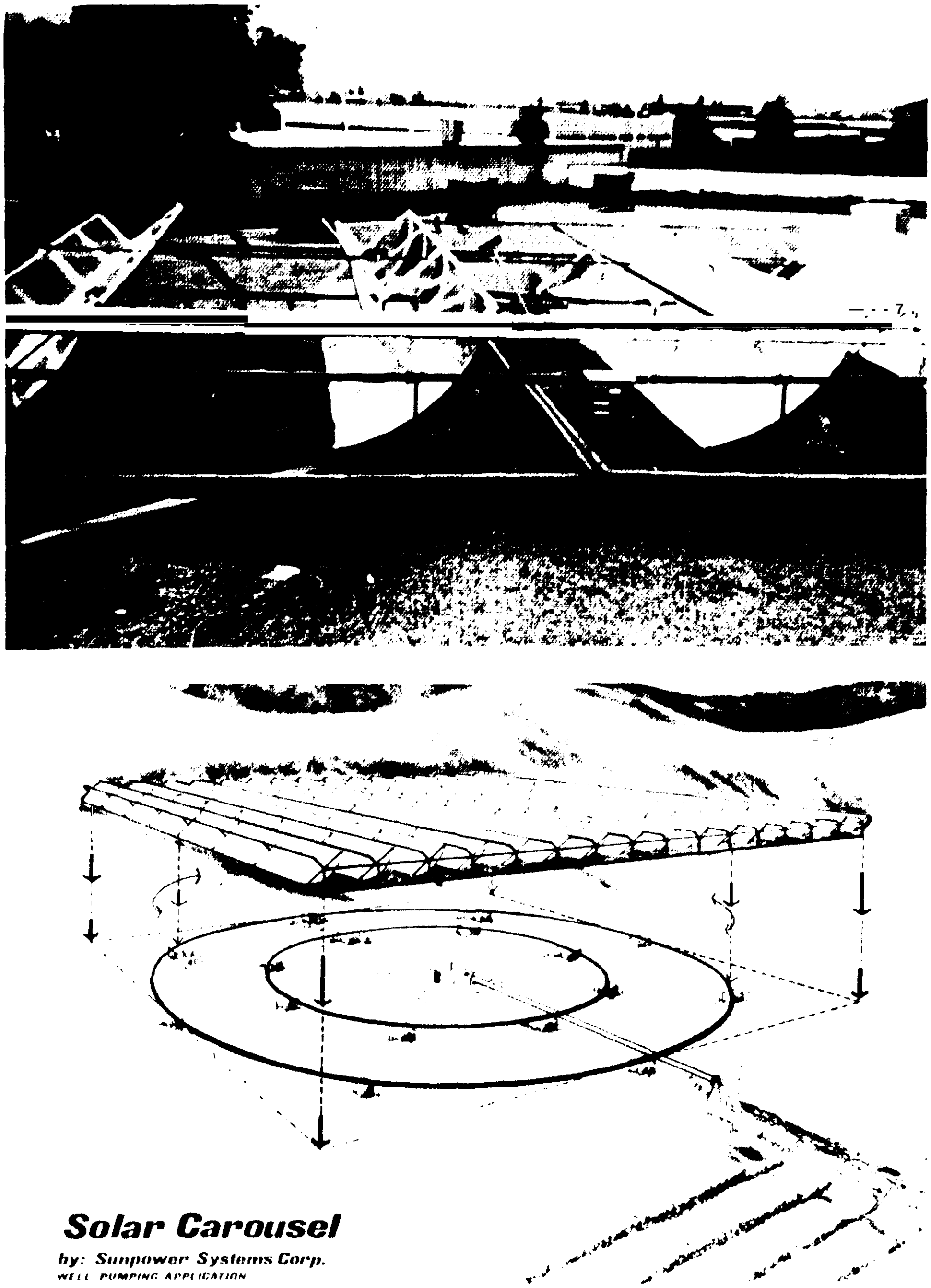
[50] G Francia, *Large Scale Central Receiver Solar Test Facilities,* Proceedings of the international Seminar on Large Scale Solar Energy Test Facilities, Las Cruces, N Mex , Nov 18-19, 1974, pp. 101-136, p 130

[51] R W. Larson (Professor, Georgia Institute of Technology), private communication, September 1976.

Figure VIII-26.— Sunpower Systems Solar Powerplant



SOURCE Sunpower Systems Corp Tempe, Ariz

Figure VIII-27.—Francia 100 kW$_t$ Solar Powerplant (Closeup of heliostats showing tracking linkage on back)

PHOTO Courtesy of Georgia Tech

porated into the test facility sold to Georgia Tech by ANSALDO.[52]

Federally Sponsored Heliostat/Central Receiver Designs.–DOE's biggest solar investment in collector development thus far has been directed to the design of large heliostat/central-receiver electric powerplants designed primarily for desert regions. A number of variations on the basic design have been funded by DOE and the Electric Power Research Institute. Present plans call for a 100 MWe **pilot plant, preceded by a 5 MWe test facility at Sandia Albuquerque and a** 10MWe demonstration plant **at Barstow,** Calif. (table VI 11-3).

Three companies designed complete systems, and Boeing contracted to design just the heliostats. The heliostats designed all have reflector areas of approximately 40 m^2, but designs differ considerably (figure VI 11-29). Boeing's design employs a thin layer of Kaptan stretched over a lightweight frame. The system is shielded from the weather with a transparent plastic bubble, The Honeywell design uses six 2.1 **x** 3.1 m (7 by 10 ft) mirrors mounted on a common turntable. The mirror mounts are aluminum "egg crate" with plastic filling, The Martin Marietta/Georgia Tech design uses 25, 1.22 by 1.22 m (4 by 4 ft) mirrors mounted on a common tracker. This array forms a crude parabola with a concentration ratio of approximately 5.3:1. The McDonnell Douglas/University of Houston design uses a single 37 m' (400 ft^2) mirror mounted on large-cell honeycomb material.[53]

The three receiver concepts also differ considerably. Martin Marietta is designing a high-efficiency cavity receiver to face a heliostat field to the north. The Honeywell receiver accepts light through an opening in its bottom, and the receiver tower is located in the center of the heliostat field. McDonnell-Douglas is designing an open panel receiver to be located slightly south of the center of the heliostat field (figure VI **11-30).**

The Department of Energy has selected the McDonnell-Douglas design for its initial 10 MW demonstration. An artist's concept of the completed 10 MW facility is shown in

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[52] G Beer and R Flores (ANSALDO S P A), private communications, Oct 28-29, 1976

[53] Data on these collectors was taken from *Survey of Several Central Receiver Solar Thermal Powerplant Design Concepts*, J PL, August 1975.

Figure VIII-28.— Mitsubishi (7 kW_t) Heliostat/Receiver Test Bed

Specifications

Energy Collected	about 7 kW_t
Mirror	0,3 x 0.4 m^2, 120 pieces
Heliostat	60 pieces
Tower Height	3m
Absorber	Cavity type 0.5 x 0.6 m^2
Heat Carrier	Air. max 800° C

SOURCE K Yanagi (Hiroshima Technical Institute Mitsubishi Heavy Industries Ltd) Solar Energy Collecting Test Apparatus

Table VIII-3.—Characteristics of Competing Designs for the 10 MW_e Solar Central Receiver Powerplant

	Boeing	Honeywell	Martin-Marietta	McDonnell-Douglas
Annual energy output (MWh)		4.3×10^4	3.4×10^4	3.6×10^4
Collector Subsystem				
Heliostat construction	metalized plastic reflector, aluminum and steel frame	glass mirror, low-profile steel frame, multifaceted, focused	glass mirror, steel frame, multifaceted, focused	glass mirror, steel frame, multifaceted, focused
Number of heliostats	3,146	2,320	1,718	2,350
Reflective surface per heliostat	29 m^2	40 m^2	37.2 m^2	30.8 m^2
Total area reflective surface	91,234 m^2	92,800 m^2	63,866 m^2	72,380 m^2
Field size		308 m radius	565 m x 565 m	527 m x 527 m
Receiver subsystem				
Receiver type		vertical cavity	horizontal cavity	external absorber
Tower height		146 m	137 m	101.4 m
Receiver working fluid		water/steam	water/steam	water/ steam
Storage subsystem				
Storage mechanism		latent heat	sensible heat	sensible heat
Storage media		salts	HITEC/hydrocarbon heat transfer fluid	rocks/ hydrocarbon heat transfer fluid
Electrical generation subsystem				
Turbine rating		15 MW	12.5 MW	15 MW
Turbine fluid		steam	steam	steam

SOURCE Department of Energy

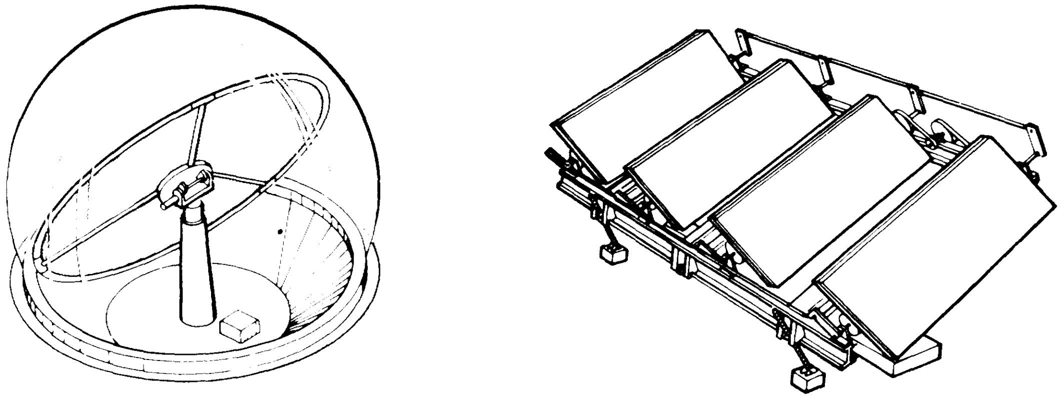
figure VIII-31, and construction of McDonnell-Douglas heliostats or a 5-MW system is shown in figure VIII-32

Stationary Concentrating Receiver

This concept uses a fixed-mirror/moving-receiver system with two dimensions of concentration. A section of a sphere made from mirror surfaces produces a radial line-focus pointing at the Sun (figure VI 11-33). Only the receiver pipe moves to follow this line of high-intensity sunlight around the inside of the stationary dish. Because the dish does not track, this system collects much less light in the early mornings and late afternoons than tracking dishes. Its success will depend on whether initial and operating costs will be sufficiently below the costs of tracking dishes to compensate for its disadvantages.

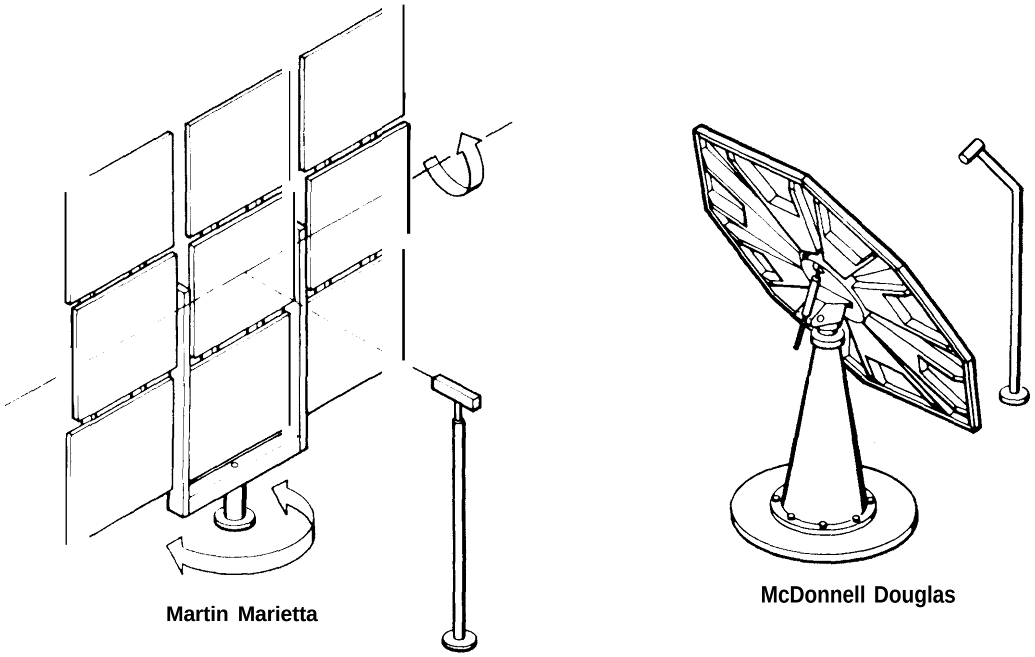
At least three organizations are currently working on this concept— Environmental Consulting Services, Inc., of Colorado, E-Systems Garland Division in Texas, and C.N.R.S. (the French national petroleum company). E-Systems is a large, high-technology company which has built and installed dozens of fully tracking parabolic communications dishes and also refinished the huge, stationary spherical radiotelescope reflector at Arecibo, Puerto Rico. As a result of the firm's experience with both types of collectors, it considers the fixed-sphere design a more economical solar collector even when the reduced performance is taken into account. Smaller collectors can be integrated into a building's roof, and larger dishes could be mounted in an excavation to serve several buildings, a factory, or a community.

Figure VIII-29.– Pilot Plant Heliostat Concepts



Boeing

Honeywell

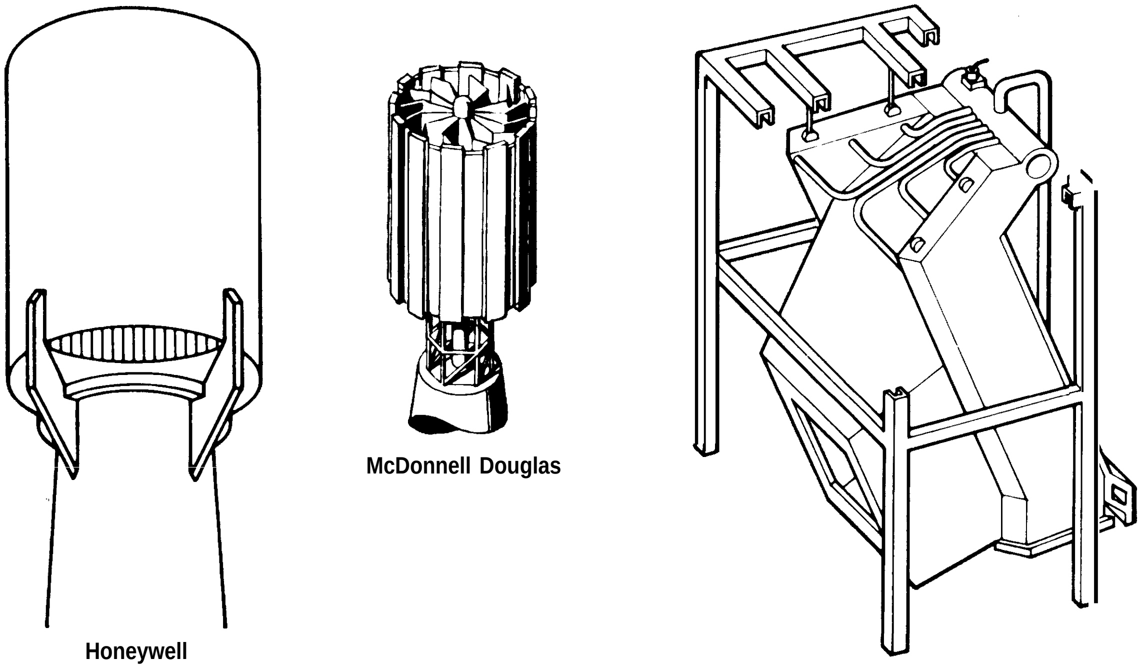


Martin Marietta

McDonnell Douglas

SOURCE Prepared by OTA using manufacturer's data

Figure VIII-30.— Pilot Plant Receiver Concepts



Honeywell

McDonnell Douglas

Martin Marietta

SOURCE Prepared by OTA using manufacturers data

Figure VIII-31.—McDonnell Douglas 10-MW Pilot Plant Design. The Heliostat Field Surrounds the Thermal Storage (Circular Tank), Tower, and Electrical Generation Subsystems. Note the Octagonal Shaped Heliostats

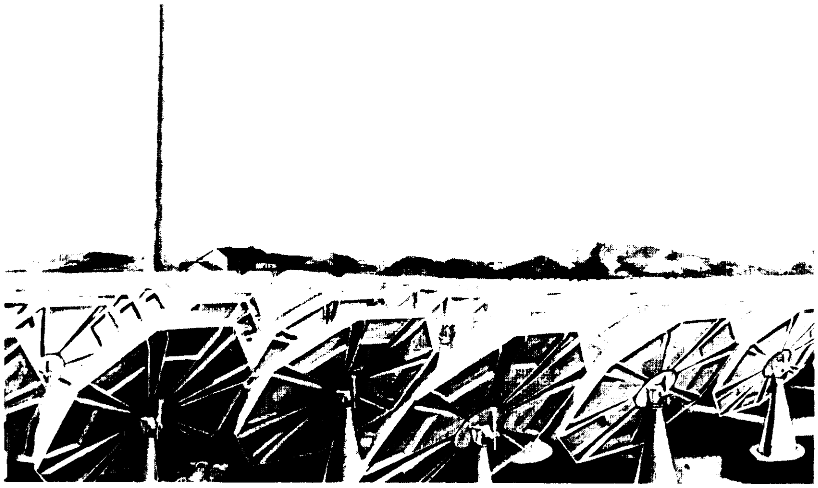
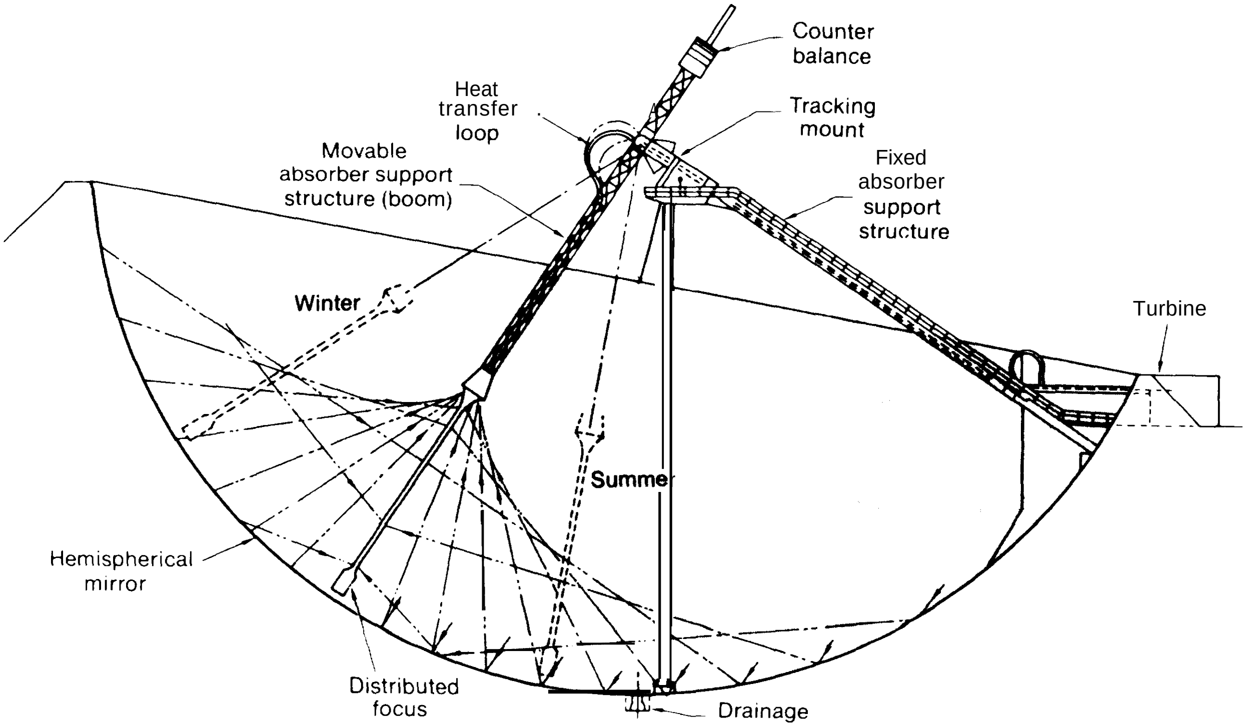


Figure VIII-32. —The 5-MW Central Receiver Demonstration Under Construction in Albuquerque, N. Mex.

Photograph by John Furber

Figure VIII-33. —Cross-Section of Stationary Hemisphere Concentrator



SOURCE E. Systems Inc

ENVIRONMENTAL IMPACTS

The two largest environmental effects of the manufacture of solar collectors result from the emissions associated with the energy generated to manufacture the devices, and the impact of the collectors on land use in cases where the collectors cannot be integrated into the roof, walls, or immediate landscape of a building. These problems are discussed in some detail in chapter VI 1. There will also be a number of occupational health and safety issues associated with the manufacture of specific collector designs,

WORKING FLUIDS

Some of the chemicals used in solar domestic water heaters to slow corrosion in the collector and to prevent the working fluid from freezing can be harmful if the collector fluid leaks through a heat exchanger and mixes with the hot-water supply. In most regions, double-wall heat exchangers are required by local codes to protect against accidental leakage when potentially harmful chemicals are used. A lethal dose of ethylene glycol which is commonly used as an antifreeze in collector fluids is about 100 gm (1.3 lb) for an average adult. About 1/2 liter (18 oz) of **the glycol-water mixture used** in typical systems would have to be ingested to obtain a lethal dose. It **is unlikely, however, that the heat exchangers would** leak so massively that undiluted collector fluid would appear in the hot tapwater without being detected. Chronic ingestion of small amounts of ethelyene glycol can, however, cause "moderately toxic systemic effects."[54]

Some of the working fluids proposed for use with higher temperature systems can also be caustic or toxic if leaks develop in the plumbing systems, but these chemicals would not come into close proximity to potable water.

Glycol and other heat transport fluids degrade, and must be replaced periodically. This disposal could also create environmental problems.[55]

MANUFACTURING HAZARDS

Many of the plastics being used or proposed for use in inexpensive solar collectors can create hazards for employees in plants manufacturing the materials, even though most of the plastics are not harmful after they are fabricated and units installed. Plastics are used in collector covers, Fresnel lenses, thin mirror surfaces, piping, and a variety of other places in solar systems. Most of these materials are manufactured in substantial volume today and the solar industry would only have the effect of increasing the number of persons exposed to any risks that may now exist. None of the materials described below are uniquely required for the manufacture of solar collectors. If it is determined that any of the materials now in use create unacceptable environmental hazards, substitutes could undoubtedly be found.

In simple flat-plate collectors, thin strips of Styrofoam or similar materials are often used as insulation or backing; these compounds contain styrine, which the EPA classifies as a suspected carcinogen. Some silicone elastomers and polysulfide-based compounds are used as sealants in solar collector units; silanes, contained in the silicone elastomers, are considered moderately to highly toxic during the manufacturing process. Organic sulfides, compounds found in polysulfide-based materials, can cause an acute reaction that could cause a person to become unconscious after one alcoholic drink.

Urethanes are contained in polyurethane foams, which are often used as insulation in

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[54] J. G. Holmes, "Environmental and Safety Implications of Solar Technologies, " ISES 1977 meeting, p. 285

[55] J G. Holmes, op. cit

plumbing connected to solar collectors. EPA suspects that urethane is a carcinogen.

The transparent covers used on flat-plate collectors are often made of acrylic plastics or plastic films such as Mylar, Tedlar, Kynar, Korad, and Teflon. Some plastics contain methyl methacrylate, which is considered to be moderately toxic by the EPA. Others contain fluorocarbons which are only slightly toxic, but can be an environmental problem. (See the discussion of fluorocarbons in chapter VI 1.)

Concentrating lenses and reflecting mirrors are generally acrylic-based plastics, which are considered moderately toxic. And coatings or encapsulant on flat-plate solar cells may be made from plastic-based films, which contain melamine, a moderately toxic material.

Vinyl chlorides are used extensively in the manufacture of a number of inexpensive collectors. Unfortunately, vinyl chlorides (along with other plastics) cause disposal problems and can be hazardous. The materials are not biodegradable, and they may produce toxic fumes if burning is used as a means of disposal. Research is underway to develop biodegradable plastics to help alleviate the plastic disposal problem.

COLLECTOR COSTS

FOB COLLECTOR PRICES

Unless otherwise noted, the collector prices cited in this chapter (including those shown in tables VII I-4 through VI 11-8) are FOB factory prices and do not include shipping or installation. Estimates of collector installation costs vary greatly (see discussion in volume **11,** chapter IV). Table VII I-9 contains an estimate of installation costs which may be obtainable in a mature market.

In a few cases involving larger systems, the companies indicated that they would install only the entire system and would not sell collectors separately, Where a price range is given, the lower price corresponds to a large order while the higher price corresponds to a small order. As noted, some manufacturers of flat-plate collectors, and the foreign distributors, will sell directly to individuals at these prices, Most, however, sell only to distributors, contractors, and architect/engineering firms,

All pricing data in this section are in 1976 dollars. Prices include headers, but exclude the controls, pumps, and interconnecting pipe which most collectors require. Prices of tracking collectors include trackers, bearings, drive motors, and tracking controls, but exclude the cost of pumps, storage, and controls. Prices for collectors other than flat plates are in dollars per-square-meter of useful aperture, while flat-plate collector prices are per-square-meter of gross collector area. This gross area includes the area blocked out by the “window frame” and thus makes the flat plates appear a bit less costly than if they were priced on a useful aperture basis.

Each manufacturer was contacted directly and asked for quantity factory prices to contractors, excluding shipping, installation, and interconnecting piping. Since most collectors other than flat plate are not yet in mass production, manufacturers were asked for both present limited-production prices and what prices they projected in mass production. All prices were requested in constant 1976 dollars and all inquiries were made in 1976,

COLLECTOR SUMMARY TABLES

The following abbreviations are utilized in tables VII I-4 through VII I-8:

Sel. Surf. –Selective surface absorber ab-

Table VIII-4.—Stationary Flat-Plate Collectors

Company	Type/feature	Present wholesale price f.o.b. factory ($/m^2)	Expected price when in mass production	Status	Design temperature
Thomason	flat plate trickle system 1 glass cover	32-43 to consumer		commercial	67° C
Sun works	flat plate sel. surf. 1 cover, glass	85-114	about same	commercial production	57 °-97“c
PPG	flat plate (opt. sel. surf.) 2 glass covers Al roll-bond (opt. Cu roll-bond)	80-107	same	commercial mass production	57°-97 “c
Reynolds Alum inure	flat plate (opt. sel. surf.) 2 Tedlar covers	54-65	same	commercial	57°-97 “c
N. V. Philips	Mark II Al or Cu roll-bond covered with evac. tubes heat mirror	—	$118	R&D	57 °-167°C
Unitspan	Cu tube and sheet 2 glass covers	86-92 to consumer	about same	commercial	57 °-97° C
Honeywell/ Lennox	flat plate Cu tube, steel sheet, 2 etched AR glass covers set. surf.	**145** or less	less	commercial	57 °-97°C
Calmac Manufacturing Corp.	Flexible mat o black EPDM tubes, 2 fiber- glass covers.	35-44 (Retail price; some on-site fabrication required)	about **same**	commercial mass production	57°-820°C

SOURCE Prepared by OTA using manufacturer's data

Table VIII-5.— Foreign Stationary Collectors on U.S. Market

Foreign company	Country	U.S. Distr.	Type	Present wholesale price f.o.b. U.S. distr. ($/m^2)	Design temperature
Miromit	Israel	American Heliothermal Corp.	flat plate 1 glass cover sel. surf. steel tube sheet	119-180	57 °-97°C
SAV	New Zealand	Fred Rice Productions, Inc.	cylindrical collector incorporates storage	500	57°-97°C
Amcor	Israel	Sol-Therm Corp.	flat plate 1 glass cover steel tube & sheet	119-147	57°-970°C

SOURCE Prepared by OTA using manufacturer's data

Table VIII-6. —Stationary Tubular and CPC Collectors

Company	Type/feature	Geometric concentration ratio	Present wholesale price f.o.b. factory ($/m^2)	Expected price when in mass production	Status	Design temp.
Owens-Illinois	evac. glass tubes sel. surf. on glass inner tube. White reflector	—	$215 (array aperture excl. headers and end caps)	107-130	pilot prod. demon. & testing	97 °-147° C
KTA	Cu absorber in glass tube. Half silvered	—	85-104	58-80	commercial production	57 °-97°C
Philips	Mark I evac. glass tubes half silvered; heat mirror coating	—	—	129	R&D	57°-167°C
General Electric	evac. glass tubes sel. surf. stationary external mirror	—	—	48-81	pilot production	57 °-167°C
Steelcraft, Inc.	alzak mirror CPC evac. glass tube/ sel. surf. receiver glass cover	—	269 (end of 1976) (excluding rack)	161-215 (end of 1977) (excluding rack)	commercial production (end of 1976)	204° C
M-7 International	solid plastic CPC for solar cells	5	—	only slightly more expensive than conventional solar cell packaging	have prototype; need capital for tooling	electricity

SOURCE Prepared by OTA using manufacturer's data

sorbs light well but does not radiate heat as well.
Flat Plate— Flat-plate solar collector.
Heat Mirror— Selective heat mirror coating on transparent cover allows sunlight to enter but reflects back infrared heat trying to escape.
Opt. —Optional; available at extra cost.
Al — Aluminum.
Cu —Copper.
CPC– Compound parabolic cross-section concentrating solar collector.
Evac. – evacuated.
AR – Antireflection coated.

COLLECTOR PERFORMANCE

The only accurate test of the value of a collector is the amount of useful output which it can provide per dollar of life-cycle investment, Unfortunately, there is no simple way to determine this useful output since the useful work done by a collector depends on the load, the quantity and quality of sunlight which is available, the size and type of storage devices used, local temperatures and wind velocities, and correlations between energy demands, weather, and available sunlight: a system which operates effectively in a home-heating system in Albuquerque may be extremely inefficient connected to an air-conditioner in Boston.

Table VIII-7. —One-Axis Tracking Collectors

Company	Type/feature	Geometric concentration ratio	Present wholesale price f.o.b. factory ($/m^2) (incl. tracker)	Expected price when in mass production	Status	Design temperature
Albuquerque-Western Inc.	parabolic trough tedlar window Cu pipe	20	**48-51** (incl. 250 tracker to drive 20-28 troughs)	(developing advanced design)	commercial production	32°-100°C
Beam Engineering	**parabolic trough**		235 or less	"much less"	commercial production	93° C
Sandia Labs	parabolic trough evac. glass tube/ sel. surf. abs.		(see Acurex)	80% learning curve to very low price	demonstration	317°c
AAI	fixed trough; tracking receiver	~ 8	—	54-65 w/roof cred. or 86-97 retrofit	R&D	117°c
General Atomic co.	fixed stepped trough; tracking receiver	60	—	(installed)	R&D	497° C
Northrup, Inc.	linear Fresnel lens; sel. surf. on Cu absorber	~ 10	**133-180**	(advance design)	commercial production	93° C
Suntech Systems, Inc.	linear heliostat	40	215-270	46-108	prototype testing	177°-317°C
Itek	linear heliostat linear cavity receiver		—	102	R&D	537° C
Acurex Corp. (6' wide)	parabolic trough anodized Al mirror glass tube sel. surf. absorber	58	160-240	less	commercial production	60°-31 1'C
Acurex Corp (4' wide)	(see above)		140-210	86	commercial production	600-1 77"C
Solartec Corp.	parabolic trough anodized Al mirror		100-172	about same	commercial production	204° C
Scientific Atlanta	(see Gen. Atomic) evac. glass tube/ set. surf. absorber glass mirror		145-161	about same	commercial production	204°-326°C

SOURCE Prepared by OTA using manufacturer's data

It is only **possible to evaluate a collector accurately by examining its performance as a part of an integrated system operating to serve a particular building in a specific geographic area.** For this reason, primary attention in this report has been directed to evaluating the performance of integrated systems.

Evaluating the performance of integrated systems requires a technique for computing the amount of output which can be expected from a collector under different conditions. The calculations used to perform this analysis are explained in some detail in the appendix to this chapter. The basic approaches to the analysis of collector per-

Table VIII-8.—Two-Axis Tracking Collectors

Company	Type/feature	Geometric concentration ratio	Present wholesale price f.o.b. factory ($/m²) (incl. tracker)	Expected price when in mass production	Status	Design temperature
ANSALDO/ Messerschmidt	ganged kinematic heliostat /tower	250-500	?	?	ready for order	600° C
E-Systems, Inc.	fixed dish tracking receiver		—	50-53/m² installed	R&D	260° C
Sandia Labs	multiple Fresnel lens w/solar cells acrylic lens	50-100	*224** *(w/o cells)*	(w/o cells)	prototype	*27°-100°C* & electricity
JPL	parabolic dish 9.75 m square glass mirror	1000	—	115	R&D	815° C
Varian	multiple parabolic dishes w/solar cel ls	1000	*650-1 ,000'* *(w/o* cells)	very low	R&D	27°-1OO°C & electricity
DOE contractors	central power station, helio-stat/tower		437-492/m² installed govt. demo)	70/m² heliostats 14/m² tower receiver		477° c
ANSALDO/ Messerschmidt	parabolic dish 832 m² 100 kWe		1,800	less	ready for order	550" C
National Patent Development	ganged glass parabolic dishes w/solar cell	300-500	—	7	R&D	*27°-100°C* & electricity
ANSALDO/ Messerschmidt	Heliostat /tower 5MWth/1MWe		385 (incl. tower& boiler)	less	ready for order	600" C
Sun power System Corp.	parabolic/trough carousel	96	175	about same	commercial product ion	500-2600C

“ Estimated based on laboratory prototype excluding design and tooling costs

SOURCE Prepared by OTA using manufacturer's data

formance will be explained briefly in the following section and some general conclusions will be drawn about the advantages and disadvantages of the major categories of collector designs.

The next two sections examine the effects which are most important in determining collector performance and a final section of this chapter compares the performance of five generic types of collectors operating in the four cities examined in this study.

THE ENERGY AVAILABLE FOR COLLECTION

The amount of light energy which ultimately reaches the receiver of a collector depends on two things:

1. The quantity and quality of the sunlight which reaches the Earth's surface, and
2. The tracking geometry of the collectors,

Table VII-9.—Assumed Collector Installation Costs for Various Collector Configurations, Excluding Overhead and Profit

Collector configuration	Installation cost in $/m^2	
—Components of installation cost	(Cost components)	Total
Air-cooled photovoltaics lying on roof		10.07
—install collectors	(8.07)	
—wiring	(2.00)	
Flat array lying on roof		18.40
—install collectors	(16.40)	
—wiring	(2.00)	
Roof replacement with air-cooled photovoltaics		1.54
—install collectors	(8.07)	
—roof credit	(- 8.53)	
—wiring	(2.00)	
Roof replacement with flat array		9.87
—install and plumb collectors	(16.40)	
—wiring	(2.00)	
—roof credit	(- 8.53)	
Air-cooled photovoltaics on frames on roof		27-47
—install collectors and frames	(10-30)	
—frame materials	(15.39)	
—wiring	(2.00)	
Flat array on frames on roof		27-57
—install and plumb collectors and frames	(10-40)	
—frame materials	(15.39)	
—wiring	(2.00)	
Tracking collectors on roof		20-40
—install and plumb collectors and frames	(20-40)	
Air-cooled photovoltaics on frames in field		31-51
—site preparation	(.90)	
—foundations	(5.02)	
—install collectors and frames	(10-30)	
—frame materials	(15.39)	
Flat array on frames in field		41-61
—site preparation	(.90)	
—foundations	(5.02)	
—install and plumb collectors and frames	(20-40)	
—frame materials	(15.39)	
Heliostats and air-cooled tracking PV in field		16-36
—site preparation	(.90)	
—foundation	(5.02)	
—install collectors and frames	(10-30)	
Plumbed trackers in field		26-46
— site preparation	(.90)	
— foundations	(5.02)	
— install and plumb collectors and frames	(20-40)	
Air-cooled photovoltaics raised on columns		37-57
—foundations	(5.02)	
—columns	(6.25)	
—install collectors and frames	(10-30)	
—frame materials	(15.39)	
Flat panels raised on columns		47-67
—foundations	(5.02)	
—columns	(6.25)	
—install and plumb collectors and frames	(20-40)	
—frame materials	(15.39)	
Heliostats and air-cooled tracking PV raised on columns		21-41
—foundations	(5.02)	
—columns	(6.25)	
—install collectors and frames	(10-30)	
Plumbed trackers raised on columns		31-51
—foundations	(5.02)	
—columns	(6.25)	
—install and plumb collectors and frames	(20-40)	

SOURCE: Prepared by OTA using manufacturer's data.

The Solar Resource

The amount of light which can be collected by a solar device on the Earth's surface is limited by the cycle of day and night, clouds, atmospheric turbidity, seasonal changes which result from the tilt of the Earth's axis of rotation (the axis tilts toward the Sun during the summer in the northern hemisphere and the elliptical shape of the Earth's orbit brings the Earth closer to the Sun during the winter) and atmospheric dust which may result from volcanic eruptions or local air pollution. It is also possible that there are long-term cycles in the amount of energy generated by the Sun itself, and there has been speculation that such cycles are responsible for cyclic ice ages and periods of severe cold which fall short of ice ages (such as the cold period which gripped Europe during the reign of Louis XIV].

There is very little information available about long-term changes in the amount of energy produced by the Sun or about long-term cycles in the net clearness of the Earth's atmosphere. **It has** been possible, however, to assemble continuous measurements of the intensity of energy reaching the Earth on a clear day from 1884 to the plesent by combining records taken at several U.S. sites. The result is shown in figure VIII-34. It can be seen that changes of 10 percent are typical, but that larger changes can result from major volcanic eruptions even though these explosions took place many thousands of miles from the site where the sunlight measurements were made. Following the explosion of Krakatoa, for example, the sunlight reaching the Earth fell by nearly 20 percent.

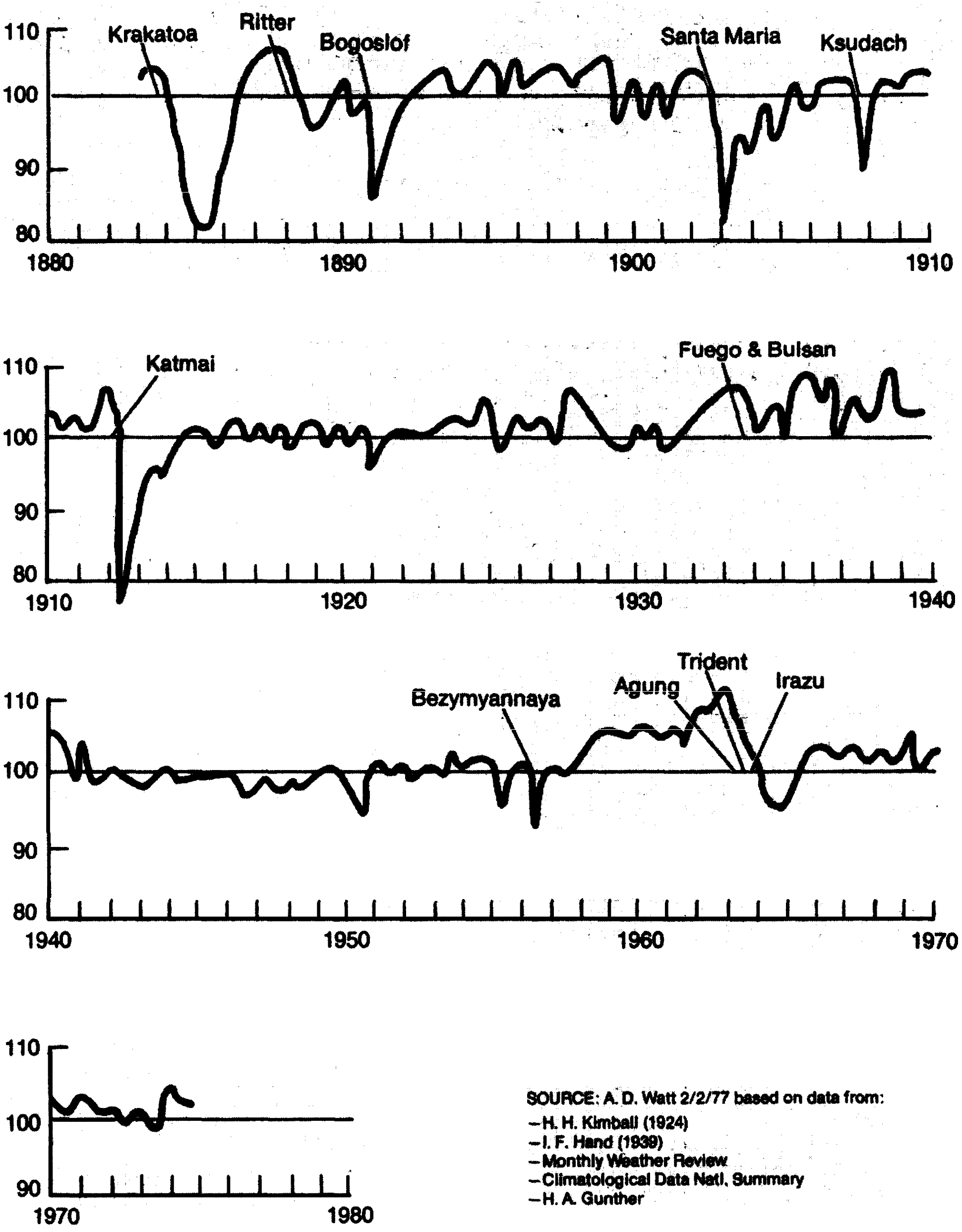
The variation in sunlight available for collection **in different parts of the United States is illustrated in figures VI 11-35 and 36.** These figures show the solar resource in two ways:

1. The total amount of sunlight falling on a horizontal surface (which includes both the energy received directly from the sun and the "diffuse energy" received by reflection from clouds and other particles suspended in the air), and
2. The "direct normal" radiation–the energy received by a collector which tracked the Sun's motion precisely, keeping the Sun perpendicular, or "norreal, " to the surface of the receiver.

Tracking systems which focus sunlight on a receiver can only make use of "direct normal" radiation. **It** can be seen that the basic solar resource varies by about 25 percent around the national average in June (which is the sunniest month in most climates) and by about 50 percent in December (which is typically the least sunny month). The pattern of distribution of direct normal radiation is somewhat unexpected since there seems to be more variation from east to west than from north to south. Thus, there is greater similarity between the amount of direct normal sunlight available in Fort Worth, Tex., and Columbus, Ohio, than there is between Fort Worth and western parts of Texas.

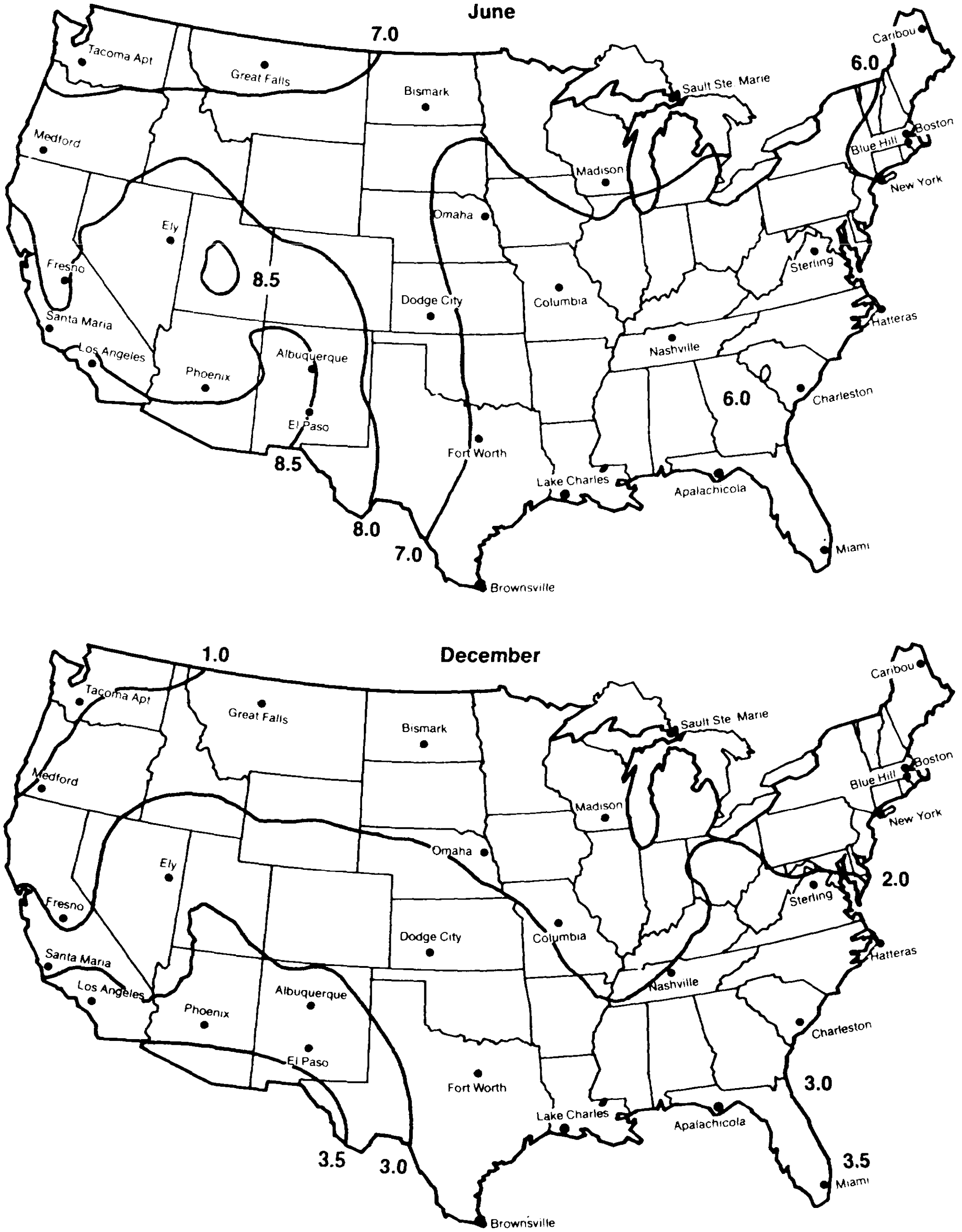
Several warnings are necessary before proceeding more deeply into an analysis of the availability of sunlight around the country. The data on which such analysis now must be based is of poor quality in most parts of the country; continuous records of direct normal radiation are almost nonexistent. (One of the primary criteria in selecting the cities used in this analysis was the availability of sunlight data.) Stations which measure direct radiation are located in three of the cities chosen (Albuquerque, N. Mex.; Blue Hill, Mass. —a town close to Boston; and Omaha, Nebr.). Even in these cities, however, complete records are difficult to obtain. Most information about direct normal radiation must be obtained indirectly by applying statistical 'techniques to measurements of the total amount of radiat;on reaching a horizontal surface. (These techniques are discussed in the appendix.) Another limitation of the analysis is that it used data taken in a single year— 1962 (1 963 for Boston). Better comparisons could be made if results were averaged over a number of years to eliminate unusual effects

Figure **VIII-34. —Variation of Direct Normal Component of Solar Radiation With Time**
Northern hemisphere values: typical of air mass = 1.5 100% corresponds to approximately 0.94 kW/m^2.
The names on the graph refer to major volcanic eruptions.



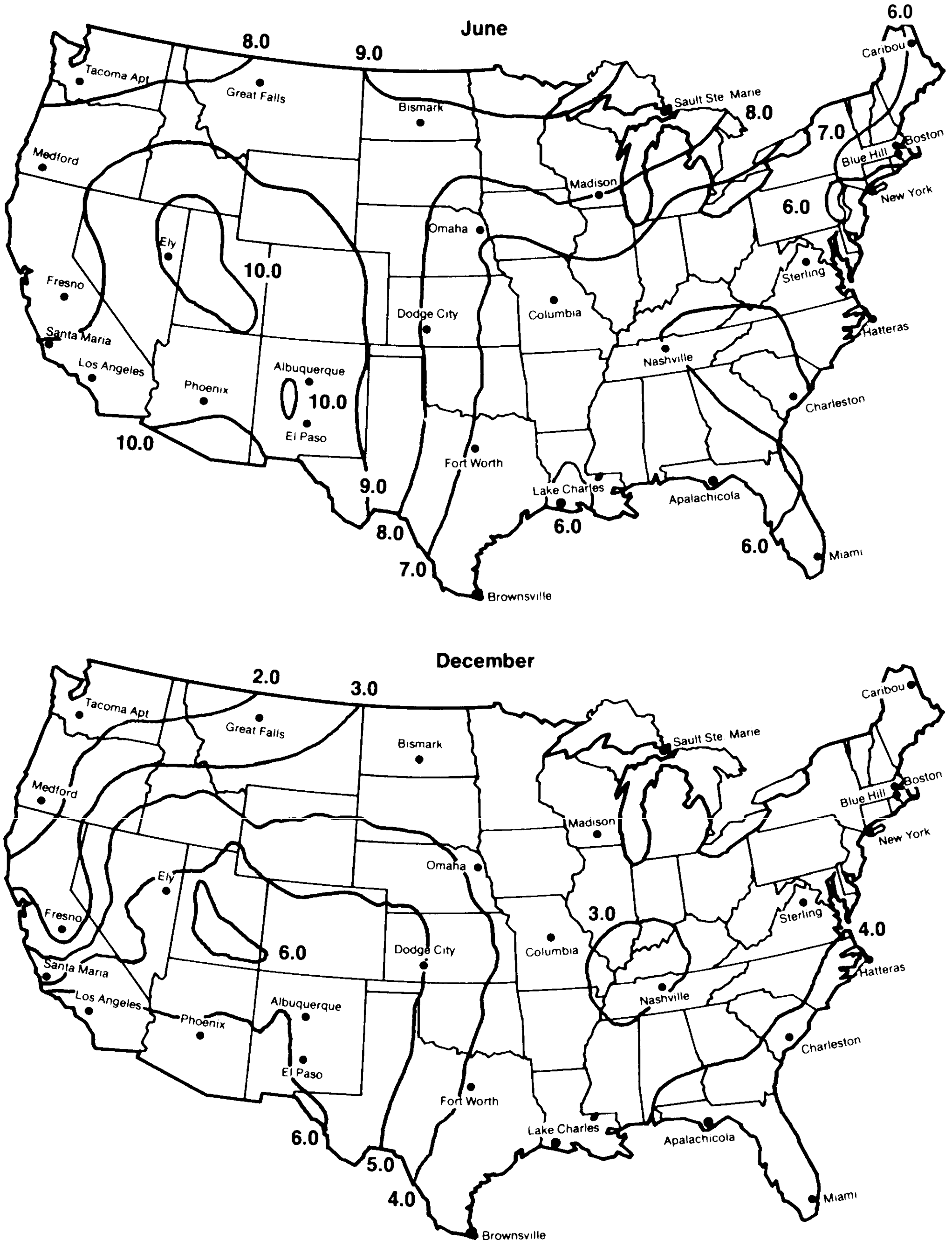
SOURCE: A. D. Watt 2/2/77 based on data from:
—H. H. Kimball (1924)
—I. F. Hand (1939)
—Monthly Weather Review
—Climatological Data Natl. Summary
—H. A. Gunther

Figure VIII-35.—Mean Daily Total-Horizontal Solar Radiation (kWh/m^2)



SOURCE: Boes, Eldon, et al., "Distribution of Direct and Total Solar Radiation Availabilities for the U.S.A." published by Sandia Laboratories (SAND76-0411) pages 19 & 25.

Figure VIII-36.–Mean Daily Direct-Normal Solar Radiation (kWh/m^2)



SOURCE: Boes, Eldon, et al. "Distribution of Direct and Total Solar Radiation Availabilities for the U.S.A." published by Sandia Laboratories (SAND76-0411), pages 19 and 25.

which may be due to weather patterns in any single year. A comparison between 1962 data and long-term averages given in the appendix indicates that, for example, in Omaha direct normal sunlight was about 13 percent below normal in 1962 while in Boston it was about 15 percent above average (see table VII I-A-2).

One of the limitations of the maps shown in figure VI 11-35 is that they seriously understate the radiation which is available for a flat-plate collector installed in a northern latitude. An optimum collector is not horizontal but tilted at an angle close to the latitude angle, In northern climates, this optimum angle is quite far from the horizontal plane in which the sunlight measurements were made.

COLLECTOR TRACKING GEOMETRY

A comparison of the sunlight available for tracking and nontracking collectors is shown in figures VI 11-37 and 38 for the four cities examined in detail in this study. Figure VI 11-37 compares the energy available for collection by a perfect flat-plate collector (e.g., one with no thermal or optical losses) tilted at the local latitude angle with the energy available for a perfect, fully tracking collector (e. g., a fully tracking parabolic dish). The annual output of these collectors is summarized in table VII J-1 O.

Albuquerque is the only city examined where the energy available for a fully tracking collector exceeds the energy collectable by a perfect flat-plate device. (It will be seen later, however, that when an analysis is done which includes the performance of real collectors, the ordering is usually reversed.) The difference between the solar resource available for the two types of collectors is, however, so small in the cities studied that it is perilous to make any kind of conclusive statement, particularly given the poor quality of the data on which these comparisons are based.

Figure VI 11-38 compares the solar resources available to a nontracking flat-plate and a fully tracking collector system with two other collector geometries: the heliostat system (in which an array of mirrors directs light to a central tower), and a one-axis tracking trough which rotates around a polar axis (an axis which points at the north star).

The heliostat system gathers less energy than other tracking devices because: 1) the heliostats are not turned to face the Sun directly (these devices must point in a direction between the Sun's direction and the direction of the receiver tower), and 2) because in the computation used to prepare the data shown, the heliostat devices were packed in a way that allowed some heliostats to be shaded during part of the day. This shading was somewhat greater than the shading which occurred with a comparable ground coverage ratio in a field of fully tracking dishes; it is necessary for a heliostat to have an unobstructed view of both the Sun and the receiving tower. This small disadvantage of heliostat systems may be compensated in cost savings when integrated systems are evaluated.

COLLECTOR LOSSES

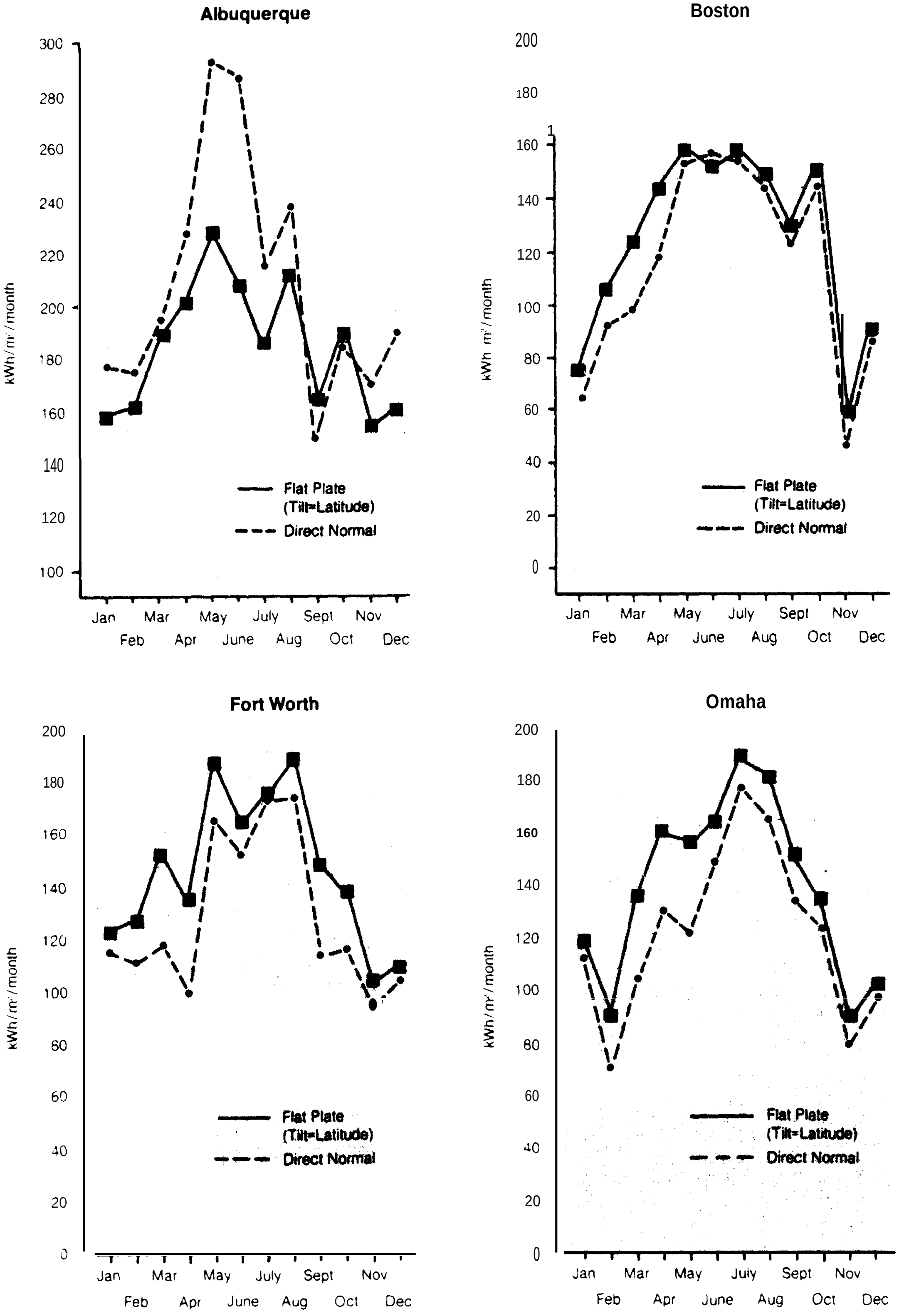
Up to this point, the analysis has shown only the amount of energy which could be provided by perfect collectors with different tracking geometries. The energy provided by real collectors falls below this theoretical value because of imperfections in the optical systems, and because some of the collected energy is lost to the environment without doing useful work.

Optical Losses

Four types of losses decrease the optical efficiency of flat-plate systems:

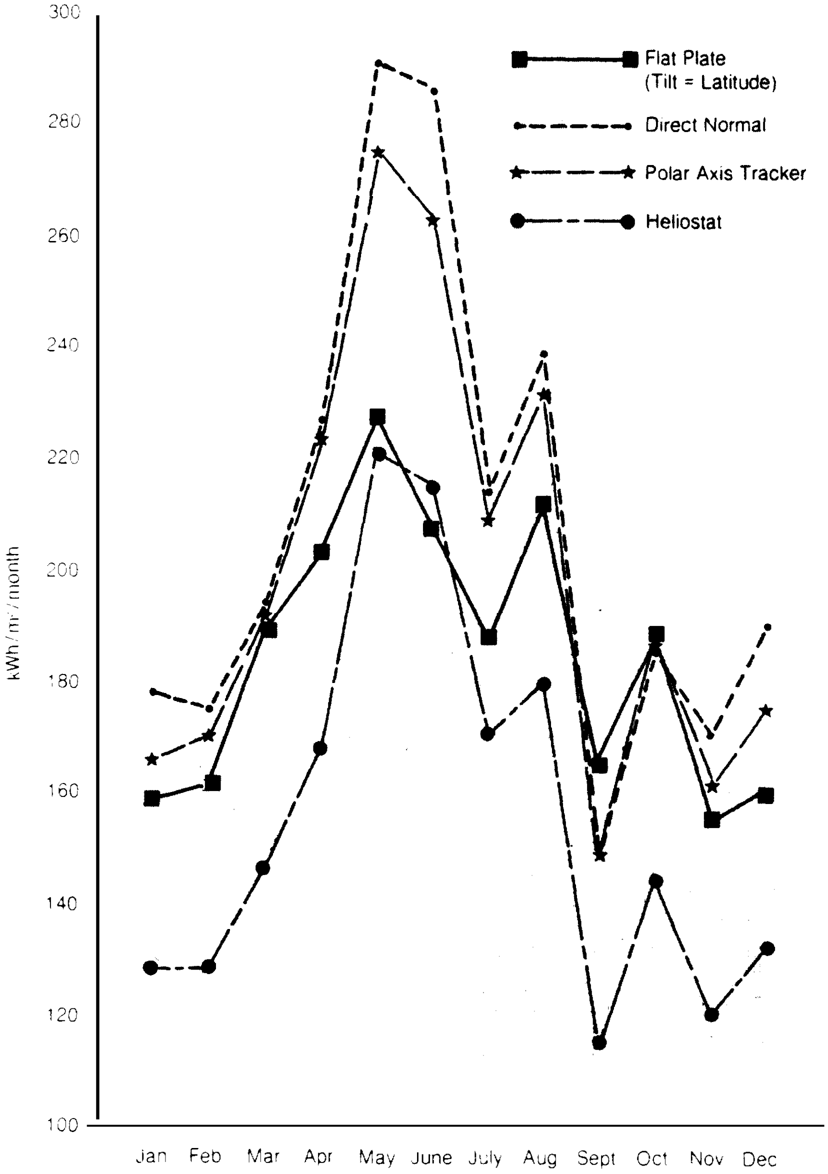
1. Reflection from glass or plastic covers is typically 8 percent for each cover used and is greater when the sunlight strikes the collector at an angle. Some thin-plastic films have lower reflective losses than glass. These losses can be reduced if antireflective coatings are used, but this adds to the collector cost.

Figure VIII-37.—Perfect Flat-Plate Collector Tilted at Latitude Angle and a Perfect Fully Tracking Collector



SOURCE: OTA

Figure VIII-38.—Comparison of the Maximum Energy Collectable by Four Types of Collectors Located in Albuquerque (1962 Radiation Data)



SOURCE: OTA.

Table VIII-10.—Useful Radiation Incident on Flat-Plate and Fully Tracking Concentrating Collectors, Four Cities, in kWh/m^2/year

Collector type	Albuquerque	Boston	Ft. Worth	Omaha
Perfect flat plate (tilted at local latitude)	2,217	1,481	1,742	1,665
Perfect fully tracking collector	**2,500**	**1,373**	**1,543**	**1,458**
Ratio (tracking/flat plate)	1.13	.93	.89	.88

SOURCE. OTA

2. **Reflections from the absorber surface are typically 2 to 10 percent, depending on the type of absorbing surface used.**
3. **About 2 to 4 percent of the energy received is absorbed and heats each cover glass used.**
4. **Dirt on the collector surface reflects** additional light if the collector has not been cleaned.

The energy actually available to heat liquids in a single cover flat-plate collector, therefore, is on the order of 80 to 90 percent of the energy incident on the device. Losses will be greater during the morning and evening when the Sun strikes the collectors at glancing angles and reflective losses are greater.

In tracking systems, losses can result from imperfect reflecting surfaces, reflections from lenses, energy absorption in lenses, inaccurate pointing of the focusing system, and inaccurate placement of the receiver. It is possible to produce mirrors which reflect over 90 percent of the light striking them but concentrating systems now on the market typically use light, inexpensive aluminum reflectors which typically only reflect about 70 to 75 percent of the light striking them. Dirt and dust pose a greater problem for concentrating systems than for the flat-plate devices since a significant amount of the energy in light which strikes dirt on the cover of a flat-plate collector eventually reaches the absorber surfaces and is absorbed. Light deflected by dirt on a focusing system, however, is lost completely. Data on the effect of dirt accumulation on performance is very preliminary at present, and may be critical in determining the net cost and performance of tracking devices.

Thermal Losses

when the absorber of a solar collector is heated, it loses energy back to the environment in three ways: direct radiation (mostly as infrared radiation) as it is lost from any hot body; conduction; and convection through the transparent covers. These losses are proportional to the absorber surface area and increase with the temperature of collection. Concentrating systems have much less absorber area per unit of collector area (it is reduced by the magnification of the concentrating optics) and typically operate at much higher temperatures. In most cases, however, the reduced absorber area more than compensates for the increased temperature. Concentrating systems usually lose a smaller fraction of the energy reaching them to thermal effects than flat-plate collectors.

The Significance of the Loss Factors

The contribution of thermal and optical losses to the net efficiency of several collector designs is illustrated in figure VIII-39. It can be seen that optical losses dominate collector performance in all cases. The effect of optical losses in flat-plate systems is, in fact, understated since the losses calculated assume that the Sun is directly over

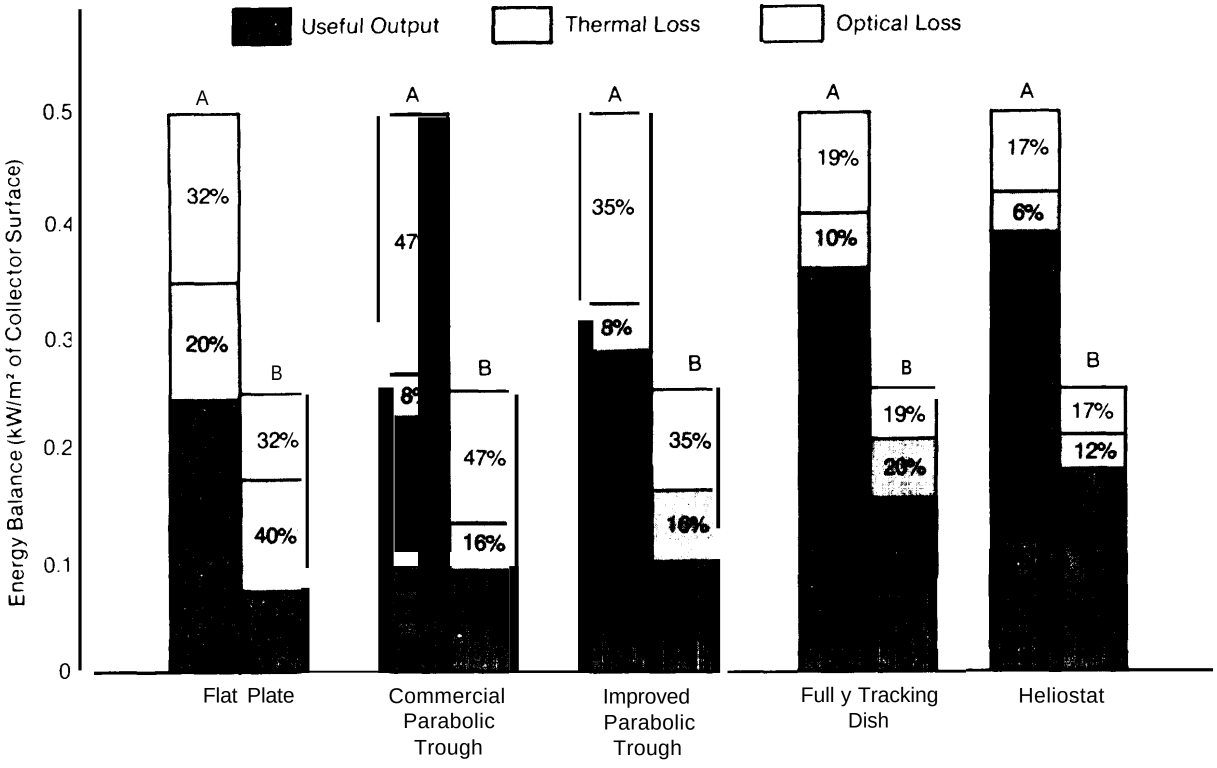
Table VIII-11.– Collector Characteristics Assumed in Preparing Figure VIII-39

	Single cover pond	Flat-plate collector (tubular design)	Commercial 1 -axis tracking parabolic trough	1-axis tracking parabolic trough with improved reflecting surface and receiver	Fully tracking parabolic dish	Heliostat
Concentration ratio	1	1	60	60	1,000	**500**
Outlet temperature (°F) (1)	90	200	300	600	1,500	**950**
Optical efficiency (including pointing inaccuracies, dirt, etc.) (2)	0.75	0.68	0.53	0.65	0.81	**0.83**
Thermal loss coefficient (including convection, conduction and radiation) in kW/m²°C (referenced to collector area) (3)	7.3 x 10^{-3}	2.0 X10-3	4.1 X1 O-4	1 .5X10^{-4}	6.2x10^{-5}	**6.4x1 0-5**

NOTES (1) In all cases the inlet temperature was assumed to be 100° F less than the outlet temperature
(2) In all tracking collectors, optical efficiency includes a 10°. loss due to dirt
(3 I In computing thermal losses. It was assumed that the ambient temperature was 60” F

SOURCE OTA

Figure VIII-39.— Energy Balance for Five Collector Designs (See table VIII- I 1 for Assumed Characteristics of Collectors)



A— Half of Maximum Sunlight
(.5 kW/m² Incident on Collector)

B — 1/4 of Maximum Sunlight
(.25 kW/m² Incident on Collector)

SOURCE OTA

the collector. The thermal losses shown in the figure are somewhat below average since in most climates solar intensity seldom is above the maximum possible solar intensity, which is typically close to 1 kW/m^2. The relative significance of thermal losses increases sharply as solar intensity decreases —e.g., during periods of partial cloudiness. Moreover, the ambient temperature chosen for comparison was 600 F to show the average performance of collectors throughout the year. During the winter months, the outside temperature will be lower and the thermal losses proportionately higher. The thermal losses of the high temperature collectors are, however, somewhat overstated since the inlet temperature assumed is only 1000 F lower than the outlet temperature. **It** is clear, however, that thermal losses are a relatively small fraction of the energy balance of high-temperature systems.

THE NET PERFORMANCE OF COLLECTORS

The results of an analysis which includes both a calculation of the sunlight available for a collector and the ability of a collector to utilize the sunlight available is summarized in tables VII 1-12 and 13. This information was computed using data on sunlight and ambient temperatures available for each city for each hour of the year 1962. Several observations can be made on the basis of these figures:

1. If systems are ranked in each city by the total annual thermal output produced, the ranking is, with a few exceptions, the same in each city.
2 The only concentrating system which produced less annual thermal output than the flat-plate system was the commercial parabolic trough system.
3. The fully tracking dish produced the largest output in all cities, giving nearly 25 percent more than the best single-axis devices and nearly 60 percent more than the f tat-plate systems.
4. Measured in terms of useful collector output, Albuquerque has almost twice the solar resources as any of the other cities examined. The performance of collectors in Boston, Fort Worth, and Omaha was strikingly similar.
5. The pond collectors typically have very low performance during the winter, particularly if high outlet temperatures are desired.

The results of this analysis indicate that concentrating systems can provide much more useful thermal output than simple flat-plate devices of the same area.

Even parabolic trough devices which make use of known techniques for improving output were superior to the flat plate in each city. This consistent inferiority of the flat-plate system occurred in spite of the fact that the flat-plate device chosen for analysis was a relatively sophisticated and efficient system. This seems to indicate that optical advantages of flat-plate systems (chiefly their ability to gather diffuse sunlight) is more than offset by the advantages offered by concentrating systems (e. g., tracking and reduced thermal losses). A valid comparison of systems can only be obtained, however, from a detailed economic comparison of the systems operating in realistic environments.

The value of this, of course, will depend on the costs added in the process of providing tracking; this can only be resolved in a detailed analysis of the relative costs of integrated systems.

Table VIII-12.—Comparison of the Annual Output of Five Collector Designs, in kWh/m^2/year

	Albuquerque	Boston	Ft. Worth	Omaha
Annual radiation on nontracking flat plate tilted at latitude	**2,217**	**,481**	**1,742**	**1,665**
Annual direct normal radiation	**2,500**	**,373**	**1,543**	**1,458**
output of:				
Single cover pond	**960**	—	—	**630**
Tubular flat plate	**952**	**538**	**705**	**619**
Commercial parabolic trough	**1,030**	**529**	**621**	**561**
Improved parabolic trough design	**1,370**	**720**	**835**	**765**
Heliostat	**1,443**	**791**	**887**	**833**
Fully tracking dish	1,901	1,023	1,150	1,085

SOURCE OTA

Table VIII-13. —Output of Single Cover and Double Cover Pond Collectors for Various Operating Conditions

		Mean collector temperature* = 90° F		Mean collector temperature = 140” F	
		Annual output (kWh/m^2)	Percent of output occurring during October-March	Annual output (kWh/m^2)	Percent of output occurring during October-March
Single cover pond collector	Albuquerque	958	23	447	13
	Omaha	630	13	259	5
Double cover pond collector	Albuquerque	804	24	470	16
	Omaha	535	15	281	8

“It was assumed that the collector was operated with a constant fluid inlet temperature 10° F lower than the mean collector temperature and a constant output temperature 100 F higher than the mean collector temperature

SOURCE OTA