BUILDING RESEARCH NOTE

SOLAR-HEATING SYSTEMS FOR CANADIAN BUILDINGS

by

J. R. Sasaki

Division of Building Research
National Research Council of Canada

Ottawa, December 1975
Revised June 1977

SOLAR-HEATING SYSTEMS FOR CANADIAN BUILDINGS

by

J.R. Sasaki

Canada is fortunate in possessing a supply of the natural resources of oil, natural gas, and hydro-electricity. As they have been available, they have provided the main sources of energy for heating Canadian buildings. The supply of these energy sources is not inexhaustible, however, and there is now concern on two counts: the rapidly increasing costs of conventional forms of energy due to their decreasing supply and the need to develop alternative sources of energy before a serious shortage occurs.

The trend has been to rely heavily on electricity generated by coal-burning thermal plants and nuclear reactors to satisfy our near and mid-term future energy needs. It is argued by many, however, that other energy sources, especially those that are non-depleting, should be developed as a possible solution to our long-term energy needs. The alternative sources that can be used to generate power or to simply provide heat include geothermal, tidal, wind, and solar. Of these alternatives, solar energy shows the most promise for near-term application for heating buildings.

This report contains a review of current solar-heating systems, a comparison of the economic competitiveness of solar heating with conventional heating methods, and some guidance on the decisions that must be made in selecting a solar-heating system.

SOLAR-HEATING SYSTEM

A solar-heating system (Figure 1) consists of a solar-heat collection circuit, heat-storage unit, and a space-heating circuit. The essential components are the collector, heat-transport fluid, fluid movers (pumps or fans), storage unit, space heater; and the controls that determine when the heat is collected and when it is distributed to the space.

Solar energy, when available, is absorbed by the solar collector which transfers it in the form of heat to the transport fluid. This fluid then flows to the space heater where the heat is released; any heat that is not needed right away for space heating goes to heat storage.

Two factors influence the form of a solar-heating system. First, the intensity of solar radiation per unit area of collector is relatively low. A solar-heating system, therefore, requires a collector area of about 1/3 to 1/2 the floor area of the "living" space in a home (excluding basement) to satisfy even half the heating requirement of a house. The second factor is that the intensity of solar radiation and the building heating load both vary on a daily and seasonal basis. Moreover, the peak heating load of the building and the peak intensity of solar energy do not occur at the same time, either seasonally or daily. It is this mismatching of load and available solar energy that makes heat storage necessary.

Figure 2 shows how the collected solar heat and the space heating load might vary in a city like Ottawa over two days in March. On a clear sunny day, more solar heat is available than is required for space heating. The excess can be stored for use during the following night and part of the following cloudy day when only very little solar heat is available. This type of storage system, with a capacity to store heat for only one or two days without sun, is usually referred to as short-term storage.

Figure 3 shows the seasonal variation of the space-heating load and the solar heat collected by two solar-heating systems of different sizes. With the smaller system A, the collected heat during spring, summer and fall exceeds the heating demand. In wintertime, however, the heating demand is greater than the collected heat and the difference must be provided by some supplementary source of heat. System B, which is much bigger, satisfies 100 per cent of the heating demand.

The figure illustrates two factors that have a significant bearing on the cost of heat derived from a solar-heating system. One is the solar-heating factor which is the ratio of the solar heat collected (and used) to the total heating load. For system A, it is the ratio of the area under curve 1-2-3-4 to the total area under the heating load curve. The other is the system or equipment utilization factor which is the ratio of the solar heat collected (and used) to the total solar heat that could have been collected by the system over the year. For system A, it is the ratio of the area under curve 1-2-3-4 to the area under the solar collection curve. An important fact to note is that as the solar-heating factor increases, the utilization factor decreases.

One way to increase both the solar-heating factor and the system utilization factor is to provide system A with a heat storage unit that is large enough to hold more than half the heat needed during the whole heating season. The storage is charged during spring, summer and fall, and this heat is used to make up the deficiency during the following winter. This is known as long-term or seasonal storage.

COST OF SOLAR HEATING

The capital investment in a solar-heating system is high but the fuel cost is zero. Thus the cost of the heat that is collected is just the cost of "servicing the debt", i.e., paying interest on the capital that is invested and regenerating the capital during the useful lifetime of the system. These fixed costs depend primarily on the area of the collector and type of collector and are independent of the system utilization factor. However, the amount of heat that is collected and used is proportional to the product of the utilization factor and the system capacity. The unit cost of heat provided by a solar-heating system is lowest, therefore, when the utilization factor is maximum.

A solar-heating system (or any other type of heating system) can be justified economically only if the unit cost of the heat supplied is lower than for any available alternative. The cost of heating by the best alternative means establishes the reference unit price for solar heat, and this in turn establishes a minimum or threshold utilization factor below which solar heating is not able to compete with alternative means.

The utilization factor of a system using short-term storage is high when the usable heat collected by the system is only a small fraction of the heat load for the building (i.e., a low solar-heating factor); the utilization factor decreases as the system capacity increases relative to the building load. Therefore, the threshold utilization factor establishes the maximum fraction of the total heat requirement that can be supplied economically by a solar-heating system, i.e., maximum value of solar-heating factor.

Factors that affect the optimum solar-heating factor are:

1) cost of the solar-heating equipment (collector, storage, etc.),
2) annual maintenance cost,
3) life of the solar-heating equipment,
4) interest on capital,
5) current cost and the anticipated rise in cost of conventional fuels, (i.e., cost of energy purchased from utilities, such as electricity, gas or oil),
6) size of the heating load of the building.

Figure 4 shows how some of the cost parameters affect the over-all cost of energy derived from a system combining solar heating and conventional heating, i.e., combined energy cost. When collector costs are high relative to the cost of purchased energy, the lowest combined energy cost is obtained with a solar heating factor equal to zero (curve 1). As collector costs decrease and purchased fuel costs increase, the proportion of the total heating load that can be economically provided by solar heat will increase, i.e., the optimum solar heating factor will increase. The optimum solar heating factor will also increase with increasing difference between rise in cost of purchased fuel and interest rate on capital. A large building heating load will also increase the optimum solar-heating factor.

The following example indicates the competitive position of solar heating with conventional heating. Consider a typical detached single-family dwelling in Ottawa, built to conform to the 1975 Residential Standards. It might have the following characteristics.

Living floor area (excluding basement) = 1500 ft^2 ($\approx$ 140 m^2)

Heat-loss characteristic $\approx$ 10,000 Btu/°F-day ($\approx$ 5.3 kW·h/°C-day)

Its annual heating requirement would then be about 85×10^6 Btu ($\approx$ 25,000 kW·h). In the 1977-78 heating season, the cost of oil will probably be about 56¢/gallon (equivalent to 1.65¢/kW·h) and cost of electricity 2.5¢/kW·h. The annual heating costs using these sources would be, therefore, between \$410 and \$630.

A solar-heating system with a collector of about 500 ft^2 [1,2] ($\approx$ 46.5 m^2) might reduce the purchased energy consumption to half and thus between \$205 and \$315 could be saved. How much investment can be justified in a solar-heating system that will save \$315 per year? The present worth approach, as outlined in reference 3, can be used to answer this question.

The present worth factor multiplied by the first year's fuel saving gives the upper limit for the investment that can be justified in an energy-saving system. The present worth factor is a function of the durability of the solar-heating equipment, the interest rate, and the rate of escalation of alternative fuel costs. It is impossible to assign precise values to each of these cost factors, but an optimistic guess for a solar-heating system is a present worth factor of 20.

Using a present worth factor of 20 and an energy saving in the first year of \$315, an investment of \$6300 could be justified for a solar-heating system with 500 ft^2 of collector. Allowing about \$1500 for the heat-storage tank, heat exchangers, pumps and controls, \$4800 could be spent on collectors (i.e., \$9.60 per square foot or \$103 per square metre). Flat-plate collectors are currently available at about \$8 to \$14 per square foot (\$86 to \$150 per square metre), although it is anticipated that volume production might bring the costs down somewhat.

When the costs of design, delivery and installation are included with the purchase price, the cost of solar collectors, installed, are more likely to be in the range of \$12 to \$20 per square foot. Thus, at current prices, a solar heating system providing 50 per cent of the space heating load does not appear to be competitive with conventional heating methods, (especially if the solar heating components have a service life that is shorter than that assumed for a present worth factor of 20).

If the current collector and energy costs are represented by curve 1 in Figure 4, a solar-heating system providing a smaller proportion of the building heating load will still not compete with conventional heating. In fact the optimum solar heating factor (SHF) would be zero.

If collector and energy costs are represented by curve 2, however, a solar-heating system providing less than 50 per cent of the heating load could be competitive with conventional heating. Curve 2, reproduced in Figure 5, shows that there is a range of SHF over which solar heating is competitive with conventional heating (that is, where the combined energy cost is equal to or less than conventional or purchased energy cost). The optimum SHF, which results in the lowest combined energy cost, would be in this range. Solar heating is uneconomical above this range because the utilization factor would be below the threshold level. Below the competitive range, solar heating is uneconomical because the energy cost saving with a very small collector is insufficient to defray the cost of the ancillary equipment (such as, pumps, pipes, controls, and storage tank).

The feasibility of solar heating in Canada is examined in much greater detail than in the foregoing, in references 4 and 5. The Waterloo study looked at the sensitivity of solar heating costs to all of the influencing factors described earlier. The study found that solar heating can be competitive with conventional heating methods for certain building types (multi-unit residential buildings) if low-interest capital were made available. Although all feasibility studies are based on a number of predictions of future trends, indications are that solar heating is sufficiently close to being competitive with conventional heating that a considerable amount of research and development on solar heating systems and hardware for Canadian conditions is justified.

DESIGN GUIDANCE

In addition to the high cost, another deterrent to an increased use of solar-heating systems in Canadian buildings has been the lack of a proven design procedure for determining the area of collector required to satisfy a given percentage of the annual heating load of a given building in a specific location. Many groups are currently engaged in activities that should lead to simple and reliable design methods[4, 6, 7, 8]. Within the next few years, the worth of these methods should be validated. Another useful source of information for those concerned with the design of solar heating systems is reference 10. Some factors that must be considered when selecting a solar heating system are summarized in the following.

Design of the House

The most important factor is the design of the house itself. Because of the relatively high cost of solar-heating equipment compared with other energy-saving methods, such as insulation[3] and double windows, the house must be so designed that heat losses are low. More insulation should be installed in the ceiling, exterior walls and basement walls than is required by existing building standards; airtight multiple-glazed windows and insulated or double doors should be used, and their number and total area minimized; and the house should be constructed with care to ensure maximum airtightness. If possible, moreover, the house should be oriented such that solar gains through south-facing windows in winter are maximized.

Selecting the System

Next, one must decide which type of solar-heating system to use. One choice would be a simple system such as that shown in Figure 1, where the solar heat is used directly for space heating; a more complex alternative would be one where solar heat is used as the heat source for a heat pump (Figure 6). The latter offers two advantages: first, by drawing heat from the low-temperature storage, the heat pump operates with the heat storage tank temperature well below the minimum working temperature of the simple system. This greatly increases the amount of solar energy that can be usefully captured by a given size of collector. The second advantage is that off-peak electricity can be used to power the heat pump and the auxiliary heater. The benefits resulting from such a system, however, may not always be sufficient to offset the increase in capital cost for the heat pump.

A choice must also be made between a system using air as the heat-transport fluid and one using water. Although it is not yet clear which type is more appropriate for Canadian conditions, the air system would appear to be better than the water system because there is no danger of its freezing, boiling, or corroding or experiencing water leakage. An air system does, however, require fairly large ducts and fans, and heat distribution costs may be higher.

Protection against freezing and corrosion are the major concerns with a water system. Freezing can be avoided by draining the collector, using an anti-freeze solution throughout the whole collection and storage system, or using a heat exchanger between the collection circuit and the storage, with anti-freeze in the collection circuit only. This last-mentioned approach means that the collector must operate at a higher temperature and consequently at lower efficiency than if no heat exchanger were used.

Corrosion in a water system can be avoided by using copper collectors and piping, but this may increase the cost of the system. With steel and aluminum collectors, non-corroding piping or corrosion inhibitors must be used.

The factors that influence the choice of a solar collector are: cost, efficiency and durability (especially glass breakage resistance and resistance to water damage from rain and condensation). First cost of the collector is an obvious determinant of whether a particular system can be purchased, as described earlier.

Collector efficiency is defined as the ratio of the heat transferred from absorber to the heat-transport fluid, to the total solar radiation incident on the collector. Efficiency is greatest when the solar energy absorbed by the collector is maximum and heat lost by the collector is minimum.

Improving Efficiency of Collector

There are many ways to improve the efficiency of collectors (Figure 7). The absorbing surface is coated black to maximize absorption of solar radiation. The losses from the absorber to ambient air are reduced by providing a transparent cover over the front face of the absorber and insulation on its back. The transparent cover provides one or more air spaces to reduce convective heat loss from the absorber, and acts as a radiation screen to reduce the heat loss by long-wave radiation.

Another method to reduce the long-wave radiant heat loss from the absorber is to use a special coating on the absorber surface, which has a high solar absorptance and a low long-wave emittance (i.e., a selective absorber coating). Long-wave radiant loss can also be reduced by applying a selective coating on the transparent cover facing the absorber. Coatings such as indium oxide and tin oxide reflect the long-wave radiation emitted by the absorber back onto itself, while permitting solar radiation to pass through freely.

In addition to multiple glazing, honeycombs placed in the air space between cover and absorber can suppress convective heat loss. An ideal method for eliminating convective heat losses is to evacuate the air space between cover and absorber, but this is not always practical.

High collector efficiency requires not only minimum losses from the absorber but also maximum solar transmission through the cover. This is achieved by using a cover material that has low solar reflectance and absorptance. Glass that has a low iron content will give minimum absorptance. Attempts are currently being made to coat glass with magnesium fluoride to minimize solar reflectance.

Figure 8 shows how the efficiency of different types of collectors varies with the temperature difference between absorber and ambient, for a given intensity of solar radiation. (It should be noted that all collectors will experience lower efficiencies at lower solar intensities.)

Although the advantages of evacuating the collector and of using selective absorbers are apparent, they will, however, increase the cost of the collectors. Double glazing greatly improves the performance of a collector with a plain absorber, but only slightly improves one with a selective absorber. For Canadian climatic conditions, it is recommended that collectors with a plain absorber should have a double-glazed cover, whereas those with a selective absorber can have a single-glazed cover, except in regions of extreme cold where a double-glazed cover is recommended.

Durability of Collectors

The durability of collectors depends on corrosion resistance, glass-breakage resistance, and life of the absorber coating. The durability of plain absorber coatings has been proved but the same is not true for many of the selective absorber coatings. These should, therefore, be provided with good protection against rain leakage and condensation.

Glass collector covers can be broken easily (by vandals) and are subject to breakage caused by thermal stresses. Thermal breakage can be minimized by using well-cut glass and by mounting the cover so that a minimum amount of glass edge is shaded. Collectors located within throwing distance of the ground should have covers of tempered glass or plastic. Condensation on the glass surfaces should also be avoided since repeated wetting can lead to surface scumming and a reduction in solar transmittance.

If plastic covers are being considered for use as collector covers, their transmission property and durability should be ascertained. The solar transmission characteristic of plastic sheets may be similar to or quite different from that of glass; and the transmission characteristic of some plastics changes with prolonged exposure to weather.

Orientation of Collector

The orientation of the collector affects the amount of solar energy collected by the system. Figure 9 shows how the amount of collectable solar energy varies with tilt angle and collector azimuth angle (that is, the direction in which the collector faces). Values are shown of the total energy that would fall on the absorber (i.e., potentially collectable) from November through March if all days were clear. (This assumption of clear winter days makes the collected solar energy appear to be more sensitive to tilt and azimuth than would be the actual case, as much of the energy collected in winter is diffuse.)

The optimum direction for the collector is facing due south, but a collector facing 15° from south will collect only 3 per cent less energy, and one facing 30° from south will collect about 10 per cent less.

The seasonal collection of solar energy is not very dependent on tilt angle. The optimum tilt angle is shown to equal latitude plus 20°, but the energy collected with a tilt angle anywhere between L + 5° and L + 30° will be within 3 per cent of the optimum collection. The energy collected with a vertical collector (L + 45°) will be about 10 per cent less than the optimum. A solar-heating system that utilizes seasonal storage will collect solar energy over the whole year. Hence, its optimum tilt angle will be 5° to 10° less than the optimum just indicated.

A reflecting surface located in front of the collector array would increase solar energy collection and increase the optimum tilt angle. The benefits of a reflecting surface are greatest where there is very little snow cover in the immediate area of the collector, such as in urban centres. The benefits will be least for houses in suburban and rural areas which are surrounded by snow-covered yards or fields, since the snow cover itself will behave as a reflecting surface.

Heat Storage

The two types of heat storage that can be used are short-term storage and seasonal storage, as described in the introduction. With short-term storage, solar heat is collected only during the heating season, when availability of solar radiation is usually quite low. Seasonal storage, on the other hand, permits collection of solar heat during those seasons when the availability of solar energy, as well as the ambient air temperature, are highest. Thus, for a given collector area, a solar-heating system with seasonal storage will satisfy a much larger proportion of the building heating load than one with short-term storage, provided the heat loss from the storage unit can be minimized. A high degree of insulation is necessary for seasonal storage because the collected heat must be conserved over a long period of time and because any heat lost from storage may create thermal discomfort if the storage unit is located within the building.

The total solar heat collected by a system with seasonal storage can be increased by the addition of a short-term storage unit. During the first half of the heating season, when the temperature of the seasonal storage unit will be quite high, solar collectors can be used to charge a smaller storage unit which will be at a lower mean temperature. The solar-heating system then operates in the same way as a system with short-term storage, except that the supplementary heat is provided by the large storage unit. The only deterrent to using a system with seasonal storage is the cost of the storage unit in terms of material and space.

Regarding the heat capacity to be provided with short-term storage, analyses[5,9] suggest from 1 to 2 imperial gallons of water storage (or its equivalent heat capacity) for every square foot of collector as being optimum (4.9×10^{-2} to 9.8×10^{-2} m^3 of water per square metre of collector). A system using short-term storage and a heat pump would use a slightly larger heat capacity. It is more difficult to recommend a size for seasonal heat storage: one example of such an arrangement will use about 100 gallons of water per square foot of collector (4.9 m^3 of water per square metre of collector).

Water and crushed rock are the most commonly used forms of sensible heat-storage media. Water is most appropriate for a system using a liquid as the heat-transport fluid. It has the highest sensible heat capacity of the commonly used storage materials, but must operate between the freezing and boiling temperatures. It can also suffer from corrosion and leakage problems. Crushed rock is most appropriate for systems using air as the heat-transport medium. Its heat capacity per unit volume is only a third that of water, necessitating a much larger storage unit. It is not restricted to any temperature range, however, and has minimal corrosion and leakage problems. Another advantage of crushed rock as storage is that the storage material is stationary and the storage bed has a low thermal conductance. These factors permit the bed to sustain a large temperature difference between the inlet and outlet of the storage.

When heat is being stored (Figure 10), the collector air enters the storage at one end and leaves at the other, at a temperature lower than the mean storage temperature. This low exit temperature improves the efficiency of collection. When heat is being extracted from storage, the return air from the space enters the storage at the cool end (where the collector air exited). The air heats up during its passage through the storage and leaves at a temperature that is greater than the mean storage temperature. With a non-stratified, i.e., well-mixed storage medium, the exit temperature for both heat collection and heat extraction would be close to the mean storage temperature.

A number of salt hydrates and paraffin waxes[10,11] are also suitable heat-storage materials because they undergo a phase change in the temperature range associated with space heating, that is, between 90 and 120° F (32 and 49° C). When these materials experience a phase change, they absorb or release a considerable amount of latent heat per unit volume. These materials, however, are not without problems: heat exchange with a material changing phase is difficult due to the associated volume change; component separation is a problem with some materials, as is supercooling; and some materials present a fire hazard. But when these problems are resolved, latent-heat storage materials will permit storage units suitable for both air and water collectors that are much smaller in size than a water storage unit of equivalent heat capacity.

Space-heating Circuit

The last subsystem of a solar-heating system is the space-heating circuit. It can be connected to just the heat storage unit, or to that unit and to the collection circuit as well. In most solar-heating systems, the space-heating circuit also incorporates the auxiliary heat source. The solar heat can be distributed to the space by hot air or by hot-water radiators.

A system of radiators can be used with a water collection and storage system (Figure 11). Each space being heated contains its own heat exchanger. Auxiliary heat can be provided by electrical space heaters, an independent air-heating system, or by a water heater connected in parallel with the solar heat storage unit.

A hot-air distribution circuit is most appropriate for a system using air as the heat-collection fluid and crushed rock as the storage medium (Figure 12). The hot air from the collector can go direct to the space-heating circuit or to storage. Similarly, the space-heating circuit can withdraw heat from the storage unit. The auxiliary heater is usually located in the main heat distribution line. The only heat exchanger in the space-heating circuit is the crushed rock in the storage unit.

A hot-air distribution circuit can also be used with a water collection and storage system (Figure 13). A heat exchanger is required to transfer solar heat to the space-heating air. The auxiliary heater can be located in a number of locations (A, B or C), but is best located at A to maximize utilization of solar heat.

One method of integrating a heat pump with a solar-heating system has already been discussed (Figure 6). An alternative method is to add a water-to-air heat pump in series with the solar heater (Figure 14). In this system, the heat pump is just an energy-efficient, on-line heater. This configuration still permits the use of solar heat at a temperature lower than is possible with direct solar heating, but it does not offer the advantage of off-peak power utilization as was the case with the arrangement shown in Figure 6.

Service-water Heating

Many parts of the world now use relatively inexpensive service water heaters located on house roofs (Figure 15). By locating the storage tank above the collector, water circulates between collector and storage by natural convection. In Canada, unfortunately, these heaters could not operate during the winter since freezing would occur.

A solar service water heating system for Canadian conditions would be very similar in appearance to that of a solar space heating system, with the exception that the service water would need to be physically, but not thermally, isolated from the fluid circulated through the solar collectors. The use of solar energy for service water heating is a much more appropriate application than the use of solar energy for space heating alone, because such a system would be used throughout the year. It has been found that, in general, a system with 50 to 100 square feet of collectors can satisfy in excess of 50 per cent of the service hot-water demand of single-family residences.

Service water pre-heating can also be integrated as a part of a solar space heating system (Figure 16) by passing the feed water to the service-water heater through a heat exchanger in the main storage unit, or by exchanging heat between the fluid leaving the collector and the service water tank.

The advantage of adding a service-water heating capability to a solar space-heating system is that the solar heating equipment could be used throughout the year, thus increasing the utilization factor of the system.

SUMMARY

The cost differential between solar heating and conventional heating is not excessively large and should decrease with time. Moreover, because of the large amount of fuel that could be saved by using solar heating, continuing development of solar-heating systems for Canadian conditions merits support.

Major questions regarding solar heating in Canada that have not yet been resolved are:

(a) the service life of the components used in current solar heating systems;

(b) whether air-heating collectors are more appropriate than water-heating collectors in a freezing climate;

(c) whether first cost of collectors should be the over-riding criterion in selecting a solar-heating system, or whether high-efficiency collectors, even at an increase in cost, are preferable in a cold climate with minimum sunny days in winter;

(d) whether seasonal heat storage is cost-effective;

(e) whether a solar system augmented by a heat pump is more appropriate for Canadian climate than a simple solar-heating system.

Studies and demonstration projects now being conducted in Canada should provide answers to some of these questions within the next few years.

References

(1) Hunn, B.D., G.J.E. Willcutt and T.B. McSweeney. Simulation and cost optimization of solar heating of buildings in adverse solar regions (Ottawa). Solar Energy, Vol. 19, 1977, p. 33-44.

(2) Willcutt, G.J.E., B.D. Hunn and T.B. McSweeney. Cost optimization of solar heating of buildings in northern regions (5 Canadian cities). American Society of Mechanical Engineers, Paper 75-WA/Sol-9, 1975, 12 pages.

(3) Stephenson, D.G. Optimum thickness of insulation. To be issued by Division of Building Research, National Research Council of Canada as Building Research Note No. 105.

(4) Orgill, J.F. and K.G.T. Hollands. Users' manual for WATSUN - A solar heating simulation and economic evaluation program. Waterloo University, April 1976, 83 pages.

(5) Hollands, K.G.T. and J.F. Orgill. Potential for solar heating in Canada. Waterloo University, Report 77-01, February 1977, 102 pages.

(6) Klein, S.A., W.A. Beckman and J.A. Duffie. A design procedure for solar heating systems (Liquid). Solar Energy, Vol. 18, 1976, p. 113.

(7) Klein, S.A., W.A. Beckman and J.A. Duffie. A design procedure for solar air heating systems. Proceedings of Joint Conference (1976) of the American Section of the International Solar Energy Society and the Solar Energy Society of Canada Inc., Aug 15-20, 1976, Winnipeg, Vol. 4, p. 271-279.

(8) Balcomb, J.D. and J.C. Hedstrom. A simplified method for calculating the required solar collector array for space heating. Proceedings of Joint Conference (1976) of the American Section of the International Solar Energy Society and the Solar Energy Society of Canada Inc. Aug 15-20, 1976, Winnipeg, Vol. 4, p. 281-294.

(9) Löf, G.O.G. and R.A. Tybout. Cost of house heating with solar energy. Solar Energy, Vol. 14, 1973, p. 253-278.

(10) Duffie, J.A. and W.A. Beckman. Solar energy thermal processes. John Wiley and Sons, 1974.

(11) Telkes, M. Storage of solar heating/cooling. ASHRAE Journal, Vol. 16, No. 9, Sept. 1974, p. 38-44.

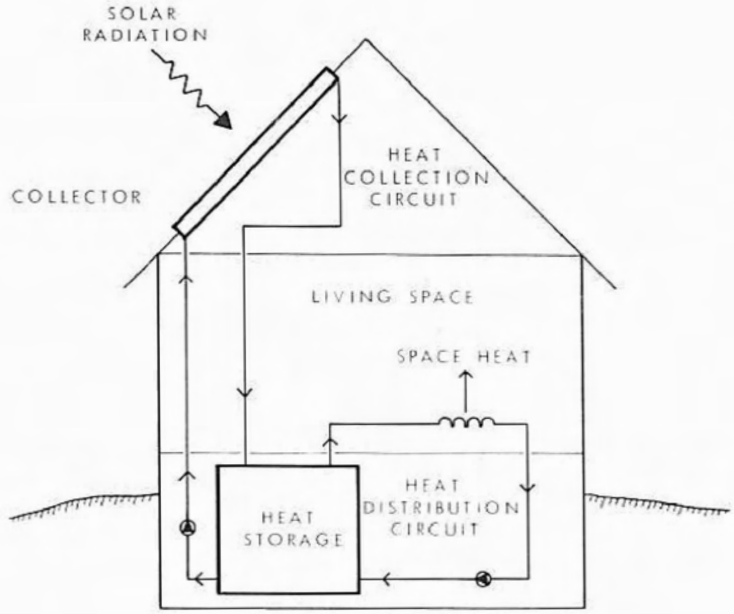


FIGURE 1

SOLAR-HEATING SYSTEM

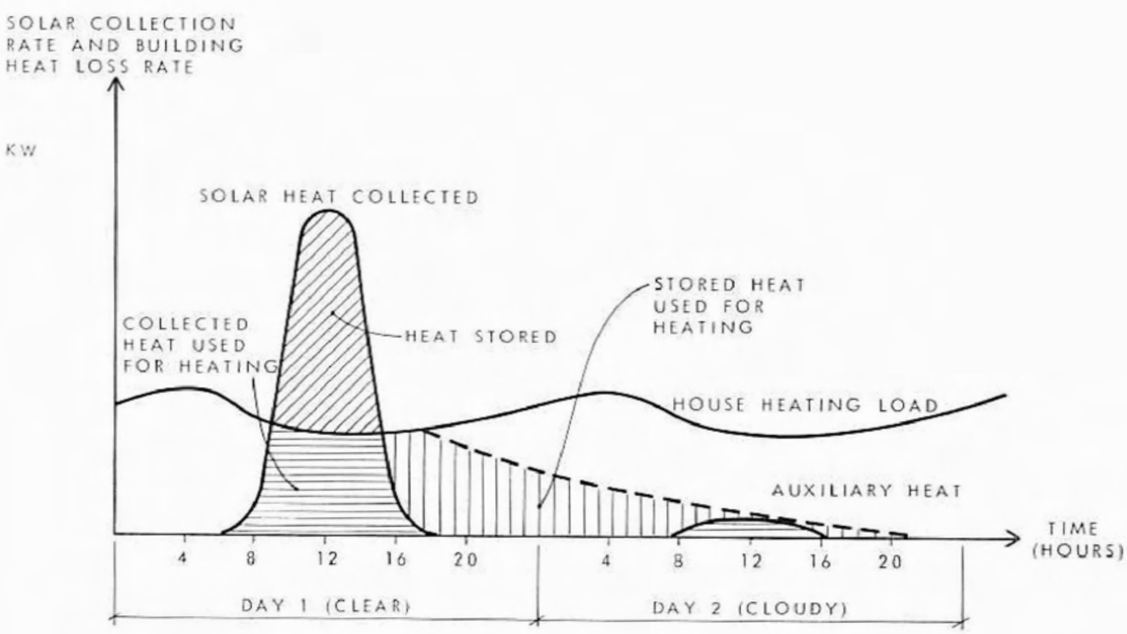
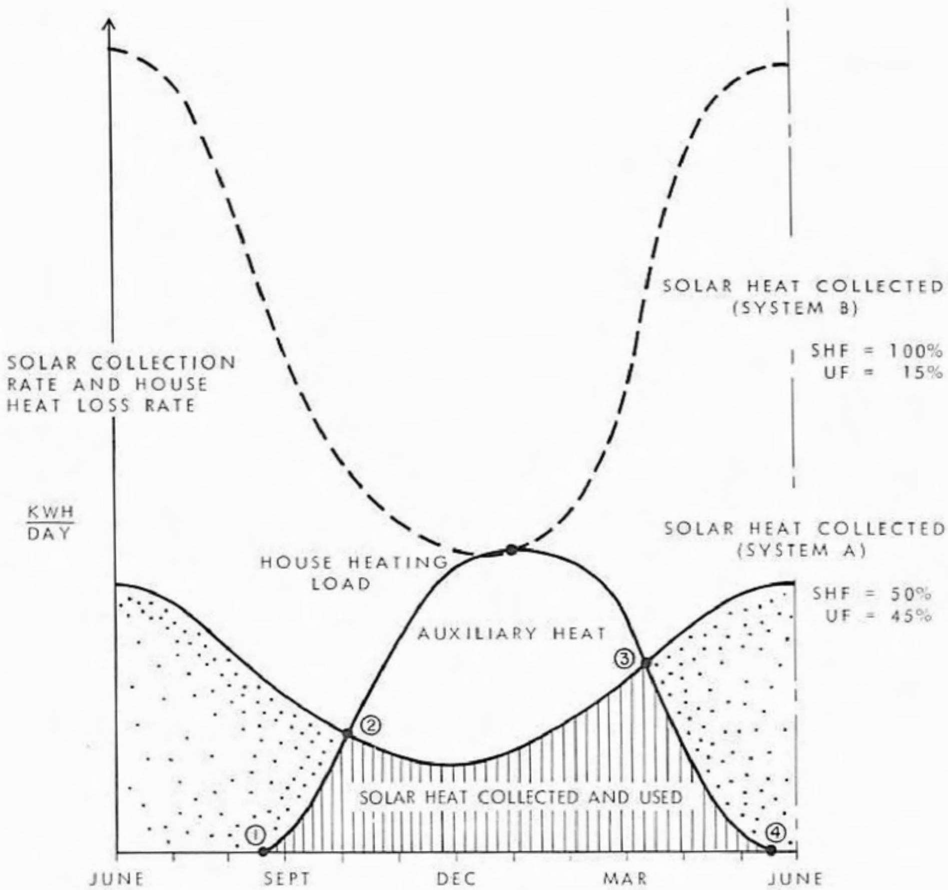


FIGURE 2

DIURNAL VARIATION OF COLLECTED SOLAR HEAT (MARCH DAYS, OTTAWA)



$$\text{SOLAR HEATING FACTOR (SHF)} = \frac{\text{SOLAR HEAT COLLECTED AND USED}}{\text{HOUSE HEATING LOAD}}$$

$$\text{SYSTEM UTILIZATION FACTOR (UF)} = \frac{\text{SOLAR HEAT COLLECTED AND USED}}{\text{TOTAL SOLAR HEAT THAT COULD BE COLLECTED}}$$

FIGURE 3

ANNUAL VARIATION OF COLLECTED SOLAR HEAT

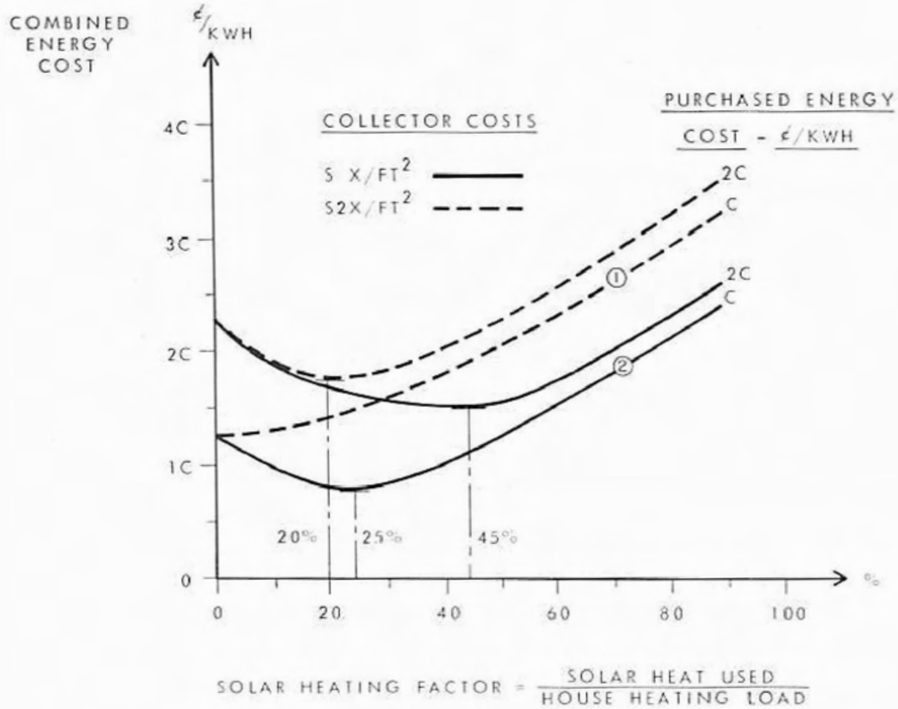


FIGURE 4

COST OF ENERGY FROM COMBINED SOLAR/CONVENTIONAL SYSTEM

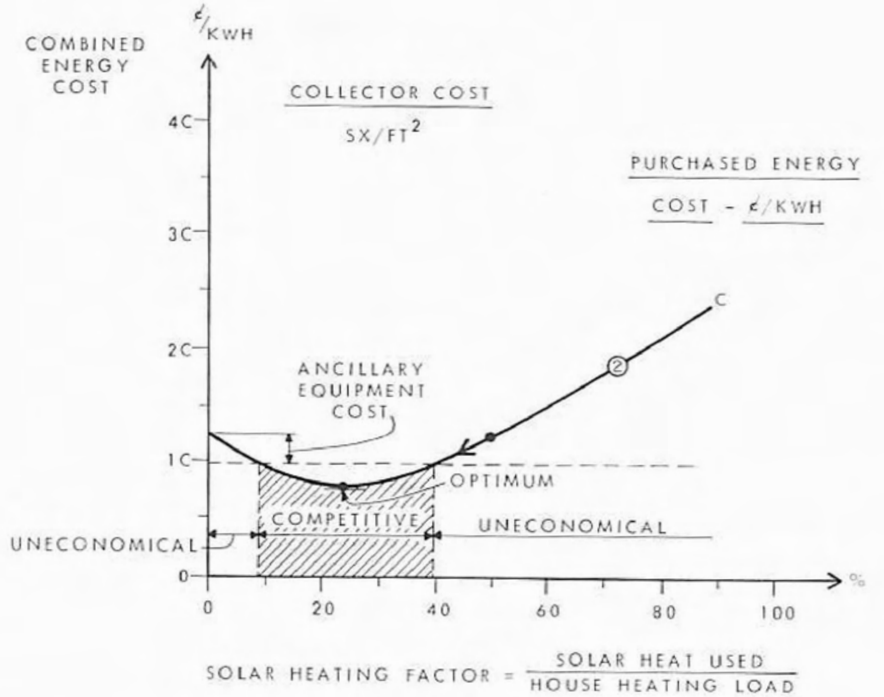


FIGURE 5

COST OF ENERGY FROM COMBINED SOLAR/CONVENTIONAL SYSTEM

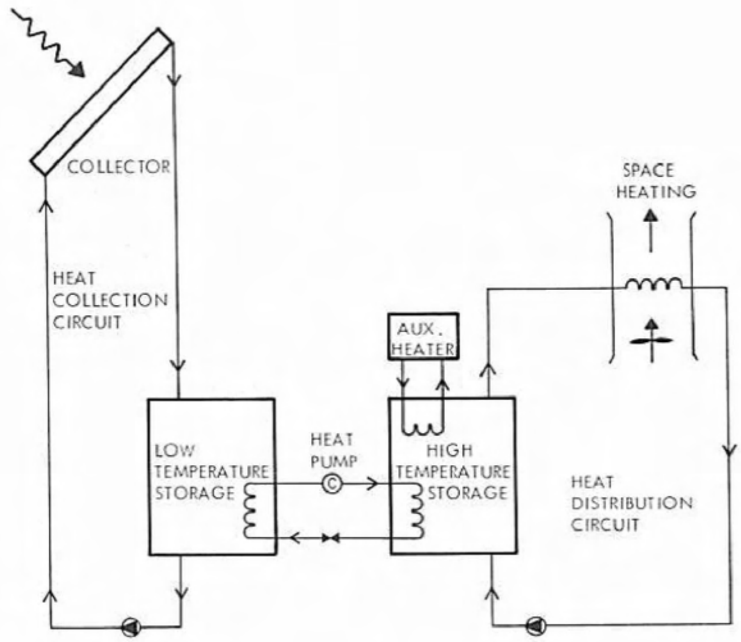
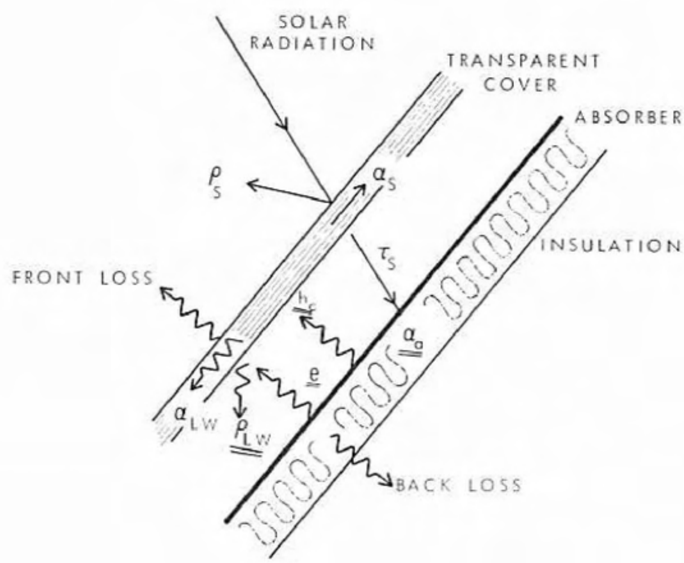


FIGURE 6

SOLAR HEATING SYSTEM WITH HEAT PUMP (1)



DESIRED ATTRIBUTES

SOLAR TRANSMITTANCE,	τ_S	= MAXIMUM
SOLAR REFLECTANCE AND ABSORPTANCE,	ρ_S AND α_S	= MINIMUM
SOLAR ABSORPTANCE (ABSORBER),	α_a	= MAXIMUM
LONG-WAVE EMITTANCE (ABSORBER),	e	= MINIMUM
LONG-WAVE REFLECTANCE AND ABSORPTANCE OF COVER,	ρ_{LW} AND α_{LW}	= MAXIMUM
AIR-SPACE CONDUCTANCE,	h_c	= MINIMUM

FIGURE 7

SOLAR COLLECTOR HEAT BALANCE

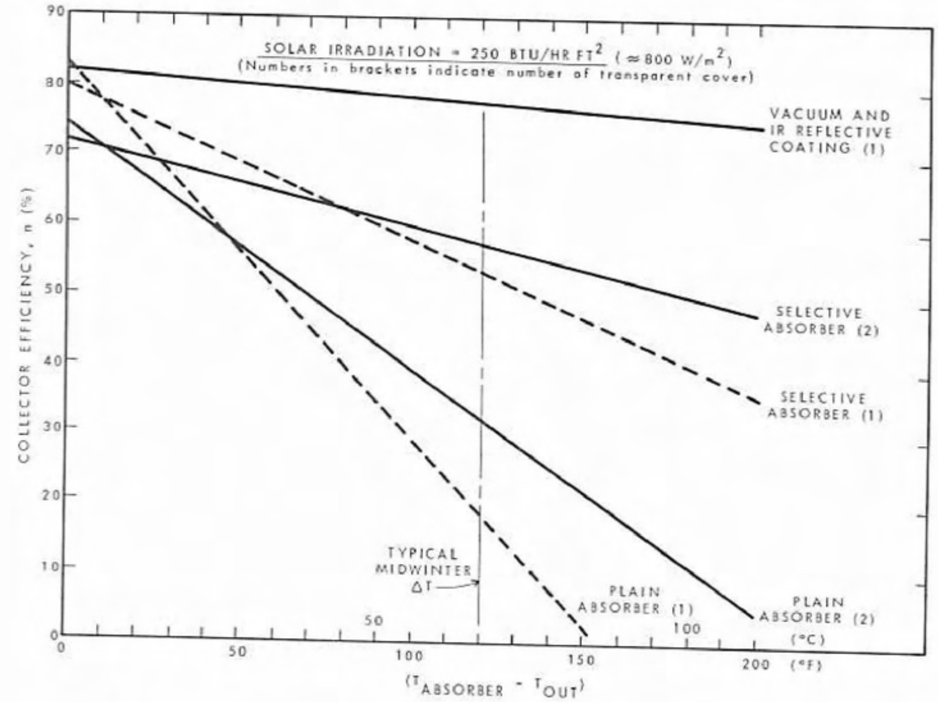


FIGURE 8
REPRESENTATIVE COLLECTOR CHARACTERISTICS

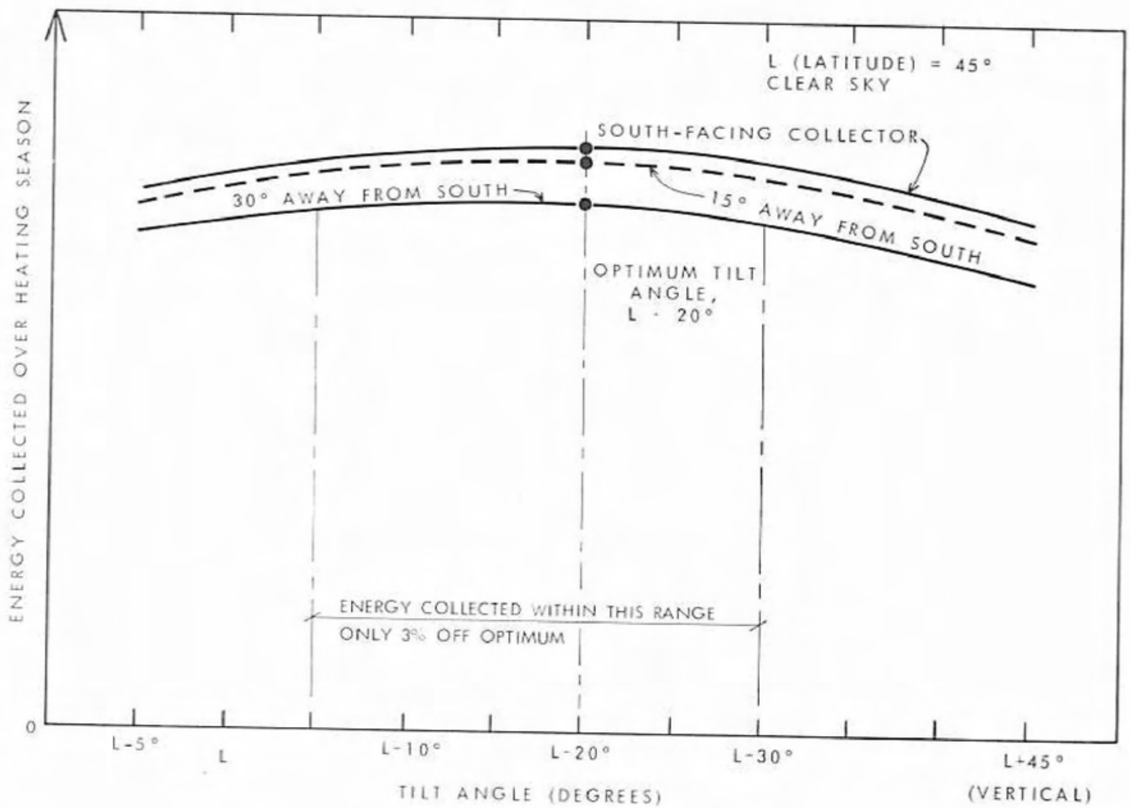
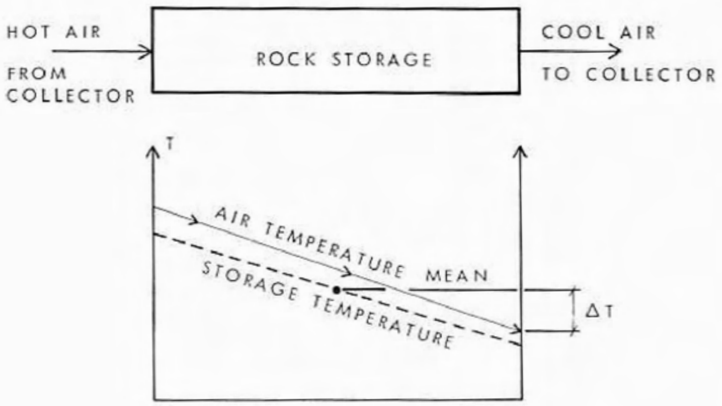


FIGURE 9
VARIATION OF SEASONAL ENERGY COLLECTED WITH TILT ANGLE AND AZIMUTH ANGLE

(A) HEAT INTO STORAGE



(B) HEAT FROM STORAGE

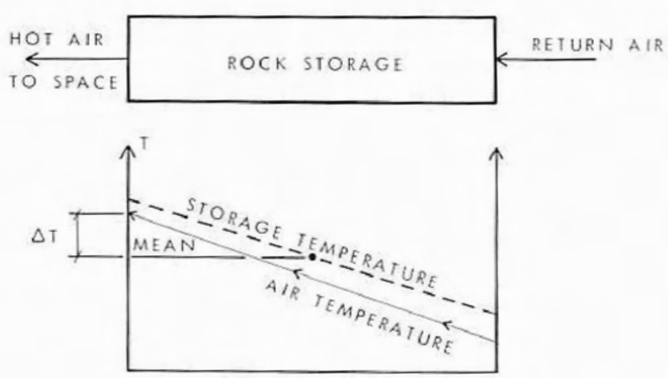


FIGURE 10
TEMPERATURE STRATIFICATION IN ROCK STORAGE

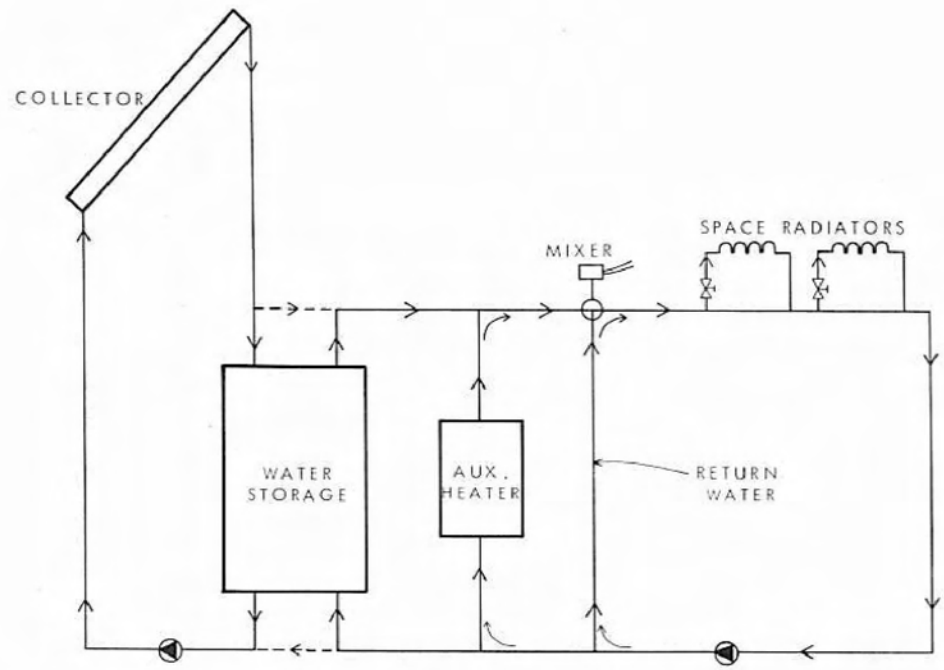


FIGURE 11
WATER COLLECTION AND DISTRIBUTION

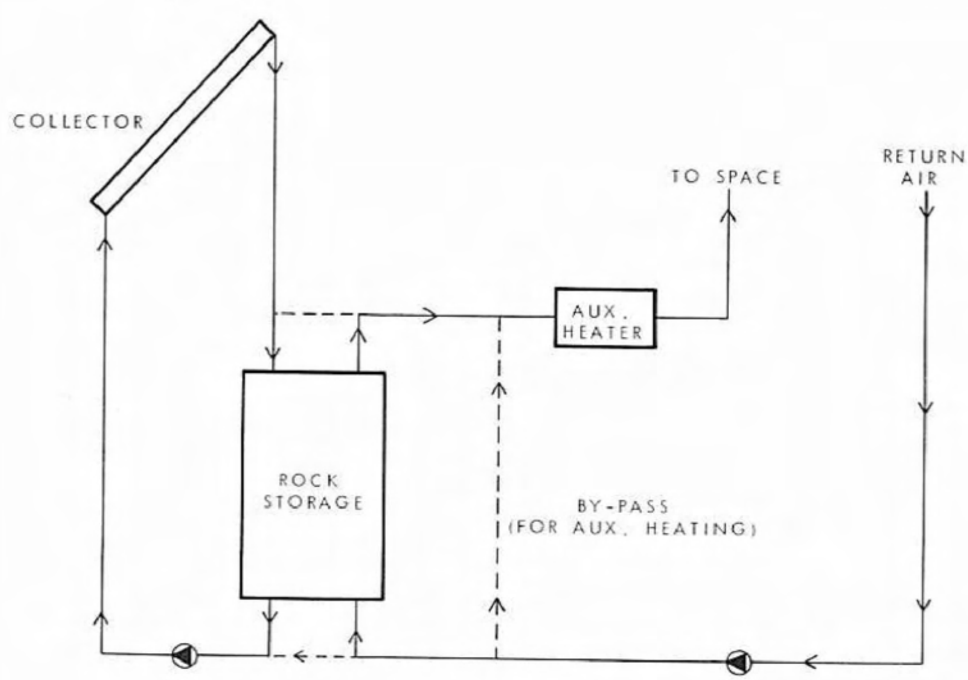
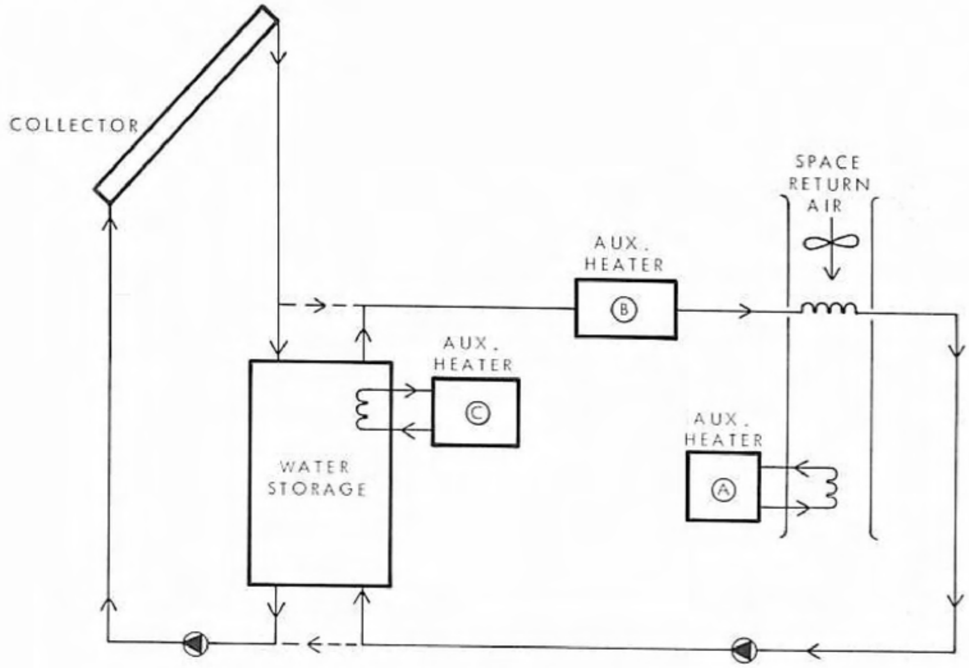


FIGURE 12
AIR COLLECTION AND DISTRIBUTION



A, B AND C = ALTERNATIVE LOCATIONS FOR AUX. HEATER

FIGURE 13
WATER COLLECTION AND AIR DISTRIBUTION

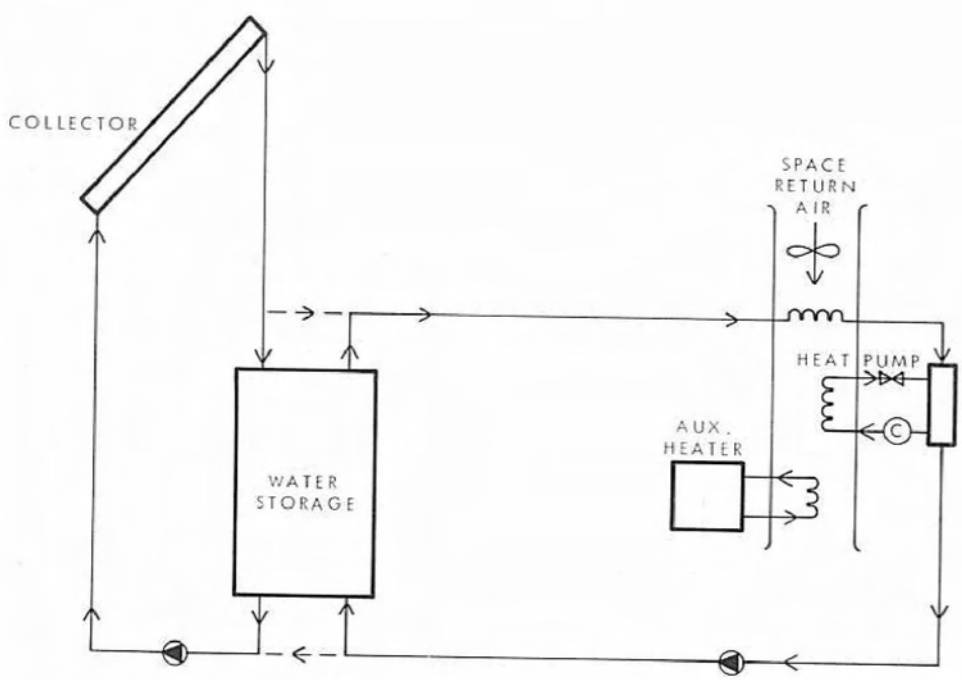


FIGURE 14
SOLAR HEATING WITH HEAT PUMP (2)

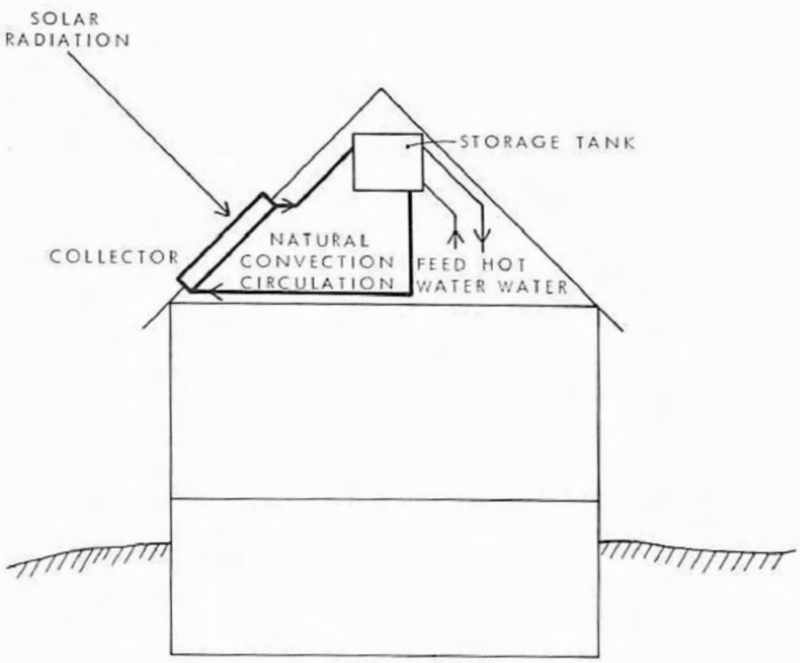


FIGURE 15
NATURAL-CIRCULATION SERVICE WATER HEATER

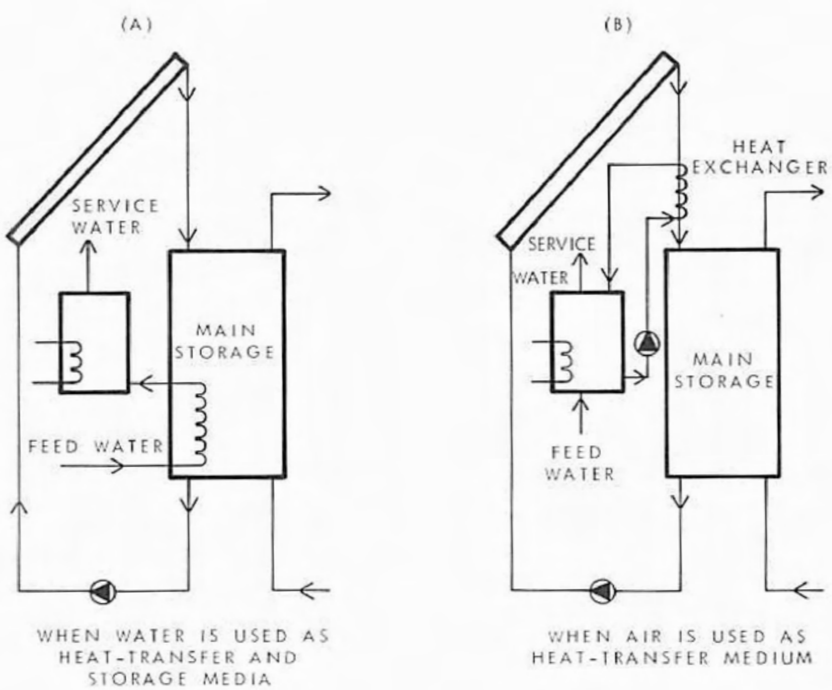


FIGURE 16
SERVICE WATER HEATING