Capturing Sunlight: A Revolution in Collector Design

Solar collectors are perhaps *the* characteristic solar technology, and much of the national enthusiasm for solar energy has been directed toward developing ingenious designs. The result has been an explosive proliferation of collector types—of metal, glass, plastic, concrete, and combinations of these materials. Although it is only in the last 5 years that a modern technology of capturing sunlight has taken form, literally dozens of designs have been proposed, each offering some particular advantage of manufacture or application. Collector designs range from low-cost, low-temperature versions to devices capable of concentrating sunlight 10,000 times and reaching extremely high temperatures. There is no sign that this upwelling of creativity has abated or that the limits of collector technology have yet been reached.

The economics of capturing sunlight is in flux, too, since an industry to manufacture solar collectors is both young and growing rapidly. A recent government survey counted nearly 200 companies now active in the business, and industry-wide production has been increasing by 168 percent a year since 1975, doubling roughly every 7 months. Output of flat plate collectors in the United States amounted to 165,000 square meters during the first 6 months of 1977. The Department of Energy estimates that as many as 24,000 homeowners installed solar energy systems during this period. Many of the newer and more efficient collector designs are just now coming into manufacture and prices do not yet reflect the advantages of mass production.

The ubiquitous flat plate collector of metal and glass is the type familiar to most people (Fig. 1). A few years ago it was the only type of collector available and it is still the commercial leader. But flat plate collectors are facing growing competition. They are being overtaken in volume by tubular plastic or synthetic rubber collectors designed to heat swimming pools—reflecting in part a ban on the use of natural gas for that purpose in most of the Southwest. Flat plate collectors are also being challenged in price by passive solar heating systems and by advanced collectors that use cheaper materials and perform more efficiently. Moreover, the advanced collectors are making possible higher-temperature commercial and industrial applications of solar heat beyond the reach of flat plate devices.

The classic flat plate collector consists of a black metal absorber enclosed in an insulated box with a glass or plastic cover. Collected heat is transferred to air or a liquid and piped to its destination, usually a storage tank of rocks or liquid. Variations among more than 100 manufacturers include the type of metal absorber used, the amount of insulation and glazing, and whether the metal surface has been treated to enhance its light-absorbing and heat-retaining properties. Flat plate collectors work more efficiently in summer than in winter, and more efficiently when producing low-temperature heat than high-temperature heat. Because their performance is so sensitive to climate, efficiencies can range from 70 percent in warm weather to less than 10 percent in very cold weather. Typical applications and temperatures include space heating via solar-assist for a heat pump (60°F); swimming pool heating (80°F); domestic hot water (130°F); and direct space heating (160°F).

Flat plate devices collect both diffuse and direct sunlight. Like most solar devices, they are predominantly used as fuel savers, providing 30 to 60 percent of space heating needs and relying on back-up energy systems for the remainder. Prices for the collectors alone vary considerably, but are generally in the range \$50 to \$150 per square meter; complete solar heating systems can run \$10,000 for an ordinary house, however, because of high installation costs. Although prices may fall somewhat as the building industry becomes more familiar with solar heating systems, the potential for cost reductions in the collectors themselves is limited by the amount of metal and other expensive materials used in their manufacture.

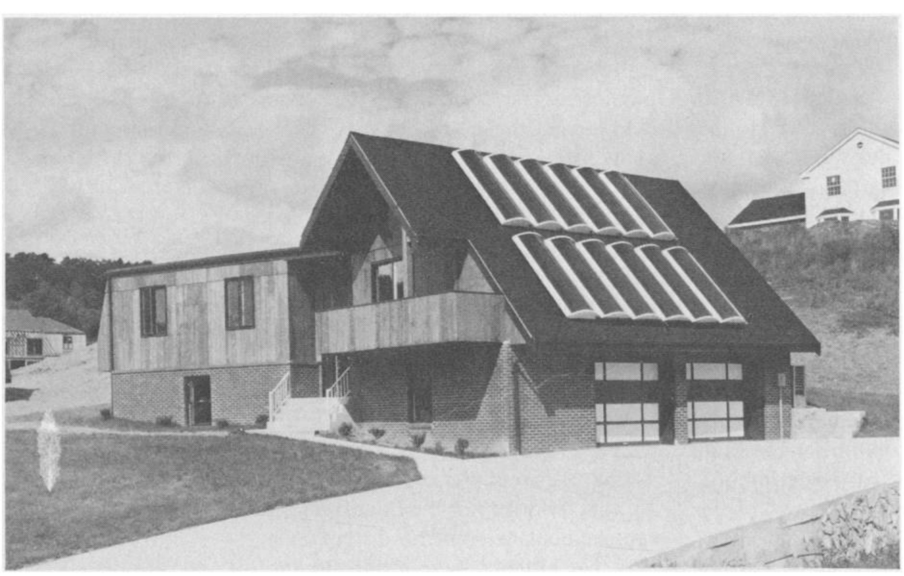

Fig. 1. West Virginia house with flat plate collectors used to heat water for domestic use and to provide a solar-assist to a heat pump. [Source: Grumman Energy Systems, Inc., Ronkonkoma, New York]

For very low temperature applications such as heating swimming pools, some 15 U.S. companies manufacture relatively inexpensive solar collectors consisting of mats of synthetic rubber tubing through which water is circulated. These simple collectors typically operate at about 80°F; they usually boost water temperatures by 5° or 10°F. Some 280,000 square meters of these collectors were produced in the first half of 1977.

Researchers at Princeton University are developing a related but more sophisticated collector consisting of multiple layers of thin, flexible plastic films—a plastic "flat plate" collector. Air-filled pockets on top and bottom would provide insulation and water would flow through a center channel. According to Theodore Taylor of Princeton, composite plastic collectors of this type made from a combination of Tedlar, polyvinyl chloride, and Teflon films have raw material costs as low as a few dollars

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per square meter and can produce temperatures as high as those attained with ordinary flat plate collectors. Actual manufacturing costs and the durability of such advanced plastic collectors remain to be determined. Rigid plastic flat plate collectors are also being developed at the Battelle Memorial Institute in Columbus, Ohio, and elsewhere.

For space heating of homes and commercial buildings, flat plate collectors face competition from passive solar systems (Fig. 2). The name arises because heat in passive systems is collected and distributed, without the use of pumps and fans, by means of natural radiative, conductive, and convective processes. This simplicity and the potential for low cost—the building itself typically serves as the solar collector—are the main attractions of passive systems.

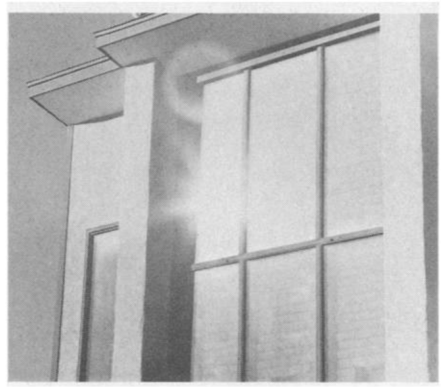

Fig. 2. Passive solar house in White Rock, New Mexico. The sun entering through the south-facing windows strikes a thick masonry storage wall, which separates the solar collector area from the living area. [Source: *The Atom*, Los Alamos Scientific Laboratory, Los Alamos, New Mexico]

The essence of passive solar systems is careful design that works with the surrounding environment to capture and retain heat in the winter and to remain cool in the summer. Thus, windows facing north are frequently made small or eliminated to a large extent, while those facing south are made large but protected from the summer sun by an overhanging roof. In addition, passive houses frequently include heavy masonry walls or other sources of thermal mass that can absorb the sun's heat during the day and reradiate it to warm the house at night—a type of concrete collector. An early example of these techniques is Montezuma's Castle, built around A.D. 700 by cliff-dwelling Indians in what is now Arizona; the castle sits in a recess of a south-facing cliff, its massive adobe walls warmed in winter but shaded in summer.

At least five distinct techniques are used in modern passive systems, alone or in combination. The simplest is direct gain through extensive south-facing windows with interior walls or floors providing storage. In a well-insulated building this is often enough to supply more than half of the heat requirements. A classic direct gain example is the Wallasey School in Liverpool, England, a two-story concrete structure with a south wall of double glass windows; electric lights and the body heat of the students provide the only supplementary heat. Direct gain buildings, however, often experience wider variations in temperature than are normally considered comfortable.

One way to limit temperature swings in a passively heated building is to partially decouple the thermal storage from the living space by means of a second technique, the thermal storage wall. In this design, sunlight entering south-facing windows is absorbed by a wall of masonry (Trombe wall) or water-filled drums (water wall); heat is vented to the building by openings at the top and bottom of the storage wall. The wall protects the interior of the building from high temperatures during the day and transmits its stored energy to warm the interior at night. An office building and warehouse belonging to a Benedictine monastery in northern New Mexico incorporates a water wall passive system that provides 95 percent of the energy needed for heating.

A third type of passive system is the roof pond. Plastic bags filled with liquid are exposed to the sun during the day and covered with an insulated panel at night, when they radiate stored heat to the house below. In summers, this cycle is reversed to provide cooling. A fourth type of system warms by circulating a fluid (air or water) in a natural convective loop. Collectors placed lower than the living space warm the fluid, which rises and carries heat to a storage unit within the house. A fifth type of passive unit is a greenhouse built into or against a house and often separated from the living space by a thermal storage wall. In addition to heat, the greenhouse can supply humidity and food.

Passively heated buildings in the United States number in the hundreds, most of them custom-built. The techniques are not yet common practice in the construction industry, nor have they received as much analytic and engineering attention as have flat plate collectors. But preliminary studies by J. Douglas Balcomb and his colleagues at Los Alamos Scientific Laboratory, New Mexico, indicate that passive systems can equal or exceed the performance of flat plate systems of comparable collector area. Balcomb finds that the optimal thickness of concrete storage walls is 30 to 40 centimeters. The passive systems need relatively more thermal storage but can be considerably less expensive overall. Innovations in passive design are continuing. They range from several types of movable insulation for shielding glass areas at night to new and more compact thermal storage systems, such as ceiling tiles developed at the Massachusetts Institute of Technology. The tiles contain a material that undergoes a phase change at 73°F, storing heat as it melts and later releasing it to the room as it solidifies.

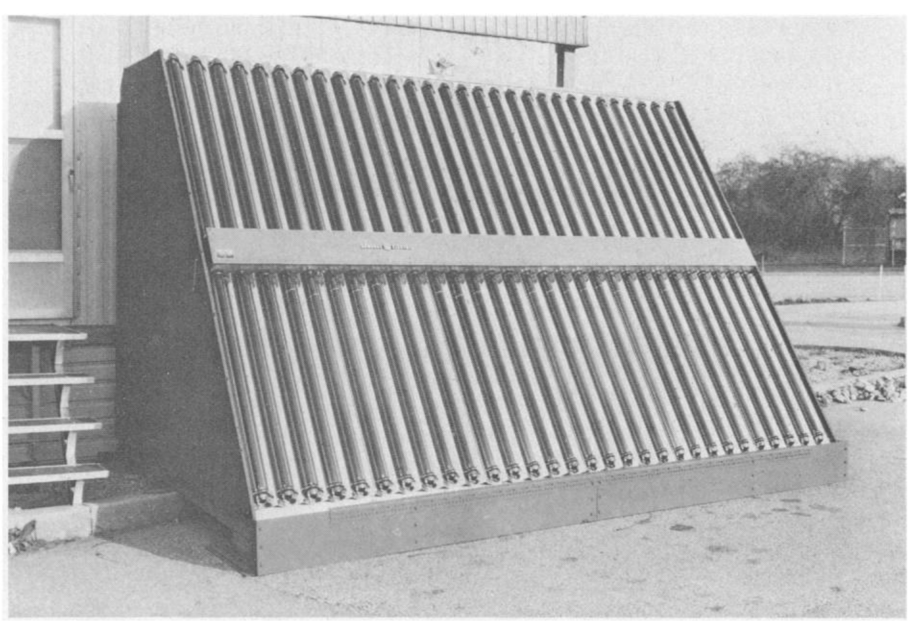

Fig. 3. Evacuated tube collectors mounted in a test stand. [Source: General Electric Company, Philadelphia, Pennsylvania]

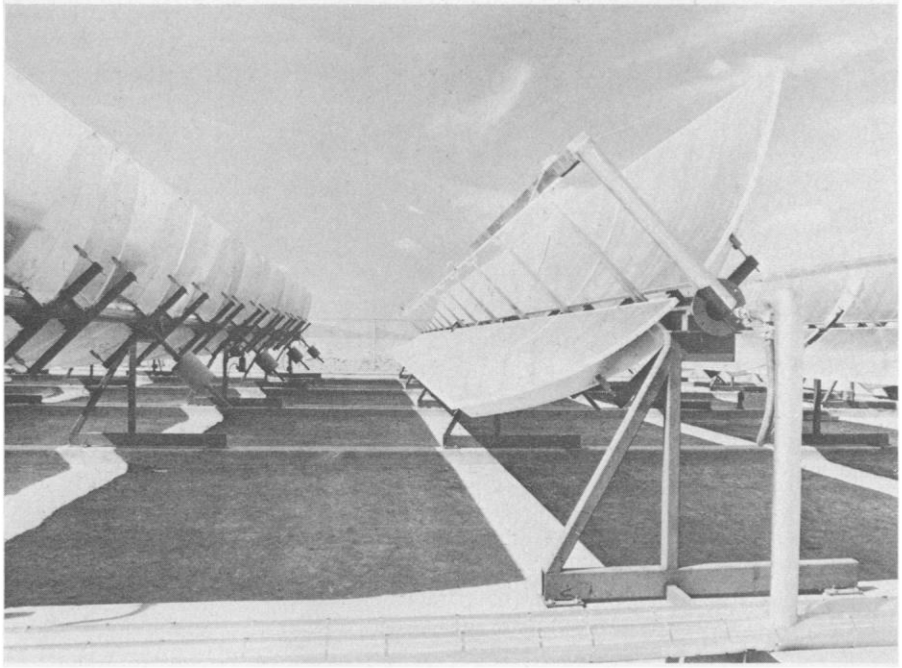

Fig. 4. Parabolic trough concentrating collector made of aluminum honeycomb with a reflecting surface of aluminized acrylic plastic. [Source: Hexcel Corporation, Dublin, California]

If passive systems represent the low-technology challenge to flat plate collectors, evacuated tubes represent a high-technology competitor (Fig. 3). Evacuated tubes can potentially give "twice the performance at half the cost" of flat plate devices, advocates say. The design consists of an inner glass cylinder blackened to absorb sunlight, enclosed within an outer protective cylinder, with the space between the two cylinders evacuated. The inner cylinder is usually coated with a material that cuts the energy lost through reradiation; the heat is transferred to a fluid, either air or a liquid, that flows through the inner cylinder.

One interesting variation on the evacuated tube collector is a corrugated glass sandwich developed by the Boeing Corporation that uses a circulating dark fluid as the absorber and evacuated channels for insulation.

Cylindrical evacuated tube collectors can absorb light coming from any direction—a 360° aperture—and to capitalize on this property they are usually mounted in arrays with a spacing of about one cylinder diameter between tubes and with a reflective material behind them. Like flat plate collectors, such arrays can make use of both direct and diffuse light, and they work somewhat better than flat plate collectors early and late in the day. The vacuum is such effective insulation that evacuated tube collectors are essentially unaffected by either high winds or cold weather, both of which degrade flat plate performance; in fact, the output of evacuated tubes is essentially independent of the ambient temperature. Their high efficiency, generally between 40 to 50 percent, translates into higher-temperature heat. Evacuated tube collectors usually operate at 180°F or above for space heating and providing industrial process heat, and with reflectors they can operate at 240°F, high enough to drive absorption air conditioners.

Evacuated tube collectors now sell for about $150 to $200 per square meter, somewhat more than flat plate collectors. Production volume is still small, however, and the glass collectors appear to have promise for greatly reduced costs. The manufacturing process for evacuated tubes is closely related to that used for producing fluorescent lights and lends itself to automated mass production. In some designs the individual tubes are removable from the arrays, and can thus be replaced like light bulbs. The collectors are far lighter than flat plate devices, use both less glass and less metal (materials costs are reported to run about $50 per square meter), and are more resistant to corrosion. Both heating and cooling applications are being vigorously pursued by manufacturers, and evacuated tubes are beginning to be used in some types of concentrating collectors as well.

To reach temperatures much above the boiling point of water with collected solar energy requires more than simply absorbing sunlight, however efficiently. Concentrating collectors increase the intensity of the energy radiating onto the absorber and hence raise the temperatures that can be achieved. Most concentrating collectors use only direct sunlight and must track the sun. Because they are more effective early and late in the day, tracking collectors can capture as much sunlight as flat plate devices in most parts of the country. However, tracking mechanisms can be expensive and the collectors more susceptible to wind damage than flat plate devices. Collectors range from low-concentration designs that concentrate sunlight fivefold (a concentration ratio of 5) or less and are capable of reaching 300°F to high-temperature devices with concentration ratios exceeding 100 that can reach 600° to 1000°F. In addition to producing higher temperatures and hence more useful energy, concentrators may have economic advantages as well. Heat losses from the absorbers become less important and the mirrors or lenses that concentrate the sunlight are usually less expensive than a comparable area of flat plate collectors.

Although dozens of designs for concentrating collectors have been proposed, three generic types can be distinguished, corresponding roughly to low, intermediate, and high degrees of concentration: nonfocusing concentrators, trough or line-focusing concentrators that track the sun by rotating along one axis, and two-axis tracking concentrators. The designs now under development include concentrators made from polished metal, metallized glass and plastics, and composite materials. A wide range of absorber materials can be used with these collectors.

Nonfocusing concentrators have the advantage that they need not continuously track the sun and do not require the optical precision of a system that must focus the sun's image on the absorber. They can use diffuse as well as direct light and thus can operate on hazy or partially cloudy days, an advantage in midwestern or eastern parts of the country; focusing concentrators, on the other hand, get much more sun in the early morning and late afternoon.

The simplest kind of nonfocusing concentrator consists of a stationary mirror or reflector placed next to a flat plate collector. Reflectors placed behind evacuated tube collectors also provide a small degree of concentration. The most sophisticated nonfocusing collector is known as the compound parabolic concentrator (CPC), developed at Argonne National Laboratory in Chicago.

The CPC is derived from light-concentrating devices used in high-energy physics experiments and consists of parabolic surfaces shaped to deliver the maximum amount of light to the absorber for a given concentration ratio. One version that concentrates sunlight 1.8 times can operate as a stationary collector and reach 250°F. Higher-concentration versions (ratios of 3 to 6) often use an evacuated tube as the absorber and can operate between 300° and 450°F; at a concentration of 6 the orientation of the collector must be adjusted once a month, but it does not require daily tracking. However, CPC designs require more reflective surface than, for example, a trough collector with the same aperture but a higher concentration ratio; the CPC designs may thus have higher manufacturing costs. Experimental CPC collectors have been made from metal, metallized plastic, and even solid acrylic. None are yet in commercial production, but costs for some designs have been estimated at about $270 per square meter.

More rapid commercialization and lower costs have been achieved with a variety of one-axis tracking concentrators (Fig. 4). More than a half-dozen companies are now manufacturing collectors of this type with concentration ratios in the intermediate range (10 to 100) and operating temperatures between 200° and 600°F. Many of these have been developed without government support and sell in preliminary versions for prices in the range of $100 to $200 per square meter, including motors and other equipment for tracking the sun; most deliver more than 50 percent of the sun's energy to the heat transfer medium in the absorber. Still other collectors are under development. Installation costs, as with flat plate collectors, can more than double the final bill, although the wide diversity of costs at present seems to reflect the newness of the industry and the wide variety of designs employed. Most companies project a cost below $100 per square meter in mass production.

Mirrors arranged to form a parabolic trough that focuses sunlight onto a linear absorber constitute one type of tracking concentrator. The mirrors are typically made of polished metal or coated plastic, the absorbers are made of blackened metal pipe or evacuated glass tubes, and the entire assembly rotates to track the sun from east to west. The applications range from heating and cooling buildings to providing industrial process heat and irrigation pumping for agriculture. The Albuquerque Western company, for example, is marketing a low-temperature version, primarily for home heating, that costs about $100 per square meter, a price that makes it competitive with many flat plate collectors. A higher-temperature version made by the Acurex Corporation and others can reach temperatures as high as 600°F. The Acurex collector is being used to drive Rankine cycle heat engines for pumping irrigation water at several locations in the Southwest, and to supply industrial process hot water at a Campbell Soup factory in Sacramento, California.

A second type of steerable trough collector uses plastic Fresnel lenses to focus sunlight on the absorber, achieving the same effect as a parabolic mirror with a smaller optical surface. A version of this concentrator developed by Northrup, Inc., a small heating and cooling company in Texas, with $250,000 of its own money produces 250°F heat with 65 percent efficiency. The collector is being used in heating and air-conditioning applications at a hotel in the Virgin Islands, a university in Texas, and many other locations; the company has orders for more than 10,000 square meters of collectors and is developing an advanced unit to produce higher temperatures.

Still a third type of one-axis tracking concentrator makes use of a fixed trough made of flat mirrors arranged in strips and held in a metal frame. Tracking is accomplished by moving the absorber. The firm of Scientific-Atlanta is marketing such a concentrator, designed to reach 600°F, for about $150 per square meter. The design, also known as a Russell collector, was developed by General Atomic, which is testing and selling research versions that can reach 900°F.

High Temperature Collectors

The highest degree of concentration and the highest temperatures are achieved with two-axis tracking collectors and heliostats that reflect light to a central tower (*Science*, 22 July 1977, p. 353). Because of the high concentrations, usually 100 to 1000 or more, extreme accuracy in pointing is required and the tracking mechanisms are more elaborate and generally more expensive than for one-axis systems. However, these systems are very efficient converters of sunlight to heat and can reach temperatures high enough to power conventional electricity generating equipment.

One of the few two-axis systems now being manufactured commercially is that of the Omnium-G Company. It consists of a tracking parabolic dish similar to those used in radar installations and is operated as a total energy system, producing both electric power and hot water at about 180°F. Energy storage is provided by a compressed-air system for electricity and a hot water tank for heat. The system sells for about $1000 per square meter of concentrator; the price corresponds to about $2 per watt of installed generating capacity. An alternative approach is to use a fixed mirror and a tracking absorber, as in the system being developed by E-Systems, Inc. The company is designing versions of the concentrator as large as 90 meters in diameter and projects costs for mass-produced systems as low as $50 per square meter. Still a third approach is that of Sunpower Systems Corporation, which is marketing a collector consisting of a series of parabolic trough concentrators arranged on a carousel; the system produces heat at temperatures up to 400°F and sells for $130 per square meter.

Concentrated sunlight can also be directly converted to electricity with photovoltaic cells. Concentrating collectors for use with these cells are very similar to those used for producing heat; the main difference is that the cells, made of semiconductor materials such as silicon or gallium arsenide, replace the absorber. With concentration factors of 100 or more, the primary cost of such a system is that of the concentrating collector. Hence the development of advanced concentrators will have an impact on both thermal and electrical applications of solar energy.

The staggering array of options for collecting sunlight—passive, flat plate, and concentrating systems—is testimony both to the inventiveness of solar engineers and to the wide range of potential applications for solar energy. Prices now range almost as widely as collector systems. Most analysts expect that prices will decrease somewhat as production increases. More striking is what appears to be a convergence of projected prices in the range $50 to $100 per square meter for flat plate, evacuated tube, and concentrating collectors—independent of operating temperature over a wide range. If these projections prove correct, higher-temperature applications such as providing industrial process heat may prove especially attractive markets, and industry, which can adjust to new energy sources more rapidly than individual consumers, may become a prime user of heat from the sun. But predictions of any kind are difficult because new collectors are still being designed, new materials are being developed, and the integration of solar collectors into practical energy systems is just beginning. What is certain is that solar collectors are a booming field of technology. If the past few years are prelude to the future, it will be a future energized by sunlight collected in myriad ways.—ALLEN L. HAMMOND and WILLIAM D. METZ