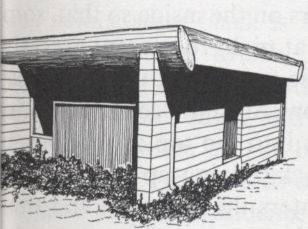
to the floor and walls, and to the occupants.
ion from the floor and walls and the occu-
mits the absorbed heat to the water. The
tion to the sky and by evaporation, if addi-
ver the bags, and is thus exposed to the sky.
as a thermal valve in the form of insulating
to cover the water ponds during winter
lar radiation is absorbed by a black lining
s in turn heats both the roof-ceiling and the
panels cover the water ponds during the
ting reflects the solar radiation back to the
ulation is rolled away and cooling takes
he panels were moved manually, but in the
adero, California (Fig. 17.4), the panels are
trolled by an ingenious thermostat. This
areas that are free of snow in the winter and
point temperatures during the hot summer



at Atascadero, California, for its inventor, Harold
essor Kenneth Haggard, California State Polytechnic

. 17.4) has been in operation since the fall
in the comfort zone throughout that entire
heating or cooling, despite the fact that the
erably colder than that of Phoenix. The
and 51 ft long, and they tie the walls of the
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em can be seen from the adjacent street,
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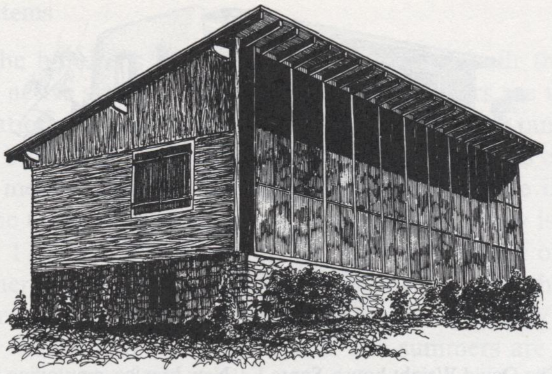

FIG. 17.5 Trombe–Michel house, developed for use in the south of France, with a massive concrete south-facing wall used as the heat absorber, insulated by double glazing, with convection space provided between the concrete and the glazing. The vertical south wall provides both heat storage and heating of the building at night.

Figure 17.5 shows the house originated by Dr. Felix Trombe, Director of the Solar Energy Laboratory at Odeillo, and designed by architect M. Michel. The Trombe system has been studied since 1956, and patents have been granted to the National Center for Solar Research, in the name of Dr. Felix Trombe, in 1956 and again in 1971 and 1972. The system is passive, because the solar radiation is absorbed by a heavy concrete south-facing wall, which is covered with a single glazing. The concrete wall extends below the floor of the living space, and entry ports are provided which enables cool air from the floor level to flow downward, and then, as the concrete is heated by the sun, the air rises in the space between the glass and the wall, and returns to the house through ports located near the roof. An overhang protects the wall from excessive insolation during the summer. Electric strip heaters are provided for standby purposes during excessively cold weather and during days with little sunshine. The location, adjacent to the resort town of Font Remeu, enjoys more sunlight than any other portion of France, and the summer weather is pleasantly cool, so that, by simply opening up dampers at the top of the windows, air can be circulated through the house from openings on the north side into the solar-heated space between the glazing and the concrete, to be discharged through the dampers to the atmosphere at night. This system is extremely simple, but it has proven its effectiveness, and much more elaborate structures than that shown in Fig. 17.5 have been constructed in the same region.

Another completely passive heating system is that used by Mr. and Mrs. David Wright in the house which they have built at Santa Fe, New Mexico (Fig. 17.6). This house is constructed with heavy double adobe walls, with

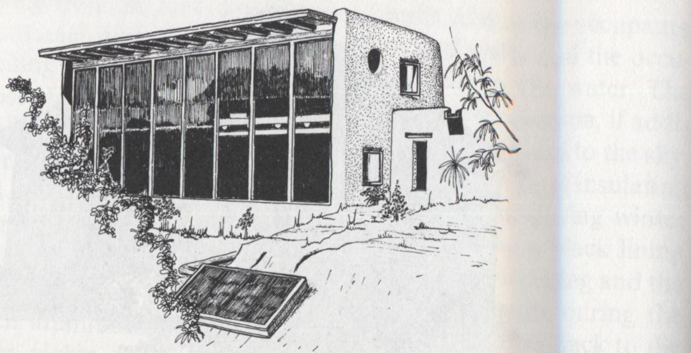

FIG. 17.6 The David Wright house, Santa Fe, New Mexico, employing large south-facing glass, internally shaded at night to minimize heat loss, and using the floor of the building as the primary heat storage means.

insulation between two 12-in. thicknesses of adobe block. The floor is also made of 24 in. of adobe, with insulation below it. The roof is heavily insulated, and the entire south wall consists of double-glazed windows. An overhang shades the windows from the summer sun, but permits the low-angle winter sun to enter freely. In order to seal the house against heat loss at night, a horizontal insulating curtain is provided, which can be retracted into space at the top of the window during the daytime, and then lowered to any desired extent to control the admission of solar energy in season when the house would tend to be overheated without this provision. At night, the insulating curtain is lowered completely, so that all of the glass is covered, and the combination of glass and curtain achieves a very high insulating value.

Domestic hot water is provided by a double-glazed thermosyphon system located on a hillside adjacent to the structure, and summer ventilation is accomplished simply by opening the windows in the east and west sides. The interior of the house is quite open, and air circulates freely to enable the heat, which is stored in the floor and walls of the building, to flow upward to the sleeping quarters on the second level. A wood-burning fireplace is the only auxiliary heat that is needed, and cooling is not needed during the summer, because, at the 6000-ft altitude of Santa Fe, high temperatures are rarely encountered, and night temperatures are always relatively cool.

The residences described in the foregoing section are treated in much greater detail in "Solar Oriented Architecture," which was prepared by the writer and a team of graduate students in the College of Architecture, Arizona State University, Tempe, Arizona, for the American Institute of Architects Research Foundation, under a contract with the National Science Foundation.

B. Active Systems

Most of the hundreds of solar-heated residences built throughout the world use the active system, in which separate collectors are used to gather the solar radiation, transfer it to air or water, and store it in tanks of water or rock piles, or both. The air and water are circulated by fans or pumps, and conventional means are used to distribute the heat to the interior of the residences. The oldest of these in terms of operating history is the structure shown in Fig. 17.7, which was built by Dr. George Löf, one of the pioneers in the solar energy movement in the United States, in a southern suburb of Denver, Colorado. The altitude at this point is approximately 5000 ft above sea level, and the winters are quite severe. The summers are characterized by brilliant sunshine and relatively cool nights, so air conditioning is not a necessity. The Löf house (Fig. 17.7) uses two long air heaters, mounted within a parapet on the roof. The heaters use the overlapping glass plate principle, invented by Dr. Löf during World War II and first tested by him in a much smaller cottage in Boulder, Colorado.

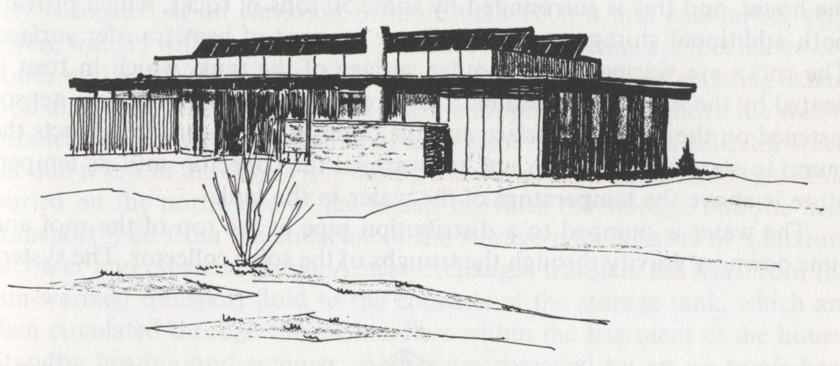

FIG. 17.7 The Löf house, erected in Denver in 1958. Two banks of overlapping glass collectors are used to warm air, which in turn heats gravel in two storage cylinders. Heating at night and during cloudy weather is accomplished by the stored sun-collected heat in the rock-filled cylinders.

The collectors utilize glass plates, with the upper half transparent and the lower half blackened. The plates are set at an angle to the direction of air flow, so that the solar radiation, entering through a cover glass, also passes through several thicknesses of clear glass and is then absorbed on the blackened lower segment of each glass plate. Temperatures as high as 76.7°C (170°F) can be attained, and the heated air is blown through two large cylinders which are filled with rocks approximately 5 cm (2 in.) in diameter. This constitutes the storage system, which is charged up during each day. Usually the house is kept sufficiently warm by solar radiation entering through south-facing windows and through sun-heated walls. At night, the house is heated to approximately 40% of its requirements on the coldest winter nights by heat that is stored in the rock-filled cylinders.

The entire structure was subjected to a very careful testing procedure during the winter of 1974–1975, and it was found that there was very little deterioration in performance of the system despite the fact that it had been in operation approximately 17 years. The backup system is a gas-fired air furnace, and domestic hot water is also provided by a gas-burning heater. It is probable that, when natural gas becomes unavailable in the Denver area, electricity will be used in resistance heaters, or in a heat pump, to provide the backup energy source.

One of the most successful and simplest solar heating systems is that devised by Dr. Harry Thomason of Washington, D.C. His *Solaris* system uses an open-flow collector made of corrugated aluminum sheets that are painted with a waterproof black. A single cover glass is used, and the collector is mounted directly on an insulated and water-proofed roof (Fig. 17.8). The primary storage is a 1600-gal water tank, located in the basement of the house, and this is surrounded by some 50 tons of rocks, which provide both additional storage and a very large amount of heat transfer surface. The rocks are warmed by the outer surface of the tank, which in turn is heated by the sun-warmed water. A differential thermostat with one sensor fastened on the collector surface and the other in the water tank directs the pump to start whenever the sun has warmed the collector until its temperature is above the temperature of the water in the tank.

The water is pumped to a distribution pipe at the top of the roof and runs down by gravity through the troughs of the solar collector. The system is "fail-safe," because the water drains from the collector whenever the pump stops for any reason. Warm air is used as the heat transport medium, and this is circulated by a small blower. For summer operation, a small compression refrigeration system is used to cool the water in the tank. A compressor operates only during off-peak periods, and cool air is circulated through the house during the daylight hours, when air conditioning is required.

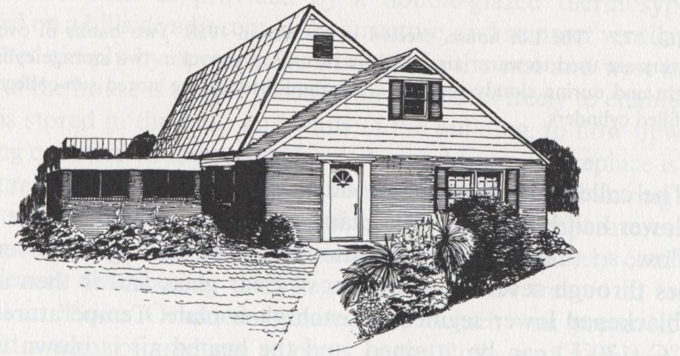

FIG. 17.8 The Thomason residence in Washington, D.C., which uses the system shown in Fig. 17.9, to provide heating by relatively low-temperature sun-warmed water. This house now has more than eighteen years of experience to demonstrate its feasibility.

The first of the Thomason houses was built in 1959, and no less than 20 were in operation by the end of 1975, in locations ranging from California and Colorado to Minneapolis, located in one of the coldest sections of the United States. Figure 17.9a, b shows a cross section of the *Solaris* system and an open-flow collector.

Representative of the high-technology systems which are now proliferating throughout the United States is *Phoenix of Colorado Springs* (Fig. 17.10), which was built during the winter of 1973 to show the citizens of Colorado Springs, Colorado, that the sun could provide most of the heating requirements of a large, well-insulated residence, despite the fact that this city is located at an elevation of more than 5000 ft and encounters very severe winters with large amounts of snow. The collectors are located on the south wall of the second floor of the residence and on a free-standing extension above the roof. The roof has a white topping applied above the waterproofed surface to reflect additional solar radiation onto this collector when the sun is low in the sky, as it is during the winter months. A 16,000 gal tank, buried on the north side of the house, provides the storage, and the heat transport fluid from the collector to the storage tank consists of a mixture of water and ethylene glycol. A heat exchanger transfers the heat from the sun-warmed transport fluid to the contents of the storage tank, which are then circulated through the air handlers within the basement of the house. Standby heating and summer cooling are provided by an air-to-air heat pump, also located in the basement. Because of the very large size of the storage tank, *Phoenix of Colorado Springs* can successfully go through a week of inclement weather without having to call upon the auxiliary heat source.

A number of active solar-heated and -cooled residences are now in operation in the United States. These use double-glazed high-performance flat plate collectors to heat water, freeze-proofed with ethylene glycol or a similar substance. In winter, the water is used directly in the heating systems of these buildings, and in summer, the hot water is used to activate a lithium bromide absorption refrigeration system. Difficulty has been experienced in obtaining a sufficiently high collection efficiency at the 93.3°C (200°F) temperature level to make such systems economically desirable at the present time, but with the introduction of a practical sun-following concentrating collector using a linear Fresnel lens, these systems offer far more promise of

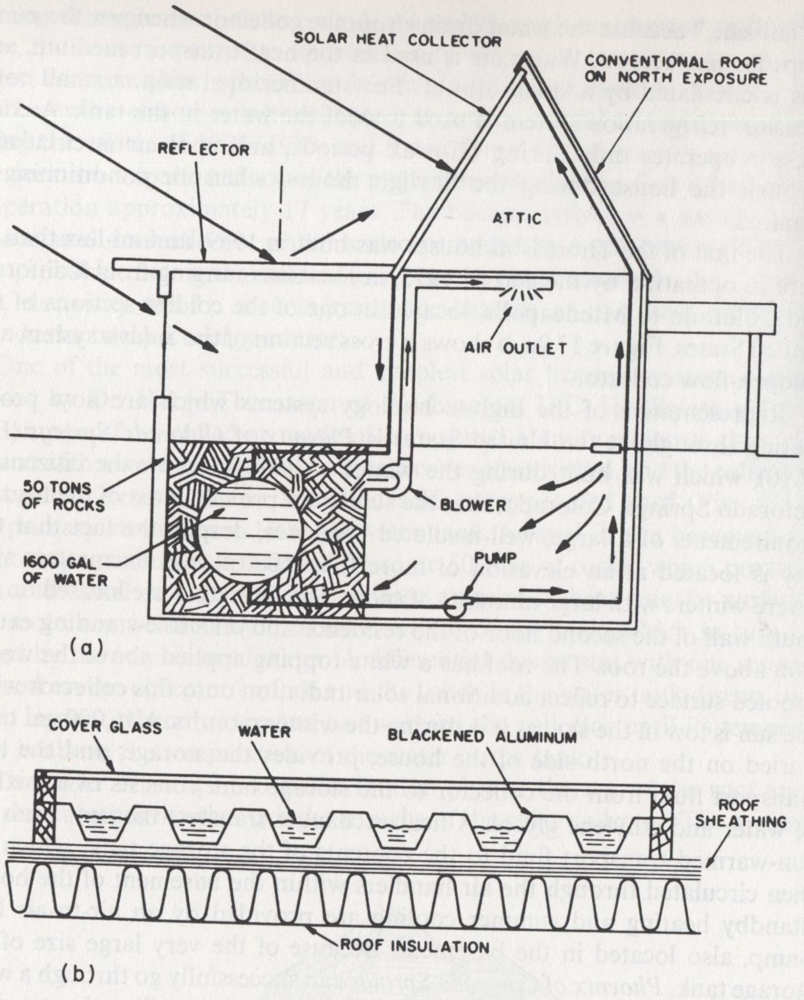

FIG. 17.9 Operating principles of the Thomason *Solaris* solar heating system, in which heat is collected at moderate temperature by a steeply tilted south-facing collector, and stored in a 1600-gal water tank. Fifty tons of rocks pick up heat from the warm water in the tank, and the rocks become both additional storage and the heat transfer surface to warm the air going to the house. (a) Thomason solar heated house; (b) cross section of roof mounted solar water heater.

being successful both technically and financially. Flat plate, south-facing collectors can generally operate in this temperature range for only about 6 h/day at the maximum, since, during the summer, the sun rises in the northeastern quadrant of the sky, and a south-facing collector does not

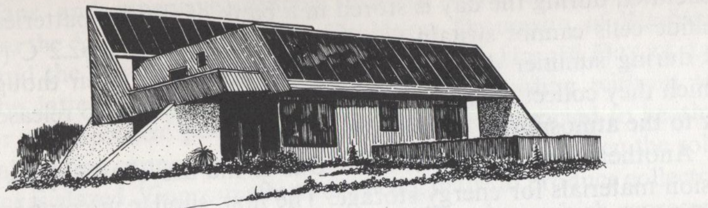

FIG. 17.10 *Phoenix of Colorado Springs*, a solar-heated and heat-pump-cooled house erected in Colorado Springs, Colorado in 1973. Flat plate collectors provide the heat required in winter, and air circulation is provided by the indoor fan of the heat pump, which serves as the auxiliary heat source and as the summer cooling means.

receive a substantial amount of direct radiation until close to 0900 h on a summer day. The sun moves again to the northwest by 1500 h, giving only approximately 6 h of collection time. The concentrating collector, on the other hand, can turn towards the east and pick up the early morning solar radiation, and follow the sun across the sky until it is about to set in the northwest. Such collectors are now undergoing extensive tests at a manufacturing plant near Dallas, Texas, and many are already in commercial use.

Representative of the highest technology yet applied to a solar house is *Solar One*, built by the Institute of Energy Conversion, University of Delaware, Newark, Delaware. Shown in Fig. 17.11, this house uses vertical south-facing air heaters to provide most of the winter heat requirements. In addition, two groups of collectors are mounted on the roof, which is tilted at an angle of 60° to the horizontal. The photovoltaic cells are intended to provide the electrical power required by the residence, and surplus power

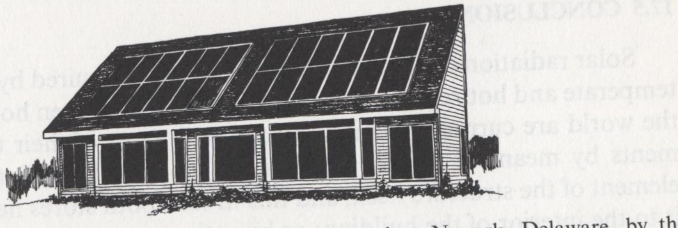

FIG. 17.11 *Solar One*, the solar-electric house erected at Newark, Delaware, by the Institute of Energy Conversion, University of Delaware. Solar heat is provided during the winter by vertical south-facing panels in bay windows, and by solar-electric panels on the roof, tilted at 60° to the horizontal. Cadmium sulfide cells produce both electricity and heat when irradiated, and since they must be kept relatively cool, the heat is stored in heat-of-fusion devices, located in the basement. The electricity generated during the day will be stored in 120-V d.c. storage batteries, for use at night to run a heat pump which will cool the building and have its excess cooling power stored in another heat-of-fusion storage bin. This is the only Type IV house in existence at the present time, but it is certainly the shape of things to come.

generated during the day is stored in a bank of storage batteries. Cadmium sulfide cells cannot sustain temperatures much above 82.2°C (180°F), and so during summer days, the cells must be cooled, even though the heat which they collect cannot be used. Vents are provided to release the heated air to the atmosphere.

Another novel feature of *Solar One* is the use of two types of heat-of-fusion materials for energy storage. The first, similar in composition to the well-known Glauber's salts, stores heat at about 40.6°C (105°F), for use when the building requires heating. The second stores heat at 12.8°C (55°F), and this is used during the summer to store coolness, produced by a heat pump during the day when the solar cells are producing electricity, for use at night. The heat pump also serves as the backup heating and cooling system to keep the house comfortable when the solar apparatus is not functioning. Although it is recognized that *Solar One* is still very much in the experimental stage, it affords a preview of what the future may bring in the way of houses that are completely self-sustaining, producing both heat and electricity from the sun, with only minimal need for assistance from the local electrical utility. Cadmium sulfide cells are recognized as being less efficient by a factor of 3 to 1 than the silicon cells which have proved their capability in the space programs of the US and USSR. However, cadmium sulfide is extremely cheap to produce, in contrast with the ultraexpensive silicon cells. There is hope and even expectation that the cost of silicon cells will be reduced by a factor first of 10 to 1 and then 100 to 1 within the coming decade, and when this takes place, it is not too optimistic to expect that systems similar to that used in *Solar One* will be in much wider use in the sunlit portions of the world.

17.5 CONCLUSION

Solar radiation can produce most of the heat required by dwellings in the temperate and hot regions of the world. Perhaps a dozen houses throughout the world are currently being provided with most of their thermal requirements by means of passive systems, in which solar radiation heats some element of the structure itself, and this in turn both stores heat and transfers it to the interior of the building; or by active systems, in which the essential components, collector, storage, standby, and energy distribution, are separated, with air or water used as a transport fluid to carry the collected heat from the collector to the storage and from the storage to the interior of the building. Most of the solar-heated houses which have been built thus far use the second system, because it is more versatile and can be applied in virtually any part of the world that has a reasonable amount of sunshine. Costs are generally lowest for the passive systems, since they avoid the use of pumps, fans, and expensive controls. For the active systems, the least expensive are the *Solaris*, advocated by Dr. Harry Thomason, of Washington, D.C., and the *Skytherm* system, invented by Mr. Harold Hay of Los Angeles. The latter can provide both heating and cooling without the necessity for any electrical power, while the former is restricted to heating, since natural cooling cannot be produced at the present time when the solar heat collector is glazed. Vigorous efforts are being made to produce collectors at a cost lower than $8 to $10 (US currency, 1977 value), which represents the selling price of the least expensive flat plate collectors. Although glass is preferred for the glazing material because of its ability to withstand both high temperatures and intense ultraviolet radiation, transparent shatter-resistant fiberglass is now coming into use, which has slightly higher solar transmittance than glass and is apparently able to offer a life of at least 20 years. It is anticipated that the decade between 1975 and 1985 will see new types of collectors with higher efficiency than those available today, while other developments will bring about lower life cycle costs for collectors and thus make the use of solar energy more attractive from the economic point of view. The technology is available today, and the major remaining problem is to bring down the cost of these systems until they offer financial incentives much greater than those offered by electricity, which is likely to be the primary energy source of the future in most parts of the world.