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Michael L. Day '79
Harvey Mudd College

Donald S. Remer
Harvey Mudd College

Daniel Hyatt '82
Harvey Mudd College

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FLAT-PLATE SOLAR COLLECTOR MATERIALS

Michael L. Day, Donald S. Remer, and Daniel Hyatt

ABSTRACT

The desirability of specific materials and designs for conventional flat-plate solar collector components is considered. Then a methodology for choosing the most economic component is presented, consisting of a computer simulation and a rate-of-return analysis. The effect of rising conventional fuel costs is examined. Examples of using the methodology are given, based on Southern California climatic and user-demand conditions. Selective absorber-plate coatings and film inner glazing are shown to be economic, yielding a rate-of-return of 23% and 29%, respectively.

1. INTRODUCTION

Solar energy has been shown to be a technically feasible way to reduce the conventional energy requirements of domestic hot water heating. Also, when the conventional energy supply is electricity or fuel oil, solar water heating systems provide an attractive return on investment. When natural gas is the fuel, however, the rate of return for solar energy is unattractive.

Solar water heating systems are not competitive with natural gas in some areas because of their high initial cost and the current regulated low price of natural gas. Solar collector panels make up about 36% of this initial expense. In this paper we will consider ways to improve the cost-effectiveness of solar collectors.

Our study concerns large-scale Solar Assisted Gas Energy (SAGE) installations which are designed to augment conventional gas boilers in multi-unit residential buildings. In Southern California an optimum-sized SAGE facility provides about 70% of the energy needed during the year for hot water heating; the other 30% is supplied by a backup natural gas boiler. SAGE facilities are sized to provide all of the energy needs on the hottest day of the year. A larger installation wastes energy during some parts of the year while a smaller one uses too much natural gas.

Our approach will have three parts:

1. We discuss material and design considerations for solar collector components.
2. We develop a technique to predict the performance of various design configurations based on a computer simulation. The simulation models the performance of each configuration in a large-scale Solar Assisted Gas Energy (SAGE) installation.
3. We apply Discoutnted Cash Flow and analysis to these performance figures to determine the rate of return on investment for various design options. We present three models for future fuel prices and the resulting equations for calculating the rate of return with each of these scenarios.

2. MATERIAL AND DESIGN CONSIDERATIONS FOR SOLAR COLLECTORS

In designing a solar collector, the engineer must be aware of the performance and reliability of the materials and components in his proposed design. This section considers these qualities in the design options appropriate to a flat-plate solar collector. When applied to specific climatic conditions, user demand estimates, and alternative energy costs, this information will aid the designer in producing the best collector design for a given installation.

Since the choice of a direct or indirect solar heating system governs many material choices, we discuss this decision first. Then we consider each component separately, noting, however, that the components must work together as a system.

Direct vs Indirect Systems

Solar hot water heating systems can be classified as either direct or indirect. A direct system circulates ordinary tap water through the collectors to absorb the heat, whereas an indirect system collects energy with a separate heat transfer fluid. This fluid then transfers heat to the water used by the residents through a heat exchanger. Typical direct and indirect systems are shown in Figures 1 and 2 respectively.

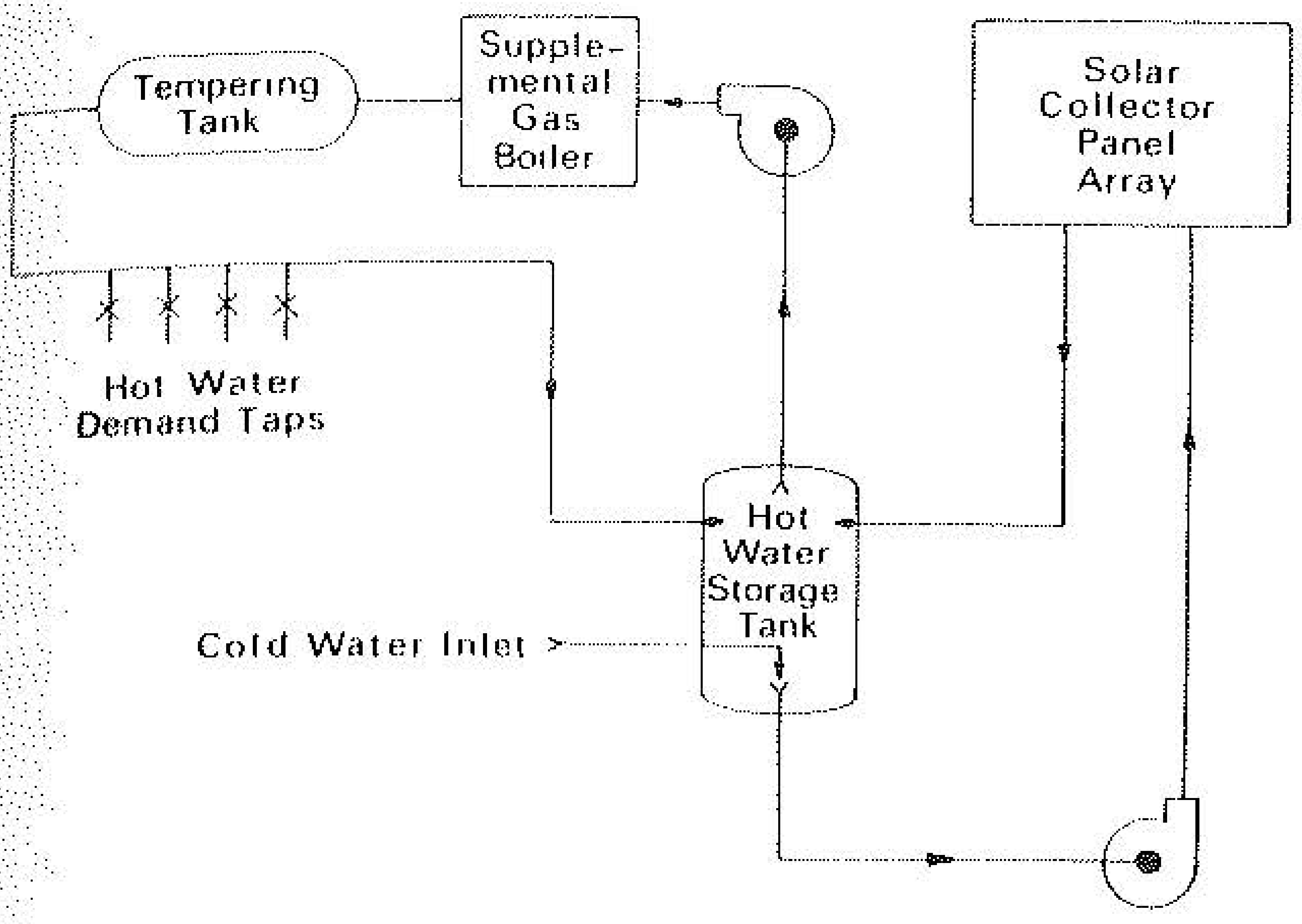


Figure 1. Direct Solar Hot Water Heating System.

Both systems have advantages and disadvantages that may make one better for a particular site. These advantages and disadvantages are summarized in Table 1 and discussed below.

TABLE 1

COMPARISON OF DIRECT AND INDIRECT SOLAR HOT WATER HEATING SYSTEMS

Direct	Indirect
1. Collectors must withstand tap water corrosiveness and main pressures. 2. Freeze protection required. 3. Hence, more expensive designs and materials. 4. No Heat Exchanger required.	1. Inhibitors may be added to water to prevent corrosion and freezing. 2. Heat exchanger required; higher operating temperatures, lower efficiencies. 3. Building codes may require double-walled heat exchangers.

In an indirect system, inhibitors may be added to the heat transfer fluid to prevent corrosion and freezing. Thus, inexpensive metals such as aluminum may be used for the collector tubing. Also, with anti-freeze agents in the heat transfer fluid, freezing temperatures do not require drain-down of the system. In a direct system, since ordinary tap water flows through the collectors, metals subject to corrosion may not be used for the tubing. In addition, direct systems require a drain-down mechanism or some other form of freeze protection.

Furthermore, a direct system generally operates at a main pressure of 60 psig, normally higher than that used in an indirect system. The lower pressures possible in an indirect system permit less expensive designs for the collectors and storage tank.

The major disadvantages of indirect systems is that they require a heat exchanger between the heat transfer fluid and the tap water supply. This means the working fluid must be hotter than the desired water temperature because of the temperature drop across the heat exchanger. This lowers the efficiency of the collectors and

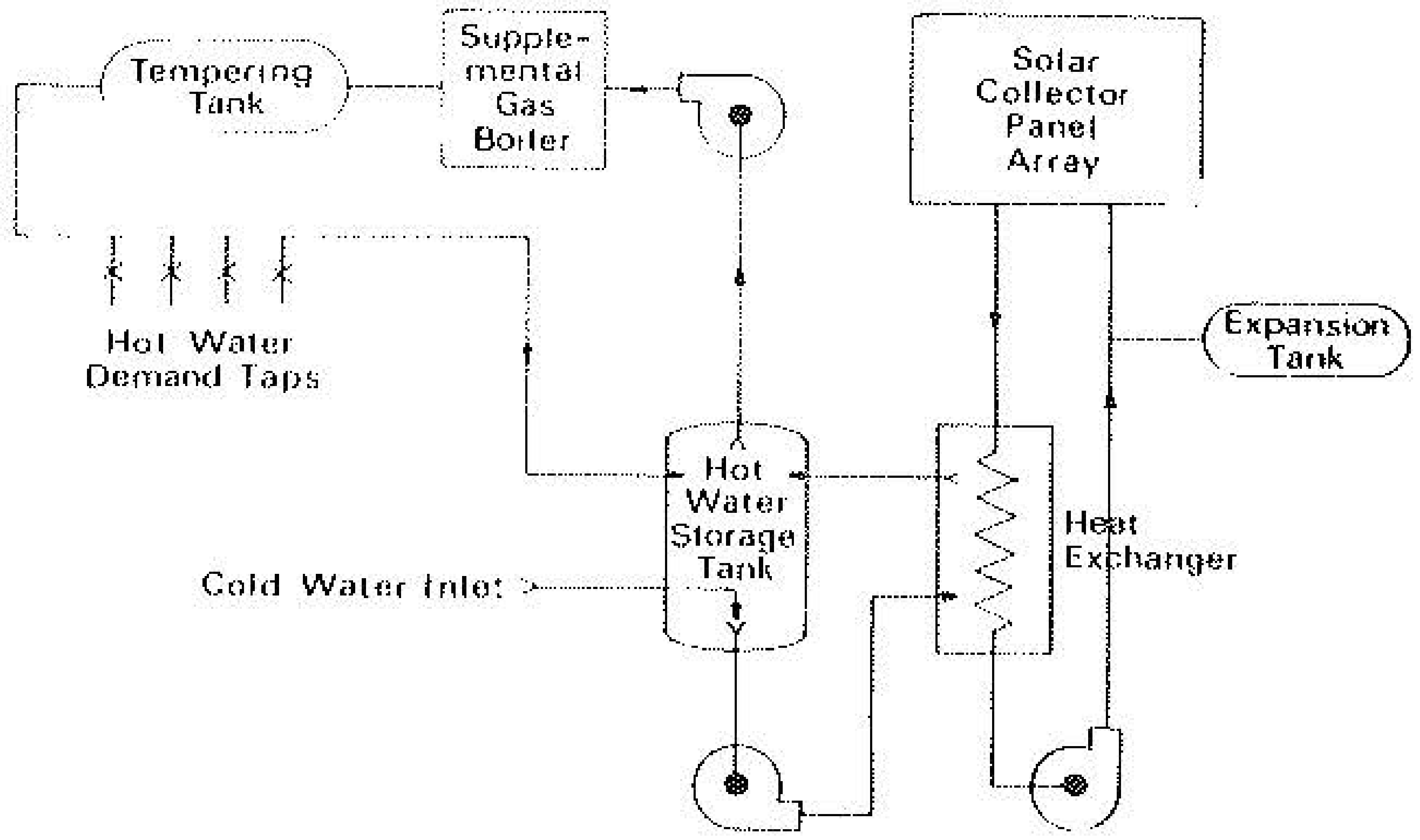


Figure 2. Indirect Solar Hot Water Heating System.

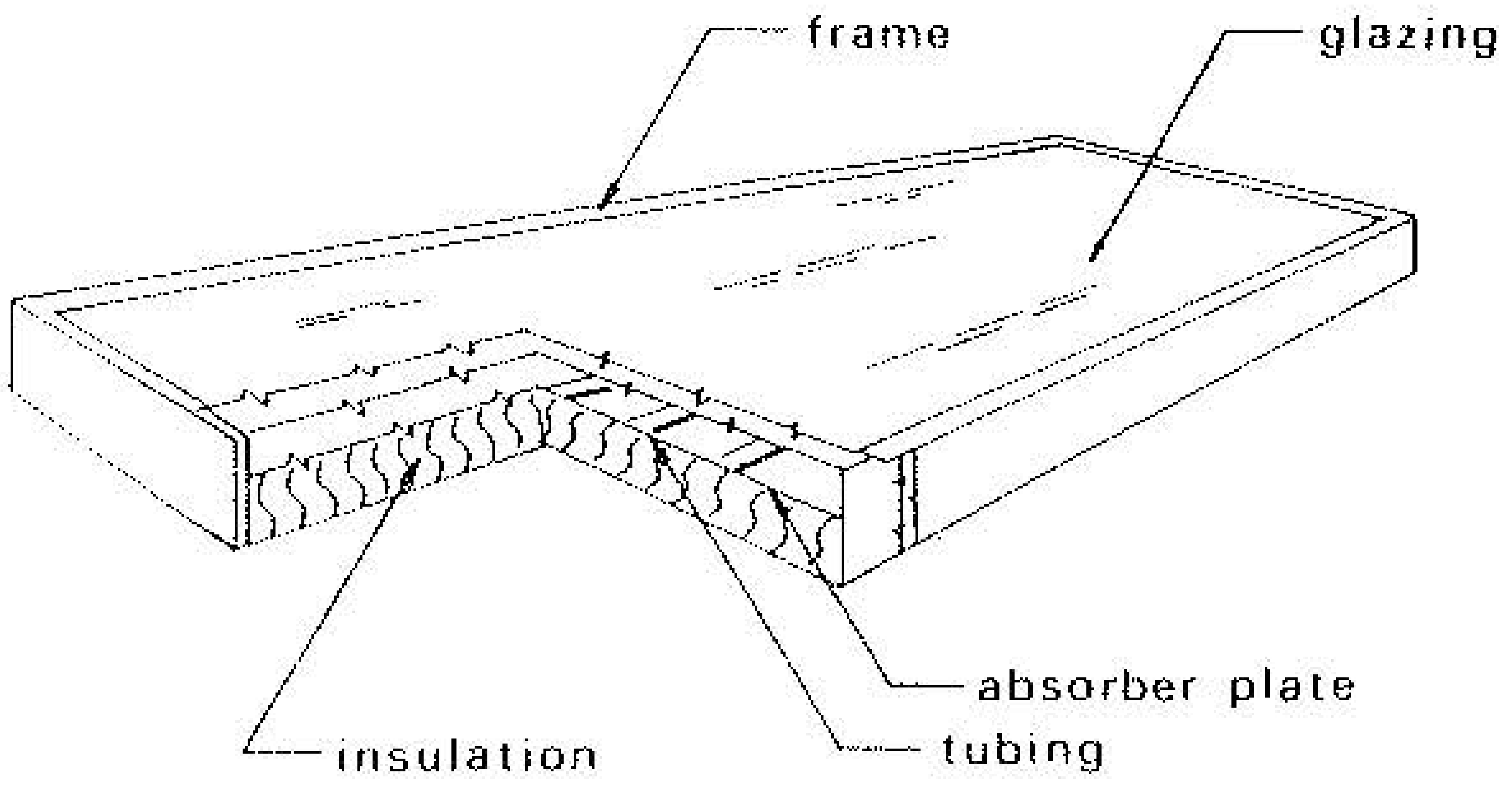


Figure 3. Cross-Sectional View of Typical Flat-Plat Solar Collector.

increases the collector area required, thereby reducing the cost-effectiveness of the system. In addition, local building codes are important, as some localities require "fail-safe," double-walled heat exchangers that further reduce the desirability of indirect systems.

Absorber Plate and Tubing

The absorber plate and tubing system is the "heart" of the solar collector as shown in Figure 3. The absorber plate converts incident solar raidiation into heat energy. This heat is then conducted to the heat transfer fluid within the tubing. Since the absorber-tubing system is such an important part of the collector, it is important to maximize its cost-effectiveness.

The absorber and tubing materials must have high thermal conductivities, since heat is to be conducted through the absorber plate and tubing wall to the heat transfer fluid. Typically, metal absorbers and tubing are used to meet this requirement. The high thermal conductivities and moderate costs of copper and aluminum make them preferable to other metals.

If the tubing is to be used in a direct system it must not corrode in the presence of uninhibited water. Copper is the only moderately priced metal meeting this requirement. In an indirect system, corrosion inhibitors can be added to the heat transfer fluid, thus allowing the use of cheaper aluminum tubing.

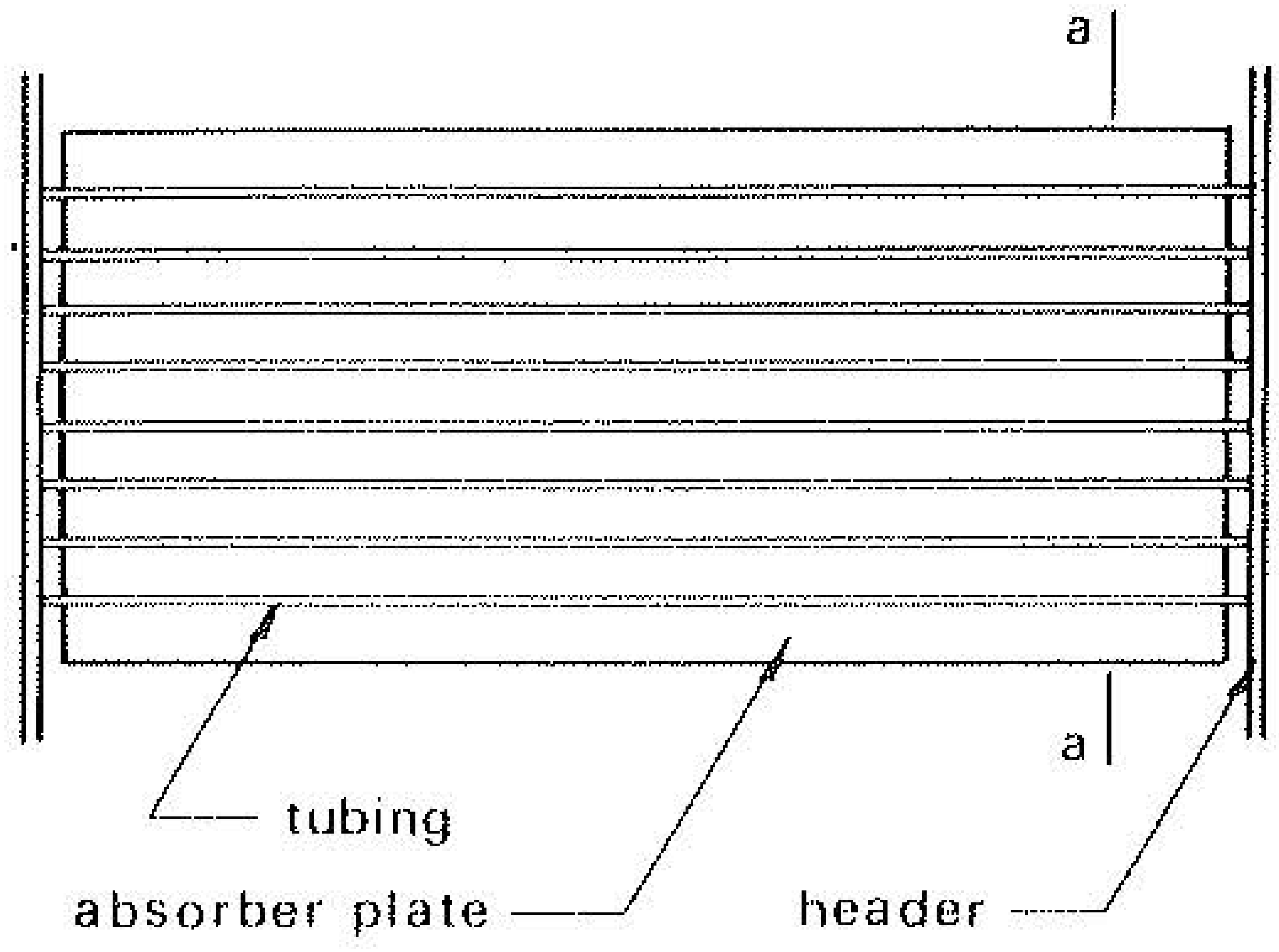
There are two conventional methods of bonding the tubing to the absorber plate. The first is brazing or soldering to achieve a metallic bond. The second is to clamp the tubing into absorber fins, forming a mechanical bond. In this latter method, temperature drops occur because there is no chemical bond between the tubing and the plate. The heat transfer properties of the chemical bond are superior to those of the mechanical bond, thus making a chemically bonded absorber-tubing system more efficient.

Both methods require extensive labor to bond the tubing to the absorber plate. Most tubing systems consist of a network of individual tubes constructed in a grid pattern. Each of these tubes must be bonded in a labor consuming process to the absorber plate.

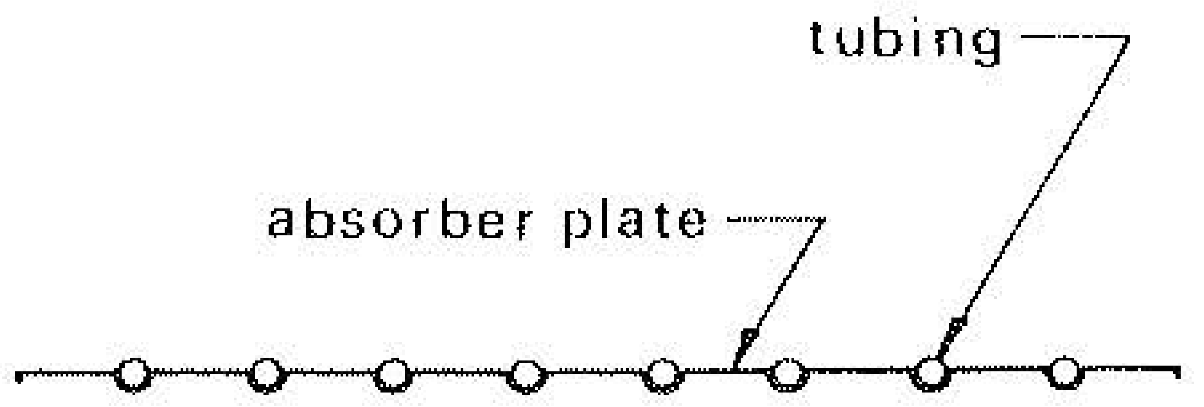
This labor cost can be reduced by using a one-piece, bonded-plate absorber. The features of conventional and bonded-plate absorbers are compared in Table 2 and discussed below.

For a bonded plate absorber, a stop-weld compound has been applied. The welded sheets are then put into a mold and the areas where the stop-weld compound has been applied are inflated with compressed air to form the tubing.

Bonded-plate absorbers have several advantages over conventional absorber-tubing systems in addition to reducing labor costs. First, the manufacturing process can provide a more efficient tubing pattern without additinal cost. Specifically, the intricate tubing pattern required to ensure evenly distributed fluid flow through each tube can be cheaply produced. Uniform flow eliminates "hot spots" that increase heat losses. Furthermore, the tubes can be spaced very close together without additional cost. This reduces the distance heat must be conducted, thereby improving performance. Typical conventional and bonded-plate tubing configurations are shown in Figures 4 and 5, respectively.



(i) Top View of Absorber

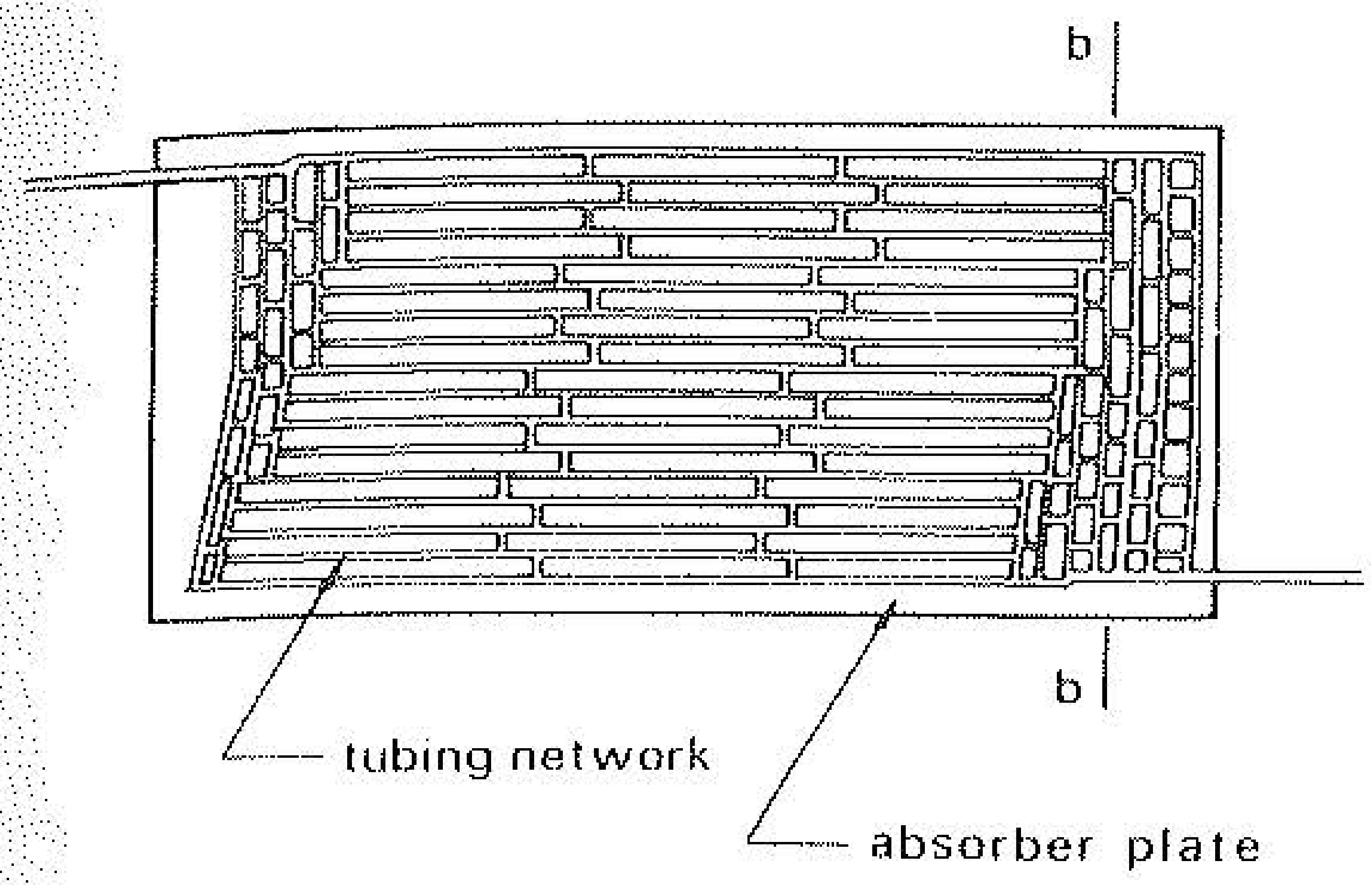


(ii) Cross Section at aa

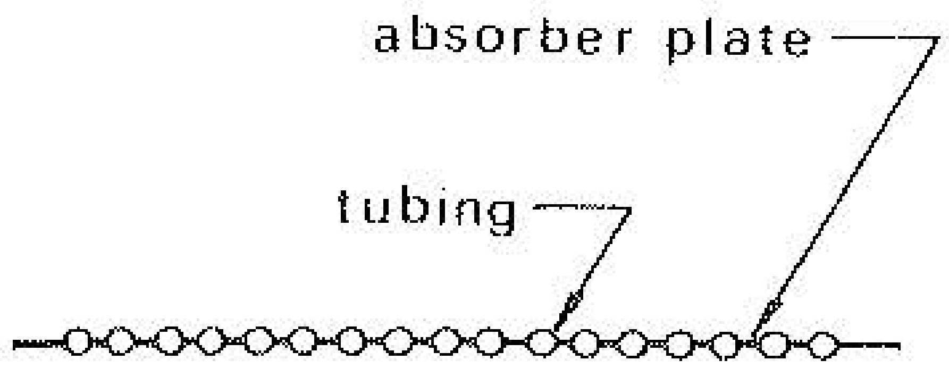
Figure 4. Conventional Solar Absorber.

TABLE 2
FEATURES OF CONVENTIONAL AND BONDED-PLATE ABSORBERS

Conventional Absorbers	Bonded - Plate Absorbers
1. Parallel tubing bonded to separate absorber plate.	1. One-piece plate and tubing.
2. Less material required in absorber plate.	2. Intricate tubing pattern to provide uniform flow.



(i) Top View of Absorber



(ii) Cross Section at bb

Figure 5. Bonded Plate Solar Absorber.

Because of the geometry of their fluid passages, bonded-plate absorbers require more material than conventional absorbers to withstand the same fluid pressure. This added cost must be weighed against the decreased labor cost and improved efficiency of the bonded-plate absorber.

As we will show later, bonded-plate absorbers perform better than conventional models and are currently less expensive as well.

Glazing

The purpose of the glazing is to reduce heat losses from the absorber plate. Glazing retards convection and re-radiative heat transfer. Since no material transmits all of the radiation it receives, the glazing reduces the amount of incident solar radiation (insolation) reaching the absorber plate. Hence, glazing is only beneficial when the reduction in convection and re-radiation losses more than offsets the decrease in the amount of insolation received at the absorber plate. Studies show that for low temperatures uses such as swimming pool heating, (operating temperature about 80°F), glazing reduces the efficiency of heat collection.[1] However, glazing is very effective at the higher temperatures required for domestic hot water heating ($\sim$160°F).

The glazing must meet three major requirements. First, it must have a high transmittance in the visible region of the spectrum to maximize the insolation passed through to the absorber. Second, it must be made of a material that can withstand solar radiation. Third, the glazing material must be fairly strong. It must withstand rough handling and harsh weather, as well as resist baseballs, rocks, and other urban hazards.

Suitably transparent materials are generally either glass or plastic. Most plastics, however, degrade with long exposure to solar radiation. They become cloudy or turn yellow, thus losing much of their transparancy. Also, the plasticizers in the plastic tend to evaporate after prolonged exposure to the sun, causing the material to become brittle and crack. In addition, dust can become embedded in the surface of the plastic and reduce the transmittance. On the other hand, most plastics are both cheaper and lighter than glass. Moreover, to withstand rough treatment the glass must be tempered, thereby increasing its costs.

Some systems use double glazing which is especially effective when the difference between the fluid temperature and the ambient temperature is extreme (greater, say, than 60°). Studies show that using glass as the inner glazing is generally not cost-effective for domestic water heating in moderate climates.[1] Thin (.001 inch) polymer films, however, may be cost-effective in some cases. The thin films have a very high transmittance and are much less expensive than glass. Though the films are too weak to be used for outer glazing, we find they are economic when used as an inner glazing. We discuss their theoretical performance as found by our methodology in the next section.

Absorber Coating

The purpsose of the absorber coating is to increase the amount of solar radiation absorbed by the absorber plate. Without a coating, much of the solar radiation is reflected off the absorber; with it, most of the radiation is absorbed.

Absorber coatings can be classified as either selective or non-selective. A selective coating has a high absorbance in the visible region of the spectrum, and a low emittance in the infra-red region. This property minimizes heat losses due to thermal re-radiation from the absorber plate. A non-selective coating also has a high absorbance, but has a high emittance as well. Because a selective coating minimizes re-radiation losses, it is more efficient than a non-selective coating. However, selective coatings are more expensive than non-selective ones, and therefore may not be cost-effective even though they improve the collector efficiency. We show later that a selective coating added to a conventional configuration provides an incremental rate of return of about 23%.

Insulation

The purpose of the insulation is to reduce heat losses from the absorber plate to the surroundings. The insulation must be stable at the stagnation temperature reached when no water is running through the collector (typically 400°F). Most types of insulation contain binders which break down at high temperatures. These binders emit vapor that collects on the glazing and reduces its transmittance. Therefore, no binders should be used in solar collector insulation.

Various types of insulation can be used in a high-temperature collector. These include mineral wool, industrial felt, foam glass, and fiberglass. The primary concerns of the designer are the cost and volume of insulation required to provide effective thermal isolation for the absorber plate.

Frame

The frame holds the components of the collector together and protects them from the environment. It must be fairly strong, and yet light enough for two men to carry during installation. The frame must also be resistant to adverse weather conditions. It must not warp, crack or corrode.

Some possible materials for a frame are wood, aluminum and steel. While steel is the strongest of the three, its weight makes handling and installation of the collector difficult. Wood is sometimes preferred for aesthetic reasons, but requires special treatment to resist warping and cracking. Aluminum is frequently used as it is resistant to adverse weather, and is reasonably light, strong and inexpensive.

3. COMPUTER SIMULATION OF SOLAR COLLECTOR DESIGN OPTIONS

We have considered some material and design options for solar collectors heating hot water. To make an economic choice, we need a performance estimate of each design configuration of interest. To obtain this performance estimate, we applied the computer simulation discussed below.

Our simulation included the following design options, but the methodology is general enough to be applied to any solar collector design with a known efficiency curve.

Glazing: Two layers of glass vs. One layer of glass
Absorber: Olin Bonded-Plate vs. Tube and Sheet
Absorber Coating: Selective vs. Non-Selective

For each design, the simulation obtained a "fuel-saved" figure. This fuel-saved figure is the amount of energy saved by the collector in an optimum-sized SAGE installation.

We used the fuel-saved figure and the cost of the design option to find the rate of return on the option. For example, adding another layer of glazing increases the cost of the collector as well as the fuel savings. The cost-increase is the "incremental" cost of the option; the increase in fuel savings is the "incremental" fuel-saved figure. Later, we calculate the rate of return on investment based on these incremental costs and savings.

To obtain reliable fuel-saved estimates for a particular design, we needed the following:

1) The efficiency curve paramenters for a sample set of collectors having that particular design.

2) A means to simulate the daily operation of a collector in a large-scale SAGE installation.

First, we will describe how we met these requirements and then summarize our results.

Collector Sample Set

To predict the fuel-savings produced by a particular design option, a number of similar collectors having that option must be simulated. This permits finding an average fuel-saved figure. We used efficiency curve parameters of different collectors tested by the Florida Solar Energy Center (FSEC), an independent solar collector test facility.[2] Table 3 shows the collectors divided into categories based on their design. The number of collectors in each category is also shown.

With this division we can predict fuel savings for each configuration using the simulation discussed next.

The resulting average fuel savings for each configuration are shown in Table 4.

TABLE 4
ANNUAL FUEL SAVINGS FOR EACH SOLAR COLLECTOR CONFIGURATION

Configuration	Fuel Saved $\times 10^{-5}$ BTU/ft^2/yr
A	2.57 ± .10
B	2.19 ± .08
C	2.78 ± .03
D	2.95 ± .01
E	2.65 ± .06
F	2.82 ± .01

TABLE 3
CONFIGURATIONS SIMULATED ON THE COMPUTER.

Configuration	Glazing	Absorber	Absorber coating	Number in Category
A	Single glass	Tube & Sheet	Non-Selective	17
B	Single plastic	Tube & Sheet	Non-Selective	12
C	Double glass	Tube & Sheet	Non-Selective	5
D	Single glass + Film	Tube & Sheet	Non-Selective	1
E	Single plastic	Bonded Plate	Non-Selective	3
F	Single plastic	Tube & Sheet	Selective	2

With this data we can find the incremental fuel savings of one configuration over another. For example, the incremental fuel savings for selective vs non-selective coating (configuration F vs B) is

$$[(2.82 \pm .01) - (2.19 \pm .08)] \times 10^5 = .63 \pm .09 \text{ BTU/ft}^2\text{/yr}$$

The incremental savings for each comparison are shown in Table 5.

TABLE 5.
INCREMENTAL FUEL SAVINGS FOR SOLAR COLLECTOR CONFIGURATIONS

Comparison	Components Compared	Incremental Fuel Savings $\times 10^{-5}$ BTU/ft^2/yr
C vs A	Double glass vs Single glass	.21 ± .13
D vs A	Single glass + film vs Single glass	.38 ± .11
E vs B	Bonded plate vs Tube & Sheet	.46 ± .14
F vs B	Selective vs Non-selective	.63 ± .09

Simulation Method

Our simulation is based on the computer program SOL.FOR, written by a team at Harvey Mudd College supported by funds from the Southern California Gas Company.^{3} Briefly, the program simulates the performances of solar collector arrays. It uses Southern California climatic data and user demand data based on the Southern California Gas Company SAGE installations in El Toro and Upland, California. The user enters the following system and collector parameters:

Site latitude
Collector mounting angle
Collector aperture area
Collector efficiency curve parameters
Storage tank volume
Desired tap water temperature
Daily hot water demand

Using this data, the program optimizes the size of the array and outputs the annual fuel savings. The optimum-sized array provides exactly all the hot water demanded on the hottest design day of the year. The annual fuel-saved is

1.5 X (ANNUAL HEAT COLLECTED).

The factor of 1.5 accounts for the assumed gas boiler efficiency of 67%.

We chose the system parameters to model the SAGE-equipped apartment complex in Upland, California. These parameters are

Volume of storage tank: 1000 gallons
Desired Tap Temperature: 130°F
Daily Hot Water demand: 1600 gallons (40 gal/unit/day)

The collector mounting angle was 32°. The aperture area and efficiency curve parameters were taken from the data provided by the Florida Solar Energy Center.

For these four comparisons, the percent deviation of the incremental fuel savings goes from a low of 14% for selective vs. non-selective coatings to a hight of 62% for double glass vs single glass. This means that the performance difference between different models within the same configuration is a significant fraction of the incremental fuel savings between two different configurations. In the next section, we will apply rate-of-return analysis to the incremental fuel savings and

CONSTANT FUEL PRICE MODEL

$$P = A\left[\frac{(1 + i)^n - 1}{i(1 + i)^n}\right] \tag{1}$$

where P = incremental investment for modifying the solar collector in dollars.

A = annual fuel savings resulting from the modification in \$/year.

n = life of the solar collector after the modification in years.

i = rate of return on the incremental investment in %/year uncertainties.

4. RATE OF RETURN ANALYSIS

We will develop a method to find the rate of return for an incremental investment in various collector design options. An incremental investment in a solar panel component has an associated initial cost and annual savings. For example, adding a second layer of glazing will increase the collector's initial cost, but it will also provide an additional annual fuel savings. The fuel savings may be predicted using the computer program SOL.FOR discussed in Section III. The incremental investment can be obtained from manufacturers. Thus, both the initial cost and the annual savings of a particular component can be found.

Given the component's expected life and a model for the future fuel price behavior, the rate of return on investment can now be found. However, the key question is how will fuel prices change in the future. We will consider three fuel price models.

First, if we assume the price of fuel is constant over the life of collector, then the following equation can be used for calculating the rate of return on investment.[4]

CONSTANT FUEL PRICE MODEL

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \qquad (1)$$

where P = incremental investment for modifying the solar collector in dollars.

A = annual fuel savings resulting from the modification in \$/year.

n = life of the solar collector after the modification in years.

i = rate of return on the incremental investment in %/year

Given P, A, and n, the rate of return can be easily obtained from Equation (1) by trial and error or by using standard economic tables.[4]

Equation (1) can only be used when the annual fuel savings remains constant over the life of the collector. This assumption is not realistic because fuel prices and hence the annual fuel savings will be rising in the future. A second method is to assume the annual fuel cost will increase in equal increments such as 25c per million BTU's per year, for example. The mathematical model for this approach has been previously developed.[5,6] The resulting equation for the rate of return is

LINEAR FUEL COST ESCALATION MODEL

$$P = R\left[\frac{(1+i)^n - (1+ni)}{i^2(1+i)^n}\right] \qquad (2)$$

where P, i, and n have the same definitions as for Equation (1), and R is the annual fuel cost escalation factor in \$ per million BTU's.

For our analysis, however, we feel it is more reasonable to assume that the fuel cost escalation rate will be constant each year. Given this assumption, then the fuel savings will rise at a constant rate, e, each year, i.e.,

initially $A_0 = A$

at the end of the first year, $A_1 = A(1+e)$

at the end of the second year, $A_2 = A(1+e)^2$

$\vdots$

at the end of the nth year, $A_n = A(1+e)^n$

We have derived the following expression for the rate of return using this fuel price escalation model.[7]

Geometric Fuel Cost Escalation Model

$$P = A\left[\frac{1+e}{i-e}\right]\left[1 - \left(\frac{1+e}{1+i}\right)^n\right], \quad i \neq e \qquad (3)$$

where P, A, i, and n have the same definitions as for Equation (1) and

e = annual fuel price escalation rate in %/year.

Note that for the special case where i = e, we have shown that Equation (3) reduces to

$$P = An \qquad (4)$$

Now Equation (3) can be rearranged to give

$$i = \frac{A}{P}(1+e)\left[1 - \left(\frac{1+e}{1+i}\right)^n\right], \quad i \neq e \qquad (5)$$

Since we know P, A, and n, and we can assume values for e, then the return on investment, i, can be calculated from Equation (5).

Though we can't obtain an explicit solution for i in terms of the known variables, we can calculate i by using iterative techniques. We will apply Equation (5) to incremental investments in film and glass inner glazing, and selective absorber coatings.

We will assume the lifetime of the collector, n, to be 15 years which is a typical life for a manufacturer's guarantee. The annual savings in the first year, A, is found with the computer simulation described earlier. The annual fuel cost escalation rate is a difficult value to predict 15 years into the future. We used values of 8%, 10%, nd 12% per year.

Finally, the present values of the incremental investments must be determined. We estimated these based on discussions with vendors and other consultants. The incremental investment in a second layer of glass glazing is about $1.00 per square foot.[8] The cost of Teflon FEP film is $.18/ft^2, but this does not include the cost of an additional frame to hold the film. We estimated this cost to be $.22/ft^2, giving a total incremental cost for film inner glazing of $.40/ft^2. The bulk unit cost of selective coating is about $1.00 per square foot.[8] Non-selective coating, applied by the manufacturer, costs about $.25/ft^2, and the retail cost is about $.40/ft^2. Thus, the incremental investment in selective over non-selective coating is $.75/ft^2.

The incremental expense and first-year savings for these three investments are listed in Table 6. The first-year savings are derived by our computer simulation. They are based on a current natural gas price of $2 per million BTUs.

The incremental rate of return on these investments for escalation rates of 8, 10 and 12% are shown in Table 7. These values have been computed using Equation 5. For the glass inner glazing, the incremental rate of return was less than 6% for all three fuel escalation rates.

The uncertainties in rate of return result from the uncertainties in the first-year annual savings. We did not try to assign uncertainties to the investment costs. These costs vary from dealer to dealer and are very sensitive to rising labor and material costs. Using our methodology, the designer might wish to compute his own rate-of-return values for particular incremental costs.

Table 7 shows an expected incremental rate of return of about 29% for inner film glazing and about 23% for selective absorber plate coatings. This makes investment in either of those components attractive. Our simulation, however, compares modified collectors to a base configuration. For that reason, we can draw no conclusions about the return on adding, say, film inner glazing to a collector already equipped with selective absorber coating.

Next, we note that glass inner glazing has a rate of return below 6% and does not appear attractive. This confirms the findings of other researchers that double glass glazing is not economic in the Southern California area.[1] In northern climates we would expect a higher rate of return for glass inner glazing.

Finally, we will compare conventional tube-and-sheet absorber plates with Olin Brass Solar-Bond absorber plates. At present, tube-and-sheet absorber plates cost the vendor about $5 per square foot and the current base wholesale price of Olin Brass Solar-Bond absorber plates is about $4.18 per square foot.[10] However, Solar-Bond panels use more material than conventional plates, so their cost is likely to rise faster in the future.

If the price of Solar-Bond panels rises above conventional absorbers, we can calculate the maximum incremental cost that will still provide a minimum rate of return. Suppose 20% is the minimum acceptable rate of return. Earlier, we found an annual fuel savings of 4.6×10^4 BTU/ft^2/yr for bonded-plate absorbers. This is a

TABLE 6.
INITIAL COST AND ANNUAL SAVINGS FOR THREE INVESTMENTS

Investment Considered	Incremental Annual Savings, A ($/yr/ft^2)	Incremental Investment ($/ft^2)
Glass Inner Glazing vs Single Glazing	.042 ± .026	1.00
Film Inner Glazing vs Single Glazing	.076 ± .022	.40
Selective vs Non-selective Absorber Coating	.126 ± .018	.75

TABLE 7.
INCREMENTAL RATE OF RETURN ON INVESTMENTS IN SOLAR COLLECTOR COMPONENTS

Investment	Incremental Rate of Return on Investment for three annual fuel cost escalation rates		
	8%	10%	12%
Film Inner Glazing	27 ± 7%	29 ± 7%	31 ± 7%
Selective Absorber Coating	21 ± 3%	23 ± 3%	25 ± 3%

first-year annual savings of $.092/ft^2/yr. If we take the fuel cost escalation rate to be 10% per year, then from Equation 3 we calculate an incremental investment of $1.87/ft^2. This incremental cost is the largest investment in a bonded-plate absorber that is justified if the minimum acceptable rate of return is 20%. Of course smaller incremental costs provide a higher rate of return.

Finally, note that the rate of return figures are for the incremental investments added to a base configuration of tube-and-sheet absorber, single glazing and non-selective coating. Although, individually, investments in bonded-plate absorber, film glazing and selective absorber coatings have a high rate of return, this does not imply that the best configuration is a combination of all three. The incremental return for, say, adding film to a panel already having a selective coating may not be favorable. To find these rates of return, we need experimental performance figures for each combination of glazing, absorber and absorber coating.

We are now pursuing experimental work to develop these performance figures. Shown in Figure 6 is the test facility which has been recently built to measure these performances variables. Our next phase of work will be to test the various design configurations directly. We hope thereby to get an independent experimental check on the economic performance figures developed in this paper.

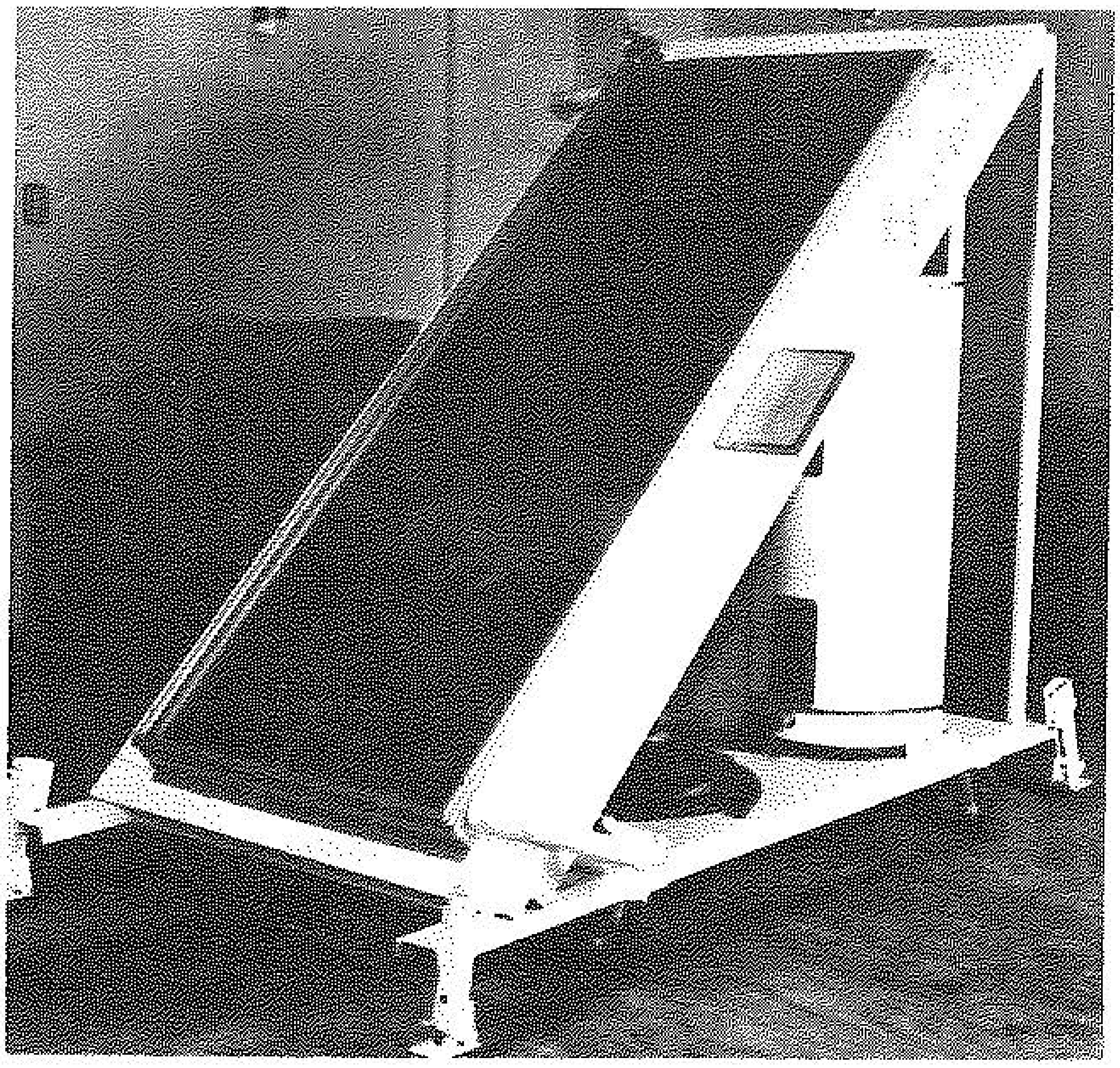


Figure 6. Experimental Solar Collector Test Facility.

5. SUMMARY

We have described some of the material and design considerations faced by a solar collector designer. Aluminum and copper are the most economic materials for the collector's absorber plate. Glass outer glazing is most effective, but is also heavier and more costly than plastics. Plastics in general have serious durability problems in solar applications. The type of system being considered is critical to solar collector designs, as is the climate at the solar installation site.

To make quantitative performance estimates of various designs, we simulated the performance of each design by computer. The simulation is based on the published efficiency curves of a number of collectors of various designs. With our simulation, we were able to predict the amount of fuel savings produced by each configuration.

We developed three equations for applying discounted cash flow rate of return analysis included a range of fuel cost escalation rates from 8% to 12% per year. We found

Michael L. Day is a recent graduate of Harvey Mudd College where he received his Bachelor of Science and Master of Engineering degrees. He is currently employed by the Western Development Labs of the Ford Aerospace and Communicattions Company in Palo Alto, California. At the Western Development Labs he is engaged in analysis of mechanical systems design of the Intelsat V Communications satellite.

Donald S. Remer is the Oliver C. Field Associate Professor of Engineering at Harvey Mudd College of Engineering and Science. He received his M.S. and Ph.D. in Chemical Engineering and Business Economics from the California Institute of Technology and his B.S.E. in Chemical Engineering from the University of Michigan. Prior to coming to Harvey Mudd College he served with Exxon Chemicals in several positions including forecasting, planning, economics, coordination, and technical service. He is a founding partner of the Claremont Consulting Group which does industrial and governmental consulting in the areas of engineering economics, and energy, pollution abatement, and materials economics. He also does life cycle cost and management science analysis for the Jet Propulsion Laboratory of the California Institute of Technology. Since 1975, he has been the Economics Chairman for the Fuels and Petrochemicals Division of the American Institute of Chemical Engineers. He is also the Case Study Editor for the Journal The Engineering Economist."

selective absorber plate coatings and film inner glazing to be attractive investments compared to a base configuration without those options. For a fuel cost escalation rate of 10% per year, selective coatings provide an annual rate of return of 23% and film inner glazing yields 29%. Glass inner glazing was found to be unattractive in the Southern California area with a rate of return of less than 6% per year. Bonded-plate absorbers appear to be both cheaper and more effective than conventional absorbers. We have begun an experimental test program to verify these results.

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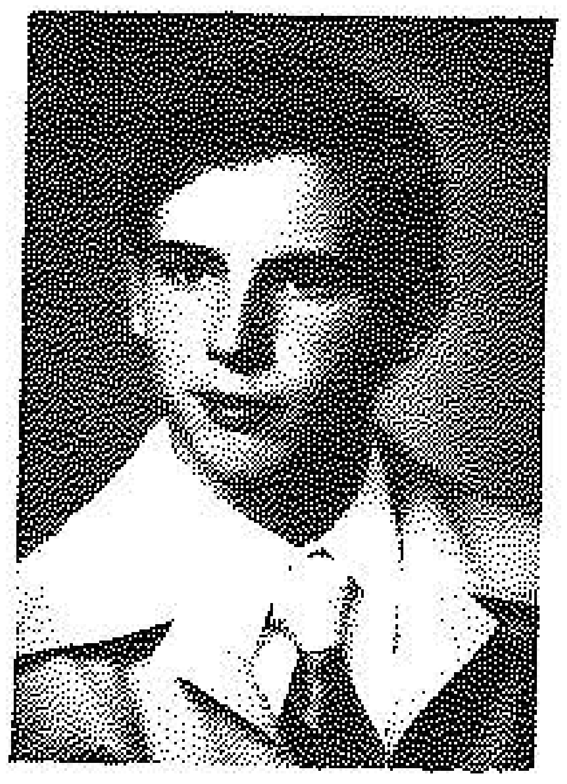

Daniel Hyatt is currently an undergraduate engineering major at Harvey Mudd College. He has been involved in solar research for the past five years. In 1978 he received the Fred H. Rohr Award for his design and construction of a solar power system, and in May, 1979, he received an award for his SAGE presentation at the Western Regional AIChE Conference. Daniel is presently conducting summer research with a $30,000 grant awarded to Solar Resources Inc. by the Southern California Gas Co.