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Lawrence Livermore Laboratory

FLAT-PLATE SOLAR COLLECTOR HANDBOOK -

A SURVEY OF PRINCIPLES, TECHNICAL DATA AND EVALUATION RESULTS

Herbert W. Newkirk

March 29, 1976

MASTER

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INTRODUCTION

Flat-plate solar collectors, delivering energy at temperatures near or below 100°C, are capable today of meeting the thermal energy needs for many types of systems such as domestic hot water heaters and building space heaters. This technology is considered to be immediately available for general use, and its application is expected to make an important contribution to a segment of the United States energy economy which accounts for one-quarter of the nation's energy use.^{1,2} For example, in space heating alone, one projection optimistically predicts that by the year 2000, four million buildings will be solar equipped, resulting in an annual energy savings of 165 billion kilowatt hours, an annual fuel value savings of \$4.5 billion (1975\$). As an added bonus, this usage would reduce air emissions by over 430,000 tons and eliminate around 20 million tons of solid waste.³

In recognition of this potential, ERDA is attempting to transfer information to the general public, and to all professional and non-professional people involved in the solar industry, about the present availability of solar sub-systems hardware. Since the most critical and unique hardware component in calculating the thermal performance of any solar energy system is the collector, it seems worthwhile to compile for transfer, information on this item.

1. National Solar Energy Research, Development and Demonstration Program - A Definition Report ERDA-49, June 1975, Energy Research and Development Administration, Division of Solar Energy, Washington, D.C. 20545.
2. National Program for Solar Heating and Cooling (Residential and Commercial Applications) ERDA-23A, October 1975, Energy Research and Development Administration, Division of Solar Energy, Washington, D.C. 20545.
3. Literature, General Electric Company, Space Division, P.O. Box 13601, Philadelphia, Pennsylvania.

Medium-temperature collectors, composed of a metal absorber component under a surface of single or double glazed glass or plastic, and collecting heat by circulating liquids or air to temperature of 180⁰ F, are currently being manufactured and sold on a growing scale in the United States after having been used for more than a decade in Australia, Israel and Japan. A recent government survey showed that the number of companies manufacturing flat-plate solar collectors jumped from 39 in 1974 to nearly 70 in 1975. During the first six months of 1975 production and sales were four times what they were during a similar period a year ago.⁴

Thirteen domestic and foreign manufacturers of medium temperature collectors have been selected for presentation in this report. They have met the criteria: (a) intention by the manufacturer that the equipment be used only for heating and cooling buildings and for domestic hot water heating and (b) evaluation of the collector by the National Aeronautics and Space Administration (NASA) using a solar simulator as a basis for collector selection and performance prediction.^{5,6} Equipment evaluated according to the National Bureau of Standards (NBS) method of testing will be surveyed in a forthcoming publication.⁷ All data were abstracted from information received from the participating companies and from the appropriate NASA report. It is presented in Appendix A for information only and includes, when available, the following data:

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4. "Solar Collector Manufacturing Activity, January-June 1975." Publications Distribution, Federal Energy Administration, Washington, D.C. 20461.
 5. K. Yass and H. B. Curlls, "Low-Cost, Air Mass 2 Solar Simulator," National Aeronautics and Space Administration, NTIS, Springfield, VA 22151, June 1974.
 6. F. F. Simon, "Flat-Plate Solar-Collector Performance Evaluation with a Solar Simulator as a Basis for Collector Selection and Performance Prediction." NASA TM X-71793. Technical paper presented at the 1975 Internal Solar Energy Society Meeting, Los Angeles, CA, July 28-August 8, 1975. Lewis Research Center, Cleveland, Ohio 44135.
 7. J. E. Hill and T. Kusuda, "Method of Testing for Rating Solar Collectors Based on Thermal Performance." NBSIR 74-635, U.S. Department of Commerce, Washington, D.C., December 1974.

1. Absorber Plate
 - a. Absorptive Coating
 - (1) Materials
 - (2) Complete absorptivity and emissivity characteristics
 - (3) Commercial identification
 - b. Base Plate
 - (1) Materials
 - (2) Fabrication (procedures/processes)
 - (3) Thermal properties (conductivity, specific heat)
 - (4) Bonding materials
2. Container
 - a. Materials
 - b. Commercial identification
 - c. Fabrication (procedures/processes)
3. Insulation
 - a. Materials
 - b. Commercial identification
 - c. Thermal properties (conductivity, specific heat)
4. Transparent Cover
 - a. Materials
 - b. Commercial identification
 - c. Complete absorptivity, emissivity, and transmissivity characteristics
5. Collector Arrays
 - a. Cooling or transport fluid
 - b. Weight
 - c. Plumbing requirements
 - d. Durability, resistance to damage, performance degradation with time and maintenance
 - e. Delivery date and cost
 - f. Installation requirements and cost

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This report begins with a discussion of flat-plate solar collector principles and will be updated periodically to include new entries and additional data. For the reader interested in a more complete listing of solar energy flat-plate collectors, three recent surveys are presently available.⁸⁻¹⁰ Anyone interested in obtaining further information should inquire directly to the author(s) designated in these reports.

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8. Solar Directory, edited by Carolyn Pesko, Ann Arbor Science Publishers, Inc., P.O. Box 1425, Ann Arbor, Michigan 48116.
 9. Survey of Solar Energy Products and Services, May 1975. Prepared for the Subcommittee on Energy Research, Development and Demonstration of the Committee on Science and Technology, U.S. House of Representatives, 94th Congress, at Session by the Science Policy Research Division, Congressional Research Services, Library of Congress, Serial G, USGPO, Washington, D.C., 1975.
 10. ERDA-75 Catalog on Solar Energy Heating and Cooling Products, October 1975. ERDA Technical Information Center, P.O. Box 62, Oak Ridge, Tennessee 37830.

PRINCIPLES

The Language of Solar Collectors

The following language will be of some help in understanding the important features of solar collector systems:

The Power Plant

The power plant in these systems is the sun - a star and the main source of radiant energy in our solar system. Every year the sun supplies the earth with 3,600 quintillion British Thermal Units (BTUs) of energy which is 18,000 times the amount needed to meet the world's current yearly energy demands.

Collector

This is a box-like assembly arranged or placed facing the sun to collect solar heat. Figure 1 shows that these heat exchangers are designed to maximize absorption of solar radiation and to minimize heat losses. The predominant heat loss mechanisms from the front face are by convection and radiation. Convection losses are controlled by the use of one or more transparent covers whereas radiation losses are sometimes reduced by means of a "selective" coating on the absorber surface, which has a high absorptance for the solar spectrum and a low emittance for the infrared re-radiation spectrum. Other minor heat loss mechanisms are conduction to the back of the collector and edge.

Figure 2 shows a series of schematic cross-sections of flat-plate collectors illustrating the many design variations currently being offered by manufacturers. The Australians have traditionally used copper tubing soldered to copper sheet similar to the thousands of solar water heaters built a generation ago in the United States. It has advantages over steel and aluminum because of its resistance to corrosion and its ease of forming and soldering.¹¹

11. "Energy Primer - Solar, Water, Wind and Biofuels," Portola Institute, Menlo Park, CA 94025, p. 8, 1974.

Figure 1. Schematic cross-section of a type flat-plate solar collector illustrating the major functional parts. This unique heat exchanger uses a black absorber plate through which a fluid is caused to flow to remove the energy.

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and B. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MS, May 1975, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

(a) Tubes integral with collector panel

(b) Tubes bonded to collector panel

(c) Corrugated sheet welded and riveted to flat base

(d) Thomason "Solaris" collector, with water flowing in open troughs

(e) Air heater using blackened corrugated steel or aluminum

(f) Löff type air heater with overlapping glass plates

Figure 2. Schematic cross-section of various flat-plate solar collector designs currently being offered by manufacturers.

Reference:

Adapted from J. I. Yellott, "Solar Energy Utilization for Heating and Cooling," Chapter 59, ASHRAE Handbook, 1974.

The collector plate shown in Fig. 2(a) represents an integral tube-in-sheet which is made in the United States under the Roll-Bond patents held by the Olin Brass Company. Their process involves printing with a proprietary "ink" of the desired tube pattern on one flat sheet of aluminum. A sandwich is then made by putting a second sheet of aluminum over the first and bonding the two together with heat and pressure over their entire surfaces, except for the printed areas. The tubes are created by inserting a special needle into an unbonded portion of the edge and inflating the tube pattern with a pressurized fluid. This is the process by which virtually all refrigerator freezing compartments are made and patterns of extreme complexity can be produced on panels to sizes of up to 3 to 4 feet by 12 feet.

The one major problem encountered with aluminum tube-in-sheet is corrosion which generally occurs when untreated water comes into contact with bare aluminum. Manufacturers are employing several different techniques to solve the problem. For example, the Showa Aluminum Company of Japan has a U. S. Patent on the use of zinc powder in the proprietary "ink" used in the Roll-Bond process and this produces the equivalent of a galvanizing action on the water passages which makes them entirely resistant to corrosion.

Cover Plate -

This component is usually made of window glass or plastic which transmits the sun's light but traps the heat, in a manner similar to the familiar greenhouse. Trapped heat is then absorbed by the other half of the collector assembly.

Heat Absorber Plate -

This component is made of metal or glass and usually blackened with black paint or a black "selective" surfacing to enhance heat absorbing qualities.

Reflector -

A shiny surface positioned so as to concentrate additional sunlight into a collector.

Banks or Arrays of Collectors -

A group of collector boxes set at an optimum collection angle with the sun. They might be part of the roof structure of a building or set up nearly at ground level.

Air Collector Heating System -

A system that circulates air instead of water in the collectors to carry heat to storage or use. Rock beds or cinder blocks are commonly used heat storage material in this type of system. The most obvious advantage of an air system over water is the elimination of leaks, frozen pipes and corrosion. Main disadvantages are that more energy is required to move air than to move water, and duct work is relatively expensive and space consuming.

Figure 3 illustrates the basic principle of using a flat-plate solar collector in a typical sun-air-collector-storage-space design context. When the collector temperature exceeds the rock bed exit temperature, the collector is on and damper C is in the position shown. Otherwise the collector is off and damper C is in the upper position.

When the building calls for heat the damper H is in the position shown. Otherwise the damper H is in the upper position. The furnace is operated as necessary to satisfy the building load. The fan is on when either the collector is on or the building needs heat.

When the collector is on, the solar heated air is routed either to the building space directly (when the building needs heat) or to the rock bed. When the collector is off, the building is heated by blowing air through the rock bed in the reverse direction and directly into the building space.

Figure 3. A schematic diagram illustrating the basic principle of using a flat-plate solar collector in a typical sun-air collector-storage-space design context.

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and B. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MS, May 1975, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

Liquid Collector Heating System -

A system that circulates liquid in the collectors to carry heat to storage or use. Liquids normally used include water or anti-freeze solution. The heat storage is usually by a tank of water which may be used to heat the house by air blown over hot water coils or by hot water radiators. The main drawbacks to liquid collectors are potential problems of leaking, freezing, and corroding.

Figure 4 illustrates the basic principle of using a flat-plate solar collector in a typical sun-water collector-storage-space design context. When the collector temperature exceeds the water tank storage temperature, pump C is operated to transfer solar heat to storage.

When the building calls for heat, pump H is operated to heat the air upstream of the furnace through a finned-tube coil. If the energy added is insufficient to maintain room temperature, the furnace is operated.

Coolants -

Air as a coolant seems to offer little problems in its application; however, the selection of a liquid collector coolant is a choice between conflicting requirements. One would desire a stable non-freezing, non-boiling, non-corroding, non-flammable, inexpensive, high specific heat, non-viscous, non-toxic, and non-energy-intensive fluid. Many liquids have been tried and all have been found deficient in one or more of these categories. Ethylene glycol/water mixtures are often used; a class of light paraffinic oils show promise such as Downtherm HP or Thermia 33.

Table I lists some of the liquid coolants used in flat-plate collectors, their properties and costs.

Figure 4. A schematic diagram illustrating the basic principle of using a flat-plate solar collector in a typical sun-water collector-storage-space design context.

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and B. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MS, May 1975, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

Table I. SOME LIQUID COOLANTS USED IN FLAT-PLATE SOLAR COLLECTORS

	<u>WATER</u>	<u>85% ETHYLENE GLYCOL/WATER</u>	<u>PARAFFINIC OIL</u>	<u>UCON (POLYGLYCOL) 50-HB-280-X</u>
FREEZING POINT, °F	32	-33	--	--
POUR POINT, °F	--	--	10	-35
BOILING POINT, °F	212	265	700	600
CORROSION	(CORROSIVE TO Fe OR Al, REQUIRES INHIBITORS)		NON-CORROSIVE	NON-CORROSIVE
FLUID STABILITY	(REQUIRES pH OR INHIBITOR MONITORING)		GOOD*	GOOD**
FLASH POINT, °F	NONE	NONE	455	500
SPECIFIC HEAT BTU/LB/°F	1.0	0.65	0.46	0.46
BULK COST (\$/GAL)	--	2.35	1.00	4.40
SYSTEM FLUID \$/FT ² COLLECTOR	--	.19	.11	.38

*REQUIRES AN ISOLATED COLD EXPANSION TANK OR NITROGEN CONTAINING HOT EXPANSION TANK TO PREVENT SLUDGE FORMATION.

**CONTAINS A SLUDGE FORMATION INHIBITOR.

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and B. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MS, May 1975, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

Performance

Methods of predicting collector performance are well established¹²⁻¹⁵ and are calculated by performing a detailed heat balance on the absorber surface and on each sheet of glazing, accounting for solar and infrared absorption and radiation, convection and conduction heat flows.

Collector efficiency is defined as the ratio of the heat removed by the coolant divided by the incident solar energy. It is not a single number but is dependent on a variety of conditions such as the coolant temperature and flow rate, the angle of the incident sunlight, and wind velocity. It is also dependent on collector design parameters.

In general, the efficiency of a collector decreases with increasing operating temperature and decreasing radiation density. It is standard practice to plot collector efficiency as a function of the parameter $\Delta T/Q$, for example,

$$\frac{\Delta T}{Q} = \frac{\text{Average Collector Coolant Temperature} - \text{Temperature}}{\text{Incident Solar Radiation}}, \frac{^{\circ}\text{F}}{\text{Btu/ft}^2/\text{hr}}. \quad (1)$$

Equation 1 and Figure 5 illustrate an important determining factor in solar energy system performance and demonstrates that collectors are uniquely sensitive to temperature and must be designed to operate at minimum temperatures above the required levels. As the collector coolant temperature rises, thermal losses approach the amount of absorbed radiation and collector output diminishes.

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12. H. C. Hottel and B. B. Woertz, Trans. Am. Soc. Mech. Eng. 64 91 (1942).
 13. H. C. Hottel and A. Whillier, Trans. Conf. on the Use of Solar Energy (Univ. of Arizona Press, Tucson, Arizona, 1958), Vol. 2, Part. 1.
 14. J. A. Duffie and W. A. Beckman, "Solar Energy Thermal Processes" (Wiley-Interscience, 1974), Chapter 7.
 15. W. C. Dickinson, R. D. Neifert, G.O.G. Löff and C. B. Wimm, "Performance Handbook for Solar Heating Systems: A Progress Report", September 12, 1975. UCRL-77208, University of California, Lawrence Livermore Laboratory, Livermore, California 94550.

For most practical designs today, zero output collector temperatures are typically 150° to 175° above ambient, and normal operating temperature ranges are less than 75°C above ambient.

Figures 6-10 illustrate the important parameters in flat-plate solar collector design, namely, the ratio of the collector size to the thermal load for all collectors, and in the special case of air collectors, the heat transfer effectiveness and the air flow rate. The data are useful in determining either the required collector array size to achieve a desired performance with a given load or the effect of changes in load with a given collector area. As the plots indicate, there is little to choose between the air and water collectors types and a final choice will undoubtedly depend on such considerations as economics, ease of installation, maintainability, convenience, availability, philosophy, or prejudice.

Other performance related factors that must be considered by anyone constructing and specifying collectors include corrosion control, expansion or absorber plate and cover plates at maximum service temperatures, freeze-up protection, moisture removal, weather proofing, cover plate durability and day-long heat collection.

Figure 5. Typical performance of a flat-plate solar collector illustrating that collectors must be designed to operate at minimum temperature above the required levels.

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and B. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MS, May 1975, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

Figure 6. Sizing of flat-plate water and air collectors for space heating applications with forced air distribution. The effect of the double glazing is to reduce the collector heat losses. However, it also reduces the sunlight reaching the absorber surface and increases the collector cost (nominal value = 0.5; building load = 12 Btu/hr²/°F/day).

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and B. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MB, May 1975, University of California; Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

Figure 7. Sizing of flat-plate water collector for domestic hot water applications. As in the case of space heating, the most important design parameter is the ratio of the collector size to the thermal load.

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and B. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MS, May 1975, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

Figure 8. Effect of air flow rate on flat-plate air collector design. As the air flow decreases the collector ΔT increases and collector efficiency decreases. A severe performance penalty will result at air flow rates below 1 cfm/ft² ($hA = 6$).

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and D. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MS, May 1975, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

Figure 9. Effect of flat-plate air collector heat transfer effectiveness, hA . This is the product of the heat transfer coefficient times the heat transfer area divided by the collector area. The area, A , can be increased by adding fins or making all sides of the flow passage effective for heat transfer. The heat transfer coefficient can be increased by increasing the flow velocity and decreasing the flow channel size.

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and B. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MS, May 1975, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

Figure 10. Flat-plate air collector performance map, $L = 10$ ft. At a nominal value of $hA = 6$ an air flow rate of $2 \text{ cfm/ft}^2\text{c}$ can be obtained in a 10 ft long collector with values of $D = 0.70$, $S = 2.10$ in. and $W = 1.40$ in. For these conditions the flow velocity is 514 feet per minute, A is $2 \text{ ft}^2\text{c}$ and h is $3 \text{ Btu/ft}^2\text{/hr/}^\circ\text{F}$. Increases in hA increase the collector pressure drop and therefore increase the required fan power. For the nominal values chosen, the collector pressure drop is 0.075 in. of water and the pumping energy lost in channel friction is about $0.12 \text{ Btu/ft}^2\text{c/hr}$ or $0.035 \text{ watts/ft}^2\text{c}$.

Reference:

Adapted from D. Balcomb, J. C. Hedstrom, S. W. Moore, and B. T. Rogers, "Solar Heating Handbook for Los Alamos" LA-5967-MS, May 1975, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 87544.

Retrofitting to New and Existing Buildings

The following are the main factors to investigate when considering solar heating and cooling for either an existing residence or building, or for one in the planning stage:

Lifecycle Costs -

The initial cost of heating and cooling equipment used to be practically the only factor in deciding on the type of system to install in a residence or building. The cost of energy, because it was inexpensive, played a small role in that decision. Now, energy costs are rising and necessarily have to be considered when analyzing the lifetime costs of owning and operating any heating and cooling system--including a supplemental solar system. So are maintenance costs, financing costs, depreciation, salvage or trade-in value, and fuel costs. Taking all these factors into consideration before a buying and installation decision is made is called lifecycle costing.

Keep in mind that the costs of solar heating and cooling systems are mainly determined by the collector and storage unit. The collector cost is the major investment and is proportional to the collector area. Figure 11 shows that collector costs are strongly influenced by their construction and performance, which in turn affects the cost of saved energy.¹⁶ Most of the flat-plate collectors on the market today, with one exception, cost \$10 or more per square foot. In addition, 50% must be added to the cost for installation and plumbing, making these systems competitive only where electricity is the sole expensive alternative.

In general, most economists agree that if the installed cost per square foot of collectors can be brought down to \$3 (i.e., if a tax break is given to the manufacturer and/or the consumer for solar equipment) or if fuel costs continue to escalate at a higher rate than 5% per year, solar energy utilization will rapidly become attractive to the consumer.¹⁷

16. J. A. Duffie and W. A. Beckman, "Solar Heating and Cooling," Science, 191 [4223] 143 (1976).

17. "Turning Toward the Sun," Volume One, Abstracts of State Legislative Enactments of 1974 and 1975 Regarding Solar Energy NCSL Renewable Energy Project, 1405 Curtis St., Suite 2300, Denver, CO 80202. RANN Document: NSF-RA-G-75-052.

Figure 11. The economics of flat-plate solar collector design dictate the need for a cost-effective high performance collector. C_F = fuel cost; C_C = Collector cost. Maximum "savings" occur at small collector areas for the expensive collector and cheap fuel, and at a collector area of 100 m² for the \$60/m² collector and expensive fuel. The savings for the collector cost of \$60/m² and the fuel cost of \$15 per Gigajoule are positive over a range of collector areas from 10 to 50 m².

Reference:

Adapted from J. A. Duffie and W. A. Beckman, "Solar Heating and Cooling," Science 191 [4223] 143 (1976).

Collector Orientation -

A clear, southern exposure is essential if the installation of a solar heating and/or cooling system is to work successfully. Practical operation of the system requires unobstructed access for the sun's rays to reach the heat collectors.

Collector Tilt -

The attitude of the sun, with respect to the horizon, varies with the time of year. To collect the maximum amount of solar energy for space heating (winter), the optimum tilt of the flat-plate collectors should be at an angle ranging from the latitude of the location of the collectors (latitude for PG&E's service area is 45°) to latitude plus 15° from the horizontal. For domestic water heating (year 'round), the optimum tilt is about at an angle equal to the latitude minus 15° . Area is more important than tilt, so build big.

Vertical Collector; Horizontal Reflector -

Theoretically, a nearly vertical collector with a horizontal reflector in front (south) of the collector can be expected to collect more energy than a collector at the optimum tilts just described. The north-south dimension of the reflector should be at least twice the height of the collector.

Sun Rights -

What if you install a solar heating and cooling system and a few months or years later someone builds a large apartment or other structure on adjoining properties that block out the direct access to the sun? It would be wise to investigate the ownership of adjoining properties and future development plans for these properties as well as to investigate zoning limitations.

Storage -

Space must be available in a basement or a yard for installation of a tank capable of holding several thousand gallons of hot water or a somewhat larger area for rock storage.

Insulation -

Higher future energy costs will usher in a new era of total insulation. Most buildings today are under-insulated and should be corrected regardless of the energy source utilized. Windows in existing structures should be inspected and additional window insulation (storm windows, shutters, etc.) should be considered.

Thermal Mass -

Concrete, masonry, sod, the earth and similar materials absorb and lose heat slowly. When these materials are used for interior walls or floors, they help stabilize the house temperature by taking extra heat during the day and giving it back to the house at night.

Structural Considerations -

Some structural changes may be necessary to adapt existing residences or buildings to solar heating and cooling. In almost all cases, additional ductwork or piping will be required. The basic design of some buildings may have to be altered to accommodate the installation of the collection system.

Aesthetics -

The necessary addition of collection systems on building exteriors or on structures adjoining buildings will have an impact on the appearance of buildings. This should be taken into account since public acceptance is somewhat dependent upon attractiveness.

Consultation -

In considering the installation of a solar heating and cooling system, it is advisable to consult both an architect and a mechanical engineer experienced in solar energy design.

APPENDIX A

TECHNICAL DATA AND EVALUATION RESULTS

NASA EVALUATION PROCEDURES

In the NASA evaluation method the parameters needed to evaluate collector performance are: liquid flow rate, liquid inlet and outlet temperatures, the simulated solar flux, wind speed, and the ambient temperature. In the NASA tests, the experimental efficiency of each collector was calculated using the following equation:

$$\eta = G C_p (T_o - T_i) / q_{dr} \quad (2)$$

where G is defined as the flow rate per unit of effective area for solar collection, for example

$$G = \dot{w} / A_e \quad (3)$$

Collector efficiencies were determined for an average flow rate of 10 lb/ft²/hr, inlet temperatures ranging between 75° to 210°F, a simulated heat flux ranging between 150 to 350 Btu/ft²/hr, wind speed of 7 mph and an ambient temperature which averaged 80°F.

The three equations useful for correlating collector performance in the NASA tests are as follows:

$$\eta = \alpha \tau - \left[\left(\frac{A_a}{A_e} \right) U_L (\bar{T}_p - T_a) \right] / q_{dr} \quad (4)$$

$$\eta = F^1 \left\{ \alpha \tau - \left[\left(\frac{A_a}{A_e} \right) U_L (\bar{T}_f - T_a) \right] / q_{dr} \right\} \quad (5)$$

$$\eta = F^1_R \left\{ \alpha \tau - \left[\left(\frac{A_a}{A_e} \right) U_L (T_i - T_a) \right] / q_{dr} \right\} \quad (6)$$

A definition of the terms used in these equations is given in Appendix B.

Table II lists the solar simulator conditions used during the evaluation procedure.

TABLE II. NASA-LEWIS SOLAR SIMULATOR CONDITIONS

<u>Radiation Source</u>
143 Lamps, 300W each
GE-type ELH, tungsten-halogen dichroic coating
12° total divergence angle
<u>Test Area</u>
4 by 4 ft, maximum
<u>Test Condition Limits</u>
Flux: 150 to 350 Btu/ft ² /hr
Flow: up to 1 gal/min (30 lb/ft ² /hr)
Inlet Temp: 75° to 210°F
Wind: 0 to 10 mph at 75°F

Reference:

Adapted from K. Yass and H. B. Curtis, "Low-Cost, Air Mass 2 Solar Simulator," National Aeronautics and Space Administration, NTIS, Springfield, VA 22151, June 1974.

LAWRENCE LIVERMORE LABORATORY

FPC

December 1975

DOMESTIC MANUFACTURER

Barber-Nichols Engineering
6325 West 55th Avenue
Arvada, Colorado 80002

Contact: Mr. Robert E. Barber
Phone: 303/421-8111

ABSORBER

Dimensions: A demonstration package using heat from incident solar radiation to produce cooling or electricity has been designed, constructed, and field tested.

Coating:

Absorptance: A 625 ft², flat plate solar collector (made by Honeywell, Inc.) to heat water providing input energy for the low

Emittance: temperature organic Rankine cycle (RC) for a three-ton Rankine cycle air conditioner, 1 kw electric system.

CONTAINER

Dimensions:

Material:

INSULATION

Installed in the Honeywell-NSF Mobile Solar Research Lab, the system has been operational since August, 1974, in various locations throughout the continental United States. Its performance has been documented for a wide variety of climatic solar situations. The coefficient of performance (supplied cooling divided by solar heat input to the Rankine cycle) is 0.50 at the design point water flows: 11 gpm of 215°F collector water and 25 gpm of 85°F cooling water.

TRANSPARENT COVER

PLUMBING

MODULE WEIGHT

COSTS AND DELIVERY

The unit is not being marketed and is not in production at the present time. All rights are owned by Honeywell, Inc., Minneapolis, Minnesota.

PERFORMANCE

NASA-Lewis Solar Simulator Test Results

Collector: Barber CuO - 1 glass

Absorber

Material and Type Copper tubes bonded to absorber plate

Collector Area

A_T , sq ft 8.6

Cover Area

A_g , sq ft 6.9

Absorber Area

A_a , sq ft 6.9

Effective Area

A_e , sq ft 6.9

Coating, Absorptance

α 0.97

Coating, Emittance

ϵ —

Collector

Heat Capacity

C_c —

Time Constant (t_c), calc min

—

Experimental Constants

a	$\ominus$	0.795	c	$\ominus$	0
b	$\ominus$	1.17	b_o		-0.11

NASA-Lewis Solar Simulator Test Results

Collector: Barber CuO - 1 glass, Al honeycomb

Absorber

Material and Type Copper tubes bonded to absorber plate

Collector Area

A_T , sq ft 8.6

Cover Area

A_g , sq ft 6.9

Absorber Area

A_a , sq ft 6.9

Effective Area

A_e , sq ft 6.9

Coating, Absorptance

α 0.97

Coating, Emittance

ϵ —

Collector

Heat Capacity

C_c —

Time Constant (t_c), calc min

—

Experimental Constants

$a \ominus 0.795$ $c \ominus 1.17$

$b \ominus 1.17$ b_o —

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: Barber CuO - 1 glass

Clear Summer Day:

Pool Heating

η_{12} 77.3

$\eta_{\text{all day}}$ 71.1

Hot Water

η_{12} 56.3

$\eta_{\text{all day}}$ 43.7

Absorption a/c

η_{12} 33.1

$\eta_{\text{all day}}$ 19.2

Solar Rankine

η_{12} 17.6

$\eta_{\text{all day}}$ 7.3

Clear Winter Day:

Heating

η_{12} 34.9

$\eta_{\text{all day}}$ 23.8

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{\text{all day}}$ 0

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector:

Clear Summer Day:

Pool Heating

η_{12} 77.3

$\eta_{\text{all day}}$ —

Hot Water

η_{12} 56.3

$\eta_{\text{all day}}$ —

Absorption a/c

η_{12} 33.1

$\eta_{\text{all day}}$ —

Solar Rankine

η_{12} 17.6

$\eta_{\text{all day}}$ —

Clear Winter Day:

Heating

η_{12} 34.9

$\eta_{\text{all day}}$ —

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{\text{all day}}$ —

Figure 1. Zero incidence performance curves for selective surface - one cover collectors - Barber CuO - 1 glass and Barber CuO - 1 glass, Aluminum honeycomb.

FPC

December 1975

FOREIGN MANUFACTURER

Beasley Industries PTY, Limited
Balton Avenue
Devon Park, South Australia
AUSTRALIA 5008

Contact: Mr. F. D. Bauer
General Manager

Phone: 46-4871

ABSORBER

Dimensions: Copper tube framework having 1 in diameter top and bottom header tubes with 1/2 in diameter. Water tubes brazed to headers.

Coating: Selective

Absorptance: 0.90

Emittance: 0.11 at 70°C

CONTAINER

Dimensions: 52 in long x 24 in wide x 4 in deep (0.75 m²)

Material: Galvanized steel

INSULATION

Mineral wool; polystyrene sides. Single or doubly glazed

TRANSPARENT COVER

4 mm clear window glass

PLUMBING

Low pressure - 10 psi fittings
High pressure - 150 psi fittings

MODULE WEIGHT

COSTS AND DELIVERY \$45.00 (Aust) for 0.75 m² Solo pak

PERFORMANCE

See accompanying sheets

NASA-Lewis Solar Simulator Collector Performance Parameters

Collector:

F^1	_____
F_R	0.90
$\bar{U}_L$	0.85 (experimental)
(Btu/ft ² /hr, °F)	_____ (theory)
α_T	_____
α	0.86
ϵ	0.10

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: Beasley CuO - 2 glass

Clear Summer Day:

Pool Heating

η_{12} 56.6

$\eta_{\text{all day}}$ 51.1

Hot Water

η_{12} 43.0

$\eta_{\text{all day}}$ 33.3

Absorption a/c

η_{12} 27.9

$\eta_{\text{all day}}$ 17.2

Solar Rankine

η_{12} 17.9

$\eta_{\text{all day}}$ 8.8

Clear Winter Day:

Heating

η_{12} 29.7

$\eta_{\text{all day}}$ 21.2

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{\text{all day}}$ 0

NASA-Lewis Solar Simulator Test Results

Collector: Beasely CuO - 2 glass

Absorber

Material and Type Copper with tubes bonded to absorber plate

Collector Area

A_T , sq ft 8.9

Cover Area

A_g , sq ft 8.0

Absorber Area

A_a , sq ft 7.9

Effective Area

A_e , sq ft 7.9

Coating, Absorptance

α 0.86

Coating, Emittance

ϵ 0.1

Collector

Heat Capacity

C_c _____

Time Constant (t_c), calc min

Experimental Constants

$a \ominus 0.59$ $c \ominus 0$

$b \ominus 0.76$ $b_o -0.18$

Figure 1. Zero incidence performance curve for a selection surface two cover Beasley collector.

FPC

December 1975

DOMESTIC MANUFACTURER

Corning Glass Works
Special Projects, Lighting
Products Division
Corning, New York 14830

Contact: Donald A. Urquhart
Phone: 607/974-7306

Tubular Evacuated Solar Collector (TESC)

ABSORBER PLATE

Dimensions: A series of evacuated 4 inch diameter glass tubes.
10 feet long. Black plate with integral fluid
flow channels. Can use heat transfer fluids other
than water.

Coating:

Absorptance:

Emittance:

CONTAINER

Dimensions: Completely - insulated manifold. Connection for
banks of six to ten tubes

Material:

INSULATION

Reduced pressure; evacuated tubes

TRANSPARENT COVER

High purity glass transmittance of 92%.

COMPOSITE COLLECTOR

Tubes enlarged from within the space evacuated
through glass to metal seals used in the lamps industry.

PLUMBING

Heat transfer passages are made from copper.
Vertical manifold.

COSTS AND DELIVERY

\$6 - \$10 per sq ft. Available in modest quantities
in 1976.

NASA-Lewis Solar Simulator Collector Performance Parameters

Collector:	Owens - selective surface - glass - evacuated tubular
F^1	_____
F_R	_____
$\bar{U}_L$	0.20 (Experimental)
(Btu/ft ² /hr, °F)	0.15 (Theory)
$\alpha\tau$	0.72
α	0.80
ϵ	0.07

NASA-Lewis Solar Simulator Test Results

Collector: Owens - selective surface - glass - evacuated tubular

Absorber

Material and Type Glass

Collector Area

A_T , sq ft 14.4

Cover Area

A_g , sq ft 21.6

Absorber Area

A_a , sq ft 17.4

Effective Area

A_e , sq ft 17.4

Coating, Absorptance

α 0.8

Coating, Emittance

ϵ 0.09

Collector

Heat Capacity

C_c 2.5 (Experimental)

Time Constant (t_c), calc min

72

Experimental Constants

a 0.45 c 0

b 0.24 b_o +0.43

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: Owens - selective surface - glass - evacuated tubular

Clear Summer Day:

Pool Heating

η_{12} 48.1

$\eta_{all\ day}$ 53.2

Hot Water

η_{12} 43.8

$\eta_{all\ day}$ 46.5

Absorption a/c

η_{12} 39.0

$\eta_{all\ day}$ 39.3

Solar Rankine

η_{12} 35.8

$\eta_{all\ day}$ 34.8

Clear Winter Day:

Heating

η_{12} 37.8

$\eta_{all\ day}$ 37.7

Cloudy Winter Day:

Heating

η_{12} 32.4

$\eta_{all\ day}$ 26.2

Figure 1. Zero incidence performance curve for selective surface - one cover Owens collector; - selective surface - glass - evacuated - tubular.

FPC

December 1975

DOMESTIC MANUFACTURER

General Electric Company
King of Prussia Park
Energy Systems Program
Valley Forge Space Center
P.O. Box 8661
Philadelphia, Pennsylvania 19101

Contact: William F. Moore

Phone: 215/962-2000

ABSORBER

Dimensions: "Roll Bond," 0.060 in, Aluminum (1100) type

Coating: Selective

Absorptance: 0.949

Emittance: 0.380

CONTAINER

Dimensions: 8 ft x 4 ft x 4-3/4 in thick

Material: Aluminum extrusion frame and back

Area: 32 sq ft

INSULATION

Upjohn CPR 9545; Isocyanurate Foam, Fiberglass batt

TRANSPARENT COVER

Double, 0.060 in Lexan UV - inhibited, poly - carbonate plastic. Transmission - 0.85; Reflectivity - 0.098

PLUMBING

Internal headers/manifolds in adjacent panels are connected through formed external jumper hoses.

MODULE WEIGHT

94 pounds

COSTS AND DELIVERY

Designed to your specifications

NASA-Lewis Solar Simulator Test Results

Collector: General Electric Company - 2 Lexan

Absorber

Material and Type Aluminum tube sheet; Selective surface

Collector Area

A_T , sq ft 25.3

Cover Area

A_g , sq ft 23.2

Absorber Area

A_a , sq ft 22.9

Effective Area

A_e , sq ft 22.9

Coating, Absorptance

α 0.95

Coating, Emittance

ϵ 0.31

Collector

Heat Capacity

C_c —

Time Constant (t_c), calc min

—

Experimental Constants

a - 0.673 c - 0

b - 0.695 b_o -0.05

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: General Electric Company - 2 Lexan

Clear Summer Day:

Pool Heating

 η_{12} — $\eta_{\text{all day}}$ 63.1

Hot Water

 η_{12} 53.8 $\eta_{\text{all day}}$ 45.3

Absorption a/c

 η_{12} 40.0 $\eta_{\text{all day}}$ 29.2

Solar Rankine

 η_{12} 30.8 $\eta_{\text{all day}}$ 19.7

Clear Winter Day:

Heating

 η_{12} 40.9 $\eta_{\text{all day}}$ 32.5

Cloudy Winter Day:

Heating

 η_{12} — $\eta_{\text{all day}}$ 3.3

Figure 1. Zero incidence performance curve for a selective surface two cover G.E. collector.

FPC

December 1975

DOMESTIC MANUFACTURER

Honeywell, Incorporated
Systems and Research Center
2600 Ridgeway Parkway
Minneapolis, Minnesota 55413

Contact: G. G. Maylan
Phone: 612/331-4141

ABSORBER

Dimensions: Aluminum, copper rollbond; two 0.035 in 1020 cold welded sheets of steel 46.5 x 31.75 in long.

Coating: Selective NiO coating

Absorptance: 0.95

Emittance: 0.08

CONTAINER

Dimensions: 3 ft x 4 ft

Material: Steel

INSULATION 3.5 in fiberglass

TRANSPARENT COVER Double or single glass with anti-reflective surface treatment.

PLUMBING Standard 125 psi plumbing

MODULE WEIGHT 120 lb

COSTS AND DELIVERY FOB price is \$10 - \$30 per sq ft; customed designed.

PERFORMANCE See attached sheets

Figure 1. Honeywell Collector performance correlation.

Figure 2. Some comparisons of different Honeywell collector types.

Figure 3. Zero incidence performance curves for Honeywell selective surface two cover collectors.

Figure 4. Zero incidence performance curves for Honeywell non-selective surface two cover collectors.

Figure 5. Zero incidence performance curves for non-selective surface one cover Honeywell collectors.

TABLE I. Honeywell collectors tested

Number	Collector	Absorber material* and type	Collector area, A_T , sq ft	Cover area, A_g , sq ft	Absorber area, A_o , sq ft	Effective area, A_e , sq ft	Coating absorptance, α	Coating emittance, ϵ	Experimental constants			
									a_θ	b_θ	c_θ	b_o
1	Honeywell black nickel-2 glass	Al(1)	16	15	13.5	13.5	0.95	0.07	0.713	0.504	0.14	-0.16
2	Honeywell black paint-1 glass	↓	↓	↓	↓	↓	0.97	0.97	0.850	1.139	0.161	-0.078
3	Honeywell black paint-mylar honeycomb-1 glass	↓	↓	↓	↓	↓	↓	↓	0.817	0.806	0.119	-0.23
4	Honeywell black paint-mylar honeycomb-2 glass	↓	↓	↓	↓	↓	↓	↓	0.735	0.497	0.284	-0.20
5	Honeywell black paint-2 glass	↓	↓	↓	↓	↓	↓	↓	0.728	0.705	0.251	-0.15
6	Honeywell black chrome-2 glass	Steel (4)	16	15	13.3	13.3	0.94	0.07	0.725	0.687	-0.050	-0.17
7	Honeywell black nickel-2 AR glass	Al(1)	16	15	13.5	13.5	0.95	0.07	0.85	0.626	C	-0.16

*Legend: 1. Tube sheet

2. Tubes bonded to absorber plate

3. Tubes clamped to absorber plate

4. Spot welded absorber plate

TABLE II. Honeywell collector performance parameters

Collector	F'	F_R	$\bar{U}_L$, Btu/hr-ft ² , °F		$\alpha\tau$	α	ϵ
			Exp.	Theory			
Honeywell black nickel-2 glass	0.96	0.94	0.56	0.46	0.74	0.95	0.07
Honeywell black-1 glass	0.97	0.90	1.3	--	0.89	0.97	0.97
Honeywell black-2 glass-honeycomb	0.99	0.96	0.57	--	0.77	0.97	--
Honeywell black paint-2 glass	0.97	0.93	0.80	0.74	0.76	0.97	0.97

TABLE III. Horeywell collector performance ranking — noon hour performance basis

Clear summer day								Clear winter day		Cloudy winter day	
Pool heating		Hot water		Absorption a/c		Solar Rankine		Heating		Heating	
Collector number	η_{12}	Collector number	η_{12}	Collector number	η_{12}	Collector number	η_{12}	Collector number	η_{12}	Collector number	η_{12}
2	83.1	7	71.0	7	58.6	7	50.3	7	60.6	7	13.3
7	82.2	3	63.2	1	48.1	1	39.8	4	52.3	6	0.11
3	78.0	2	62.2	4	48.0	4	38.2	3	51.6	1	0.1
4	70.7	4	60.9	3	45.9	6	36.1	1	49.9	2	0
5	70.5	1	59.6	6	44.7	3	33.9	6	46.5	3	0
6	69.9	6	57.8	5	40.4	5	28.2	5	45.1	4	0
1	69.0	5	57.1	2	37.8	2	20.9	2	43.7	5	0

TABLE IV. Honeywell collector performance ranking — all day performance basis

Clear summer day								Clear winter day		Cloudy winter day	
Pool heating		Hot water		Absorption a/c		Solar Rankine		Heating		Heating	
Collector number	$\eta_{\text{All-day}}$	Collector number	$\eta_{\text{All-day}}$	Collector number	$\eta_{\text{All-day}}$	Collector number	$\eta_{\text{All-day}}$	Collector number	$\eta_{\text{All-day}}$	Collector number	$\eta_{\text{All-day}}$
2	77.4	7	60.0	7	44.7	7	35.8	7	50.7	7	15.7
7	76.1	1	49.8	1	35.5	1	26.6	4	41.9	1	7.5
3	69.7	3	49.7	4	34.1	6	23.7	1	40.5	6	6.4
5	64.9	4	49.7	6	32.4	4	23.2	3	39.6	4	6.2
4	64.5	2	49.1	3	30.6	3	18.8	6	37.1	3	2.5
6	64.1	6	47.4	5	25.7	5	15.2	5	34.2	5	1.1
1	63.9	5	45.8	2	22.5	2	9.0	2	31.6	2	0

LAWRENCE LIVERMORE LABORATORY

FFC

December 1975

DOMESTIC MANUFACTURER

Intertechnology Corporation
Box 340
Warrenton, Virginia 22168

Contact: Dr. George Szego
President
Phone: 703/347-7900

Contact: Esther Bennett
703/347-7900

ABSORBER

Dimensions: Copper or aluminum Rollbond.
Coating: Selective coating by an etch technique.
Absorptance: 0.94
 α/ϵ 0.34

CONTAINER

Dimensions: 3 ft x 8 ft
Material: _____

INSULATION

TRANSPARENT COVER

PLUMBING

Standard 125 psi rating

MODULE WEIGHT

120 lbs; expected life - 20 years.

COSTS AND DELIVERY

Designed to specifications

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector:

Clear Summer Day:

Pool Heating

η_{12} 64.5

$\eta_{all\ day}$ 59.5

Hot Water

η_{12} 52.9

$\eta_{all\ day}$ 43.3

Absorption a/c

η_{12} 40.0

$\eta_{all\ day}$ 28.6

Solar Rankine

η_{12} 31.4

$\eta_{all\ day}$ 19.8

Clear Winter Day:

Heating

η_{12} 41.6

$\eta_{all\ day}$ 32.7

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{all\ day}$ 3.8

NASA-Lewis Solar Simulator Test Results

Collector: ITC - selective surface - 2 glass

Absorber

Material and Type Aluminum tube sheet

Collector Area

A_T , sq ft 27.9

Cover Area

A_g , sq ft 24.8

Absorber Area

A_a , sq ft 23.0

Effective Area

A_e , sq ft 22.0

Coating, Absorptance

α 0.9

Coating, Emittance

ϵ 0.3

Collector

Heat Capacity

C_c 0.71 (experimental)
0.55 (estimated)

Time Constant (t_c), calc min

9

Experimental Constants

a $\ominus$ 0.665 c $\ominus$ -0.0007
b $\ominus$ 0.648 b_o -0.15

Figure 1. Zero incidence performance curve for a selective surface two cover ITC collector.

FPC

December 1975

DOMESTIC MANUFACTURER

Martin-Marietta
Aerospace Denver Division
Mail #LEO455
P.O. Box 179
Denver, Colorado 80201

Contact: Floyd A. Blake
Marketing Department
Phone: 303/794-5211

Contact: David H. Bachman
303/794-5211

ABSORBER

Dimensions: Aluminum "Roll Bond"
Coating: Optical black surface
Absorptance: 99% in the solar region
Emittance: _____

CONTAINER

Dimensions: Coastal region vertical grain fir
Material: 3 ft x 8 ft x 5-1/2 in

INSULATION

3-1/2 in Zonolite insulation

TRANSPARENT COVER

Two glazings of ASG Industries Crystal
76 water glass, 5/32 in thick-93 transmissive.

PLUMBING

MODULE WEIGHT

COSTS AND DELIVERY

Custom made on request.

NASA-Lewis Solar Simulator Test Results

Collector: M-M black paint - 2 glass

Absorber

Material and Type Aluminum tube sheet

Collector Area

A_T , sq ft

Cover Area

A_g , sq ft

Absorber Area

A_a , sq ft

11.8

Effective Area

A_e , sq ft

11.8

Coating, Absorptance

α

0.996

Coating, Emittance

G

0.996

Collector

Heat Capacity

C_c

Time Constant (t_c), calc min

Experimental Constants

$a \ominus 0.748$

$c \ominus 0.197$

$b \ominus 0.719$

$b_o 0.15$

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: M-M black paint - 2 glass

Clear Summer Day:

Pool Heating

η_{12} 72.5

$\eta_{\text{all day}}$ 66.8

Hot Water

η_{12} 59.0

$\eta_{\text{all day}}$ 47.6

Absorption a/c

η_{12} 42.6

$\eta_{\text{all day}}$ 28.9

Solar Rankine

η_{12} 30.8

$\eta_{\text{all day}}$ 17.2

Clear Winter Day:

Heating

η_{12} 47.3

$\eta_{\text{all day}}$ 36.5

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{\text{all day}}$ 1.9

Figure 1. Zero incidence performance curve for a non-selective surface two cover Martin Marietta collector.

FPC

December 1975

FOREIGN MANUFACTURER

Miromit, Ltd.
Israel
Distributed in the U.S. by

Daylin Incorporated
9606 Santa Monica Blvd.
Beverly Hills, California 90210

Contact: David Collins
Vice President

Sunsource (USA) and
Miromit, LTD (Israel)

ABSORBER PLATE

Dimensions: 3 ft x 6 ft cold rolled steel.
Operating pressure - 125 psi.

Coating: Tabor selective black NiO - 1 mm thick.

Absorptance: Absorptivity 0.89 to 0.92

Emittance: Emissivity 0.9 -1.2. Maximum service
temperature - 300°F. Lifetime - 15 years.

CONTAINER

Dimensions: 38 in by 73 in by 6 in deep.

Material: 24 gauge Galvanized steel painted finish.
Lifetime - 15 years.

INSULATION

2-1/2 in Rockwool, or fiberglass, with 1 inch of
the same insulation on the sides.

TRANSPARENT COVER

Single layer glass.

COMPOSITE COLLECTOR

92% transmittance; 35 in sq. Cover spacing - 1-1/4 in

PLUMBING

Horizontal manifold/vertical transfer pipes. Complies
with Uniform Plumbing Code and Southern Building Code
Congress

MODULE WEIGHT

110 pounds

COSTS AND DELIVERY

\$179.95 ($10.58/\text{ft}^2$) retail - small orders;
\$106.25 ($6.25/\text{ft}^2$) for larger units.

F.O.B. Beverly Hills, guarantee of two-years
on workmanship and materials; expected lifetime - 15 years.

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: Miromit

Clear Summer Day:

Pool Heating

 η_{12} 66.9 $\eta_{\text{all day}}$ 61.7

Hot Water

 η_{12} 49.9 $\eta_{\text{all day}}$ 39.3

Absorption a/c

 η_{12} 31.8 $\eta_{\text{all day}}$ 20.2

Solar Rankine

 η_{12} 20.3 $\eta_{\text{all day}}$ 10.4

Clear Winter Day:

Heating

 η_{12} 33.3 $\eta_{\text{all day}}$ 23.9

Cloudy Winter Day:

Heating

 η_{12} 0 $\eta_{\text{all day}}$ 0

NASA-Lewis Solar Simulator Test Results

Collector: Miromit

Absorber

Material and Type Steel with bonded tubes

Collector Area

A_T , sq ft 19.1

Cover Area

A_g , sq ft 15.6

Absorber Area

A_a , sq ft 15.7

Effective Area

A_e , sq ft 15.3

Coating, Absorptance

α 10.9

Coating, Emittance

ϵ 10.1

Collector

Heat Capacity

C_c

Time Constant (t_c), calc min

Experimental Constants

$a \ominus 0.689$ $c \ominus -0.125$

$b \ominus 0.976$ $b_o -0.11$

Figure 1. Zero incidence performance curve for a selective surface - one cover Miromit black nickel - 1 glass collector.

December 1975

DOMESTIC MANUFACTURER

PPG Industries, Inc.
One Gateway Center
Pittsburgh, PA 15222

Contact: Mr. Neill Barber
412/434-3552

Contact: Mr. Ray Gallagher
412/434-3553

ABSORBER

Dimensions: 1100 - type alloy aluminum "Roll Bond" R.

Coating: Black paint (Duracron R. Super 600 L/G
U C 40437

Absorptance: α 0.95

$\frac{\alpha}{\epsilon}$ 0.95

CONTAINER

Dimensions: 34 3/16" x 76 - 3/16" x 1 5/16"

Material: Anodized aluminum

INSULATION

3 inches of fiberglass

TRANSPARENT COVER

Two pieces of 1/8 inch Herculite tempered glass.

PLUMBING

Standard plumbing and connectors

MODULE WEIGHT

6 lbs/square ft.

PRICE AND DELIVERY

	<u>\$/ft²</u>	<u>External Dimension</u>
Single-glazed, copper Rollbond absorber plate	11.50	22" x 96"
Same, but double glazed	12.00	22" x 96"

Single-glazed with aluminum Rollbond absorber plate, without insulation housing	5.50	34" x 76"
Same, with housing	6.70	34" x 76"
Double glazed, Aluminum rollbond without insulation housing	6.00	34" x 76"
Same, with housing	7.20	34" x 76"

4 - 6 week delivery

COSTS AND DELIVERY

Designed to specifications

NASA-Lewis Solar Simulator Collector Performance Parameters

Collector:

F_L^1	0.94
F_R	0.85
$\bar{U}_L$	1.1 (experimental)
(BTU/hr-ft ² , °F)	— (theory)
α_T	0.73
α	0.95
ϵ	0.95

NASA-Lewis Solar Simulator Test Results

Collector: PPG black paint - 2 glass

Absorber

Material and Type Aluminum tube sheet

Collector Area

A_T , sq ft 18.1

Cover Area

A_g , sq ft 17.9

Absorber Area

A_a , sq ft 17.9

Effective Area

A_e , sq ft 17.9

Coating, Absorptance

α 0.95

Coating, Emittance

ϵ 0.95

Collector

Heat Capacity

C_c 0.43 (experimental)
0.55 (estimated)

Time Constant (t_c), calc min

11

Experimental Constants

$a \ominus$ 0.615 $c \ominus$ -0.013

$b \ominus$ 0.954 b_o -0.15

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: PPG black paint - 2

Clear Summer Day:

Pool Heating

η_{12} 59.3

$\eta_{\text{all day}}$ 53.6

Hot Water

η_{12} 42.2

$\eta_{\text{all day}}$ 31.8

Absorption a/c

η_{12} 23.4

$\eta_{\text{all day}}$ 12.9

Solar Rankine

η_{12} 10.9

$\eta_{\text{all day}}$ 4.2

Clear Winter Day:

Heating

η_{12} 28.4

$\eta_{\text{all day}}$ 19.7

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{\text{all day}}$ 0

Figure 1. Zero incidence performance curve for a nonselective surface two cover PPG collector.

FPC

December 1975

DOMESTIC MANUFACTURER

Solar Products Corporation
1001 Laguna Drive
Venice, Florida 33595

Contact: Harry Drehouse

Phone:

ABSORBER

Dimensions: Serpentine Copper tubes soldered
to copper absorber plate.

Coating: Black paint - 1

Absorptance:

Emittance:

CONTAINER

Dimensions: 2 in x 4 in redwood frame with 2 sheets of
1/4 inch asbestos millboard

Material:

INSULATION

2 inches of styrofoam

'TRANSPARENT' COVER

One sheet of tempered glass.

PLUMBING

MODULE WEIGHT

COSTS AND DELIVERY

Custom made on request.

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: Solar Products Corporation

Clear Summer Day:

Pool Heating

η_{12} 57.8

$\eta_{\text{all day}}$ 53.0

Hot Water

η_{12} 36.9

$\eta_{\text{all day}}$ 26.6

Absorption a/c

η_{12} 13.1

$\eta_{\text{all day}}$ 5.4

Solar Rankine

η_{12} 0

$\eta_{\text{all day}}$ 0

Clear Winter Day:

Heating

η_{12} 18.5

$\eta_{\text{all day}}$ 10.5

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{\text{all day}}$ 0

NASA-Lewis Solar Simulator Test Results

Collector: Solar Products Corporation

Absorber

Material and Type Copper with tubes clamped to absorber plate

Collector Area

A_T , sq ft 12

Cover Area

A_g , sq ft 9.6

Absorber Area

A_a , sq ft 10.5

Effective Area

A_e , sq ft 9.3

Coating, Absorptance

α _____

Coating, Emittance

ϵ _____

Collector

Heat Capacity

C_c _____

Time Constant (t_c), calc min

Experimental Constants

$a \ominus 0.593$ $c \ominus -0.0861$

$b \ominus 1.153$ $b_o -0.078$

Figure 1. Zero incidence performance curve for a non-selective surface one cover Solar Products collector.

FPC

December 1975

DOMESTIC MANUFACTURER

Solaron Corporation
Stapleton Field Industrial Park
4850 Olive Street
Denver, Colorado 80022

Contact: Dr. George Lof
Director of Research
Phone: 303/289-2288

ABSORBER

Dimensions: Steel, spot welded.
Coating: Selective 3M black velvet
Absorptance:
Emittance:

CONTAINER

Dimensions:
Material:

INSULATION Fiberglass, 3-1/2 inch thick

TRANSPARENT COVER Double strength glass, net transmittance of 0.80

PLUMBING

MODULE WEIGHT Custom designed

COSTS AND DELIVERY \$6.00/ft² F.O.B. Denver

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: Solaron Corporation (L.O.F.)
Collector selective surface - 2 glass

Clear Summer Day:

Pool Heating

η_{12} 41.8

$\eta_{\text{all day}}$ 37.7

Hot Water

η_{12} 29.8

$\eta_{\text{all day}}$ 22.4

Absorption a/c

η_{12} 17.1

$\eta_{\text{all day}}$ 9.9

Solar Rankine

η_{12} 9.5

$\eta_{\text{all day}}$ 4.7

Clear Winter Day:

Heating

η_{12} 18.1

$\eta_{\text{all day}}$ 12.4

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{\text{all day}}$ 0

NASA-Lewis Solar Simulator Test Results

Collector: Solaron Corporation - L.O.F.
Collector selective surface - 2 glass

Absorber

Material and Type Steel, spot welded

Collector Area

A_T , sq ft 6.3

Cover Area

A_g , sq ft 5.5

Absorber

A_a , sq ft 5.3

Effective

A_e , sq ft 5.3

Coating, Absorptance

α —

Coating, Emittance

ϵ —

Collector

Heat Capacity

C_c —

Time Constant (t_c), calc min

—

Experimental Constants

a	$\ominus$	0.433	c	$\ominus$	-0.175
b	$\ominus$	0.718	b_o		-0.15

Figure 1. Zero incidence performance curve for a selective surface two cover L.O.F. collector.

FPC

December 1975

DOMESTIC MANUFACTURER

SOLTEC
P.O. Box 6844
Denver, Colorado 80206

Contact: Mr. Richard S. Speel
President
Phone: 303/758-0318

ABSORBER

Dimensions: Copper with tubes bonded to absorber plate

Coating:

Absorptance:

Emittance:

CONTAINER

Dimensions:

Material:

INSULATION

TRANSPARENT COVER

PLUMBING

MODULE WEIGHT

COSTS AND DELIVERY

PERFORMANCE

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: SOLTEC

Clear Summer Day:

Pool Heating

η_{12} 55.1

$\eta_{\text{all day}}$ 49.5

Hot Water

η_{12} 40.6

$\eta_{\text{all day}}$ 31.1

Absorption a/c

η_{12} 25.4

$\eta_{\text{all day}}$ 15.5

Solar Rankine

η_{12} 15.9

$\eta_{\text{all day}}$ 7.8

Clear Winter Day:

Heating

η_{12} 27.1

$\eta_{\text{all day}}$ 19.1

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{\text{all day}}$ 0.6

NASA-Lewis Solar Simulator Test Results

Collector: SOLTEC

Absorber

Material and Type Copper with tubes bonded to absorber plate

Collector Area

A_T , sq ft 12

Cover Area

A_g , sq ft 10.8

Absorber Area

A_a , sq ft 10

Effective Area

A_e , sq ft 10

Coating, Absorptance

α —

Coating, Emittance

ϵ —

Collector

Heat Capacity

C_c —

Time Constant (t_c), calc min

—

Experimental Constants

$a \ominus 0.574$ $c \ominus -0.141$

$b \ominus 0.837$ $b_o -0.18$

Figure 1. Zero incidence performance curve for a selective surface two cover Soltec collector.

FPC

December 1975

DOMESTIC MANUFACTURER

Tranter, Inc.
735 East Hazel Street
Lansing, Michigan 48909

Contact: Mr. R. S. Rowland

Phone: 517/372-8410

ABSORBER

Dimensions: Carbon steel or stainless

Coating: Black paint

Absorptance:

Emittance:

CONTAINER

Dimensions: 4 ft x 10 ft

Material:

INSULATION

Double glass; 1/8 inch thick, 88% transmission level

TRANSPARENT COVER

PLUMBING

Standard 75 - 100 psi operating pressures

MODULE WEIGHT

55 lbs for 2 ft x 10 ft size

COSTS AND DELIVERY

Custom designed

NASA-Lewis Solar Simulator Test Results

Collector: Tranter, Inc.

Absorber

Material and Type Steel with spot-welded absorber plate

Collector Area

A_T , sq ft _____

Cover Area

A_g , sq ft _____

Absorber Area

A_a , sq ft _____

Effective Area

A_e , sq ft 14.9

Coating, Absorptance

α _____

Coating, Emittance

ϵ _____

Collector

Heat Capacity

C_c _____

Time Constant (t_c), calc min

Experimental Constants

a $\ominus$ 0.701 c $\ominus$ 0.601

b $\ominus$ 0.548 b_o -0.15

NASA-Lewis Solar Simulator Collector Efficiency Results

Collector: Tranter, Inc.

Clear Summer Day:

Pool Heating

η_{12} 68.0

$\eta_{all\ day}$ 62.7

Hot Water

η_{12} 56.3

$\eta_{all\ day}$ 45.0

Absorption a/c

η_{12} 38.9

$\eta_{all\ day}$ 24.4

Solar Rinkine

η_{12} 24.9

$\eta_{all\ day}$ 12.0

Clear Winter Day:

Heating

η_{12} 43.7

$\eta_{all\ day}$ 32.4

Cloudy Winter Day:

Heating

η_{12} 0

$\eta_{all\ day}$ 0

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Figure 1. Zero incidence performance curve for a non-selective surface two cover Tranter collector.

APPENDIX B

GLOSSARY OF TERMS USED
IN NASA LEWIS SOLAR SIMULATOR
PERFORMANCE EVALUATION

A_a	absorber area, ft^2
A_e	effective collector area, ft^2
C_p	fluid heat capacity, $\text{Btu/lb, } ^\circ\text{F}$
F'	collector plate efficiency factor, dimensionless
F_R	collector plate heat-removal efficiency, dimensionless
G	flow rate of collector fluid, $\text{lb/ft}^2/\text{hr}$ of absorber surface = W/A_e
q_{dr}	incident direct solar radiation, $\text{Btu/ft}^2/\text{hr}$ (in collector plane)
T_a	ambient temperature, $^\circ\text{F}$
$\bar{T}_f$	average collector fluid temperature, $^\circ\text{F}$
T_o	fluid outlet temperature, $^\circ\text{F}$
$\bar{T}_p$	average collector plate temperature, $^\circ\text{F}$
T_l	fluid inlet temperature, $^\circ\text{F}$
t	time, hr
U_L	overall collector heat loss coefficient, $\text{Btu/ft}^2/\text{hr, } ^\circ\text{F}$
W	flow rate of collector fluid
α	collector surface absorptance, dimensionless
$\overline{\alpha\tau}$	$\alpha\tau$ product for diffuse radiation, dimensionless
ϵ	collector surface emittance, dimensionless
η	collector efficiency, dimensionless = $G C_p (T_o - T_l)/q_{dr}$
τ	effective transmittance

Superscript:

— average conditions

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