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SOLAR COLLECTOR RELATED RESEARCH AND DEVELOPMENT
IN THE UNITED STATES
FOR HEATING AND COOLING OF BUILDINGS *

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ABSTRACT

This paper describes some of the research funded by the Research and Development Branch of the Heating and Cooling Division of Solar Energy of the United States Energy Research and Development Administration.[†] Specifically, this paper deals with collector and collector materials research reported on during FY-1977. The R&D Branch has funded research in open and closed cycle liquid heating flat plate collectors, air heating flat plate collectors, heat pipe collectors, concentrating collectors, collector heat transfer studies, honeycomb glazings, evacuated tube collectors, ponds both salt gradient and viscosity stabilized, materials exposure testing, collector testing standards, absorber surface coatings, and corrosion studies. A short description of the nature of the research is provided as well as a presentation of the significant results.

INTRODUCTION

The following is a description of research funded by the Research and Development Branch of the Heating and Cooling Division of Solar Energy of the United States Energy Research and Development Administration. Specifically, that research dealing with collectors and collector materials which was reported on during FY-77. A short description of the nature of the research is provided as well as a presentation of the significant results.

Los Alamos Scientific Laboratory¹

This collector was developed as a roof integrated structure for the National Security and Resources Study Center (NSRSC) in Los Alamos. It consists of two steel sheets seam-welded together and then separated by high pressure air to form a quilted pillow-like device. An electro-plated black chrome selective surface is applied to that portion utilized as the absorber with the remainder formed such that it also serves as

*Work performed under the auspices of the U. S. Department of Energy.

[†]Presently Research and Development for Heating and Cooling, Office of the Assistant Secretary for Conservation and Solar Applications, U. S. Department of Energy.

the building roof when properly assembled together. A cross-sectional view of the collector as well as its instantaneous thermal performance is shown in Figs. 1 and 2, respectively.

Owens-Illinois²

Owens-Illinois has completed testing of their evacuated tube air heating collector array. The design is essentially identical to their Sunpak^R liquid heating collector except that the delivery tube has been increased to 1" o.d. The material for the delivery tube is still borosilicate glass. A cross-sectional view of a tube pair and manifold arrangement is shown in Fig. 3.

The thermal performance of the air cooled collector compared to the liquid cooled collector is shown in Fig. 4. Due to the fact that these arrays utilized a diffuse background, the collector array will perform better in the morning and afternoon than at noon and will perform better in diffuse radiation than in direct. This is shown in Fig. 5. Notice that the efficiencies shown are daily efficiencies.

Corning Glass Works³

Corning has completed the design, manufacture and testing of an evacuated glass tube collector utilizing a copper heat pipe absorber and an internal cusp type reflector. A cross-sectional view of the concept is shown in Fig. 6. The instantaneous thermal performance is shown in Fig. 7 compared to that of the conventional Corning evacuated flat plate design.

Lockheed^{4,5}

Lockheed has developed plastic honeycombs for use as convection suppression in flat plate solar collectors. They examined two processes and three materials. The processes examined were the Hexcell expanded cell process and the Norfield thermal forming process. The materials investigated were mylar, lexan and teflon. Of the above combinations, the expanded cell lexan was found to be the most cost effective. A comparison of both instantaneous and daily efficiencies for different collector designs are shown in Figs. 8 and 9. The superior performance of the flat black absorber with lexan honeycomb even during off-axis illumination should be noted. An unresolved problem is the lifetime of the plastic honeycomb under actual operating conditions.

UCLA⁶

The UCLA effort is parallel with that of Lockheed except that glass honeycombs are being developed rather than plastic honeycombs. Initial studies were performed using glass tubes standing on end and sintered together to form a honeycomb structure. Later studies were performed using very thin sheet formed into a wavy pattern and then stacked on end to form a honeycomb structure. A comparison of the instantaneous thermal performance of various collector designs is shown in Fig. 10. Again, the honeycomb, flat

black design is shown to have superior performance. By using glass honeycombs, the problem with long-term durability is solved. Studies are continuing to develop cost effective glass honeycomb fabrication techniques.

Argonne National Laboratory⁷

Argonne has pioneered concentrating collector development of the Winston "ideal" designs. Their latest effort has been to design, build and test two collector module designs. One is a 3X CPC design and the other is a 1.5X cusp design. The 3X module utilizes aluminized plastic reflectors and Corning evacuated flat plate receivers while the 1.5X module utilizes Kinglux^R aluminum reflectors and G.E. TC-100 evacuated tube receivers. The instantaneous thermal performance for each design is shown in Figs. 11 and 12, respectively. The possible performance of the 1.5X design with improved receiver tubes is shown in Fig. 13.

Jet Propulsion Laboratory⁸

JPL has designed, built and tested a concentrating collector of nominally 2X concentration which utilizes flat trough type reflectors which can be reversed twice a year to give year round solar acceptance. A schematic of the design is shown in Fig. 14. The reflectors in their reversed position are shown by the dotted lines.

Corning flat plate evacuated collectors are used as receivers in this collector. Performance curves for various reflector materials are given along with the performance of a "bare" tube in Fig. 15. It should be noted that the comparison is made on aperture area. Therefore it would take twice as many evacuated tubes to form the same area array as that for the concentrating collectors. The thermodynamic breakeven point may be at 300°F temperature difference but the cost effective breakeven point may be much lower. Data collection on the present test array is continuing.

Giner, Inc.⁹

Giner has determined the corrosion resistance of aluminum alloys in water/ethylene glycol mixtures under experimental conditions directly relevant to the operation of existing solar thermal energy collector systems. An aqueous ethylene glycol solution with 35% ethylene glycol by volume was chosen as the typical heat transfer medium. The results of overall and pitting corrosion rates on various aluminum alloys are shown in Tables 1 and 2. Notice that the pure solution yields very low corrosion rates while the presence of ions (Cl^- , Cu^{+2} and Fe^{+3}) increases corrosion, especially pitting, manyfold. Glycol decomposition products do not seem to accelerate the corrosion rate. However, the corrosion rate is pH sensitive and should be checked periodically. Organic heat transfer fluids, such as Therminol 55 are inert with respect to aluminum. Even with the addition of the deleterious contaminants, such as Cu^{+2} , Cl^- and Fe^{+3} ions at 200 ppm each, minimal corrosion was encountered. The next phase of this project is to develop corrosion inhibitor schemes to make

the aluminum/water/ethylene glycol system work satisfactorily as components of a practical and economical solar collector system.

University of Wisconsin¹⁰

Local and average heat transfer coefficients for natural convection between parallel plates have been experimentally studied using interferometric techniques. The experimental conditions were similar to those existing in flat plate solar collectors. Figure 16 shows a schematic of the test facility that provides a two-dimensional enclosure with isothermal surfaces. Figure 17 shows the results for the conduction regime. That is, the Grashoff number is sufficiently low such that no mass transfer occurs across the spacing. Notice that considerable convection takes place at the leading edge. Figure 18 shows typical results for the free convection regime as a function tilt angle. The effect of aspect ratio was investigated. The local Nusselt number was found to change but the integrated average Nusselt number was insensitive to aspect ratio. For the range of tilt angles between 45 and 90 degrees, the empirical correlation

$$N_{UL} = 0.118 [R_{al} \cos^2 (\phi - 45^\circ)]^{0.29}$$

adequately represents the data.

H	plate length	N_{UL}	average Nusselt number
A	aspect ratio, H/L	R_{al}	Rayleigh number
L	plate spacing	ϕ_{UL}	tilt angle

Lehigh University¹¹

Two solar collectors using a pebble bed design were constructed and tested using air as the heat exchange medium. One collector had pebbles of metallurgical grade coke, and the other had a frothy volcanic material called scoria. The pebble size for both materials ranged from 6 to 19 mm in diameter. The pressure drop and mass transfer data for the two collectors are shown in Table 3. Typical collector efficiencies are shown in Figs. 19 and 20.

University of Waterloo Research Institute¹²

Two studies were performed both of which are related to methods for improving the efficiency of flat plate solar collectors.

The first study dealt with the free convective heat loss from a V-corrugated absorber plate to a plane transparent (glass) cover. Nusselt numbers were determined as a function of Rayleigh number for angles of inclination of the plate from the horizontal of 0, 30, 45 and 60 degree. The values of the depth ratio (the ratio of the average depth of the air layer to the depth of the V's) investigated were 1, 2.5 and 4; the angle

of opening of the V's was 60°. It was concluded that the heat transfer is greater than that for two parallel plane plates having the same average spacing, by up to 50% for a depth ratio of unity. However, for the larger values of the depth ratio, the increase in heat transfer is slight.

The second study dealt with the free convective heat transfer occurring in a honeycomb solar collector in which the honeycomb consists simply of a set of horizontal partitions (or slits) oriented normal to the plate. Aspect ratios (plate spacing to distance between partition) of 5 and 10 were investigated, as were slit materials both opaque and transparent to thermal radiation. A significant conclusion is that for angles of inclination of the plate from the horizontal ranging from 70 to 90 degree, the horizontal slit honeycomb gives superior convection suppression to a square-celled honeycomb, for the same amount of honeycomb wall material.

University of Virginia¹³

The "solaris" solar collector is a patented design utilizing open channel flow of the heat transfer fluid over a blackened absorber with a single glazing. The University of Virginia has completed both a theoretical and an experimental evaluation of this collector design. A cross-section of the collector tested and analyzed is shown in Fig. 21. A comparison of the thermodynamic collector efficiency between the theoretical model and the experimental results are shown in Fig. 22. The two variables which influenced collector performance most were ambient temperature and wind. These two variables determine the amount of water droplet condensation on the inner glazing. This formation of this condensate was shown to reduce the transmittance of the inner glazing by 10 to 20 percent. Various techniques such as changing glazing materials and varying the number of glazings were experimented with in order to reduce the "drop-wise" condensation.

Honeywell, Inc.¹⁴

The development of a jet-impingement solar air heater was the objective of this work. The intention was to increase the efficiency of the air heater, over that of a "conventional" parallel-plate type, by increasing the absorber plate-to-air stream heat transfer coefficient. A comparison was made, both theoretically and experimentally, between the two designs. A schematic of the two designs compared is shown in Fig. 23. A comparison of the thermodynamic collection efficiency is shown in Fig. 24. For fixed pumping power, it is doubtful that the nominal increase in collector efficiency is enough to compensate for added complexity of the air jet system.

Honeywell^{15*}

A selective paint coating has been developed with solar absorptance (α) of 0.92 and room temperature emittance (ϵ) of 0.10. It was made through the optimization of coating thickness, pigment volume concentration, and pigment particle size. The selective paint has also been successfully scaled up to a sample size of 1 ft x 1 ft. The coating cost (materials and fabrication) was estimated at about 5¢/sq ft, a factor of 10 lower than the selective plated coatings investigated.

Accelerated humidity and outdoor exposure tests have been conducted for black chrome, black nickel and black iron coatings. The black chrome coating is most durable and its life was estimated to be greater than 30 years. The use of surface roughening to improve the optical properties of black chrome resulted in a sample with $\alpha = 0.95$ and $\epsilon(100^\circ\text{C}) = 0.09$. A method has been developed which reduced the cost of black chrome by about 30 percent.

Dipped AR coatings on glass using low refractive index Teflon FEP resulted in a transmittance increase of about 4.9 percent over the 0.35 μm to 0.75 μm region. The feasibility of AR coating Tedlar by glow-discharge polymerization was investigated. Strength and durability of etched AR glass were tested. Studies on the chemistry of glass etching for better process control have also been initiated.

National Bureau of Standards^{16,17}

Test standards have been developed for liquid heating flat plate collectors. Presently, standards are being developed for air heating collectors and thermal storage devices.

IIT Research Institute¹⁸

A large number of actual and potential materials for solar energy utilization were exposed to natural weathering at three sites: Chicago, IL; Phoenix, AZ; and Miami, FL. The materials were exposed to conventional weathering simultaneously at three sites for periods of 3, 6, and 12 months. Accelerated testing (exposed to multiple suns) was conducted at the Phoenix, AZ site. Tests performed included:

- 1) Visual inspection.
- 2) Normal spectral transmittance of transparent materials.
- 3) Hemispherical spectral reflectance of opaque materials.
- 4) Hemispherical spectral reflectance of selective absorber coatings.
- 5) Dynamic tensile strength and elongation measurements of plastics.

*Material taken directly from Ref. 15.

- 6) Izod impact tests on all transparent cover materials.
- 7) Abrasion resistance tests on rigid plastic cover materials.
- 8) Bidirectional reflectance measurements on selective solar absorbers and mirrors.
- 9) Static dimensional stability tests on all plastic cover materials.

The materials chosen are too numerous to itemize here. They include a wide variety of glazing, absorber and reflector materials.

Dynatherm¹⁹

The objective of this program was to investigate the use of heat pipes as heat transport elements in flat-plate solar collectors. During the early phases of the program, analytical models for heat pipe collectors were developed and configuration and integration studies were performed. The feasibility of wickless heat pipes, fabricated from commercial Roll-Bond material, was investigated in the laboratory. These heat pipes performed satisfactorily with Freon 11 as the working fluid. Two complete heat pipe solar collectors, which utilized converted Roll-Bond panels as heat pipes, were tested along with a conventional reference collector of the same basic design. The second roll bond heat pipe absorber is shown in Fig. 25.

With steady solar input, the heat pipe and the reference collector yielded approximately the same instantaneous efficiency (~60%). But with intermittent insolation, such as on a partly cloudy day, the heat pipe collector collected up to twice as much energy as the reference collector. This effect is shown in Fig. 26. This improvement is attributable to the thermal diode capability of the heat pipes. Heat is transported only when the absorber temperature exceeds the fluid temperature in the manifold. During periods of low insolation, the heat pipe collector is automatically inactivated.

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TABLE 1

OVERALL CORROSION RATES OF ALUMINUMAT 210°F UNDER LAMINAR FLOW

<u>Solution</u>	<u>Alloy</u>	<u>R_{corr} (mpy)</u>
Pure E.G./H ₂ O (35 Vol.%)	1100	0.19
	99.9%	0.16
	3003	0.13
	3004	0.10
E.G./H ₂ O + Cl ⁻ (200 ppm)	1100	8.5
	99.9%	7.0
	3003	9.9
	3004	3.5
E.G./H ₂ O + Cu ⁺² (200 ppm)	1100	5.5
	99.9%	17
	3003	4.5
	3004	14
E.G./H ₂ O + Fe ⁺³ (200 ppm)	1100	30
	99.9%	18
	3003	14
E.G./H ₂ O + Fe ⁺³ + Cl ⁻ + Cu ⁺² (200 ppm each)	99.9%*	71
	3003	74
	3004	120

* Under turbulent flow.

TABLE 2

PITTING CORROSION OF ALUMINUM IN AQUEOUS
ETHYLENE GLYCOL SOLUTIONS AT 210°F UNDER LAMINAR FLOW

<u>Solution</u>	<u>Alloy</u>	<u>$V(u/day^{1/3})$</u>	<u>Estimated Penetration Depth for Actual Plant in 20 Yrs. (mils)*</u>
Pure E.G./H ₂ O	1100	2	15
(35 vol. %)	99.9%	3	20
	3003	1	15
	3004	0	0
E.G./H ₂ O + Cl ⁻	1100	37	300
(200 ppm)	99.9%	2	15
	3003	24	190
	3004	17	140
E.G./H ₂ O + Cu ⁺²	1100	47	380
(200 ppm)	99.9%	36	290
	3003	19	150
	3004	171	1400
E.G./H ₂ O + Fe ⁺³	1100	5	42
(200 ppm)	99.9%	5	42
	3003	3	25
E.G./H ₂ O + Cl ⁻ + Cu ⁺² + Fe ⁺³	99.9%	152	1100
(200 ppm each)	3003	187	1500

* Based on a plant with 1.5×10^4 cm² of wetted surface area.

TABLE 3

Pressure Drop and Mass Transfer for Collectors

	<u>Low Air Flow</u>		<u>High Air Flow</u>	
	<u>Scoria</u>	<u>Coke</u>	<u>Scoria</u>	<u>Coke</u>
Pressure Drop				
in H ₂ O	0.06	0.24	0.42	0.59
Mass Transfer				
(m ³ /c.m ²) . 10 ⁻³	1.90	2.35	4.20	3.65

Fig. 1. Cross-sectional view of the LASL roof integrated solar collector.

Fig. 2. Instantaneous thermal performance of the LASL roof integrated solar collector.

Fig. 3. Cross-sectional view of the Owens-Illinois air heating collector tube pair and manifold.

Fig. 4. Comparison of the daily thermal performance between the Owens-Illinois air and water heating collectors.

Air Driven Spaced Evacuated Tubular Collector Design $\dot{m} = 8 \text{ LBS/HR. FT.}^2$

Fig. 5. Effect of insolation on the daily thermal performance of the Owens-Illinois air heating collector.

Fig. 6. Cross-sectional view of the Corning tubular cusp collector with heat pipe absorber.

Fig. 7. Comparison of the instantaneous thermal performance between the Corning evacuated flat plate collector and the cusp-heat pipe collector.

Fig. 8. Comparison of efficiency between a glass covered flat-black collector with and without Hecel lexan honeycomb and a selective black no honeycomb collector.

Fig. 9. Comparison of diurnal performance between glass covered flat black honeycomb collector, and a selective black no honeycomb collector.

Fig. 10. Comparison of the instantaneous thermal performance of various collectors with and without glass honeycombs.

Fig. 11. Performance curve for 1.5 X cusp collector.

Fig. 12. Performance curve for 3X CPC Collector.

Fig. 13. Predicted performance of an "advanced design" 1.5X cusp collector.

Dimensions of vacuum
tube receiver cour-
tesy of Corning Glass
Works, Corning, N.Y.

DIMENSIONS

$W = 1.75"$
 $\delta = 0.010"$
 $\Delta = 0.125"$
 $D = 4"$
 $l = 0.125"$
 $d_0 = 0.3125"$
 $d_1 = 0.250"$
 $l = 7"$ (plate)
 $\gamma = 0.005"$
 (ELECTRON
BEAM WELD)

Fig. 14. Reversible asymmetric vee-trough collector with vacuum tube.

Fig. 15. Test data for collector efficiency versus temperature of the reversible vee-trough collector.

Fig. 16. Schematic of the University of Wisconsin test apparatus.

Fig. 17. Local Nusselt number as a function of non-dimensional plate length for the conduction regime.

Fig. 18. Local Nusselt number as a function of non-dimensional plate length for various values of tilt angle.

Fig. 19. Instantaneous thermal efficiency for scoria at high mass flow rate.

Fig. 20. Instantaneous thermal efficiency for coke at the low mass flow rate.

Fig. 21. Cross-sectional view of the "Solaris" collector.

Fig. 22. Experimental and model predicted performance curves for the "Solaris" collector.

Schematic of Jet-Impingement, Concept Collector
Fig. 23(a)

Schematic of Baseline Parallel-Plate Collector
Fig. 23(b)

Fig. 24. Performance comparison between various jet designs and the baseline configuration.

Fig. 25. Heat pipe roll bond collector.

Fig. 26. Performance of reference and second heat pipe solar collectors during intermittent insolation.