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# FLAT-PLATE COLLECTOR PERFORMANCE DETERMINED EXPERIMENTALLY WITH A SOLAR SIMULATOR

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## SUMMARY

The NASA is constructing a new office building at Langley Research Center that will utilize solar energy for heating and cooling. The project is a joint effort between Langley and Lewis Research Center. A collector technology program being conducted at Lewis will provide the basis for selecting collectors for use at Langley. The technology program includes testing collectors in an indoor facility under simulated solar radiation. Tests have been conducted on five collectors to date and performance data are presented herein. The collector performance obtained with the solar simulator will be correlated with data obtained by conducting tests outdoors at Lewis.

## INTRODUCTION

About 25 percent of the energy consumed in the United States is used to heat and cool buildings (ref. 1). Presently that energy is almost entirely obtained from depletable fossil fuels. If solar energy were economical, efficient, and reliable, a significant portion of the fossil fuels used for heating and cooling could be conserved for other purposes.

NASA is constructing a new office building at its Langley Research Center at Hampton, Virginia, that will use solar energy for heating and cooling (ref. 2). A conventional hot water space heating system and an adsorption refrigeration (cooling) system will be used.

One of the most important components in any solar system is the collector. The function of the collector is to absorb solar energy and transfer it to a working fluid. The thermal energy thus obtained is used directly in the heating and cooling equipment or is stored for later use. NASA Lewis is conducting a program to find the most practical and practicable collector systems. The results will provide the basis for selecting the collectors for the Langley building. A test facility incorporating a solar simulator has been built to evaluate solar collectors under controlled conditions. Reference 3 discusses the merits of using a solar simulator to evaluate collectors among them: (The key performance parameters can be determined with the simulator using standard test procedures. Modifications can be made to collector components, and the effect of the modification readily determined.)

This paper presents a detailed description of the NASA-Lewis collector test facility, and some performance data for the five collectors tested in the facility to date.

## EXPERIMENTAL FACILITY

A drawing and a photograph of the facility are presented in figures 1 and 2. The primary components of the facility are the light source (solar simulator), the liquid flow loop, and the instrumentation and data acquisition equipment. A summary of information describing the facility is presented in table I.

### Solar Simulator

The solar simulator provides a good approximation of an air-mass 2 spectrum (ref. 4). The variation of spectral irradiance as a function of wavelength is shown in figure 3 for both the simulator and for air-mass 2.

A useful method of determining how well a solar simulator's spectral distribution matches the sun is to compare how various materials respond when irradiated by the simulator and by the sun (refs. 5 and 6). Table II provides a comparison of properties, including absorptivity of a selective coating (ref. 7) the transmittance of ordinary window glass, the reflectance of a silicon oxide coated aluminum mirror (ref. 8), and the calculated efficiency of a silicon solar cell (ref. 6), under radiant flux with the spectral distribution of air mass 2 and of the solar simulator. The spectral irradiance from the simulator was shown to be essentially constant over the range of lamp voltages used during testing (90 to 120 V) (ref. 4).

The simulator is composed of lamps, lenses, and cooling equipment. The lamps are commercially available units (General Electric model ELH) consisting of an integral tungsten-halogen lamp and reflector assembly. The reflector has a dichroic coating that absorbs infra-red radiation, thereby reducing the infra-red content of the reflected radiation. During operation the lamp voltage is adjusted with two autotransformers, each transformer supplying power to half the lamps.

The lenses are commercially available fresnel type (Cryton Optics, Inc.). The acrylic plastic is specified as optical grade. During initial operation of the simulator several lenses cracked and had to be replaced. The cracking occurred in two ways; around the screw holes, and also along the outside edges (see fig. 4).

Cracking around the screw hole was eliminated by fabric-reinforced neoprene washers placed between the screws and the lenses. Cracks also were found to originate at small nicks along the straight edges of the original set of lenses. The nicks occurred during cutting of the lens to a hexagonal shape from the square lens blank. The replacement lenses were cut slightly oversize, approximately 1/32 inch, and then sanded to final size. No cracking has occurred with the replacement lenses.

One simulator design question that occurs repeatedly concerns the operating life of the tungsten-halogen lamps used in the simulator. To date, two sets of lamps have been used. The original set was operated for 35 hours before the rate of lamp failure dictated replacing the entire array. An investigation disclosed that the quartz envelope of the bulb was operating at too low a temperature. The flow rate of the cooling air was reduced and the second set of lamps was recently replaced after about 65 hours of operation. Provision is now being made to monitor the lamp temperature on several lamps during operation, and to regulate the air flow rate to maintain the temperatures within the limits of $450^{\circ}$ F to $550^{\circ}$ F to increase lamp life.

## Coolant Flow Loop

The flow loop consists of storage and expansion tanks, pump, filter, test collector, and the required piping shown schematically in figure 5. The hot fluid storage tank is a commercially available water heater for home use. The tank has two electrical immersion heaters, 5 kilowatts each, and has a capacity of 80 gallons. The pump is a gear type unit driven by a 1/4 horsepower electric motor through a variable speed drive.

A heat-exchanger using city water as a coolant is used to control the temperature of the collector coolant fluid at the collector inlet. A one kilowatt immersion heater was added near the collector inlet to compensate for heat loss from the piping between the storage tank and the collector. Collector inlet temperatures were limited to about 175° F without the additional heater.

A mixture of ethylene-glycol and water was used in the liquid loop. The specific gravity of the mixture was checked with a precision grade hydrometer at the start and finish of testing for each collector. The entire flow loop was pressurized to approximately 15 psig by applying a regulated inert gas pressure to the top of the expansion tank.

The collector to be tested was mounted on a support stand that allows rotation about either the horizontal axis or the vertical axis. This permits variation of the incident angle of the radiant energy to simulate both seasonal and daily variations.

## Instrumentation and Data Acquisition

The parameters needed to evaluate collector performance are: liquid flow rate, collector inlet and outlet temperatures, the simulated solar flux, and the ambient temperature. The flow rate was determined with a calibrated turbine-type flow meter that has an accuracy better than one percent of the indicated flow. The collector inlet and outlet temperatures were measured with ISA type E thermocouples (chromel-constantan). The thermocouples were calibrated at 32° F and 212° F. The error in absolute temperature measurement was less than 1° F and the differential temperature error between the inlet and outlet thermocouples was less than 0.2° F. The initial ambient air temperatures were measured with a mercury-in-glass thermometer. Subsequent ambient temperatures were more conveniently determined with an ISA type E thermocouple mounted in a radiation shield.

The simulated solar flux was measured with a water-cooled Gardon type radiometer having a sapphire window. The radiometer was calibrated with a National Bureau of Standards irradiance standard.

The millivolt-level electrical outputs of the instruments were measured with a digital voltmeter and recorded manually. Recently the data acquisition has been automated. Digitized data is now recorded on magnetic tape, reduced in a digital computer, and printed out in the test facility within minutes after being recorded. This allows a more rapid evaluation of test results as they are obtained.

## TEST PROCEDURE

The collectors were mounted on the test stand, and positioned so that the radiant flux was normal to the collector, which was tilted $60^{o}$ from the horizontal. The flow rate was adjusted to a value corresponding to 10 pounds per hour per square foot of collector absorber area. When the collector inlet temperature was obtained, the desired radiant flux was obtained by adjusting the lamp voltage. After steady-state conditions occurred, usually in 10-15 minutes, data were recorded. The radiant flux was then readjusted to a second value at the same collector inlet temperature, steady-state conditions obtained, and data again recorded. The collector inlet temperature was then varied and the procedure repeated.

## DESCRIPTION OF COLLECTORS

This report presents data obtained for five solar collectors including: a unit fabricated at Lewis for the primary purpose of checking out the facility, two types purchased from Professor E. Barber of Yale University, and two identical commercial "Solapak" units purchased from Beasley

Industries of South Australia. A general description of each collector follows.

### Collector Fabricated at Lewis

Two commercially available copper heat transfer panels (Thermon Manufacturing Company) were connected in a parallel flow arrangement and mounted in a common frame. Each panel was nominally 22 by 45 inches, and the outside dimensions of the frame were 48 by 49 inches. The waffle-like panel construction, figure 6, results in a large percentage of the absorbing area being wetted by the working fluid. A non-selective black paint, Nextel Velvet Coating (3M Company) was sprayed on the absorbing side of the panels. Two glass covers, one inch apart, were placed over the panels and 4 inches of fiberglass insulation were installed in back of the panels. The inlet temperature and mixed outlet temperature were used to determine performance of the collector, along with the measured radiant flux.

### Collectors Obtained From Professor Barber

Two separate collectors were supplied in a common frame as shown in figure 7. Each collector incorporated a copper sheet absorber with a single-pass, "serpentine" shaped copper tube bonded to the sheet. The surface of each sheet had a selective coating. One collector incorporated a honeycomb consisting of individual tubes rolled from thin aluminum foil. The foil tubes rested on the absorbing sheet. Each absorber sheet was nominally 20.75 by 48 inches and the frame size was 48.25 by 51.5 inches. A single glass cover was installed over each absorber, and 4.5 inches of fiberglass insulation was placed behind the absorbers. Each collector was tested individually. The two collectors obtained from Prof. Barber were prototype models. Modified collectors are now reported to be available.

Solapak Units Obtained From Beasley Industries

These commercially available collectors incorporate a copper absorber sheet with four parallel copper flow tubes soldered to the sheet. Two identical collectors are shown mounted on the test stand in figure 8. The dimensions of the absorber and manifold together were 22.5 by 50.75 inches. The overall dimensions of the collector were 24 by 52 inches. The absorbers and manifold had a selective coating. The collectors each had two glass covers over the absorber, and 2 inches of fiberglass insulation behind the absorber. Each collector was tested individually.

## DISCUSSION OF RESULTS

The efficiency of each collector was calculated with the following equation:

$$\eta = Gc_p (T_o - T_l)/q_i \qquad (1)$$

where

$\eta$ = collector efficiency

$G$ = fluid flow rate per unit area of absorbing surface, lb/(hr) (ft$^2$)

$c_p$ = specific heat of liquid, Btu/(lb) ($^{o}$F)

$T_o$ = fluid temperature at collector outlet, $^{o}$F

$T_l$ = fluid temperature at collector inlet, $^{o}$F

$q_i$ = incident radiant flux, Btu/(hr) (ft$^2$)

Performance characteristics of one solar collector (a Solapak) is presented in figure 9. The collector efficiency is plotted as a function of collector inlet temperature for two radiant flux levels. For a given radiant flux (constant energy input to collector) an increase of collector inlet temperature increased the heat loss from the collector and consequently the collector efficiency decreased. When the radiant flux was increased (increased energy input to collector) at a given fluid inlet temperature, the heat loss from the collector remained about constant, and the collector efficiency therefore increased.

Reference 9 presents several factors useful in the design of solar collectors. One factor, $F_R$, the collector plate flow efficiency factor is defined as the ratio of actual useful heat collected to the useful heat that would have been collected if the entire absorber surface had been at the temperature of the fluid at the collector inlet. This factor, $F_R$, is related to the collector efficiency by:

$$\eta = F_R \left[ \alpha \tau - \frac{U_L (T_l - T_a)}{q_i} \right] \tag{2}$$

where

$\alpha$ = absorptivity of absorbing surface, dimensionless

$\tau$ = transmittance of the glass cover assembly, dimensionless

$U_L$ = collector overall heat loss coefficient, Btu/(hr) ($ft^2$) ($^oF$)

$T_l$ = fluid temperature at collector inlet, $^oF$

$T_a$ = ambient temperature, $^oF$

$q_i$ = incident radiant flux, Btu/(hr) ($ft^2$)

As shown in references 3 and 10, when collector efficiency is plotted as a function of $(T_l - T_a)/q_i$, the parameters $F_R$ and $U_L$ can be readily determined. The data for all five collectors tested are presented in this form in figures 10, 11, and 12. The data for the two collectors obtained from Prof. Barber figure 11 indicate that the performance of the collector with the honeycombs was not significantly different than the one without the honeycombs. A single performance line is therefore shown on the figure. No significant difference in collector performance was evident for the two identical Solapak collectors, so a single line is also presented in figure 12 for that collector type.

When $T_l = T_a$, the corresponding value of collector efficiency is equal to the product of $F_R$, $\alpha$, and $\tau$. The absorptivity of the absorber surface, $\alpha$, and the transmittance of the glass, $\tau$, were determined experimentally for each collector, enabling determination of $F_R$ for each collector. The slope of the line through the data is equal to the product of $F_R$ and $U_L$. Having determined $F_R$, the overall heat loss coefficient, $U_L$, was then determined. The values for these performance parameters, calculated by the method of Whiller (ref. 11), are presented in table III for the collectors tested.

Table III displays the key parameters which determine collector performance and also cites the relative strengths and weaknesses of the collectors tested. The rather high values of $F_R$ are typical of copper collectors. The slightly lower value for the Solapak collector is possibly due to incomplete bonding of the tubes to the absorber plate. The very low emissivity value of the Solapak collector compared to the Lewis collector suggests that the overall heat loss coefficient, $U_L$, should be lower for the Solapak collector than shown. When conduction losses are subtracted out from these $U_L$ values, heat loss coefficients of 0.80 and 0.66 are obtained for the Lewis and Solapak collectors respectively. This represents an 18 percent difference as compared to only a percent difference in $U_L$. This can be attributed to the greater thickness of insulation present in the Lewis collector. Table III also indicates that the collector obtained from Prof. Barber did not exhibit the low heat loss normally expected from a selective surface.

The effect of these collector characteristics on collector performance becomes apparent from figure 13, where the performance of all collectors is presented. The transmittance of each glass cover was about the same (see table III). Therefore, the single cover and relatively high value of absorptivity for the collectors supplied by Prof. Barber explains why they had the highest efficiency at low values of $(T_l - T_a)/q$. As the inlet temperature was increased, the heat loss through the single cover was larger than that through the two glass covers. Therefore the performance of the collectors with a single cover decreases more rapidly than the performance of the collectors with two covers.

The Solapak collectors had the lowest efficiency as a result of the two glass covers and a relatively low absorptivity of 0.86. The collector fabricated from the copper heat transfer panels benefitted from the high percentage of absorber area wetted by the fluid, and a relatively high value of absorptivity, 0.97. The heat loss for the collectors with two covers was about the same, as indicated by almost parallel performance shown on figure 13. The Solapak collectors had a lower emissivity, 0.10 at 8 microns, than the nonselective paint applied to the copper panels, $\epsilon = 0.97$ at 8 microns. This effect tended to be offset by the difference in insulation thickness for the two types of collectors. The Solapak collectors had two inches of insulation behind the absorber, while there was four inches of insulation in back of the copper panels.

In addition to the continuing indoor tests, outdoor testing of collectors will begin soon at Lewis Research Center. A facility has been constructed, figure 14, with the capability of obtaining data for ten collectors operating simultaneously. The outdoor facility is presently in the final check-out phase. This facility can accommodate collector sizes up to 4- by 8-foot.

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TABLE I

NASA-LEWIS SOLAR SIMULATOR SUMMARY

RADIATION SOURCE
- 143 LAMPS, 300 W EACH
- GE TYPE ELH, TUNGSTEN-HALOGEN, DICHROIC COATING
- $9^0$ TOTAL DIVERGENCE ANGLE

TEST AREA
- 4 BY 4 FT, MAXIMUM

TEST CONDITION LIMITS

| | |
|---|---|
| FLUX: | 150 TO 350 BTU/HR-$FT^2$ |
| FLOW: | UP TO 1 GAL/MIN (30 LB/HR $FT^2$) |
| INLET TEMP: | 75 TO $210^0$ F |
| WIND: | 0 OR 5 MPH AT $75^0$ F |

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TABLE II

COMPARISON OF SOLAR SIMULATOR AND AIR-MASS 2 PERFORMANCE

| | | AIR-MASS-2 SUNLIGHT | SIMULATOR |
|---|---|---|---|
| ENERGY OUTPUT (PERCENT) | ULTRAVIOLET | 2.7 | 0.3 |
| | VISIBLE | 44.4 | 48.4 |
| | INFRARED | 52.9 | 51.3 |
| ENERGY USES | ABSORPTIVITY (SELECTIVE SURFACE) | 0.90 | 0.90 |
| | GLASS TRANSMISSION | .85 | .86 |
| | AL MIRROR REFLECTIVITY | .86 | .88 |
| | SOLAR CELL EFFICIENCY, % | 12.6 | 13.4 |

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TABLE III

COLLECTOR PERFORMANCE PARAMETERS

| COLLECTOR | $F_R$ | α | τ, PER COVER | $U_L$, BTU/HR $FT^2$ °F | ε, AT 8 M |
|---|---|---|---|---|---|
| COLLECTOR FABRICATED AT LEWIS (2 GLASS COVERS) | 0.95 | 0.97 | 0.87 | 0.88 | 0.97 |
| PROF BARBER'S (1 GLASS COVER) | 0.93 | 0.97 | 0.87 | 1.27 | NOT OBTAINED |
| SOLAPAK (2 GLASS COVERS) | 0.90 | 0.86 | 0.86 | 0.85 | 0.10 |

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NOTES:
1. THE ABSORPTIVITY WAS INTEGRATED FOR THE SOLAR SIMULATOR SPECTRAL DISTRIBUTION.
2. THE GLASS TRANSMISSION WAS DETERMINED WITH THE SOLAR SIMULATOR.

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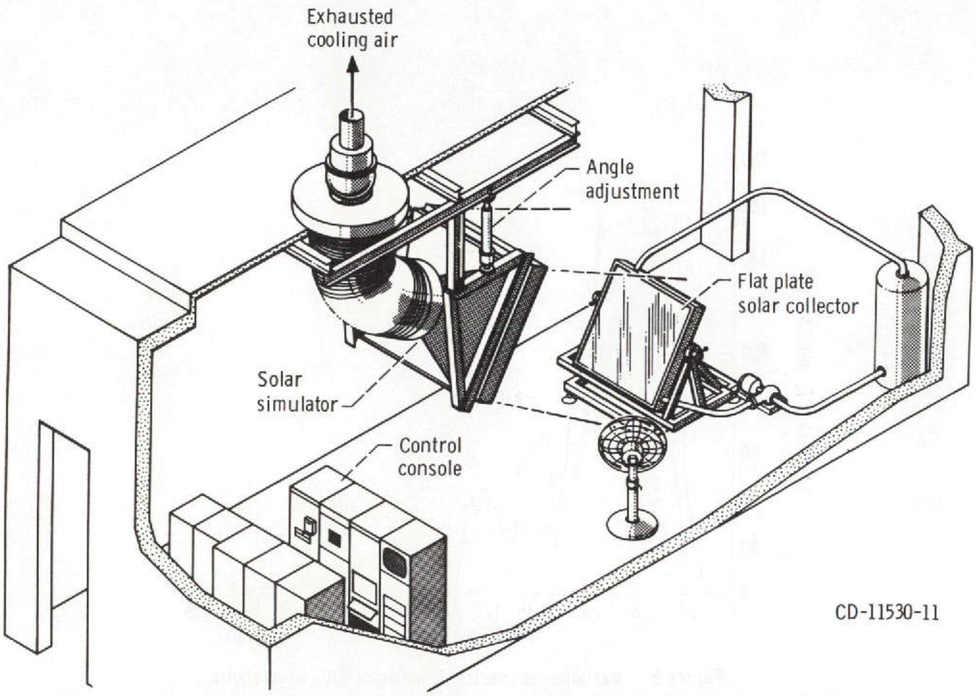


Figure 1. - Indoor test facility.


Figure 2. - Indoor facility used to experimentally determine solar collector performance.



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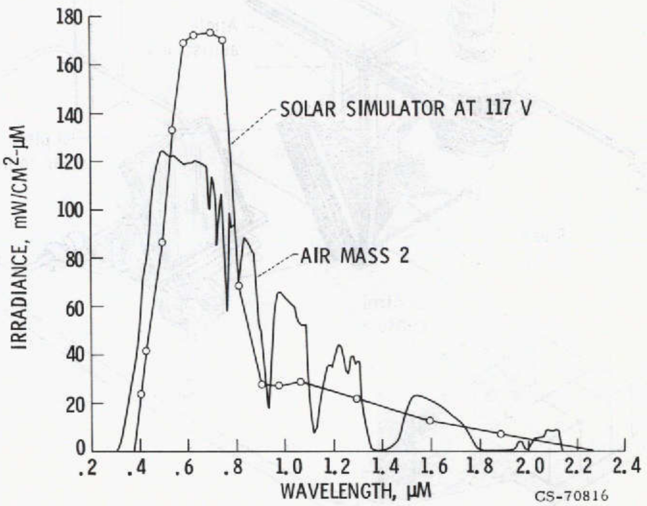


Figure 3. - Variation of spectral irradiance with wavelength.

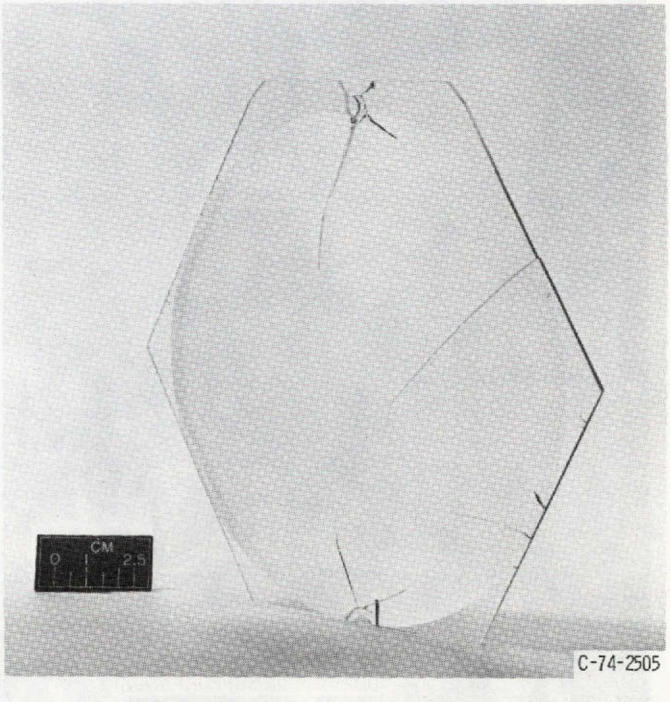


Figure 4. - Cracked lens from solar simulator.



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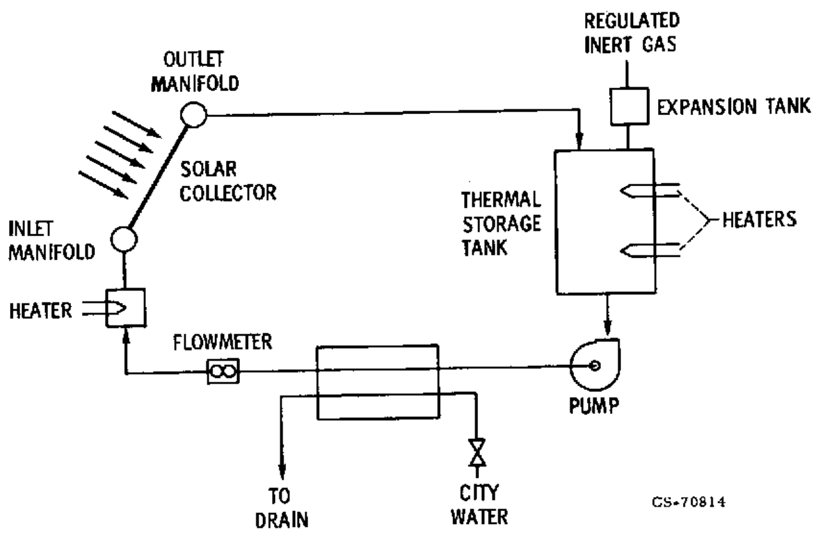


Figure 5. - Schematic of liquid flow loop.

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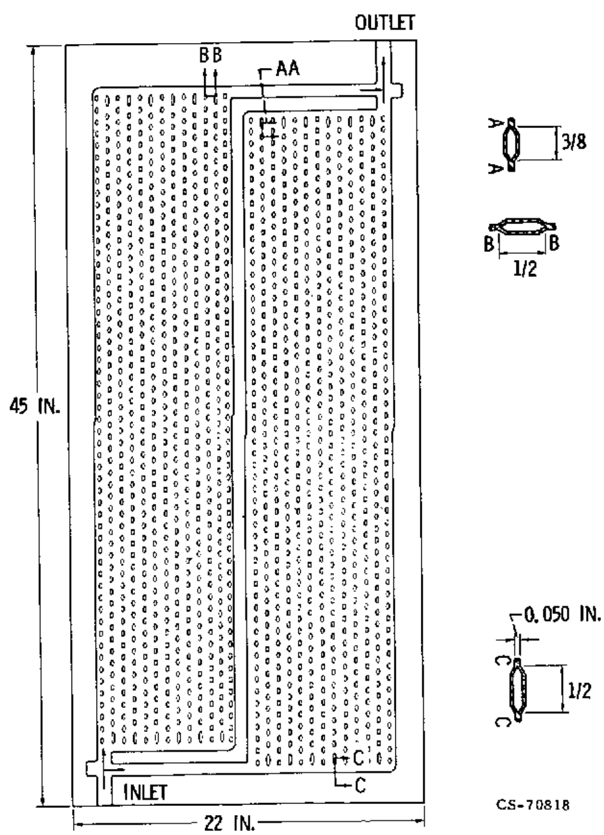


Figure 6. - Thermon heat transfer unit.

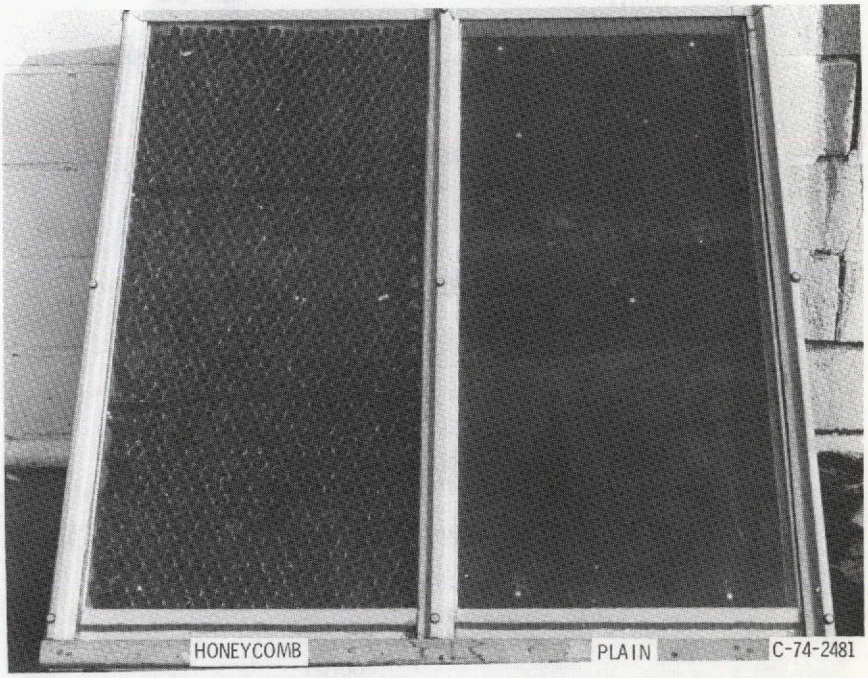


Figure 7. - Collectors obtained from Prof. Barber. Right side is plain, honeycomb on left side.

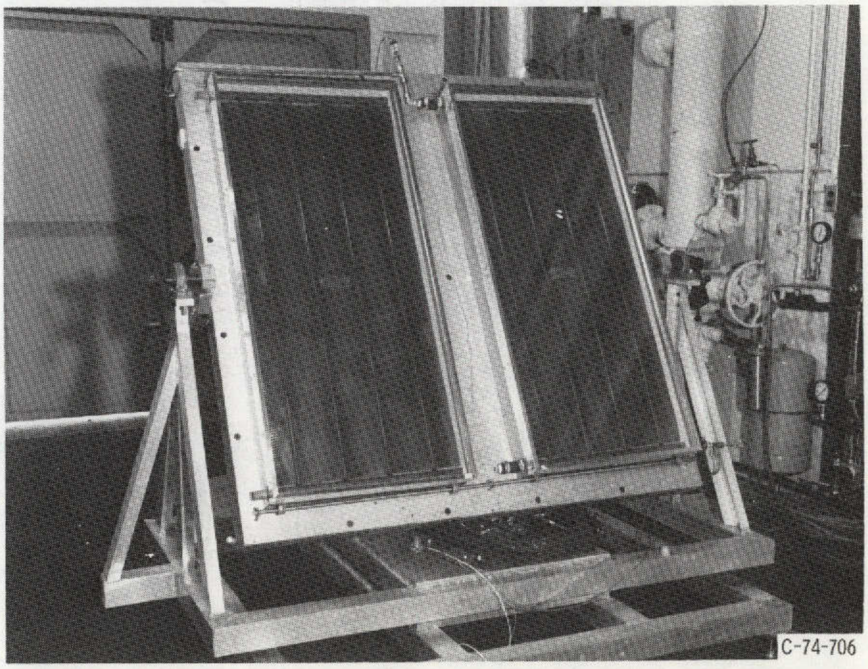


Figure 8. - Solapak collectors mounted on test support stand.

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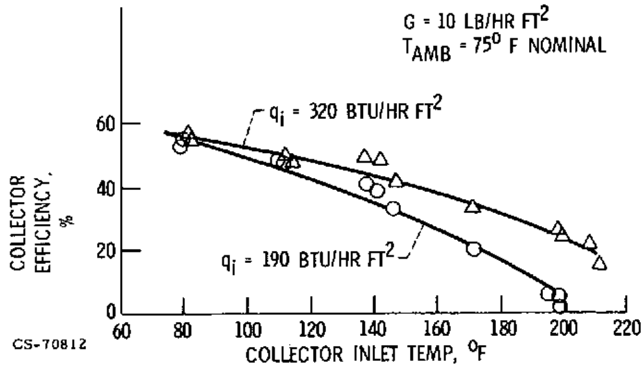


Figure 9. - Performance of a Solapak collector as a function of inlet temperature.

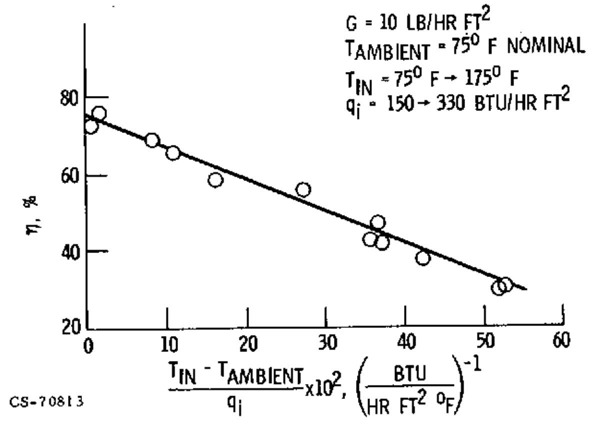


Figure 10. - Performance of collector incorporating copper heat transfer panels.

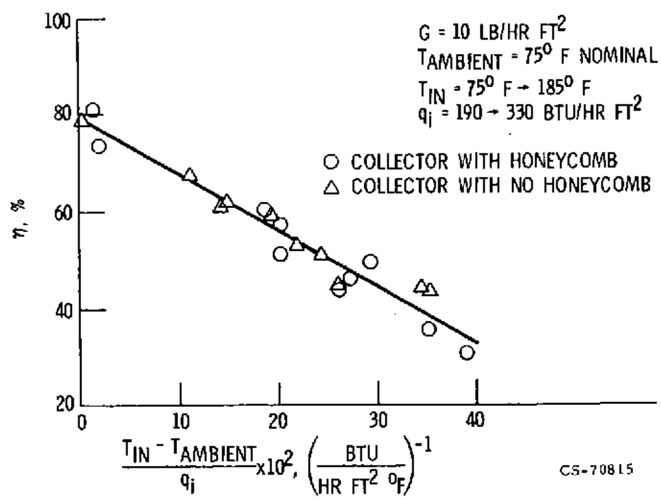


Figure 11. - Performance of collectors obtained from Professor Barber.

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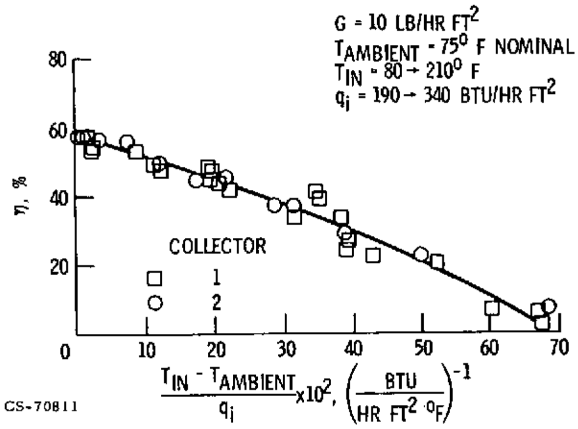


Figure 12. - Performance of Solapak collectors obtained from Beasley Industries.

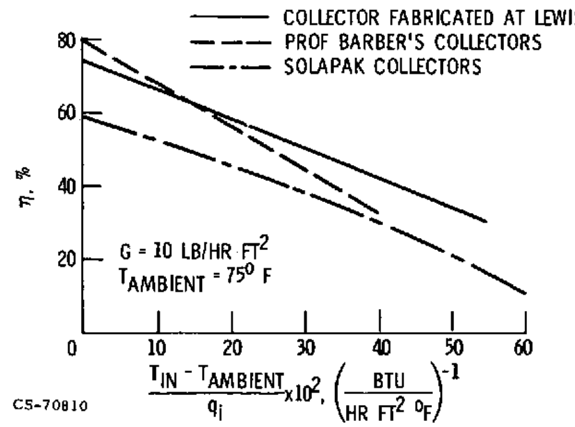


Figure 13. - Collector performance.

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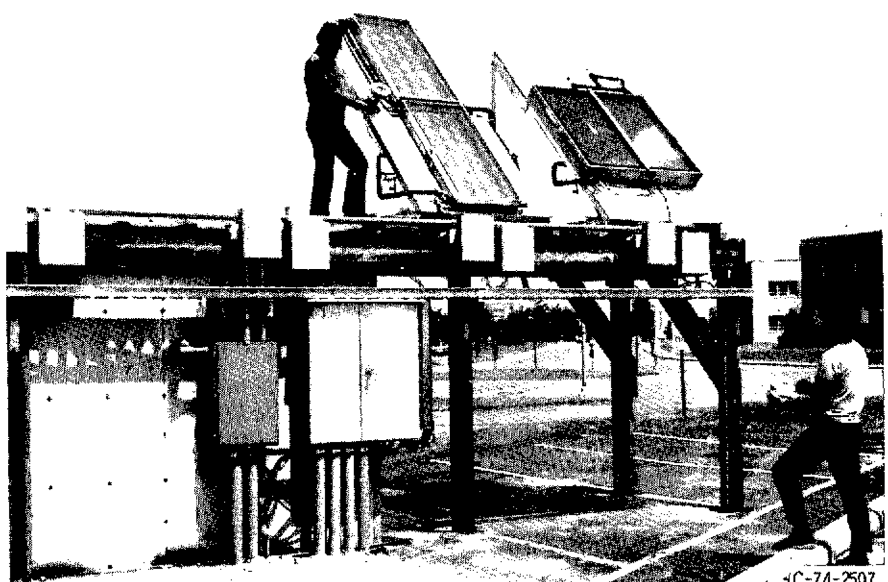


Figure 14. - Outdoor solar collector test facility.



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