THE DESIGN,
CONSTRUCTION
AND TESTING
OF A LIQUID-HEATING FLAT-PLATE
SOLAR COLLECTOR

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In 1979, Robert Tuttle, Instructor in Welding, Bakersfield College, Bakersfield, California, completed the requirements for a Master of Arts degree in Industrial Education at California State University, Long Beach. As part of his requirements Tuttle designed, constructed and tested a liquid heating flat-plate solar collector. The process employed is described in this paper. Tuttle has agreed to share this information through the League for Innovation in the Community College project, "The Installation of Solar Energy Systems: Training Community College Faculty", funded by the Department of Energy. Questions concerning the content of this paper should be directed to the author.

THE DESIGN, CONSTRUCTION, AND TESTING OF A LIQUID-HEATING FLAT-PLATE SOLAR COLLECTOR

Introduction

The acceptance of active solar heating and cooling systems for residential buildings by the American public will depend largely on the operational and economical success of the initial systems installed. Of the several types of solar energy systems used for heating and cooling residential buildings, the ones incorporating the flat-plate liquid-heating collector are reportedly the most frequently used. The relatively basic concepts involved in the design and construction of this type of collector often stimulate consumers to build them. Because of the importance of an efficient collector to the operational and economical success of a solar heating and cooling system, it was deemed prudent to design and construct an efficient solar collector that could be duplicated by people who have a limited access to basic materials and equipment. The collector could be used to provide space heating or domestic hot water in a home.

The Problem

Statement of the Problem

The purpose of this study was to design, construct, and test a liquid-heating flat-plate solar collector.

Limitations

The solar collector designed and constructed in this study was to be one that could be duplicated by students at the thirteenth and fourteenth grade levels who have access to the required materials and equipment.

Importance of the Study

The results of this study should be helpful to those who desire to design and construct liquid-heating flat-plate solar collectors that will deliver to storage, in the form of heat energy, the highest fraction of solar energy intercepted by the collector and that will withstand constant and long-term exposure to direct sunlight and constant changes in weather conditions. Also, this study may be helpful to those who are interested in purchasing manufactured solar collectors. By introducing others to design criteria, construction considerations, and methods of determining collector performance, they might become better consumers and better able to make wise decisions when considering construction or purchase of any solar heating and cooling equipment or systems.

Definition of Terms

To facilitate interpretation of data presented in this study, the following terms and phrases have been defined.

British thermal unit (Btu). The quantity of heat required to raise the temperature of one pound of water 1° Fahrenheit. (7:221).

Diffuse radiation. Radiation that has been scattered in passing through the atmosphere. (4:Ch. 4:iv).

Direct radiation. Radiation that has not been scattered in passing through the atmosphere. (4:Ch. 4:iv).

Effective absorber area. The portion of a transparent cover's outside surface that is exposed to the sun's rays. (6:Ch. 4:3).

Electroplating. The process of putting a metallic coating or plating on a base material, which usually is metal or plastic, by means of electrodeposition. That is, the metallic plating is deposited on the base by passing an electric current through a plating bath in which are dipped the objects to be plated. (7:222).

Emissivity. The relative power of a surface to emit heat by radiation. (7:222).

Flat-plate collector. A flat-plate collector is a solar collector in which the solid surface absorbing the incident solar radiation essentially is flat and employs no concentration. (5:189).

Incident. In reference to solar radiation, those light rays falling on or striking a surface. (7:223).

Infrared. Situated beyond the red end of the visible spectrum, as certain heat rays. (8:408).

Insolation. Solar radiation received by the earth or other planets. The rate of delivery of such radiant energy per unit of horizontal surface. (8:1362).

Pyranometer. A device used to measure the total incident solar energy per unit time per unit area upon a surface which includes the beam radiation from the sun, the diffuse radiation from the sky, and the shortwave radiation reflected from the foreground. (5:190).

Transmissivity. Transmissivity is a function of the quality of the transparent cover and the angle at which the solar radiation reaches the transparent cover. (3:Ch. 11:9).

REVIEW OF THE LITERATURE

General Principles

An explanation of the basic principles of a flat-plate solar collector was presented by the authors of a manual prepared at the Solar Energy Applications Laboratory at Colorado State University. In this manual, the authors stated that the purpose of a flat-plate solar collector is to intercept incident solar radiation, convert this radiation into heat, and deliver useful energy to a building. The collector consists of three major components: an absorber plate, transparent covers, and an insulated box and frame assembly. The absorber plate, commonly a black metal surface, absorbs the incident solar radiation and converts this solar energy to heat. A portion of this heat is transferred to a heat transfer medium which carries it to another part of the system. In the process of collecting energy and transferring the heat to the heat transfer medium, some of the heat is lost to the absorber plate surroundings. The transparent covers and the insulated box and frame assembly reduce this heat loss. (4:Ch. 5:1-2).

Also stated in the manual is the information that the useful energy from a liquid-heating flat-plate solar collector is delivered, via the heat transfer fluid, directly to a building or to

storage where it can be used at a later time. This type of collector normally uses as a heat transport medium water or a solution of water and ethylene glycol, but numerous other liquids can be used. (4:Ch. 5:1-2). The authors further indicated that liquid-heating flat-plate solar collectors absorb both direct and diffuse solar radiation. This fact is an important aspect of this type of collector because in most areas, a large portion of solar radiation is in the form of diffuse or reflected radiation. (4:Ch. 5:1-2).

Heat Losses from the Collector

Another point made in the manual was that the heat loss from the absorber plate occurs by radiation, convection, and conduction. Losses through the back and side of the collector can be reduced significantly by the addition of insulation beneath and on the perimeter of the absorber plate. The use of transparent covers can reduce the heat loss from the front of the collector. A glass cover, which is opaque to the thermal radiation emitted by the absorber plate, will reduce convection losses to the outside air because convective air movement is restricted by the relatively stagnant air space between the absorber plate and the cover. (4:Ch. 5:2).

Solar Energy Absorption

In a solar training manual prepared at the Educational Products Division of Lennox Industries Incorporated, the authors stated that the percentage of solar energy incident on the surface of the collector, that is absorbed by the absorber plate, is dependent on three basic variables: the transmissivity and reflectivity of the glass cover(s), and the absorptivity of the absorber plate. Some energy is lost during the travel of the radiant energy through the glass cover(s). This is called "transmittance loss" and is affected by the quality, thickness, and number of glass covers. The amount of sunlight reflected from the collector cover(s) is known as reflectivity, which also affects the efficiency. When solar radiation strikes the collector cover at an angle, some of the radiation is reflected back into the atmosphere. (6:Ch. 4:3). The authors of a second manual prepared by the Solar Energy Applications Laboratory at Colorado State University indicated that the solar absorptivity of the absorber plate is dependent on the optical property of the materials exposed to solar radiation. Surfaces which appear black to the eye have high absorptivity values. The solar radiation that reaches the absorber surface that is not absorbed is reflected upward through the glass covers. (3:Ch. 11:10).

The authors of a publication prepared by the Sheet Metal and Air Conditioning Contractors National Association stated that when the solar energy, which is composed of ultraviolet, visible, and infrared rays, passes through the transparent cover(s) and the stagnant air mass and strikes the black absorber plate, the waves are absorbed. At this point the phenomenon of wavelength conversion occurs. Not all of the shortwave solar radiation that reaches the absorber plate is absorbed, some energy is re-radiated as long waves and strikes the inner surface of the transparent cover. The composition of the glass cover causes it to be opaque to most long waves, and the heat is trapped; consequently, it is not lost. This phenomenon is often called "the greenhouse effect." (9:Ch. 3:3).

Collector Components

The basic components of a flat-plate liquid-heating solar collector include the transparent covers, absorber plate, box and frame assembly, and the sealants.

Transparent Covers

The number of transparent covers to be used on a collector is determined by the collector design, collector use, and the annual average outdoor temperature for a specific geographic area. No covers may be required where average annual temperature readings are above 70° Fahrenheit. Because of the reduction of solar energy reaching the absorber plate by transmittance loss through a cover and the relatively small difference in temperature between the absorber plate and ambient temperature, a transparent cover is not

recommended. Two covers are required where the annual average temperature is below 50° Fahrenheit. While each cover reduces the amount of solar energy transmitted, it also reduces frontal heat loss from the collector which is a major concern in colder climates. (9:Ch. 3:3).

In the manual prepared by the Sheet Metal and Air Conditioning Contractors National Association, the authors said that from outward appearances it would seem that both plastic and glass would be acceptable materials for use as transparent collector covers. These materials share many of the same characteristics of light and heat transmission. (9:Ch. 3:3). An example of a cover material, given in the Lennox training manual, is Tedlar, the trademark name for a plastic transparent film, which has a transmittance factor of 94 to 95 percent. (6:Ch. 4:4). However, in the sizing, installation and operation of systems the authors stated that the physical and optical stability of thin transparent plastic films and sheets under prolonged ultraviolet radiation and high temperatures generated within a solar collector are not well established. (4:Ch. 5:5). Also pointed out in the Lennox manual was that most thin plastic films and sheets require a supporting frame and are susceptible to tearing, mechanical damage and abrasion. (6:Ch. 4:4).

As stated in the Lennox solar training manual, intensive research is being conducted to develop improved cover materials to better meet the needs of solar collector covers. Resistance to hail, vandalism, ultraviolet radiation, temperature changes and extremes, and airborne contaminants are all factors to be considered. At this time glass is considered to be the best cover material, despite relative disadvantages of cost and weight. (6:Ch. 4:3-4).

In one of the Colorado State University manuals, the authors indicated several methods were being studied to increase the efficiency of glass used as collector covers. One method is to reduce the reflection of solar energy from the surface of the glass. Metallic films, formed by vapor deposition, commonly are used as lens coatings for photographic equipment; however, this process is too costly at present for use on solar collectors. (3:Ch. 11:10). Another process, pointed out in the same manual, involves a delicate etching of the glass surface using an acid treatment, rendering a slightly porous silica surface. Using this process, solar reflectivities as low as 1 to 2 percent can be obtained. Another concept is to reduce the impurities, principally iron, in the glass which will result in lower radiation absorption within the glass. Typical window glass one-eighth inch in thickness will absorb 1 to 5 percent of incoming radiation per sheet. Glass of the same thickness with a reasonably low iron content will absorb about 2 percent per sheet. (3:Ch. 11:9-10). A third approach is to coat the lower surface of the cover nearest the absorber with a substance that would help redirect more long wave radiation back toward the absorber plate. (9:Ch. 3:3).

In the Lennox manual the authors stated that these methods of treating glass are relatively difficult and a costly process and that the advantage of increased transmittance efficiency must be weighed carefully against additional costs. For example, a sheet of window glass has a transmissivity value of 85 to 87 percent. Low-iron glass has the effect of increasing transmissivity to 90 to 92 percent. Surface etching of low-iron glass will allow transmittance values of 97 to 98 percent. (6:Ch. 4:3)

Absorber Plate

Although it appears simple, the absorber plate is a rather complex component. As stated by the authors of the Lennox training manual, the absorber plate receives the solar energy that is transmitted through the transparent covers. The plate is designed to absorb that energy by converting the short wave radiant energy to longer wave heat energy in the infrared range. (6:Ch. 4:5). The authors of another manual wrote that the absorber plate often is referred to as the "black-body" because in theory it totally absorbs all visible light radiation and the color "black" represents the lack of visible light reflection. However, there is no such thing as a perfect absorber; no surface will absorb all the radiation falling upon it with none of it being reflected. Surfaces which appear black to the eye have a high absorptivity for the visible portion of the solar spectrum, which accounts for about 40 percent of the solar radiant energy which is 5 percent ultraviolet and 55 percent infrared. A

black surface absorbs about 92 percent of the radiant energy falling upon it, while a white surface absorbs only 40 percent. (9:Ch. 3:4).

As expressed by the authors of one of the Colorado State University manuals, the type of black coatings used is limited by certain requirements. Besides being an efficient energy absorber, the black coating material must be able to resist deterioration and not contain material that would give off gas when exposed to radiant energy, air, moisture and temperatures of 300 to 400° Fahrenheit, which can occur easily in double glazed collectors. The absorber coatings which meet minimum requirements and are used most commonly are special heat-resistant black paints, usually applied by sprayings, followed by curing with heat to eliminate solvents and to secure permanence. (3:Ch. 11:10).

Another point brought up is that, unfortunately, these black paints, which act as efficient absorbers of radiant energy, also act as efficient re-radiators of heat energy. A significant amount of energy can be re-radiated back through the collector covers and into the atmosphere. However, certain combinations of coatings, referred to as selective surfaces, are capable of absorbing solar radiation effectively while at the same time radiating heat at a low rate. Most selective coatings consist of a very thin black metallic oxide deposited on a bright metal base. The thin black oxide coating is sufficient to act as a good solar absorber but is essentially transparent to long wave thermal radiation. Since bright metals have low emissivity values for thermal radiation, and since the thin oxide coating is relatively transparent to such radiation, the combination results in a poor heat radiator. Consequently, the radiation loss from this type of surface is considerably lower than from a non-selective type surface. (3:Ch. 11:11).

The most successful and stable selective surface developed to date is a black chrome bright nickel electroplate coating. This coat is made by electroplating a layer of nickel on the absorber plate then electro-depositing an extremely thin layer of chromium oxide on the nickel substrate. (3:Ch. 11:11). As expressed in the Lennox manual, a typical black nonselective surface may absorb 95 percent of the radiant energy but also emit 95 percent of the infrared energy. By comparison, a black chrome bright nickel selective coating can absorb 95 percent or more of the radiant energy and emit less than 10 percent of the infrared energy. Selective coatings, however, are more expensive than nonselective coatings and the cost effectiveness of each type of coating must be evaluated in terms of performance, cost and durability. (6:Ch. 4:6).

A description and comparison of potential absorber plate material was covered in the Lennox manual. The author stated that the absorber plate is heated by the radiant energy from the sun, and this heat is transferred by conduction through the plate into the cooler heat transfer fluid. This fluid is channeled through tubes in contact with the absorber plate. The tubes must be thermally bonded to the absorber plate to conduct the heat from the plate to the tube wall. The best material for absorber plates are metals, including steel, aluminum and copper or any combination of these. Steel is the least expensive of these materials but lacks the weight advantages of aluminum and the corrosion resistance of copper. Steel does not conduct heat as effectively as either copper or aluminum. In liquid-heating collectors the use of aluminum presents potential corrosion problems. Copper combines the advantages of corrosion resistance and heat transfer efficiencies but has the disadvantage of being the most expensive of these materials. Consequently, an evaluation of construction materials must be made in the terms of durability, cost, efficiency and weight. (6:Ch. 4:6).

A number of design problems are encountered when determining liquid movement through a collector. As indicated in a governmental publication the design and sizing of the tube configurations and their attachment, or integration, to the absorber plate must provide for uniform flow through the collector. The flow rate is selected on the basis of desired temperature rise in the heat transfer fluid from inlet to outlet. A reasonable design basis is a temperature increase of about 15° Fahrenheit across the collector at peak insolation. A flow rate of about 0.02 gallon per minute for each square foot of collector will generate this increase in fluid temperature. Satisfactory flow distribution in a solar collector is achieved using a grid-reverse-return tube configuration. Using this design concept, the fluid enters

the collector from a bottom corner. A header runs along the bottom width of the absorber plate. Risers branch off the headers at equal intervals and travel along the absorber plate length to the top of the collector. A return header runs along the width of the absorber plate at the top of the collector and exits at the corner diagonally opposite the inlet. This design allows for equidistant runs of header and riser regardless of the fluid path. If the cross-sectional area of the headers is designed to allow for a pressure drop of less than 10 percent of the drop in the risers, even flow distribution is assured. (4:Ch. 5:6-8).

Box and Frame Assembly

The box and frame assembly as a unit has many important functions. As pointed out in an article by Brady, the box and frame assembly must be weather tight and must resist constant exposure to the elements. The unit must be able to withstand daily temperature differentials of up to 500° Fahrenheit and temperature changes of as much as 100° Fahrenheit within a few minutes. In addition, the assembly must be designed to expand and contract as a result of these temperature changes and still maintain air-tight seals. (1:36). Other considerations, stated in the Lennox solar training manual, are that the assembly must support the transparent covers, absorber plate and fluid transfer system and must contain sufficient insulation to limit heat loss from the back and sides of the collector. The authors also pointed out that a well designed collector box and frame has provisions for service access to the interior of the collector. (6:Ch. 4:8).

According to leading authorities in this field, the insulating material used in a collector must have low thermal conductivity, low bulk density, and a high melting point, and it must be resistant to rot, weather, insects and rodents. These criteria can be met by using various types of fiberglass and polyurethane foam. The suggested maximum overall heat transfer coefficient, of the insulation to minimize conductive heat losses through the back and sides of the collector is 0.04 Btu per hour per square foot. (5:60) (9:Ch. 3:8).

Sealants

An explanation of the requirements of seals for a flat-plate solar collector was presented by Brady. Brady stated that the differential expansion and contraction of the materials used in the construction of a flat-plate solar collector created a sealing problem. This type of collector must be sealed tightly to help prevent heat losses. Also, any condensation of moisture or volatile components of the sealant on the underside of the glass cover will reduce the efficiency of the unit. In addition, solar collectors should operate trouble and maintenance free for many years. To ensure this type of performance, no moisture can be allowed to enter the unit which otherwise could cause corrosion and damage of the insulation. (1:36-37).

Brady mentioned several other requirements of the seals. They must not soften or degrade at the extremely high temperatures occasionally experienced by the collector, and the seal must remain flexible at temperatures below 0° Fahrenheit. The seal also must remain flexible when exposed to ultraviolet radiation and ozone, the effects of which are magnified by high temperatures. (1:37).

Brady explained that because they meet all of these criteria, silicone sealants and silicone rubber gaskets are used in 80 percent of the flat-plate solar collectors being built in the United States today. In most cases, the silicone sealant used for glazing is designed especially to accommodate the relatively large movement found in the joints of many modern buildings. For example, Dow Corning 790 construction sealant can accommodate 50 percent expansion and/or contraction of a joint without tearing or losing its adhesion. (1:37).

Brady also said that silicone sealants and silicone rubber exhibit the same weathering properties and high and low-temperature performance characteristics. Although prolonged exposure does tend to harden even silicone rubber, a test conducted in Florida indicated that after 20 years of exposure, silicone rubber samples still retain almost half their original elongation and more than two-thirds of their original tensile strength. (1:37).

Silicone rubber also maintains flexibility at very low temperatures. One method used to

measure the ability of a rubber to recover from torsional deformation at low temperatures is the Gehman flexure test. This test shows that silicone rubber remains flexible to below -40° Fahrenheit. (1:37-38).

Also, according to Brady, silicone rubber sealants adhere well to almost any surface, including glass, metals, fiberglass, and many plastics and elastomers. Glass panels as large as 200 and 300 square feet often are joined with silicone sealants serving as adhesive. Such butt-joined panels have withstood measured wind velocities in excess of 130 miles per hour. (1:37-38).

Collector Performance

Solar collector efficiency is defined in a governmental manual as the fraction of solar energy intercepted by the collector that is converted to heat energy and is delivered to the building. This equation can be shown as follows:

$$\text{Efficiency} = \frac{\text{Btu/hr output}}{\text{Btu/hr input}} \quad (4:\text{Ch. 5:17}).$$

The main factors affecting efficiency include absorber surface coating, absorber plate design, fluid flow distribution through the collector, number and type of transparent covers, fluid temperature, outdoor air temperature, and the intensity of solar radiation on the collector area. (4:Ch. 5:17).

Once a collector has been designed and constructed, a performance curve can be developed by test. According to the authors of the Lennox manual, there are three main variables affecting collector performance during testing. The first is the available solar radiation on the collector glass area over a period of time, referred to as the "incident flux," or Q_{inc} . The incident flux is expressed in terms of the Btu per hour per square foot, or Btu/hr-ft², of effective absorber area. The second variable is the temperature of the liquid at the inlet of the collector, or T_{in} , expressed in degrees Fahrenheit. The third variable is the ambient temperature that surrounds the collector, or T_{amb} , expressed in degrees Fahrenheit. (6:Ch. 4:8).

These variables effect the solar energy input to the collector, the heat energy losses from the collector, and, consequently, the useful heat energy delivered by the collector. The relationship of these variables, as explained in the Lennox manual, is referred to as the "energy ratio" and is expressed as follows:

$$\frac{\left[\begin{array}{c} \text{collector} \\ \text{inlet fluid} \\ \text{temperature} \end{array} \right] - \left[\begin{array}{c} \text{ambient} \\ \text{air} \\ \text{temperature} \end{array} \right]}{\text{solar radiation on collector surface}}$$

or

$$\frac{(T_{in} - T_{amb})}{Q_{inc}} = \frac{^{\circ}\text{F}}{\text{Btu/hr-ft}^2} = ^{\circ}\text{F-hr-ft}^2/\text{Btu.} \quad (6:\text{Ch. 4:9}).$$

As indicated, collector efficiency is not a constant factor but varies with conditions. For example, if the fluid inlet temperature and solar incident flux are constant but the outdoor temperature decreases, the efficiency of the collector decreases. This decrease is a result of greater heat loss caused by the increase in temperature difference between the absorber plate and the ambient. For the same reason, if the temperature of the fluid entering the collector increases, the collector efficiency will decrease. As explained in one of the Colorado State University manuals, if experimental data on collector heat delivery were measured at various fluid inlet temperatures, ambient temperatures, and solar condition, and if this information is plotted on a graph, with efficiency,

$$\frac{\text{Btu/hr output,}}{\text{Btu/hr input}}$$

as the vertical axis and

$$\frac{T_{in}-T_{amb}}{Q_{inc}}$$

as the horizontal axis, the best straight line through the data points, as shown in Figure 1, is a complete representation of the collector performance over its entire operating range. (4:Ch. 11:17).

Figure 1. Typical Collector Performance Curve

The Lennox manual included information that the value for collector efficiency at any one given time is determined by calculating the heat energy removed per unit time and comparing it with the solar energy incident upon the collector for the same time period. The heat energy removed is affected by two factors. One factor is the change in temperature of the fluid across the collector, and the other factor is the volume of the fluid circulating through the collector. For example, 10 gallons of water at an inlet temperature of 100° Fahrenheit may be circulated through a collector in one hour. The water temperature leaving the collector may be 115° Fahrenheit. The weight of water may be 8.3 pounds per gallon. Considering the above factors, 83 pounds of water is circulated through the collector per hour. Since the water temperature is increased 15° Fahrenheit, and it takes one Btu to raise the temperature of one pound of water 1° Fahrenheit, the rate of heat removal from the collector plate is 15° times one Btu per degree times 83 pounds, or 1,245 Btu per hour. If this value is compared to a solar flux of 1,750 Btu per hour, the collector efficiency would be equal to 71 percent. (6:Ch. 4:13).

Typical Collector Performance Curve

The efficiency curve of a typical liquid-heating flat-plate collector has been illustrated in Figure 1. The curve essentially is a linear curve. The authors of the Lennox manual further explained that the two main parts of the performance curve are its intercept and slope. The intercept is the point at which the plotted curve intersects the vertical axis. This is the highest efficiency the collector can achieve. The slope is the degree of slant of the curve in relation to the horizontal axis. The intercept of this curve is calculated by setting up the parameters so that the value of

$$\frac{T_{in} - T_{amb}}{Q_{inc}}$$

is equal to zero. The slope is determined by dividing the intercept by the value of the point at which the curve intersects the horizontal axis at zero efficiency. (6:Ch. 4:11).

The process of determining the Btu capacity was also explained in the Lennox manual. When the amount of available incident solar radiation, Q_{inc} , is known, the performance curve can be used to determine the Btu capacity of a collector by using the energy ratio formula. For example, to simulate an actual problem, assume the available radiation is 250 Btu/hr-ft², the inlet temperature, T_{in} , is 110° Fahrenheit and the ambient temperature, T_{amb} , is 30° Fahrenheit. Next, subtract the ambient temperature from inlet temperature which will result in an 80° temperature difference. Next, determine the energy ratio by dividing the temperature difference by the solar radiation, 250 Btu/hr-ft², which equals 0.32. Then, refer to the collector performance curve, Figure 1, and follow the line from 0.32 of the horizontal axis vertically to where it intersects the curve. Then read horizontally to the vertical axis from the point of intersection. This line indicates an efficiency of about 62 percent. Thus, the collector is 62 percent efficient under these conditions. To calculate the Btu capacity of the collector, in this instance, multiply the incident flux, 250 Btu/hr-ft², by 62 percent, which results in 155 Btu/hr-ft². (6:Ch.4:12).

DESIGNING THE SOLAR COLLECTOR

The design of the solar collector was divided into three distinct parts: the transparent covers, the absorber plate, and the box and frame assembly. One of the most important considerations in the design of the solar collector was that it meet personal requirements.

Prior to the design and construction of the collector, the following design limitations were established:

1. After the design of the collector was completed, two collectors would be constructed and used as part of a solar hot water heating system to be installed on the writer's home in Bakersfield, California.
2. Construction processes would be limited to the facilities available at Bakersfield Community College, Bakersfield, California.
3. The collector would be designed and constructed to operate at the highest efficiency considered economically reasonable.
4. The overall dimensions of the collector would be comparable to presently available commercial solar collectors.

Transparent Covers

As a result of the research, a decision was made to use low-iron, acid-etched, tempered glass as the transparent cover material. Tempered glass cannot be cut successfully; consequently, the size, type, and number of transparent covers had to be determined before designing the absorber plate or box and frame assembly. As stated, the collector designed in this study was to be used on a solar domestic hot water heating system to be built on the writer's home in Bakersfield, California. From information supplied by the National Weather Service, the average annual outdoor ambient air temperature for Bakersfield was calculated to be 65° Fahrenheit. (2:C). According to the literature search, a collector with one transparent cover would be the most efficient in this particular geographic location. The required type of glass was supplied by ASG Industries, Kingsport, Tennessee. The glass had the following overall dimensions: three-sixteenths inch thick, 34 inches wide, and 96 inches long.

Absorber Plate

The design considerations used in the construction of the absorber plate were as follows: (1) the absorber plate would have an effective absorber plate area that would conform to the dimensions of 33 inches wide, and 96 inches long, or 22 square feet; (2) the plate would be constructed entirely of copper with the exception of the bonding agent; (3) the cross-sectional area of each header would be equal to, or greater than, the sum of the cross-sectional areas of the risers; (4) the risers would have a thermal bond to the full length of the absorber sheet; (5) a grid-reverse-return fluid flow pattern would be used; (6) all component parts of the absorber plate would be joined with 95-5 grade solder, or 95 percent tin, 5 percent antimony; and, (7) the black absorptive coating on the top surface of the absorber plate would be a paint which would offer the best combination of high thermal absorptivity, low emissivity, and good adherence properties.

The materials to be used in the construction of the solar collector were as follows: 24-ounce, or 0.0323 inch, copper sheet for the plate, five lengths of one-half-inch diameter Type-L copper tube for the risers, and the inlet and outlet headers constructed with one and one-quarter-inch diameter Type-L copper tube and fittings. These particular sizes were readily available and were incorporated in the design in the event any future repairs would be required. The details of the manifold arrangement are shown in Figure 2.

Box and Frame Assembly

The design considerations used in the construction of the box and frame assembly were as follows: (1) the box would be constructed using 18-gauge galvanized sheet steel, and all parts of the box would be welded together to form a unit structure; (2) the insulation used would be rigid enough to support the absorber plate; (3) the insulation would have a maximum overall heat-loss coefficient of 0.04 Btu per hour per square foot and contain no materials that would give off gas at temperatures less than 300° Fahrenheit; (4) provisions would be made to provide access to the interior of the collector for servicing; (5) all sealants would be made of silicone; (6) the bottom glass support would be an integral part of the box

and be constructed with 14-gauge galvanized sheet steel for rigidity; (7) the frame would be constructed of 14-gauge galvanized sheet steel and all parts of the frame would be welded together to form a unit structure; (8) one-quarter-inch diameter drain holes would be drilled at both ends of the collector to allow for draining of any liquid which might enter the collector interior and to eliminate the possibility of internal pressure; and, (9) the complete exterior of the box and frame assembly would be painted to make the finished product most pleasing aesthetically.

Figure 2. Absorber Plate Manifold Arrangement

The details of the box are shown in Figure 3. The required dimensions of the box were calculated to be five and one-half inches deep, 37 inches wide, and 109 inches long. The depth dimension allowed for four inches of rigid insulation, the amount required to meet the minimum heat-loss coefficient of the basic design. The depth selected also allowed for the thickness of the absorber plate, the proper amount of air gap between the absorber and the transparent cover, and the transparent cover with seals. The width dimension allows for the width of the transparent cover with enough space to allow for thermal expansion of the glass. The depth also allowed for the fastening system required to attach the frame to the box. The length dimension allowed for the desired length of the transparent cover, and the absorber plate including the inlet and outlet headers and box end insulation.

Figure 3. Solar Collector Box Details

The details for the construction of the frame are shown in Figure 4. The required dimensions of the frame were calculated to be $37 \frac{1}{4}$ inches wide by $109 \frac{1}{4}$ inches long. These dimensions allowed easy assembly and disassembly of the frame from the box. The frame was attached to the box using bolts through the frame into the lower glass support member which was an integral part of the box assembly. Nutcerts, available from the Auveco Corporation, Newport, Kentucky, and shown in Figure 5, were used to increase the amount of thread contact in the 14-gauge galvanized steel lower support member. These increased the thread depth one-quarter inch. This fastening system was used not only to attach the frame to the box but also supply enough pressure to both sides of the glass sealant to ensure an adequate seal. The designed overlap of the frame to the box sides was two inches. When the bolts attaching the frame to the box were tightened, the pressure pulled the overlap of the frame away from the box side and ends. In the resulting space, a bead of silicone sealant was applied to reduce the chances of moisture and ambient air from entering the interior of the assembly. The designed overlap of the frame to the top of the assembly was two inches. This

dimension allowed enough overlap onto the glass to provide an adequate seal. The designed amount of overlap of the frame ends to the top of the assembly was seven and one-half inches. This additional overlap was required to allow for additional space required by the inlet and outlet header arrangements.

A one and five-eighths-inch diameter hole was provided at each end of the box and frame to allow the inlet and outlet headers to pass through the assembly. This hole detail is shown in Figure 3. A small 14-gauge galvanized steel plate with a one and five-eighths-inch diameter hole drilled into it was attached to the inside of the box end, at the point where the headers extended through the assembly. A bead of silicone sealant was placed between the box end and the plate. When the plate was secured tightly, the silicone sealant provided a seal around the headers. This seal arrangement allowed for movement caused by different thermal expansion rates of the box and frame assembly and the absorber plate, and still maintained an adequate seal against moisture and ambient air.

Figure 4. Solar Collector Frame Details

END SECTION

Figure 5. Solar Collector Cross-Sectional View and Fastening System Detail

CONSTRUCTION OF THE SOLAR COLLECTOR

Using the design considerations for the solar collector, the facilities at Bakersfield Community College were used to construct the components of the collector.

Absorber Plate

After complete and careful design of the absorber plate, construction of the unit began. First, the headers and risers were carefully measured and assembled using 95-5 grade solder. A 24-ounce copper sheet with overall dimensions of 36 inches in width and 96 inches in length was used as the plate material. The five, one-half-inch diameter Type-L copper tube risers were then soldered to the full length of the absorber plate material. To increase the thermal conductivity between the sheet material and the riser material, the cross-sectional area of the thermal bond was increased. This increase was obtained by forming the sheet to match the curvature of the risers at the point where the two components were to be joined. This forming was accomplished by making grooves in particle board, laying the copper on the board, and driving on a piece of pipe to force the copper into the grooves. Upon completion of all soldering, the absorber was trimmed to the desired width of 33 inches.

The final step in the construction of the absorber plate consisted of the application of the black absorptive coating, as shown in Plate I. As a result of the literature search, the decision was made to apply Nextel Brand Velvet Coating, a product of the Decorative Products Division of the 3M Company. Prior to the application of the 3M Nextel Brand Velvet coating, the copper substrate had to be prepared properly. The entire surface of the absorber plate first was scrubbed with Sparex No. 2, an acid wash treatment produced by Quimby and Company, Chester, New Jersey, and then flushed with clear water. This process was followed by scuffing all surfaces with 120-grit abrasive cloth. Just prior to the initial prime coat, the surface was cleaned with steel wool and Metalprep, a product of the Neilson Chemical Company, Detroit, Michigan. The plate was then primed with Cardinal Primer #4860-50, a product of the Cardinal Industrial Finishes, El Monte, California. This initial primer was followed within one hour of application, to ensure proper intercoat adhesion, with 3M Primer 911-P4. The second primer was followed, again within one hour of the application of the preceding coat, with 3M Black Velvet Coating #101-C10.

Plate I
Absorber Plate

Box and Frame Assembly

The components of the box and frame assembly were then constructed. First, the box, shown in Plate II, was constructed using 18-gauge galvanized sheet steel, 48 inches wide and 109 inches long. The sides were fabricated five and one-half inches deep on a power brake. The end pieces also were made with 18-gauge galvanized sheet steel and were fabricated to overlap, on the bottom and sides of the inside of the box, by one-half inch. The end pieces were then arc welded to the box to form a unit structure. The welding was accomplished using a shielded metal arc welding process and one-eighth-inch diameter E-6013 electrodes.

Next, the angle iron pieces, used as both the lower glass support members and as part of the fastening system used to attach the frame to the box, were fabricated from two inch 14-gauge galvanized angle iron. The angle iron was then attached to the sides of the box by three-eighths-inch diameter plug welds on six-inch centers.

Plate II
Solar Collector Box and Insulation

Plate III
Solar Collector Box with Absorber
Plate and Transparent Cover
in Position

To support the ends of the transparent cover, two pieces of 14-gauge galvanized sheet steel, shown in Plate III, were fabricated to form a three-inch-wide channel with a one-half-inch flange dimension. This piece was then mounted flush with the top of the angle iron support members, using a one-quarter-inch by one and one-half-inch by four-inch steel strap and three machine screws. Making these end pieces removable facilitated future repairs.

Next, the frame, shown in Plate IV, was constructed from 14-gauge galvanized steel. The side pieces were fabricated from two lengths of two-inch by two-inch by 109¼-inch angle iron. The frame ends were fabricated to form two pieces two inches by seven and one-eighth inches by 37¼-inches long. The side and end pieces were mitered and welded together to form a unit structure. Notches were cut in the ends of the frame to allow it to slide down on the box completely without interference from the inlet and outlet headers. One-quarter-inch diameter holes were drilled into the frame for insertion of the tie-down bolts used to fasten the frame to the box.

The frame was then placed in its proper position on the box, and the locations of the one-quarter-inch diameter holes for the tie-down bolts were transferred to the lower glass support members in the box. The frame was then removed from the box and three-eighths-inch diameter holes were drilled at the points transferred from the frame. The Nutserts, with ¼-20 threads, were secured into place with a special tool, designed for that purpose, supplied by the company.

Plate IV
Top View of Completed
Solar Collector

The box and frame assembly were then cleaned with steel wool and Metalprep solution, painted with automotive primer-surfacer, and finished with two-tone acrylic enamel.

Assembly of the Solar Collector

After construction of all components was completed, the solar collector was assembled. The rigid insulation, Thermax, a product of Celotex Industries, was cut and fitted into the box, as shown in Plate II. The absorber plate was then placed into position. The small steel plates were then secured into position around the inlet and outlet headers after a bead of silicone sealant had been applied to the inner surface of the plate. The lower glass end support pieces then were put into position as shown in Plate III, and secured tightly. At this point, a bead of silicone sealant was placed on the lower glass support members one-quarter inch in from the inside edges. The transparent cover was then carefully placed on the lower support members. Another bead of silicone sealant was then placed on the glass directly above the first bead. Finally, the frame was placed over the box and secured tightly with the tie-down bolts. The completed collector is shown in Plates IV and V.

Plate V
End View of Completed
Solar Collector

TESTING THE SOLAR COLLECTOR

After the solar collector was assembled completely, tests were conducted to obtain the data required to develop a collector performance curve. The collector was mounted on an angle iron support frame built to support the collector at an angle, where it cast the longest shadow, which would allow it to intercept the highest amount of insolation during the time of testing. The equipment required for the testing included the following: a circulation pump; a flow meter valve, which is a device used to measure and adjust the fluid flow rate through the collector; an inlet temperature thermometer; an outlet temperature thermometer; a compression tank, which is a device used to absorb expansion forces caused by heating and cooling of the fluid in the collector loop; air vents; a pressure relief valve; a pressure gauge; a fill valve; and the required plumbing. Because of the complexity and cost of the equipment required for the testing of the collector, a Lennox AP-3 Solar Systems Trainer, available from Lennox Educational Products, Marshalltown, Iowa, with all of the required components was used. The inlet and outlet piping was removed from the Lennox solar collector provided, and the solar collector designed and constructed in this study was attached to the trainer. As a result, all required data from the collector could be monitored.

According to the literature search, a collector performance curve could be developed if the volume of fluid circulating through the collector and the three main variables affecting collector performance could be measured. The first variable is available solar radiation on the collector glass area over a period of time, referred to as the "incident flux," or Q_{inc} , which was measured with a pyranometer. The incident flux is expressed in terms of Btu per hour per square foot, or $Btu/hr-ft^2$, of effective absorber area. The second variable is the collector inlet temperature, T_{in} , expressed in degrees Fahrenheit. The temperature was measured with the inlet thermometer. The third variable is the ambient air temperature that surrounds the collector, or T_{amb} , expressed in degrees Fahrenheit. The value of the ambient air temperature was obtained from the National Weather Service at Meadows Field, which serves Bakersfield, California. (2:C).

The flow rate through the collector, according to the literature search should be 0.02 gallon per minute per square foot of effective absorber area. The effective absorber area of the collector designed and constructed in this study was 22 square feet; consequently, the required flow rate was equal to 0.44 gallon per minute, or 26.4 gallons per hour. To be used most effectively in the development of the collector performance curve, the fluid flow rate had to be expressed as mass flow rate. The mass flow rate was determined by multiplying 26.4 gallons per hour times the weight of water, which is approximately 8.34 pounds per gallon. The result of this computation indicated that 220 pounds per hour were traveling through the collector.

As explained previously, parameters affecting the heat delivery rate were measured at various fluid inlet temperatures, ambient air temperatures, and solar intensity. The measurements were taken every hour for 12 consecutive hours. The data recorded each hour included the following: collector fluid inlet temperature, or T_{in} , collector fluid outlet temperature, or T_{out} , ambient air temperature, or T_{amb} , and the incident solar flux, or Q_{inc} .

As indicated in Chapter 2, a performance curve was developed by plotting on a graph the value of efficiency,

$$\frac{\text{Btu/hr output}}{\text{Btu/hr input}}$$

on the vertical axis and the value for the energy ratio,

$$\frac{T_{in} - T_{amb}}{Q_{inc}}$$

on the horizontal axis. The best straight line through the data points is a complete representation of the collector over its entire operating range. The value for Btu/hr output was calculated by multiplying the mass flow rate time T_{in} minus T_{out} times the specific heat for water, which is equal to one Btu per pound per degree Fahrenheit. The value for Btu per hour input was calculated by multiplying the incident flux times the effective absorber plate area. All the data measured and calculated are included in Table 1.

Table 1. Required Data Measured and Calculated to Develop a Collector Performance Curve

Time of test	T_{in} (°F)	T_{out} (°F)	T_{amb} (°F)	Q_{inc} (Btu/hr-ft ²)	Energy ratio $\left(\frac{T_{in} - T_{amb}}{Q_{inc}} \right)$	Input (Btu/hr)	Output (Btu/hr)	Efficiency $\frac{\text{(Btu/hr output)}}{\text{(Btu/hr input)}}$
7:00 AM	80	92.5	75	175	.03	3850	2750	71.4
8:00 AM	85	100.5	80	230	.02	5060	3410	67.4
9:00 AM	96	113.0	82	270	.05	5940	3740	63.0
10:00 AM	120	136.5	86	310	.12	6820	3630	53.2
11:00 AM	141	156.0	89	320	.16	7040	3300	46.9
12:00 PM	152	168.0	93	320	.18	7040	3520	50.0
1:00 PM	152	165.5	95	310	.18	6820	2970	43.5
2:00 PM	153	167.0	99	280	.19	6160	3080	50.0
3:00 PM	153	163.0	103	235	.21	5170	2200	42.6
4:00 PM	153	159.0	103	180	.28	3960	1320	33.3
5:00 PM	154	158.0	104	120	.42	2640	880	33.3
6:00 PM	154	156.0	105	70	.70	1540	440	28.6

After all the measurements and calculations were completed and tabulated, points which corresponded to the values of both efficiency and energy ratio were plotted on a graph. The graph is shown as Figure 6. The best straight line was drawn through the data points. The line was a representation of the performance of the collector designed and constructed in this study, over its entire operating range.

The intercept value of the collector, according to the data received in testing, was approximately 0.7. The value for the slope was calculated to be 1.06. As indicated in one of the Colorado State University manuals, a similar collector manufactured by NASA/Honeywell, with a black paint absorbtive coating, and one glass transparent cover had an intercept value of approximately 0.8 and a slope of 1.2.(4:Ch.5:18-19). These values indicate that the collector designed and constructed in this study operated at an efficiency slightly less than the NASA/Honeywell collector at high ambient air temperatures and approximately the same efficiency at low ambient air temperatures.

Figure 6. Performance Curve of Collector Designed and Constructed in the Study

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The purpose of this study was to design, construct, and test a liquid-heating flat-plate solar collector. To accomplish this, it first was necessary to study the basic principles incorporated in the design and construction of the collector. These principles included three basic variables, transmissivity and reflectivity of the transparent cover and absorptivity of the absorber plate, which affect the amount of solar energy absorbed by the collector. Another principle considered was the modes of heat loss from the collector. From this literature search, information was gathered concerning the basic components of the collector, the different processes and materials that can be used in the construction of these components, and their advantages and disadvantages. The literature search also revealed a method used to measure the performance of the collector in terms of efficiency and heat output. Design considerations were then listed for each of the major components as well as the collector as a single unit. Then, each component was designed, taking into consideration the final assembly of the completed unit. Detailed designs were required for the absorber plate and the box and frame assembly because of their complexity in construction and assembly. Once the components were designed, the construction details were arranged in a logical sequence, again considering the final assembly of the unit. The collector was then carefully constructed and assembled following the design details. After the solar collector was assembled completely, tests were made, data were obtained and recorded, and a collector performance curve was developed. The data obtained from the testing of the solar collector designed and constructed in this study were compared to data received from a similar collector manufactured by NASA/Honeywell. The results of this comparison indicated that the collector designed and constructed in this study operates at an efficiency slightly less than the NASA/Honeywell collector.

Conclusions

The following conclusions were formulated concerning the design, construction and testing of the solar collector:

1. Information concerning the design, construction, and testing of a flat-plate liquid-heating solar collector was located easily, which aided the successful completion of this study.
2. The total cost of the collector was \$357.61.
3. Because of the time needed to build the collector, and the cost of materials, purchase of a commercial model is recommended.
4. Two units of the size constructed should produce, in the Bakersfield area, 65 to 75 percent of the annual hot water heating load of a family of four.
5. The collector designed and constructed in this study could be duplicated by students at the thirteenth and fourteenth grade levels who have access to the required materials and equipment.
6. The collector could have been designed to use a standard six foot long transparent cover. This change would have resulted in a lower cost for basic materials and greater ease of handling because of smaller size and weight. Because of the strength requirements for an eight-foot span, the transparent cover used in this study had a minimum thickness of three-sixteenths inch. A six foot long cover requires less thickness; consequently, it is lighter and less expensive per unit area. Also found was that material purchased in lengths longer than standard eight foot is more expensive per unit measure.
7. Other problems encountered using longer construction materials included difficulty in finding machinery large enough to form the material and, in this particular case, the increased waste of using 10 foot long material.
8. The manifold arrangement of the absorber plate could be designed to require fewer purchased fittings.

Recommendations

As a result of this study some recommendations for further study concerning increasing the intercept value and slope are appropriate.

1. Further study should be conducted by applying a selective coating to the absorber plate.

2. Further study should be conducted by increasing the amount of insulation surrounding the edges of the absorber plate.

3. Study should be conducted to eliminate the use of solder between the risers and the absorber plate. The use of four pounds of solder, at a cost of 10 dollars per pound, increased the weight and cost of the unit constructed in this study. A method should be developed to provide a more efficient thermal bond in terms of cost and heat transfer capabilities than that obtained by using solder. Two thin sheets of copper, formed around a pipe, with the pipe removed and the sheets fastened together with a resulting riser might be attempted.

4. Further study is needed to determine sizes and thicknesses of materials to reduce weight and cost. Study should be given to reducing the size of the angle iron, thickness of the copper plate, and elimination of solder.

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Table 2
MATERIAL SUPPLIERS AND COST

Item number	Material description and supplier	Total*
1.	Steel: 18-gauge galvanized sheet, 48 in. x 120 in., Jim's Supply Company, Bakersfield, California	\$29.63
2.	Steel: 14 gauge galvanized sheet, 24 in. x 120 in., B and B Supply Company, Bakersfield, California	19.04
3.	Copper: 24-ounce sheet, 36 in. x 96 in., Kern County Regional Occupation Center, Bakersfield, California	74.20
4.	Plumbing supplies: copper tube, 50 ft., Type-L, 1/2 in. dia. copper tube, 6 ft., Type-L, 1-1/4-in. dia. copper Ell 90°, 4 each, 1-1/4 in. dia. copper Tee, 8 each, 1 1/4 x 1 1/4 x 1/2 in. dia. copper Ell 90°, 2 each, 1 1/4 x 1/2 in. dia. copper bushings, 4 each, 1 1/4 x 1/2 in. dia. copper adaptors, 2 each, 1/2 in. dia. tubing to 1/2 in. pipe thread solder, 4 1-lb. rolls, 95-5 flux, 3 2-oz. cans, Nokorode soldering paste B.E. Terman Plumbing, Bakersfield, California	107.01
5.	Nutserts: 28 each, 1/4-20, Mayo Manufacturing and Supply Company, Bakersfield, California	7.42
6.	Silicone sealant: 4 16-ozs. tubes, Rhodorsil 3B, American Glass Company, Bakersfield, California	25.44
7.	Paint supplies: 1 1-gal. can, enamel reducer 2 1-qt. cans, acrylic enamel Ben's Paint and Supply Company, Bakersfield, California	18.76
8.	Paint supplies: 1 1-qt. can, Black Velvet #101-C10 1 1-qt. can, primer #4860-50 1 1-qt. can, primer #911-P4 Suntappers Solar Energy Store, Tustin, California	30.53
9.	Glass: 1 sheet, 3/16 in. x 34 in. x 96 in., low-iron, acid-etched, tempered, ASG Industries, Kingsport, Tennessee	.45.58
10.	Insulation: 150 ft. ² , rigid, "Thermax" by Celotex, donation, Raypak, Inc., West Lake Village, California	0.00
11.	Machine Screws: 28 each, 1/4-20 x 1 1/2 in., Hex head, donation, Bakersfield Community College, Bakersfield, California	0.00
	Total	\$357.61

*All prices include taxes.

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