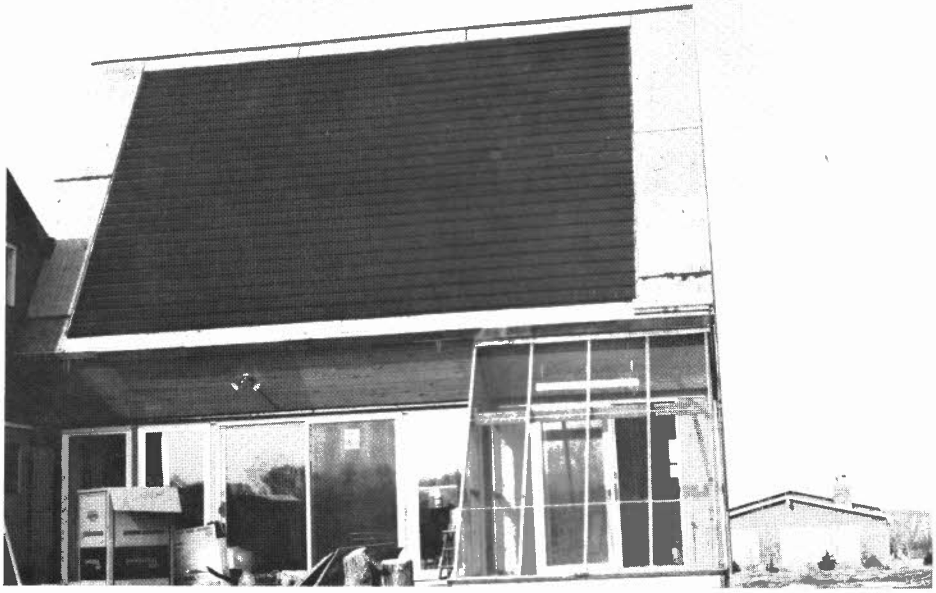
Chapter Two
Design Rationale

2.1 Concept

The purpose of the development of this solar design was to significantly lower the cost of active solar systems by 1) designing a collector which shares several of its components with the building, reducing duplication of materials, and 2) developing a low cost delivery and storage system. Since commercially available active systems have only been marginally cost-effective in residential applications, TEA believed the introduction of an effective low-cost design would fulfill a tremendous need. In the predicted growth of residential solar applications there was clearly a definite role for economical active systems, even though passive solar systems prove an attractive option for much new construction. It was felt that for many buildings a combination of active and passive solar systems would be the best solution, while for others only one type would be appropriate.

Any new building design should be influenced by the principles of passive solar, at least to the extent of having some direct gain windows on the south wall. In cases where it might be difficult to integrate a passive system requiring a large aperture area on the wall, (for example, when a traditional house design is desired), the best option may be an active roof collector. In addition, in many climates the only way of achieving a high solar fraction (fraction of total heating need supplied by solar) is by combining both passive wall systems and active roof systems. Active collectors also have the advantage of permitting a large aperture area over a fully insulated wall or roof. This means the rate of heat loss or gain of the building is not increased--a particularly important consideration in cold climates which do not have a great deal of sun, and in climates which experience hot summers.

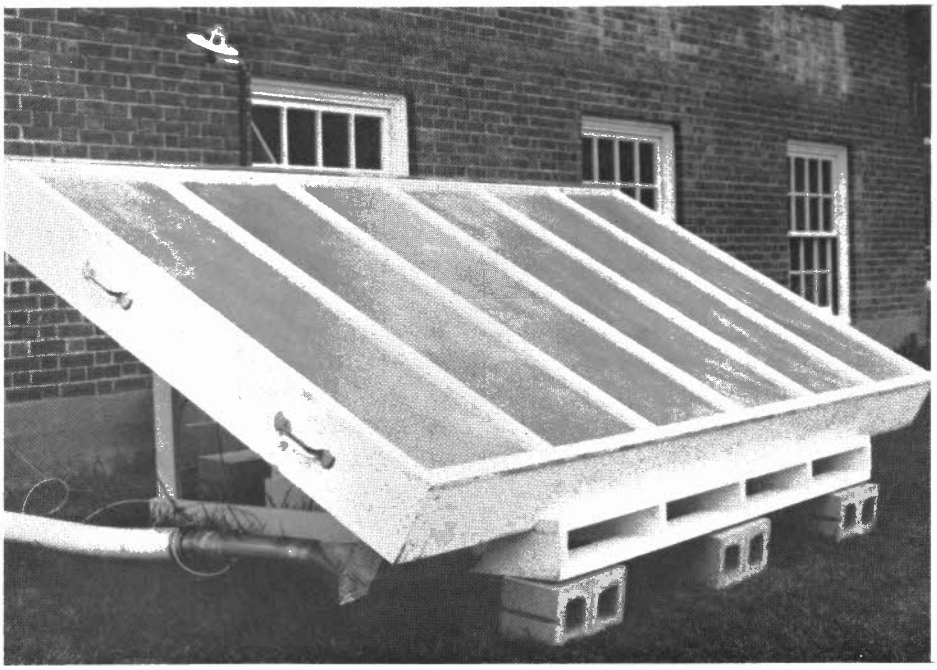


Direct Gain

In retrofitting existing buildings for solar, active becomes an even more likely option. Existing buildings often do not have a large wall area with a solar exposure, but do have a well exposed roof. Then a large roof collector and a complete storage system is the best way of achieving a sizeable solar heating fraction. Even if there is a wall with good solar exposure, the plan of the house may not allow for the use of passive systems -- for example the south wall may be the garage wall. In these situations an active wall collector can be very useful, delivering the heat wherever it is most needed. If the collector area is not large, no storage is required (the collector being run only when heat is needed) and costs are dramatically reduced.

TEA's decision to develop an air system, rather than a liquid design, was based on the consideration of a number of issues. Air collectors are simpler to build on-site for those without plumbing skills, and the collector materials are usually less expensive. The collectors are not subject to catastrophic freezing, and long-term corrosion is not a problem. The only long-term degradation problem is air leakage. The MODEL-TEA collector is initially assured to be air tight by incorporating a smoke test into the construction process; at anytime thereafter the collector can be retested and recaulked if leaks are suspected. Liquid collectors have the distinct advantage of a potentially higher heat removal efficiency factor (F_R). In addition, the liquid delivery and storage systems occupy much less space than those for air. Altogether the advantages and disadvantages of the two types of systems seem fairly equal. TEA's decision to develop an air system was influenced by the belief that it could produce a design which costs less, did not leak, and could be easily integrated (including duct work) into most buildings.

The final design had to fulfill many criteria. In order to promote widespread use, it had to be low cost, simple, and easy to build using conventional techniques. Visual appearance was very important; the collector had to be considered an attractive addition to homes, or at least not a detractive one. But at the same time the system had to perform well, be reliable, and maintain long term durability under very demanding conditions of extreme temperature variations and weathering. This set of requirements established a very challenging project goal.



Collector Test Module

2.2 Development of Project

TEA began the project by conducting a nationwide survey of site-built installations. A detailed questionnaire was mailed to all site-builders who could be first contacted by phone and introduced to the project, and 20 questionnaires were returned. Descriptive information on materials used, problems experienced during construction, and durability of materials was fairly complete in most questionnaires, whereas quantitative performance information was very sketchy. The project staff learned a great deal from the questionnaires.

The next phase of the project was an extensive review of all materials available for site-fabricated air collectors. Information was gathered primarily from manufacturers, but many independent sources such as testing laboratories and actual builders were incorporated as well. Glazing materials, absorber plates, collector paints, sealants, fasteners, and structural materials were evaluated with respect to available sizes, physical properties, and cost. Particular emphasis was given to ease of handling, reliability, and durability.

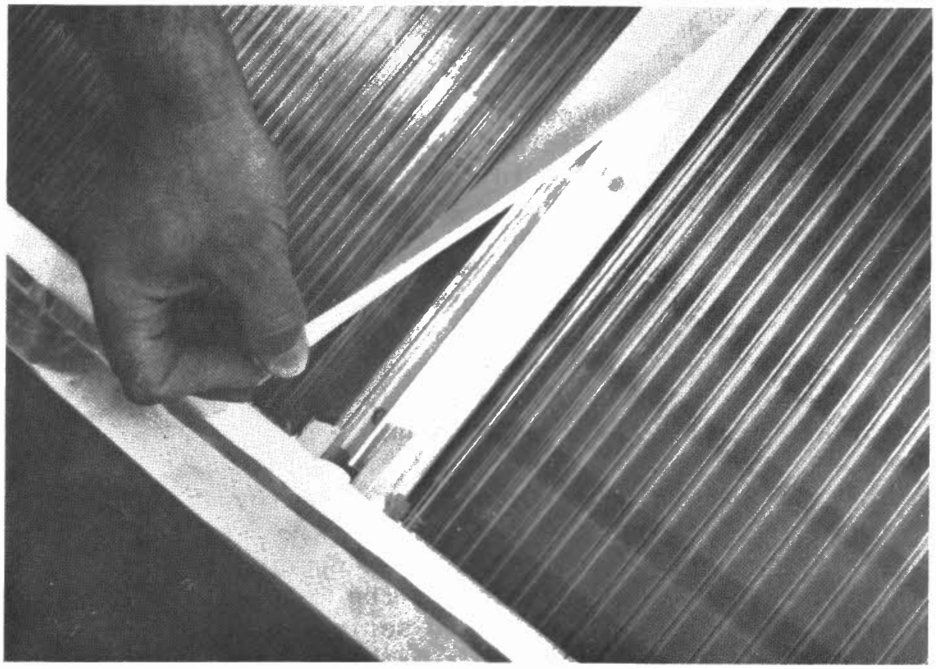
The third phase of the project was the creation of six collector designs based on the questionnaire results, the materials survey, and TEA design experience. Collector performance parameters were theoretically determined for each design, collector efficiency curves were calculated, and annual performance was determined in two cities using the f-Chart computer method. Material and labor costs were established for each design, and construction simplicity, care of building integration, reliability, durability, and aesthetics were evaluated. Through this process the TEA staff selected the best design of the six. The project continued with the optimization of this design. The effects on collector performance of 1) air mass flow rate, 2) collector plate length, 3) collector channel configuration, 4) paint emissivity, 5) insulation, and 6) glazing alternatives were studied. In addition, procedures were developed to determine the optimum air flow rate, collector path length, and channel size for various specific applications.

To pursue the study of this optimum design, five collector test modules were constructed and tested according to strict industry test procedures (ASHRAE 93-77 standards and the HUD 30-day stagnation test). A standard, commercially manufactured air collector was tested on the same equipment for direct comparison. This allowed not only a direct check of the site-fab design vs. the manufactured, but also allowed a comparison with testing results on the manufactured collector obtained by another nationally recognized independent testing laboratory. The overall purpose of the testing program was to provide basic performance numbers for comparison with the theoretical predictions, and to allow a direct evaluation of the collector modules regarding such considerations as durability, ease of construction, weathering, and aesthetics. The modules differed in the types of glazing material, absorber surface, and amount of caulking material.

The testing program produced a wealth of valuable information. The measured efficiency of the basic design showed excellent agreement with TEA's theoretical calculations. In addition, after more than 30 days of summertime stagnation, the collector efficiency did not decrease. The test modules showed no degradation due to weathering or high temperature stagnation. All the collector modules were tested for leakage, and the results demonstrated that eliminating leaks is probably the most critical aspect of site-building an air collector. As a result of these tests TEA has specified a smoke test as an integral part of the construction process, and it has been demonstrated in actual installations that the collector can readily be made air tight.

One of the most valuable results of this testing program concerned glazing materials. Although the project staff was seriously considering glass, due in large part to aesthetic considerations, three types of plastic glazing materials were tested on the modules. One type was a total failure, and the other two showed serious problems, making glass the ultimate choice. The search for a method of fastening the glass to the collector arrived at three alternatives, and to assist in choosing among these, another testing program was begun. A full scale mock-up of a 60° tilt roof was constructed, and the three glazing systems were mounted side by side. The test provided information about the ease of installation and weathering characteristics of each system. With the final selection of a glazing system the collector design was completed.

The next major phase of the project was the development of the air-handling systems. After surveying current designs, TEA began work on a simple low cost design which could be integrated into existing buildings or used in new construction. For small collectors (usually on walls) only a very simple system was required, as no storage would be employed. In these applications a fan and ductwork would deliver the heated air from the collector directly to the living space whenever there was both demand for heat and sufficient sunshine. But for larger collectors a storage rock bin would be used, and a more complicated air-handling system would be required. It was important that this system not depend on any particular building configuration, since it had to be adaptable to either new construction or retrofit.



Failure of Acrylic Glazing

There were basically two possible approaches, either employing a commercially manufactured air-handler, or one built on site from separate components. Most manufactured residential air-handlers cost from $1500 to $2000, including controls, although there are two innovative products available for approximately $1000. Separate components can be purchased to build a system on site for roughly $1000. The labor cost of the site-built air-handler increases the total cost to roughly the same as that of the standard commercial air-handlers, but the resulting site-built product is of better quality. By buying separate components and assembling on site, the fans and dampers can be better integrated into the ductwork. This results in two major advantages. First, during construction it is easier to accomodate the relative positions of the rock bin and duct runs. It can be difficult to install a manufactured air-handler in a limited space, especially in retrofit situations where positions of rock bins and duct runs are dictated by other considerations. Secondly, since the site-assembled system allows for straighter duct runs and less bends near fans, the pressure drops are lower, resulting in greater system efficiency.

Thus the site-assembled air-handler was preferred over the manufactured, despite similar costs. The $1000 innovative commercially available air-handlers (see Chapter 9) were, however, attractive alternatives. Still, the project staff preferred not to depend solely on one or two commercial products, especially innovative designs which had not experienced widespread use. This consideration was the basis for one of the major advantages of the site-assembled system; all of the components could be purchased from more than one source, and had proven track records. However, the commercially available air-handlers discussed in Section 9.1 may prove to be the best answer for many applications. They offer a significant advantage in simplifying the installation of both air-handling equipment and controls.

Based on TEA's research, and its experience with design and installation of solar air heating systems, a final design was completed which uses two fans and three standard low leakage dampers. In existing buildings this system is installed independently of the present conventional heating system (in parallel). This enables a straightforward installation, no matter what type of heating system is present. In new construction the solar system replaces a conventional heating system. Auxiliary heating is accomplished by inserting the heater in the ductwork so it is in series with the solar system, resulting in beneficial pre-heating by solar even when the latter cannot carry the entire load. This series installation is possible in new construction since the auxiliary can be carefully integrated with the design of the solar system, and since new buildings do not require an extensive heat distribution system, due to their high level of insulation. Thus, a properly designed new building (Section 3.1) can result in a substantial savings due to the synthesis of the solar and auxiliary heating systems.

In addition to this relatively conventional air-handling system, TEA developed an innovative system suitable only for new construction. This design allows a substantial cost savings for buildings where the designer is willing to carefully integrate the system needs with the building design. The system utilizes a one-way rock bed, one fan, and two mechanically connected dampers. The rock bed is integrated into a wall or under a floor. This design is described in detail in Chapter 9.

The rock bin which accompanies the conventional air system in either new or existing buildings is a proven TEA design. It is a two-way rock bin which uses a compact U-shaped air flow path, allowing for duct connections at the top, low height, and simple construction.

The only remaining project task was the design of controls to govern the air-handling systems. Consistent with the overall philosophy of the project, a site-assembled control system was developed. The controls utilize standard components which can be purchased from a number of sources. The completion of the control system constituted the final phase of the design development, the only remaining task being then the dissemination of the design.

2.3 Materials

The review and selection of materials was perhaps the single most critical aspect of the design development. The material requirements of the delivery and storage systems were somewhat familiar, but the collector provided a very challenging set of demands. The materials required for a typical solar collector are the glazing, absorber plate, paint or coating, caulk, insulation, frame, and fastening hardware. In choosing these materials, the most important considerations are usually performance, durability, cost, and attractiveness. But for a site-fabricated collector, materials must also be readily available and easy to handle and fabricate. Ideally, a site-built collector should be constructed from standard building materials which are familiar to the builder.

However, a collector is a much more demanding application of materials than normal building construction. The collector materials are subject to extreme temperature variations over a twenty-four hour period, and large daily temperature differences between the inner and outer layers. They must endure intense ultra-violet radiation and high temperatures for at least twenty years, while still maintaining all their desirable physical properties and retaining the air-tight and water-tight joints. It is a difficult problem, because on the one hand the materials should be standard, familiar, inexpensive, and commonly available, but on the other hand they must perform outstandingly well in an application which is far more exacting than standard building construction.

The final choices for the MODEL-TEA were the result of an extensive assessment of all materials available for site-built solar systems. Clearly, in order to satisfy conflicting requirements, some compromises had to be made. Standard aluminum industrial siding was chosen for the absorber plate. The only reasonable alternative was galvanized steel siding, but that is not readily available in the configuration required. The aluminum necessitated the use of more expensive fasteners in order to prevent galvanic corrosion, but that was considered to be an acceptable compromise. The exact configuration of the siding was determined by theoretically optimizing the collector performance. Thermo-ply, a foil-faced impregnated fiber sheathing, was selected to be placed over the studs or rafters, forming the back side of the air channels. The Thermo-ply provides an air tight surface and prevents the wood from being directly exposed to the hot air blown through the collector. It also has the benefit of reducing the collector's thermal capacitance by helping to thermally separate the collector from the mass of wood in the rafters or studs. The foil face of the Thermo-ply together with the unpainted back of the aluminum absorber greatly reduces heat transfer from the absorber to the sheathing. This results in a slight decrease in instantaneous collector efficiency, but that was calculated and found to be offset by the increase in daily performance due to the lower thermal capacitance.

The ends of the absorber are closed with EPDM rubber end closure strips which are purchased with the absorber. There are many different types of EPDM and these differ in their tolerances of high temperatures. The type of EPDM used in the rubber end closures should endure normal collector operating temperatures (140°F) with no significant degradation. At temperatures above 250°F to 300°F the material begins to outgas and will slowly harden over time. Polyvinyl chloride (PVC) is the only other material commonly used for rubber end closures. It is definitely <u>not</u> recommended. It will soften and significantly shrink at temperatures below 200°F.

Caulking materials are essential to obtaining air-tight joints, and it is critically important that the manifold pans and absorber make a leak-free envelope. Two types of high performance caulk are recommended for the MODEL-TEA. Silicone caulk is a high performance material capable of withstanding temperatures up to 400°F without serious degradation. However, its skin-over time is too short (less than ten minutes) to allow its use in normal sandwich or layered joints in site-built construction. Silicone can only be used to seal corner-type joints, after the pieces have been fastened together. Urethane caulk is the recommended material for the standard layered joints in the collector. Its tack-free and skin-

Painted Absorber Plate

over times are sufficiently long to allow proper caulking and positioning of large sheets of collector materials. The adhesive properties are excellent, and it can tolerate temperatures up to at least 275°F without degradation.

The absorber requires a flat black surface which has long-term durability under extreme temperature variations. Both paints and selective coatings were evaluated, and although selective coatings improve collector efficiency, they were not chosen due to their higher cost and incompatibility with the site-built approach. Epoxy base paints have often been used in collectors because the paint cures by chemical reaction, minimizing outgassing. However, these paints are very expensive and are not really necessary unless the construction schedule does not allow several days for drying. TEA believes that standard enamel paints, which dry by solvent evaporation, will not cause outgassing problems if they are allowed to dry completely (at least two full days). The recommended paint for the absorber is any standard oil base flat black enamel of proven durability and sufficient temperature tolerance.

Vertical battens are placed over the absorber plate to support the glazing. Good, straight, dry wood should be used for these, either spruce or fir, but definitely not pine. Pine outgasses at low temperatures and the resin will coat the glazing, reducing transmittance. Aluminum can be used for the battens, probably providing longer term durability, but at a significant extra cost. The details of the aluminum batten option are given in Chapter 9.

Steel screws cannot be used to fasten the battens to the aluminum absorber, as galvanic corrosion will result. The recommended fasteners are stainless steel or aluminum.

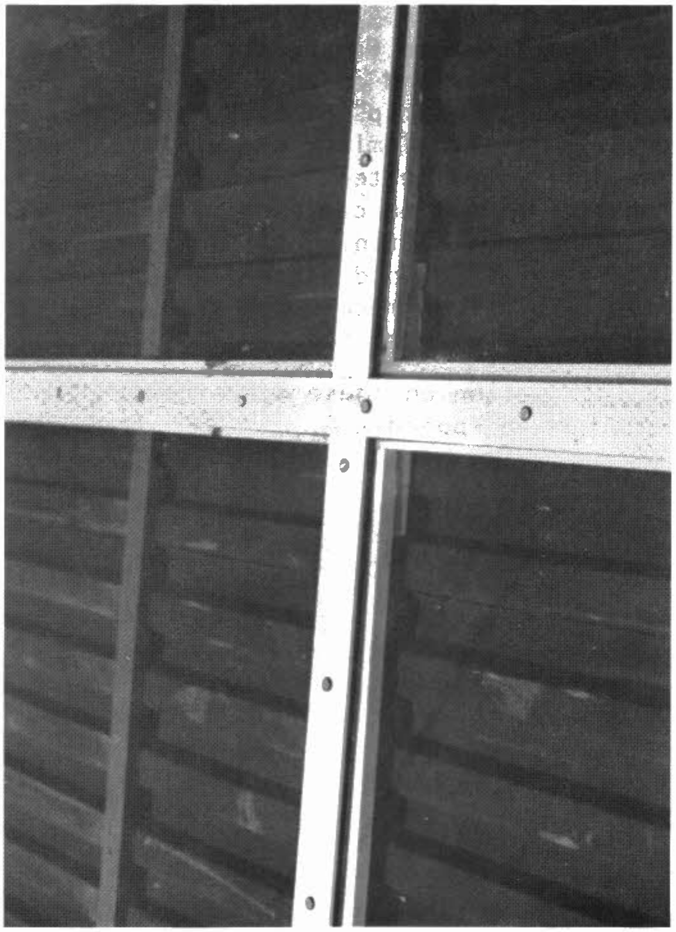
The recommended glazing material is single glass for the roof collector and double glass for the wall. TEA conducted computer simulations of collector performance and cost for double vs. single glazing and found that if collector area is optimized according to life cycle economics, single glazing is competitive with double in all parts of the country. A slightly larger collector with single glazing will deliver roughly the same energy at the same cost as a smaller collector with double glazing. In other words, the increased efficiency (in most areas of the country) of double glazing is roughly offset by the extra cost. Thus, on the roof, where there is usually more area than needed, a large single-glazed collector can be constructed, with the added advantage that single glass is much easier to handle on a roof than double glass. But on a wall application, area is usually very limited, so double glazing is used to collect the most energy per square foot. Handling double glass in vertical wall applications is not as difficult as it would be on a roof.

Glass was chosen as the best glazing material after a thorough evaluation of all available materials. Its durability and visual aesthetics are unsurpassed. High transmittance solar glass can be purchased with either an ordinary flat surface on a textured surface which reduces reflections and glare. TEA tested acrylic, fiberglass-reinforced polyester, and thin film glazings in the hope that one such lower cost material would be acceptable. None were. (See Appendix A for more detailed information.)

The glazing system chosen to fasten the glass to the collector consists of strips of EPDM rubber and an aluminum bar as the outer batten. The glass is held between two strips of EPDM, the inner one being fastened to the wood batten. The outer aluminum batten is screwed to the absorber through the EPDM and the inner batten. This glazing system is very easy to install, and requires almost no caulking material. TEA thoroughly investigated other methods of fastening the glazing, and actually tested three other glazing systems. A wood batten and caulk system was tested on collector modules. On a roof mock-up, a standard greenhouse system and an extruded EPDM system were tested.

More detailed information on these decisions and on specific materials and sources is contained in Appendix A.

Roof Glazing Systems Test



Final Fastening System Choice

2.4 Major Design Decisions

Two categories of key design decisions are discussed here, the first relating to problems caused by high temperatures in the collector, and the second dealing with air-handling and storage matters. The collector normally operates at about 140°F, and all the collector materials can easily tolerate these temperatures indefinitely. However, if the roof collector is allowed to stagnate in the summer (no air flow), temperatures up to 250°F or even 300°F will be reached. This only occurs with the roof collector, not the wall collector. The vertical wall collector does not receive enough solar radiation from the high summer sun to reach temperatures above 250°F. The tilted roof collector receives much more radiation from the high sun angle, especially if instead of being at the optimum tilt (latitude plus 15°) it is at a lower pitch (say 30°) in a retrofit application. During the summer season, a stagnating 30° tilt roof collector would experience temperatures above 250°F for roughly 600 hours in Massachusetts, and 1000 hours in New Mexico. Maximum temperature would be near 350°F.

While these high temperatures do not cause immediate failure of any part of the collector, the long-term effect of temperatures above 250°F is to accelerate the ageing process. The EPDM, caulk, and any wood in or near the collector, are particularly susceptible to accelerated degradation above 250°F. Expansion and contraction of the absorber plate also becomes more severe at these temperatures. All of these factors combine to shorten the lifetime of the collector and increase the probability of developing air leaks. Even the wood in the rafters under the Thermo-ply would begin to suffer significant drying and weight loss over a long period of time.

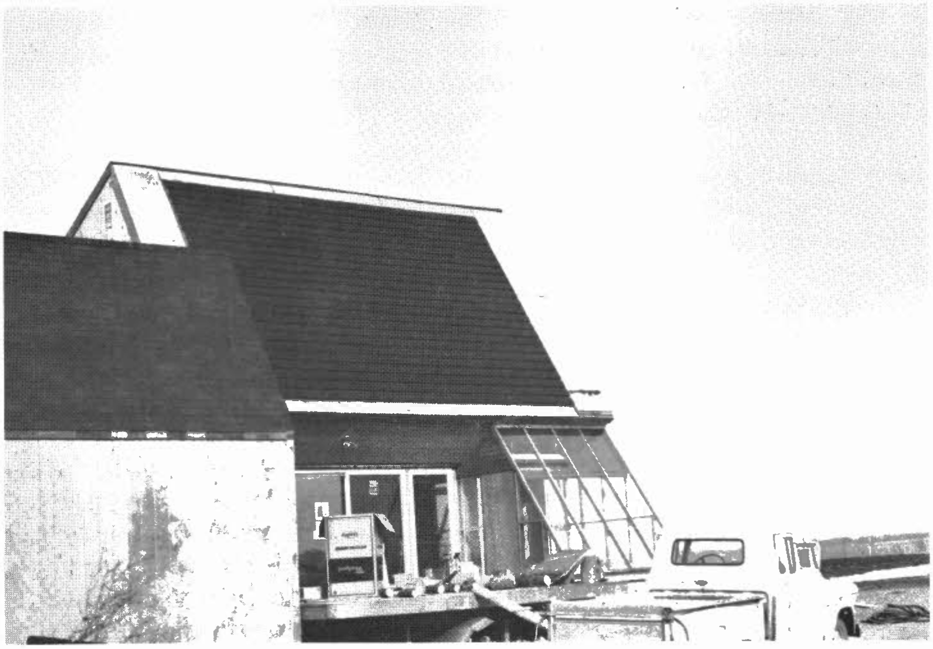
There are basically two ways to deal with these temperature problems. One is to simply let the collector stagnate every summer, but choose materials and a design such that no serious degradation will result for at least twenty years. The other approach is to prevent the collector temperature from rising above 250°F by either venting the collector or shading it from the sun. TEA explored both alternatives. The first approach, designing for stagnation, was studied and rejected. Wood could easily be removed from the collector by replacing the wooden inner battens with aluminum (see Chapter 9). In addition the rafters could be protected from high temperatures by replacing the Thermo-ply with a better insulator, such as Isophenol. But the major problems with the caulking, EPDM, and the thermal stresses on the absorber remain. While short-term exposures to high temperatures are not a problem, the long term-effects of many thousands of hours above 250°F cause significant degradation.

The second approach, preventing temperature rise above 250°F, was adopted. Consideration was given to shading the roof collector, perhaps with a roll-down cover or some other seasonally positioned shade. But the use of any such cover is accompanied by a number of problems. The cover must be very strong and durable to withstand high winds and long term weathering. Visual appearance is important; it should either be very attractive or blend in with the roof. A requirement of manual seasonal placement presents a serious disadvantage, since many users might procrastinate using, or perhaps fail to use the cover. And one of the most serious problems is that with the summertime cover in place, the collector cannot be used to heat domestic hot water. Probably the option which comes closest to satsifying all requirements is a partial shading accomplished by either a whitewash on the glass, or bamboo curtain or snow fence fastened securely to the collector. An appropriate amount of partial shading together with running the fan for domestic hot water will protect the collector from excessive temperatures. However, these options still do not meet the objections of visual appearance and user participation.

The other means of preventing excessive temperature rise is venting the collector. Venting can be accomplished either by thermosiphoning (natural vertical flow of heated air) or by using the fan to power vent. In order to maintain the collector temperature within reasonable limits a minimum air flow of 2 CFM per square foot of collector must be assured. This flow rate is difficult to achieve by natural venting (thermosiphoning) without a very large cross-sectional area of vent openings. In many collector designs it is nearly impossible to successfully integrate a sufficiently large vent area. In addition, a large vent area is very difficult to seal. At the beginning of each heating season the user must insure that all vents are closed, absolutely air tight. Another problem with natural venting is associated with the fact that the space most readily vented is that between the glazing and the absorber. Venting this area allows air to flow under the glazing, resulting in an accumulation of dirt. This reduces transmittance and is impossible to clean without totally removing the glazing. A final problem is cost -- the cost of installing such a large vent area is almost as great as the cost of power venting.

TEA decided to protect the collector by power venting. This option does not require any alterations whatsoever to the collector -- only to the air-handling system. Two extra duct runs to the outside are required along with two manual guillotine-type dampers. It is critical that these dampers are perfectly sealed at the beginning of the heating season, but that is easily done since they are so small and accessible. The power venting mode, engaged seasonally, takes in outside air, blows it through the collector at the standard flow rate, and returns it to the outside. The electrical operating cost of the fan is approximately $25 to $35 per year for an operating time of 1000 to 1400 hours. That is the annual operating time necessary to maintain the collector temperature below 200°F.

Most roof system installations will use domestic hot water (DHW) coils in the system ductwork. The collector will be cooled somewhat by the fan running in the summer to provide DHW, and TEA originally thought that this DHW-related fan operation might be sufficient to entirely cool the collector. However, some computer simulations were conducted and they showed that additional power venting was necessary.



Active Solar Collector Construction

The second category of major decisions deals with the air-handling and storage systems. As discussed in Section 2.2, Development of Project, essentially three system options were developed: 1) a simple 1-fan, no storage system for small collectors, 2) a site-assembled conventional type system utilizing a two-way rock bin, suitable for either retrofit or new construction, and 3) a low-cost innovative system employing a one-way rock bed, requiring careful engineering, and only suitable for new construction. A number of important design decisions were involved in the development of the conventional two-way rock bin system. This basic type of system was chosen because it is proven, flexible, and reliable, but careful planning was required to make the system efficient for both new and retrofit situations.

A fundamental decision was made to install the solar system in parallel with the auxiliary for retrofit, and in series for new construction. In some cases existing buildings being retrofitted with air site-built systems may already have forced hot air heating systems. However, the solar system often cannot be simply connected to the existing ductwork. The solar air-handling system must be properly balanced, and often the pressure drop in the existing delivery ductwork may be larger than optimum. Active air solar systems are significantly different than standard forced air systems. Air is moved in larger volumes, and pressure drops and leakage are more critical. Undersizing of ducts or blowers reduces the volumetric air flow rate which tends to lower the collector efficiency and reduce performance. The house distribution system must be carefully sized to avoid these difficulties. So even though the existing auxiliary is forced air, new ductwork may be required to move the solar system air to the living space.

In many retrofit installations the building will have a different type of heating system, such as hot water or steam, and thus the solar system must be considered to be a separate heating system. TEA decided that the best solution to all of these retrofit situations was to have one design which was always installed separately from the existing auxiliary. The control system insures that the two systems are efficiently used, although they do not share the same delivery system.

In retrofitting the MODEL-TEA to multi-story buildings with basements or crawl spaces, the solar heated air should be supplied only to the first floor. This eliminates the difficult problem of integrating new ductwork into the living space. If the house has been properly insulated prior to the solar installation, there should be good mixing of heated air. In some cases, particularly where the collector is capable of meeting the entire house heating load over a good part of the year, it may be advisable to install through-the-floor grills between the first and second floor to improve air circulation. The floor and ceiling grills can be horizontally offset to afford visual privacy. In cases where the collector area is small and the house heating load large, a zoned auxiliary by floors can be considered. Thus, in houses with basements, it is reasonable to locate there the rock bin, air-handling equipment, and all the delivery ductwork.

Retrofitting houses on slabs presents a more difficult building integration problem. The rock bin and air-handling equipment must be integrated into a space on the first floor, and the ductwork must be fitted into the ceiling. The only alternative is to use a smaller collector area and an air system without storage. This will be the most attractive option for many applications because of its low initial cost.

Since in retrofit applications the solar system is in parallel with the auxiliary, the control system must be carefully designed to allow optimum utilization of the solar heat. A system which stopped solar heated air flow to the living space whenever the entire heating load could not be met, would definitely not be desirable. If this were the case, much useful solar heat would be wasted. TEA's control design for retrofit systems delivers solar heated air to the living space whenever both the house thermostat calls for heat and the solar heated air is above 85°F. If more heat is required, it is provided by the auxiliary heating system simultaneously.

In new construction this situation does not exist, since the solar and auxiliary systems are in series. The auxiliary heater is placed in the solar-to-house ductwork, so that solar heated air always passes through the auxiliary on its way to the living space. If the solar air temperature is not sufficient to meet the house load, the second stage of the thermostat activates the auxiliary. Thus air heated by the auxiliary has been pre-heated by either the collector or rock bin, assuring good utilization of solar energy.

Some of the problems associated with retrofit can be designed away in new construction. A basement or utility room area can be planned for the rock bin, well-integrated duct runs from the collector to the basement can be provided, and there is more flexibility in the design of the duct system to the living space. A new building can be better insulated than a retrofit case, and with full insulation a more even temperature distribution will exist in the living space. Thus heated air need only be supplied to the first floor, and if necessary, through-the-floor grills can be used to circulate air to a floor above. If desired, the return air system can be used to circulate second-floor air back down to the first floor. Finally, with well-insulated new construction the building heating load is smaller, so the entire solar system and auxiliary can be made smaller and more efficient.

As another option for new construction, TEA decided to develop a low cost innovative system, applicable to buildings which could be carefully designed to accommodate the solar system. This system employs a one-way rock bed in close proximity to both the collector and living space. Although this design requires more careful sizing and engineering than the conventional system, it can perform as well and at a much lower cost. The innovative system is further explained in Section 9.2

2.5 Costs

The MODEL-TEA Solar Heating System costs roughly one-half as much as a commercially manufactured solar system. Full-size residential air and liquid manufactured solar systems average $45 to 55 per square foot of collector[1] fully installed, whereas a large MODEL-TEA installation, complete with storage, costs approximately \$21 per square foot. The MODEL-TEA roof collector, with single glass glazing, costs \$7.20/ft^2 installed for a 16x24 foot collector. A small wall version, with double glass panels, costs about \$11.30/ft^2. These prices are conservative; they reflect small quantities of materials, purchased at high unit costs, and high labor estimates which assume no prior experience with building this type of design.

Cost figures such as these are inevitably uncertain for many reasons. High inflation rates will cause dramatic increases in both the material and labor components of the final figure, and geographical location can also have a significant impact on these numbers. In addition, material costs vary tremendously depending upon source of supply and quantities purchased. For most materials, purchasing in sufficiently large quantities can reduce prices by at least 50%. Contractors who build many solar systems can easily lower both material and labor costs by buying large quantities of materials and gaining familiarity with the design. On the other hand, builders installing a single small system may incur higher costs.

Two methods have been used to estimate costs of collector materials, and where the results differed, the higher value has been taken. TEA contacted manufacturers, distributors, and dealers to determine current prices, and from this information estimated material costs at approximately \$4.00/ft^2 for the roof collector and \$6.30/ft^2 for the wall version. The alternative method, using 1978 Means Cost Data[2], and giving credit for building insulation, vapor barrier, sheathing, and roofing or siding (-\$1.80 for roof and -\$2.00 for wall), results in collector material costs of \$4.20/ft^2 for the roof collector and \$7.76/ft^2 for the wall version using 8 inch rib aluminum. TEA carefully documented labor times for some actual installations and, using a labor rate of \$10/hour, estimated labor costs for the two collectors at \$3.00/ft^2 for the roof and \$3.50/ft^2 for the wall. Thus, the total collector costs are approximately \$7.20/ft^2 for the roof collector, and \$11.25 or \$11.80/ft^2 for the wall version, depending upon whether 8 in. or 4 in. rib aluminum is used (the 4 in. rib results in greater wastage of material in the given wall design).

Tables 2.1 through 2.5 present costs for different parts of the MODEL-TEA Solar Heating System. Table 2.6 summarizes the total costs

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[1] King et al, Mueller Associates, Inc., "Cost-Effectiveness--An Assessment Based on Commercial Demonstration Projects," Presented at Second Annual Solar Heating and Cooling Operational Results Conference, Colorado Springs, November, 1979.

[2] Building Construction Cost Data, Robert Snow Means Company, Inc., Duxbury, Ma.

for the entire system. The air-handling material costs presented in Table 2.5 are estimates based upon typical costs of standard products. These numbers will vary, depending upon the actual item purchased. TEA obtained an estimate from a heating contractor for an example retrofit installation. Though the ductwork and other materials could be estimated fairly accurately, a large amount of uncertainty exists in the labor figure. The contractor estimated $1500 for labor, covering all air-handling and control system installation. But it was explained that this figure contained a large safety margin because this type of work was unfamiliar; with experience, the estimate would come down to $800 or $1000. Thus, at the end of part 1 of Table 2.5, a final cost figure is given taking into account a $600 reduction in the labor cost.

Though the total costs of the MODEL-TEA Solar Heating System are given in Table 2.6, the question remains--how cost-effective is it? In other words, how does it compare to the alternative, the non-solar option? It is clear that the MODEL-TEA is much less expensive than manufactured solar heating systems, but that does not necessarily mean that it is an economically attractive option. The question of cost-effectiveness can only be answered by somehow comparing the solar system option with the cost of the conventional alternative over the same period of time.

This type of analysis is referred to as the life-cycle costing. It is a complex endeavor, because it must take into account not only the heat output of the solar system, its initial cost, and the current cost of the fossil fuel alternative, but it also must account for general inflation, fuel inflation, down payment and the interest rate on the solar system, discount rate, maintenance costs, resale value, and other parameters. If an attempt is made to calculate life-cycle costs over a term of 25 years, inflation rates, discount rates, tax rates, and so on must be predicted 25 years into the future. This cannot be done with much certainty.

Then, once these bold economic assumptions are made, there are many measures of cost-effectiveness among which to choose. One can use return-on-investment, cumulative solar savings, or various types of payback definitions. The payback period is basically the time it takes for the cost of the fuel saved to equal the cost of the solar system. But there are various ways of defining these costs, depending upon whether the calculation accounts for inflation, interest earned on money not spent, mortgage rates, etc.

TEA decided to use the f-Chart Method, by Beckman, Klein, and Duffie (see Appendix C). This is available as a computer program which does two basic calculations: 1) it calculates the thermal performance of the solar system, based on solar radiation, weather data, and collector physical parameters, and 2) performs a life-cycle economic costing based on the input of all necessary economic parameters. This program was run for two systems, a full-size roof collector with storage and DHW, and a small wall collector with no DHW and only minimal storage. Calculations were done for both of these systems in each of 5 cities: Atlanta, Baltimore, Boston, Denver, and Sacramento. Some of the results are summarized in Table 2.7. The results in the first 4 columns are based only upon the performance calculation and the initial cost of the solar system. The numbers in the last 2 columns stem from the economic analysis. The first represents a payback period given by f-Chart and defined as the years until undiscounted fuel savings equals investment. The second is the present worth of cumulative solar savings over the 25 year period. According to these numbers, the MODEL-TEA is cost-effective.

Many assumptions had to be made in order to run the f-Chart analysis. TEA chose numbers which were realistic and would not necessarily favor the collector's performance. For example, it was assumed that the house was very well-insulated, had high internal heat gains, and that the roof collector was at a 45^{o} pitch, rather than the optimum. All of these assumptions may tend to reduce the apparent annual performance of the system. The following are some of the economic assumptions which were made: roof collector cost = $21/ft^2, wall collector = $15/ft^2, mortgage interest rate = 12%, term = 25 yr, discount rate = 8%, inflation = 11%, fossil fuel cost = $11.90/million Btu, and fuel inflation = 15%. Again, it should be remembered that since these economic parameters cannot really be predicted for 25 years into the future, this entire economic analysis is highly questionable, and perhaps only useful for setting limits.

MATERIALS COST FOR ROOF COLLECTOR

16 x 24 ft. module (16'-4" x 23'-4½" act.)

MATERIAL	QTY.	UNIT COST	TOTAL COST
Manifold pans 30 gauge (4½"x22½"x16') including labor	2	74.58 ea.	149.16
Thermo-ply 1/8" Blue Super Strength 4'x8' sheets	12 sheets	7.92 ea.	95.04
8" Rib Industrial Siding 49-5/8" x 23'	4 sheets of 368 ft^2	1.19/ft^2	437.30
EPDM End Closure Strips 40" long	10 pieces	1.14 each	11.40
Urethane Caulk	16 tubes	3.79 each	60.64
Flat black paint and primer	2 gallons	22.82 gal.	45.64
Wood	70 FBM	.35 FBM	24.50
Aluminum screws, boxes of 100			
#12 x 1¼"	8	13.50/box	108.00
#12 x 1½"	2	18.00/box	36.00
#12 x 2½"	1	29.50/box	29.50
Temperature sensors	2	5.00 ea.	10.00
Smoke Bomb	5	.50 ea.	2.50
6 mil poly vapor barrier	384 ft^2	.07/ft^2	26.00
1" fiberglass board insulation	64 ft^2	.20/ft^2	12.80
R-19 Fiberglass batt insulation	422 ft^2	.40/ft^2	169.00
3/16"x34"x96" solar glass, bought in quantities of less than one case* (42 panes per case)	16 panes of 22.67 ft^2/each	38.50/pane (1.70/ft^2)	616.00*
CY/RO U.G.S bought in standard 25' lengths	9 pieces	41.50 each	373.50
Aluminum screws, boxes of 100 #12 x 1½"	3	18.00/box	54.00
Silicone caulk	2 tubes	4.50/tube	9.00
Flashing 10"x.019"	90 ft^2	.40/ft^2	36.00
		ROOF COLLECTOR MATERIALS TOTAL:	$2305.98
		$/FT^2$:	$6.03

* If the glass were bought in quantities of one full case, the price per pane drops to $28.78 or $1.27/ft^2$. This would drop the price of the collector materials to $2150.63 or $5.60/ft^2$.

Table 2.1 Materials Cost for Roof Collector

MATERIALS COST FOR WALL COLLECTOR

(8 x 16 ft. module (8'-3½" x 15'-9½" act.)

MATERIAL	QTY.	Unit Cost	Total Cost
Manifold pans 30 ga. 4-1/2" x 22 1/2 x 8') including labor	2	38.00	76.00
Thermo-ply 1/8" Blue Super-Strength 4 x 8 sheets	4 sheets	7.92	31.68
4" rib industrial siding 45-5/8" x 16'	3 sheets or 176 sf	1.30	228.80
EPDM End Closure strips 40" long	6 pieces	1.14	6.84
Urethane caulk	8 tubes	3.79	30.32
Flat Black paint and primer	1 gallon	22.82	22.82
Wood	40 FBM	.35	14.00
Alum. screws			
#12 x 1-1/4	4	13.50/box	54.00
#12 x 1-1/2	1	18.00/box	18.00
#12 x 2-1/2	1	29.50/box	29.50
Temp sensor	1	10.00	10.00
Smoke bomb	5	.50	2.50
1" fiberglass board insulation	50 sq. ft.	.20	10.00
Fiberglass batt R-19	156 sf	.25	39.00
6 mil poly vapor barrier	156 sf	.07	10.92
3/16"x46"x96" insulated solar glass with 1/2" air space, bought in quantities of less than one per case* (18 panels per case)	4 panels of 30.67 ft^2 each	150.28 ea. (4.90/ft^2)	601.13*
Pre-shimmed glazing tape	1136 lf	.05/lf	56.80
CY/RO U.G.S. without the lower EPDM gasket, bought in standard 25' lengths	3 pieces	26.25 each	78.75
Aluminum screws, boxes of 100 #12 x 1½"	1	18.00/box	18.00
Silicone Caulk	1 tube	4.50/tube	4.50

WALL COLLECTOR MATERIALS TOTAL: $1343.56
$/FT^2: $10.26

* If the glass were bought in quantities of one full case, the price per panel drops to $139.86 of $4.56/ft^2. This would drop the price of the collector materials to $1301.85 or $9.94/ft^2.

Table 2.2 Materials Cost for Wall Collector

TOTAL COST FOR MODEL-TEA COLLECTOR

	MATERIALS	SIDING CREDIT	INSULATION & V.B. CREDIT	LABOR	TOTAL
ROOF COLLECTOR single glazed with solar glass	\$6.03/SF	\$1.11/SF	\$ .70/SF	\$3.00/SF	\$7.22/SF
WALL COLLECTOR double glazed with solar glass	\$10.26/SF	\$1.52/SF	\$ .45/SF	\$3.52/SF	\$11.81/SF

Table 2.3 Total Cost for MODEL-TEA Collector

MATERIAL		PRICE	384 FT³ OF ROCK QTY	TOTAL	600 FT³ OF ROCK QTY	TOTAL
Anchor bolts or spaces		.75/ea	23	17.24	26	19.50
Sill sealer		.07/lf	45.25	3.17	53.5	3.75
Stud wall		333/MFBM	.318	105.89	.340	113.22
Outer 1/2" CDX		.35/sf	362	126.70	465	162.75
Bolts		.55/ea	20	11.00	20	11.00
Divider		333/MFBM	.050	16.65	.104	34.63
Lag screws		.46/ea	10	4.60	10	4.60
Fib. batt R-19 (5 1/2")		.26/sf	362	94.12	465	120.90
Inside 1/2" CDX		.35/sf	398	139.30	638	223.30
Gypsum Board		.14/sf	258	36.12	290	40.60
Caulk		4.50/tube	1	4.50	1	4.50
Insulation - rigid		.50/sf	(2) 105	105.00	(2) 170	170.00
Block		.92/ea	88	80.98	132	121.44
Lath		.40/sf	150	60.00	232	92.80
Gravel		11.16/cy	17.5	195.30	27	301.32
Sensors		10.00/ea	2	20.00	2	20.00
Pipe, collar, cap		4.03/ea	2	8.06	2	8.06
Duct, Collar		10.00/ea	2	20.00	2	20.00
Cover:	Lumber	322/MFBM	.067	21.57	.113	36.39
	1/2" CDX	.35/sf	123	43.05	193	67.55
	Gypsum Bd.	.14/sf	(2)160	44.80	(2)253	70.84
	1" polystyrene	.23/sf	123	28.29	193	72.68
	Fib. Batt (R-11, 3 ½)	.17/sf	123	20.91	193	32.81
	Caulk	4.50/tube	3	13.50	3	13.50
	Gasket	.38/lf	46	17.48	58	22.04
	Lag Screws	.58/ea	29	16.82	35	20.30

	TOTAL	$/ft³	TOTAL	$/ft³
MATERIALS	$1255	$3.26	$1809	$3.01
LABOR	$1004	$2.61	$1447	$2.41
TOTAL COST	$2259	$5.87	$3256	$5.43

Table 2.4 Materials Cost for Rock Bin

1. Example, complete, full-size system:

	Qty.	Unit Cost $	Total Cost $
Motorized Damper low leakage with low voltage motor	3	230	690
Blowers with motor and drive	2	160	320
Controls			
Relays	3	10	30
Thermostat	1	30	30
Differential Controller	1	60	60
Additional Sensors	2		45
Miscellaneous			35
Ductwork estimate obtained for example retrofit system			900
		Subtotal	$ 2110
Labor professional estimate obtained on example retrofit system, for all controls and air-handling (may be reduced to $900 with experience)			1500
DHW			
60 Gal Tank	1		200
Hot Water Coil	1		200
10 gmp Pump	1		90
Differential Controller with sensors	1		60
Plumbing valves			100
			$ 650
		Total	$ 4260
Allowing for reduction in labor cost with experience			-600
			$ 3660

2. Wall collector system, 200 ft^2, no storage

	Qty.	Unit Cost $	Total Cost $
Blower	1	125	75
Controls	1		100
Ductwork			150
Labor			300
			$ 625

Table 2.5 Total Cost for Air-Handling System and Controls

1. Complete system, 384 ft^2 roof collector, with storage and DHW:

	$	$\$/ft^2$
Collector	2770	7.20
Rock bin	1690	4.40
System	3660	9.50
	$ 7920	$\$21.10/ft^2$

2. Wall collector, 200 ft^2, no storage:

Collector	2260	11.30
System	620	3.10
	$2880	$\$14.40/ft^2$

Table 2.6 MODEL-TEA System Costs

1. ROOF COLLECTOR, 45°, STORAGE AND DHW

	Solar[1] Fraction (%)	MBtu/yr	Btu/ft^2-yr	Initial Cost$/MBtu-yr	Payback[2] Period (yr)	Cumulative Solar Savings ($)
Atlanta	63	30.70	87,700	239	10	5740
Baltimore	45	32.41	92,600	227	10	6880
Boston	36	30.26	86,500	243	11	5445
Denver	69	60.94	174,100	121	7	25123
Sacramento	69	30.11	86,000	244	11	5372

2. WALL COLLECTOR, 90°, NO DHW

	Solar[1] Fraction (%)	MBtu/yr	Btu/ft^2-yr	Initial Cost$/MBtu-yr	Payback[2] Period (yr)	Cumulative Solar Savings ($)
Atlanta	52	8.26	51,600	290	12	741
Baltimore	33	9.53	59,600	252	11	1551
Boston	25	8.78	54,900	273	11	1083
Denver	57	21.57	134,800	111	7	9348
Sacramento	64	7.99	49,900	300	12	568

1 Solar Fraction: percent of total heating load supplied by the solar system

2 Payback Period: number of years until undiscounted fuel savings equals investment.

Table 2.7 f-Chart Computer Simulations of MODEL-TEA Performance and Cost