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DEVELOPMENT OF A LOW-TEMPERATURE LOW-COST, BLACK
LIQUID SOLAR COLLECTOR

Final Report for September 12, 1977—October 31, 1978

By

D. K. Landstrom

S. G. Talbert

G. H. Stickford, Jr.

R. D. Fischer

R. E. Hess

MASTER

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Battelle Columbus Laboratories
Columbus, Ohio

U.S. Department of Energy

Solar Energy

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DEVELOPMENT OF A LOW-TEMPERATURE
LOW-COST, BLACK LIQUID
SOLAR COLLECTOR

FINAL REPORT

FOR PERIOD
SEPTEMBER 12, 1977-OCTOBER 31, 1978

D. K. Landstrom, S. G. Talbert
G. H. Stickford, Jr., R. D. Fischer
and R. E. Hess

October 1978

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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ABSTRACT

Battelle's Columbus Laboratories (BCL) has developed an efficient, low-cost, low-temperature, nonconcentrating, liquid-heating solar collector suitable for use as a thermal energy source for heat pumps or other heating applications. The collector incorporates a "black liquid" heat transfer medium permitting solar radiation to be absorbed directly by the liquid. This type of collector has the potential of having significantly lower costs when compared to a conventional flat-plate collector with comparable thermal performance in the temperature ranges suitable for heat-pump operation or lower temperature direct space heating.

Based on detailed measurements of the spectral absorption properties on many "black" liquids, and on the results of computer analysis of collector performance, it has been shown that the black liquid collector concept has the potential of significantly improved performance compared with an unglazed (i.e., swimming pool type) black-absorber collector of comparable cost. On the other hand, it has the potential of significant cost savings compared with the single-glazed collector of comparable performance. Experimental data obtained on two black liquid collectors constructed during this project closely match the predicted curves obtained from a theoretical computer analysis.

Results of the systems analysis studies have shown that the black liquid collector, when used as a heat source for a solar-assisted heat pump, has comparable performance to that of a single-glazed conventional collector but at considerably lower cost. Another important result is that currently available heat pump systems are not ideally matched or compatible with a solar-assisted system. A solar-assisted system will require design of heat pumps which can take advantage of the higher system coefficient of performance (COP) possible with a heat source at elevated temperatures.

Based on current technology, the black liquid collector is one of the few possibilities which can provide a solution to a workable, efficient, cost-effective series heat pump system within the next few years. The combination of a low-cost collector with an improved COP heat pump is necessary for this option to be viable as a competitive solar system. In addition, the black liquid collector has definite potential for low-cost direct space heating applications.

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1.0 EXECUTIVE SUMMARY

The primary objective of this research project was to develop a cost-effective low-temperature nonconcentrating black liquid solar collector. This objective has been met by the design and fabrication of two prototype collectors. These collectors fulfilled all design criteria and performed as predicted during extensive field tests.

It was also determined that the black liquid collector has several potential advantages over the conventional flat-plate collector for specific applications. Some of the most important advantages are interdependent: stagnation problems are eliminated; therefore the use of an all-plastic collector is possible, which means that there is no corrosion of the collector panel, thus, drain down operation is possible to eliminate freezing. Another prime advantage is the potential for low-cost, one-piece, extruded-type construction which will eliminate much of the labor, materials fabrication, and installation cost inherent in a conventional collector. Costs and weight are reduced by employing plastics instead of metallic and glass materials.

It is possible to purchase an extruded panel cheaply, and for volume solar collector use, the panel dimensions can be optimized. The ends of the panel are milled to match a manifold tube which is pre-drilled and glued in place. The panel is placed on foil-faced foam insulation, and fastened in place with commercially available hardware. The unused edge channels on the panel provide some edge insulation. No expensive mounting container is needed. Thus, one has a lightweight, site-fabricated collector which is easily shipped as parts in bulk quantity.

Potential advantages of the black liquid collector are summarized below:

- Stagnation problems eliminated with drain down of black liquid so collector does not overheat
- All plastic construction (one-piece extrusion)
- Corrosion problems in the collector are eliminated
- Performance exceeding that of conventional collectors in the lower temperature range
- Potential for cost-effective use in solar-assisted series heat pump systems

- Application to service water heating, direct space heating, industrial water heating, and possible agricultural uses
- Collectors can be easily mass produced for even further cost reduction
- Collector design is suitable for "do-it-yourself" construction and installation (site assembly)
- Lightweight; easily shipped as unassembled parts
- Collector could be distributed through the building trades industry.
- Collector properties easily tailored for specific applications (can be manufactured in glazed or unglazed versions)
- Repair and replacement much easier than for conventional flat plate collectors
- Long life (15-20 years) appears possible with present data
- Direct application to several paths in the DOE National Solar Program Plan.

A secondary objective of this program was to define the specific advantages of a black liquid collector when used as a thermal energy source for a heat pump or other low-temperature applications.

It was found that the coupling of a low-cost collector with a properly engineered heat pump has the potential to produce a truly cost-effective solar-assisted heat pump system which is competitive with the stand-alone heat pump and, at the same time, consumes considerably less electrical energy. This is possible since high COP heat pumps can use the low temperatures provided by a black liquid collector operating in its highest efficiency range.

Based on current technology, the black liquid solar collector is one of the few known collectors which can be used in a workable, efficient, cost-effective solar-assisted series heat pump system within the next few years. An improved COP heat pump is necessary for this option to be viable as a competitive solar system.

This program has demonstrated the practicality of black liquid collectors and provides the incentive to the development of a commercial

quality system. In particular, the black liquid itself requires refinement for commercial use and the service life of the plastic extrusion must be established in commercial service.

2.0 OBJECTIVES

The primary objective of this project was to develop a cost-effective and high efficiency low-temperature nonconcentrating black liquid type solar collector. Two secondary objectives were also pursued: (1) to determine if such a collector will have specific advantages when used as a thermal energy source for a heat pump or other low-temperature application, and (2) to provide the DOE and the solar energy community with some of the necessary technical and economic data to evaluate and compare a black liquid collector with conventional flat-plate collectors.

3.0 INTRODUCTION

This report summarizes work performed during the period from September 12, 1977 to October 31, 1978 on the development of a cost-effective, high efficiency, low-temperature nonconcentrating black liquid type solar collector. Eight basic tasks were initially identified:

- Task 1. Survey Potential Black Liquids/Transparent Covers
- Task 2. Construct Small Black Liquid Test Cell
- Task 3. Evaluate Black Liquids/Transparent Covers
- Task 4. Black Liquid/Conventional Systems Analysis
- Task 5. Construct Full Size Collector/Test Loop
- Task 6. Collector Test/Performance Parameters
- Task 7. Project Data Integration
- Task 8. Reporting/Information Dissemination.

The black liquid collector is an innovative concept with some real advantages over conventional collectors for specific applications. Prime among these advantages is the potential for low-cost, one-piece, extruded-type construction which will eliminate much of the labor (soldering, welding, mechanical assembly, etc.) inherent in the manufacture of a conventional collector. Also, materials costs can be reduced by using suitable plastics or glass components instead of metallic materials. The panel is cheap and for volume solar collector use can be optimized for the application. No expensive mounting container is needed and the collector can be mounted using commercially available hardware. Thus, one has a lightweight, site-fabricated collector which is easily shipped as parts in bulk quantity.

A black liquid collector incorporating a plastic transparent plate or plates with typical heat insulating properties can exceed the performance and efficiency of a conventional collector (with cover plate) in the lower-temperature-differential range. Most suitable plastics will not structurally perform well at high operating temperatures and tend to deform; however, the lower operating range (below approximately 82 C, 180 F) is a region where plastic collectors can have significant advantages.

Solar-assisted heat pump systems have been extensively analyzed in the past few years and have generally been found not to be cost effective. (3-1 to 3-5) Based on the current heat pump manufacturing technology, this is generally true, since current heat pumps cannot take advantage of the potential significant increase in COP where the source temperature is elevated through use of a solar collector (or other heat source). Heat pumps designed to fulfill the requirements of stand-alone heating functions are not readily adaptable to the solar assisted system and the thermodynamic potential is not realized when standard heat pumps are forced into solar systems.

The coupling of a low-cost collector (such as the black liquid collector), with a properly engineered heat pump based on present state of knowledge of the vapor compression cycle has the potential to produce a truly cost-effective solar-assisted heat pump system which is competitive with the stand-alone heat pump and at the same time consumes considerably less electrical energy than the heat pump alone. The heat pump becomes the major energy distribution vehicle, and the collector can operate at the lower temperatures easily obtained by simple black liquid collectors or other low-cost collector options.

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4.0 BACKGROUND

The flat-plate nonconcentrating solar collector is proving to be the device which will first demonstrate the significance and practicality of solar energy in the home and for some segments of industry. Most of the collectors developed to date are similar, in that they rely on a blackened metal absorber surface to collect the incident solar flux. This surface heats up and subsequently transmits its energy to a circulating fluid. To prevent the absorber surface from losing most of the collected energy through convection and radiation to the environment, various methods of insulation have been developed. Most rely on transparent cover plates or other means such as honeycomb cells and/or vacuum, to prevent excessive losses. This type of collector can be highly efficient over large temperature ranges; however, materials and construction requirements have driven costs quite high.

The black liquid collector is an innovative concept with some real advantages over conventional collectors. Prime among these advantages is the potential for low-cost one-piece extruded-type construction which eliminates much of the labor (soldering, welding, mechanical assembly, etc.) inherent in the conventional collector. By the use of suitable plastics or glass, the material costs can also be reduced by the elimination of metallic components.

The black liquid collector combines the absorbing medium with the heat transfer medium. In this case, the conventional absorber plate is replaced by a transparent material through which the "black" or solar absorbing liquid flows. The solar radiation is transmitted directly to the heat transfer fluid and is absorbed within the depth of the fluid. A comparison of the two absorbing mediums is shown in Figure 4-1. In the case of the conventional black absorber, the solar radiation, I , is incident on the absorber and heats it to temperature T_s . This heat energy must then be transmitted to the heat transfer fluid. The primary heat loss from the collector is proportional to the temperature difference $T_s - T_a$. This heat loss can be compared to the black liquid collector where the solar radiation is transmitted through the transparent plate and heats the fluid directly. The temperature of the black liquid will always be the hottest part of the collector structure. As with the conventional absorber, the primary heat loss is proportional to

CONVENTIONAL BLACK ABSORBER COLLECTOR

T_a = Ambient Temperature

T_s = Surface Temperature

T_f = Fluid Temperature

BLACK LIQUID COLLECTOR

FIGURE 4-1. COMPARISON OF THE TEMPERATURE DISTRIBUTION BETWEEN A CONVENTIONAL BLACK ABSORBER SURFACE AND A BLACK LIQUID COLLECTOR

$T_s - T_a$; however, this temperature difference will always be less for the black fluid collector and, if the transparent plate has a low conductivity, the temperature difference can be significantly less. As will be seen in the section on Systems Analysis, a black liquid collector incorporating a plastic transparent plate with typical heat insulating properties can exceed the performance and efficiency of a conventional collector (with cover plate) in the lower temperature differential range. At higher temperature differentials, however, the efficiency will drop off faster than a conventional collector. One major problem is that most suitable plastics will not structurally perform well at higher temperatures and tend to deform. Thus, it is in the lower temperature region (below 180 F, 82 C) where a plastic collector will have considerable advantages.

The analysis performed also shows the addition of a cover plate to the basic black liquid collector configuration (single-glazed) will produce an efficiency curve which closely matches the performance of the conventional single-glazed, selective-surface collector. Obviously, the plastic black liquid collector could not operate in the higher temperature region which would cause excessive distortion or even melting of some components. However, a drain down system would be satisfactory for this configuration since the empty black liquid collector will not absorb appreciable solar energy and will remain cool.

One potential major advantage of the low-cost black liquid collector is its use with a series solar assisted heat pump concept (Figure 4-2). In this system, simple low-cost collectors are essential for cost-effective design.

Parallel solar systems (systems employing independent heat pump and solar collection systems) and solar systems which have no heat pump require collectors which can supply the direct heating load. Collector outlet temperatures in the 130-180 F (54-82 C) are required. Collectors capable of supplying such temperatures at reasonable efficiencies are presently on the market and typically cost about \$15-20 per sq ft of collector delivered to the site but not installed.

The series system, since it can make good use of lower temperatures, is an ideal candidate for low-temperature, low-cost collectors. Operation in the low-temperature region means that many of the extensive (and expensive) solutions to losses at high temperature can be minimized or dispensed with.

SERIES SYSTEM

PARALLEL SYSTEM

FIGURE 4.2. SIMPLIFIED DIAGRAM OF SERIES AND PARALLEL SOLAR ASSISTED HEAT PUMP SYSTEMS

The black liquid collector, which is suitable for such a system, could probably be produced for installed costs of \$5 per sq ft or less.

The use of a low-temperature, black liquid collector in a series heat pump system has two other features which should be mentioned: (1) this type of collector will have high efficiency at the time of year when high efficiency is most needed, i.e., the winter months, since it will be operating with a small temperature difference between storage and ambient; (2) the black liquid collector can also produce temperatures in the summer which are suitable for heating of domestic hot water (120 - 160 F, 49 - 71 C). These two features are not unique to the black liquid collector; however, system cost would be lower with the black liquid collector as compared to conventional collectors designed to do the same job.

Stagnation would not be a problem since the system can be designed for drain down (black liquid collectors do not collect appreciable energy when empty) or the heat losses can be balanced such that the collector never will see excessive or damaging temperatures even under stagnation conditions.

Proper utilization of the black liquid collector (or other low-cost collector) will require the development of a proper heat pump component capable of utilizing the higher temperatures available from the collectors as a source temperature. The U.S. DOE is presently sponsoring development of such heat pumps⁽⁴⁻¹⁾ and the coupling of the low-cost collector with the improved heat pump in a series system is certainly a viable option for a cost-effective solar energy system.

Another factor of significance when comparing the black liquid collector with conventional collector systems is the potential of easy on-site construction and assembly of the black liquid system. Conventional collectors require structural rigidity for transport and installation. This has resulted in the production of material-intensive solar panels weighing as much as 8-10 pounds per sq ft (39-49 kg/m²). There is a direct relationship between weight and cost in the fabrication of solar collectors and heavy panels are obviously more costly. The black liquid collector manufactured from extruded plastic weighs less than 1 lb per sq ft (4.8 kg/m²) in a form which is structurally rigid and which can be easily handled and installed on site. The black liquid collector design is readily adaptable to a "do-it-yourself" type of installation where individual parts could be distributed

through the building materials industry, resulting in lower price markups from manufacturer to distributor to ultimate user. Precise fits, close tolerances, and extensive caulking are not required or even desirable for the black liquid collector.

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5.0 TECHNICAL DISCUSSION

5.1 Physical Basis for the Black Liquid Collector

Conventional flat-plate collector performance is generally described by a relation similar to equation (5.1)^(5-1,-2,-3)

$$F' [\tau\alpha I - U_t (T_f - T_a)] \quad (5.1)$$

where

- q_u = useful energy gain
- I = solar flux measured in the plane of the collector
- $\tau\alpha$ = product of transmittance of the cover plates and the absorptance of the absorber plate (or black liquid)
- F' = collector efficiency factor
- T_f = mean temperature of collector plate (or black liquid)
- T_a = ambient temperature
- U_t = overall coefficient of heat loss of the collector fluid to ambient air.

Collection efficiency q_u/I is thus

$$\epsilon = q_u/I = F' \tau\alpha - [F' U_t (T_f - T_a)/I] \quad (5.2)$$

Equation (5.2) can be used to provide a one-dimensional, steady-state comparison between the black liquid collector, a black absorber (swimming pool type), and a conventional single-glazed collector.

As was mentioned in the Background section (Section 4.0), the primary heat loss from a collector is proportional to the difference in temperature between the absorber surface and the ambient temperature. This temperature difference is always less for a black fluid collector than in a collector where a metal plate is heated and the heat transferred to a working fluid. In the case of the black liquid, the heat transfer fluid and the absorber are the same. In addition, for the black liquid, the absorption process is a direct conversion of electromagnetic radiation energy to fluid thermal energy within the absorbing volume. The collector efficiency factor, F' , is therefore unity for the black liquid, whereas for the conventional metal plate collector, F' varies typically in the range 0.88 to 0.98.

The effective transmittance-absorptance ($\tau\alpha$) for the black liquid collector will also differ from that of a conventional collector. In particular, the absorptance of the absorbing surface or medium, can be taken as unity for the black liquid (assuming that the concentration of blackening agent and the thickness is great enough for total absorption). It should be noted that in the unglazed configuration the black liquid is in direct contact with the cover plate material and one reflecting surface is essentially eliminated.

Since the black liquid is in direct contact with the cover plate, the overall coefficient of heat loss, U_t , will be greater than in a conventional collector; however, this can be minimized by increasing the thickness of the cover (i.e., plastic) or by the addition of one additional cover plate (single-glazed). The latter option will essentially make the performance of the black liquid collector equivalent to that of a good conventional metal plate (single-glazed) collector; however, at considerably less cost (see Systems Analysis Section 5.2.3).

Figure 5.1 was generated from the BCL-developed computer model, SOLCOL (see Systems Analysis Section 5.2.3 for details), and represents theoretical projections of several collector configurations. The curves labeled "black absorber" are what might be expected from a simple swimming, i.e., unglazed, pool type black plastic collector. The two curves for the "unglazed black liquid" represent a basic black liquid collector with two different cover plast thicknesses (0.15 and 1.0 cm). For comparison, a conventional single-glazed metal plate type collector (LennoxTM) is also shown. The curve labeled "single-glazed black liquid" represents expected performance if the basic black liquid collector has an additional cover plate added.

5.2 Summary of Results by Task

5.2.1 Task 1. Survey Potential Black Liquids/Transparent Covers

The objectives of this task were to investigate potential black liquids which would be suitable as absorbers for direct and diffuse sunlight, and to evaluate potential transparent cover materials suitable for use with the black fluids.

FIGURE 5.1. AVERAGE COLLECTOR EFFICIENCY FOR VARIOUS COLLECTOR CONFIGURATIONS

These objectives were satisfied by accomplishing the following:

(1) obtaining as much information as possible about potential black liquids from the literature and previous experience, (2) obtaining spectral absorption profiles for promising liquids, (3) determining the chemical concentration effects, chemical properties, and effects of mixing two or more of the absorbing solutions, (4) finding compatible liquids to be absorbing across the entire solar spectrum, (5) compare suspension black liquids (carbon black, metal powders, etc.) with organic dyes and with true solution black liquids (totally soluble solutions of chemical salts or dyes).

Due to time and funds limitations, the entire range of potential black liquids could not be covered under the scope of this project and only previously reported^(5-4 to 5-8) and known in-house liquids could be investigated. DOE, under a separate program is currently examining other potential black liquids and it is likely that several suitable liquids can be found for specific applications.

The criteria for selection of the most promising black liquids was (in approximate descending order of importance): (1) absorption profile (maximize percentage of solar spectrum absorbed, (2) chemical stability, (3) physical stability (resistance to fading, deposition, plastic staining, spectral profile changes etc.), (4) cost, (5) toxicity, (6) corrosion properties, and (7) availability. Of these, items (1), (2), and (3) were regarded as the most important for this project, where it is important to demonstrate that the black liquid concept is valid. For this to be demonstrated requires an essentially 100 percent absorbing solution over the entire solar spectrum. From a practical standpoint, the other criteria are also important, since practical systems will probably require metallic heat exchangers, and cost, toxicity, and availability are essential aspects of a practical fluid.

Black Liquid Studies. Some of the potential black liquids investigated are listed in Table 5-1. Only those which were actually tested for properties or have known potential are listed. Several other candidate liquids were dropped when it was found that they could not satisfy some of the important selection criteria. Many potential dyes and other black liquids could not be obtained during this program and a partial list is given in Appendix A. Some of the solutions listed in Table 5-1 are absorbing only in specific portions of the solar spectrum; however, they were included in the study as possible mixture materials to be used to close absorption gaps of other potential liquids.

TABLE 5-1. POTENTIAL "BLACK LIQUIDS" FROM TASK 1

	Liquid	Type	Primary	Remarks
			Spectral Absorption	
1.	CuCl_2	True Solution	Infrared	Essentially 100 percent absorbing for wavelength larger than 660 NM (6600 A) at <5 percent concentration (1 cm thickness)
2.	CuSO_4	True Solution	Infrared	Similar to CuCl_2 but slightly less effective
3.	$\text{FeNH}_4(\text{SO}_4)_2$	True Solution	UV	Essentially 100 percent absorbing between 300 and 450 NM (3000 to 4500 A)
4.	CoSO_4	True Solution	UV and Visible	Maximum absorbtion at 520 NM (5200 A)
5.	Black Liquid #1 (combination of 1, 3, and 4)	True Solution	UV through IR	Good absorption across entire solar spectrum - high concentrations (20 percent required)
6.	Parker Ink (acid organic dye with iron salt - Permanent Quink)	True Solution	UV and Visible	100 percent absorbing UV to 675 NM (6700 A) at low <1 percent concentration (1 cm thick). Ink fades with long-term (greater than one month) sunlight exposure.
7.	Black Liquid #2 (Combination of 1 and 6)	True Solution	UV through IR	100 percent absorbing 300 - 1500 NM (Ink portion faded with long-term sunlight exposure)
8.	Black Liquid #3 (combination of 1 and 4)	True Solution	Visible and IR	Essentially the same as #5 but eliminate $\text{FeNH}_4(\text{SO}_4)_2$
9.	University of Dayton Fluid ^{(5-4)*}	Carbon-suspension (India Ink)	Total Spectrum	Agglomerated and settled out

TABLE 5-1. (CONTINUED)

Liquid	Type	Primary Spectral Absorption	Remarks
10. Anderson Fluid ⁽⁵⁻⁵⁾	Carbon suspension	Total Spectrum	Agglomerated and settled out
11. ARCO Graphite Oil	Oil (Graphite suspension)	Total Spectrum	Suitable as oil fluid only, will not mix well with water. Very good absorber.
12. Organic Dyes	True Solution	Variable, some are suitable	Not enough known about long-term stability. Many available - See Appendix B
13. Metallic Suspension	Suspension	Total Spectrum	Cost and availability criterion did not allow testing of this category
14. Metallic-Organic Dyes	True Solution	Variable, some should be stable and suitable	Cost and availability criteria did not allow testing of this category
15. Loveland Fluid ⁽⁵⁻⁹⁾	CaCl ₂ solution with carbon suspension	Total Spectrum	Used at DSET for black liquid collector evaluation. Coagulation and settling problems. Best when diluted at least 50 percent
16. DJinnii Fluid ⁽⁵⁻¹⁰⁾	Plastic encapsulated carbon	Total Spectrum	Received late in program. Preliminary measurements indicate good properties. Long-term exposure properties unknown.
17. Flint Ink ⁽⁵⁻¹¹⁾	Carbon suspension	Total Spectrum	Did not mix well with water-good absorption
18. Cyanamid Cycal 1452 ⁽⁵⁻⁷⁾	Suspension	Most of Spectrum (Some IR transmission)	Precipitation noted in reference

Table 5-1. (CONTINUED)

Liquid	Type	Primary Spectral Absorption	Remarks
19. Wyandotte Acidol Dye (5-8)	Dye Solution (Metal Complex)	Most of Spectrum (Some IR transmission)	Fading with long-term exposure - Some plastic staining
20. Aquadag (5-4) (Acheson)	Carbon suspension	Total Spectrum	Severely stained plastics

* References listed at end of each Section.

Figures 5-2 through 5-7 show typical absorption profiles for some of the black liquids studied. The typical carbon or graphite suspension liquids (Figure 5-7) actually provided the greatest absorption across the entire solar spectrum; however, the black liquid formed by mixing a 5 percent CuCl_2 and 1/4 percent Parker Ink was essentially identical and is a true solution. The carbon suspension solutions (University of Dayton⁽⁵⁻⁴⁾ J. H. Anderson⁽⁵⁻⁵⁾, ARCO graphite Oil, Loveland Fluid⁽⁵⁻⁹⁾ etc.) tended to settle and deposit, especially after heating. the ARCO oil was only suitable as an oil fluid and would not mix with water. The viscosity of this material is also high.

One black liquid chosen for the evaluation of the collectors which were constructed under Task 5 was the combination of copper chloride and Parker Ink (Permanent Quink) which provided essentially 100 percent absorption across the entire solar spectrum, (Black Liquid 2 in Table 5-1). The measured spectral absorption of the two components is shown in Figure 5-8. Since the combination of the two components is a true solution, no problems of settling were encountered. Laboratory tests in the solar simulator constructed under Task 2 did not indicate any long-term stability problems, however, since the ink component contains an organic dye, outdoor exposure tests in an acrylic container over several months were carried out to determine the long-term stability of this combination. Results of this study are shown in Figure 5-9 and indicate definite fading with time and sunlight exposure.

This effect is generally the case when organic dyes are exposed to sunlight for extended periods. In one respect, this is not a serious problem since the ink component is present in low-concentrations and can be periodically added at low cost, however the stability problem coupled with the known corrosive properties of CuCl_2 for metals, effectively rule out this liquid as an entirely satisfactory black liquid. For this application, however, corrosion is no problem with respect to the black liquid collector and associated connecting components, which are all constructed of plastic. The problem would arise in a practical system where a metallic heat exchanger would be used to transfer heat to the storage tank and/or heat pump.

It was unfortunate that the black liquid stability problem did not surface until actual sunlight exposure tests were undertaken. Early tests with the collectors constructed under Task 5 were carried out using this

FIGURE 5-2. ABSORPTION BY WATER (1 CM THICKNESS)

FIGURE 5-3. ABSORPTION OF CuCl_2 (5 PERCENT, 1 CM THICKNESS)

FIGURE 5-4. ABSORPTION OF BLACK LIQUID NO. 1
(EFFECT OF CONCENTRATION)

FIGURE 5-5. ABSORPTION OF PARKER PERMANENT QUINK INK
(5 PERCENT, 1 CM THICKNESS)

FIGURE 5-6. ABSORPTION OF BLACK LIQUID NO. 2
(CuCl_2 + PARKER INK)

FIGURE 5-7. ABSORPTION OF TYPICAL CARBON OR GRAPHITE SOLUTION

FIGURE 5-8. MEASURED SPECTRAL ABSORPTION OF CuCl_2 AND PARKER INK (BLACK LIQUID 2)

FIGURE 5-9. BLACK LIQUID 2-SUNLIGHT EXPOSURE TEST

liquid with results as predicted by the computer analysis, indicating essentially 100 percent absorption in the black liquid.

A second black liquid supplied by Loveland Industries⁽⁵⁻⁹⁾, Loveland, Colorado, was also investigated and seemed to have many of the desirable black-liquid properties. This liquid is a suspension type and some problems with settling, agglomeration and deposition on the plastic surfaces were encountered during the collector tests. Considerable development remains to determine a commercial black liquid; however, workable black liquids exist and can be used within certain limitations.

Based on absorption, price, availability, chemical stability, toxicity, and corrosion properties the best all-around fluids are currently those based on carbon suspensions, although considerable development remains to eliminate the settling, agglomeration, and thixotropic properties at the low flow conditions encountered in current collector design parameters.

One possibility is experimentation with higher velocity flow in the black liquid collector which, although lowering the ΔT across the collector may have some real advantages with respect to total heat collection and system efficiency when coupled with the heat pump system.

One potential black liquid that shows great promise in preliminary tests is the one supplied late in the program by DJinnii Industries⁽⁵⁻¹⁰⁾, Dayton, Ohio. This is a proprietary fluid based on plastic encapsulation of carbon particles. This allows some control of particle density and may greatly reduce the settling and agglomeration problems typical of ordinary carbon suspensions. Long-term stability might be a problem, however, tests of this nature and actual collector tests were not possible within the time frame of this program.

Collector Cover Plate. Several types of glass and several plastic materials (primarily acrylic and polycarbonate) were considered for the cover plate of the black-liquid solar collector. Plastic materials received greater attention on the basis of thermal conductivity, price, weight, ease of fabrication, and breakage aspects. An acrylic plastic Acrylite[®] was chosen for the first collector on the basis of optimizing performance, ease of construction, and long-term life when exposed to solar radiation. This material is also commercially available and CYRO Industries (a partnership of Cyanamid Plastics, Inc. and Rohacryl, Inc.) supplied panels of this material for

evaluation under this program as a potential collector. (See Appendix B for a description of the properties of this and other considered materials). It is recognized that there may be problems with the chosen plastic material (primarily cracking and crazing); however, the objective was to maximize the performance of the prototype collector to prove the validity of the black-liquid concept. At this time no recommendation of this material should be implied since long-term stability of acrylic plastic in contact with liquids is not known. There exist surface treatments which can minimize these problems. However, this aspect was not investigated during the program. Table 5-2 lists some of the potential advantages and disadvantages of transparent plastic solar collectors.

TABLE 5-2. TRANSPARENT PLASTIC SOLAR COLLECTORS
POTENTIAL ADVANTAGES AND DISADVANTAGES

Potential Advantages	Potential Disadvantages
Low Cost	Susceptible to Weathering
Light Weight	Staining by Liquids
High Efficiency	Temperature Limits
Easy Fabrication	High Expansion Coefficient
Shape and Size Variable	Reactions to Moisture and Liquids
Mass Production	Heat Exchanger Required
Easily Transported	Electrostatic Dust Attraction
Easily Installed	Burning Characteristics
No Metals Required	Stagnation if not Drained
Properties Tailored for Application	
Elasticity	
Drain Down Prevents Stagnation and Freezing	
Easy Repair	

5.2.2 Tasks 2 and 3. Construct Small Test Cell and Evaluate Black Liquids/Transparent Cover

A small test cell was constructed to obtain experimental verification of the predictions obtained from the absorbance measurements of the black liquids and cover materials investigated in Task 1. A small solar simulator (NASA-Lewis design, Air Mass 2)⁽⁵⁻¹²⁾ was used to irradiate a confined volume of liquid in the test cell to measure the temperature rise as a function of time.

The test cell is shown in an overall view in Figure 5-10 and a close up view in Figure 5-11. The test cell is approximately 10 cm (4 inches) in diameter with an axial length of 2.54 cm (1 in.). Provision was made for installing and sealing various cover plates on the top of the test cell.

Since the main objective of these tests was to verify the absorbing ability of the confined liquid, the test cell was designed for once-through passage of the radiation. Consequently, the bottom cover was fabricated of glass and an absorbing copper plate painted black was located approximately 0.6 cm (1/4 in.) below the lower glass cover. A cooling coil was attached to the copper to maintain the plate at or below room temperature. Thus, any radiation which was not absorbed in the fluid would be absorbed on the copper plate and reradiation was minimal because of the low temperature maintained on the absorbing plate.

Within the interior of the cylindrical test volume, a thermocouple was located just below the upper cover plate, and a second thermocouple was located just above the lower glass cover. A magnetically actuated stirring rod was installed on the lower glass cover. The purpose of this rod was to prevent stratification of the liquid and the creation of convection currents. By adequately stirring the liquid, a uniform temperature could be obtained that would be representative of the heat absorbing capability of the liquid. Stratification can be a problem in the collector, especially with the thixotropic properties of some of the suspension fluids at low flow conditions.

Since absorption in a black liquid is proportional to the concentration of the "blackening agent" and the depth, this arrangement allowed us to observe stratification by turning off the stirring motor. Liquids with a high concentration of blackening, where the absorption occurred near the surface,

FIGURE 5-10. OVERALL VIEW OF SMALL TEST CELL

FIGURE 5-11. CLOSE UP VIEW OF TEST CELL

produced a great deal of stratification and consequently greater conductive losses through the cover plate. Ideally the concentration of the black liquid should be adjusted so that 100 percent absorption will take place in the liquid layer desired in the collector design. Absorption in a black liquid system follows the well known absorption law

$$I = I_o e^{-KCL} \quad (5-3)$$

where

- I = Intensity at depth L
- I_o = Incident solar intensity
- K = The absorption coefficient
- C = The absorber concentration
- L = Path length.

While K is normally a function of wavelength, for the black liquids considered, K is essentially a constant, and the liquid can be made totally absorbing by having a liquid with a high concentration of blackening agent and a small penetration depth or a low concentration of agent and a larger depth. For practical purposes, the liquid depth in a collector should be from approximately 0.6 cm (1/4 in.) to 1.3 cm (1/2 in.). Thicker layers impose a severe weight penalty on the collector, while thinner layers require excessive concentration of the blackening agent.

Several of the more promising black liquids from Task 1 were run in the test cell as well as some of the candidate cover materials. The conclusions obtained from this study indicate that any black liquid having absorption throughout the solar spectrum would be suitable strictly as an absorber. The true solution black liquids had essentially the same temperature rise characteristics as the carbon suspension fluids. It was noted that the carbon suspension fluids would settle out if the stirrer was not used, and some deposition on plastic cover plates was also observed.

On the basis of these tests, the black liquid initially chosen for the collector tests was the combination of $CuCl_2$ and Parker Ink, and initial collector testing at BCL used this fluid with considerable success. At the time of selection, the stability problem described under Task 1 was not apparent. Later, the Loveland Fluid⁽⁵⁻⁹⁾ was tested and although

some stratification effects were noted it was decided after consultation with the program technical monitor to use this fluid in the outdoor testing program and the ASHRAE 93-77 tests at the independent laboratory. The results of the coverplate evaluation indicated acrylic type plastics to be superior from a transmission and heat transfer aspect although polycarbonates were not appreciably different. It was recognized that there may be long-term problems associated with the chosen plastic; however, the objective was to maximize the performance of the prototype collector at least for the short term to prove the black liquid concept and provide the necessary data for evaluation.

5.2.3 Task 4. Systems Analysis

An engineering analysis of the black-liquid collector was conducted to evaluate the performance of the collector when used in combination with a heat pump to supply space heating. Several existing BCL and other computer models have been modified to treat the various components of this solar-assisted heat-pump system. The models have been integrated into the BCL/TRNSYS (University of Wisconsin) systems analysis computer code and the overall performance has been determined for various configurations.

Collector Model. The BCL developed computer model, SOLCOL, was used to predict the performance of the black-liquid solar collector. In this model, the incident solar flux is separated into its direct and diffuse components, and each component is treated in its full spectral detail. The solar energy incident on the collector is computed each hour and depends on the latitude and collector tilt. The flow through the collector is assumed to be one dimensional and time dependent. The collector is divided into a number of finite elements, and a detailed energy balance is computed at each element and at each time step. The energy gain at each element depends on the amount of solar flux transmitted through the cover plates and absorbed by the liquid, and the energy loss depends on conduction through the back insulation; conduction, convection, and radiation through the cover plate(s); and the energy convected from one element to the next by the flow of the liquid. Thus, the model predicts the temperature distribution along the collector, as well as accurately predicting the transient collector performance. The collector considered has a transparent cover plate

below which the black liquid passes and is exposed to the solar radiation. Part of the incident solar radiation is absorbed by the liquid, and the remainder is transmitted to the bottom plate where it is either absorbed as heat energy and transmitted back to the liquid by convection, or is reflected back up through the liquid to be further absorbed. In the latter case, when the bottom plate is reflective, the radiation that is not absorbed upon making two passes through the liquid is lost to the system. In either case, the detailed spectral absorption profile of the liquid and the solar spectrum are considered in determining the amount of energy absorbed by the liquid.

In addition to the above capabilities, the collector simulation program was modified to include the effect of the absorption of the incident radiation by the cover plate bounding the black liquid.

The SOLCOL model can be coupled with the BCL/TRNSYS systems analysis model to provide the maximum flexibility in analyzing various collectors when used in combination with a heat pump. However, it was found to be most efficient to use SOLCOL to determine the performance characteristics of each new collector, and then use the results as input to BCL/TRNSYS.

Using the SOLCOL model which was modified to treat a black-liquid collector, the collector performance was first computed for an ideal black liquid, i.e., a liquid that is 100 percent absorbing across the solar spectrum. The results of the calculations are presented in Figure 5-12, where the basic black-liquid-collector performance is compared with that of a single-glazed, black-absorber collector (LennoxTM collector). Presented is the collector efficiency as a function of the parameters $\Delta T/I$, the ratio of average collector temperature minus the ambient temperature divided by the incident solar flux. Results were obtained for four cover-plate thicknesses: 0.15, 0.5, 1.0, and 1.5 cm. The plate absorptivity was taken to be 0.1 cm^{-1} , a typical value for the type of acrylic material being considered for this collector. It can be seen that the performance of the collector continues to improve for this range of cover thicknesses. It is likely that the performance of the black-liquid collector could equal that of the single-glazed collector if the cover plate were thick enough. However, this would not be a cost-effective design because of the large amount of material required. Note that with this configuration the collector is quite sensitive to wind velocity and the curves are based on a continuous 5 m/s (11 m/hr) wind directly on the collector. Performance increases considerably for lower wind velocity and decreases for higher velocity.

FIGURE 5-12. AVERAGE COLLECTOR EFFICIENCY FOR VARIOUS COVER THICKNESSES

Addition of a single air spaced acrylic cover plate provides a predicted curve equal to or better than the LennoxTM curve shown in Figure 5-12 (see also Figure 5-1). Such a cover plate also minimizes the effects of wind on collector performance.

A sensitivity analysis was performed to see if a change in cover-plate absorptivity has any appreciable effect on the collector performance curves. The results (Figure 5-13) indicated that large changes have a minor effect. Therefore, it is not necessary to select a cover-plate material which has very low absorptivity (less than 0.1 1/cm). In fact, it is not necessary to know the actual plate absorptivity to a high degree of accuracy. An error of 10 to 20 percent in the plate absorptivity will have a negligible effect on the overall collector efficiency.

Performance Using Real Black Liquids. The results presented in Figure 5-12 were obtained assuming the black liquid absorbed 100 percent of the radiation transmitted through the cover plate. The collector performance was also computed for some of the black liquids which were developed in Tasks 1 and 3. The actual measured absorption profiles were used to determine the amount of energy absorbed for each liquid. Two cases were examined. First, the collector back plate (bounding the fluid on the bottom of the fluid channel) was assumed to absorb all the radiation transmitted through the fluid. Most of this energy is subsequently transmitted back into the fluid by conduction; the remainder is lost through the insulation to the cooler outside air.

Second, the collector back plate was assumed to be 100 percent reflecting. In this case, the radiation essentially makes two passes through the liquid. Thus, more energy is directly absorbed by the liquid. However, that radiation which is not absorbed upon making two passes is transmitted through the cover plates and is lost to the system. All of the results to be presented were made for a top cover plate thickness of 1 cm, and a plate absorptivity of 0.1 1/cm and a liquid thickness of 1.3 cm (1/2 inch). In order to compare the various black liquids, a collector performance parameter is defined which is felt to be indicative of the overall collector performance. The parameter is proportional to the area under the linearized collector efficiency curve, and is defined as:

$$\text{Performance Parameter} = (\tau\alpha)^2 / U_L .$$

FIGURE 5.13. EFFECT OF PLATE ABSORPTIVITY ON COLLECTOR PERFORMANCE

Using this parameter, three potential black-liquid solutions are compared with the ideal black liquid in Table 5-3 for a 100 percent absorbing back plate. The results indicate that the black-liquid #2 solution performs nearly as well as the ideal black liquid. The reduction in performance is only 3 percent for a 2.5 percent black-liquid solution. The black liquid performs much better than the CuCl solution alone which shows a 9 percent performance reduction for a 2.5 percent solution.

The results for a 100 percent reflecting back plate, shown in Table 5-4, are similar except in the case of the 2.5 percent CuCl . The reduction in performance for this liquid is five times greater than the 2.5 percent black liquid. This is due to the large gaps in the CuCl_2 absorption spectrum where radiation is transmitted, even after two passes through the liquid. From these results, it was concluded that the black-liquid #2, at concentrations of 2.5 percent or above, has a performance which is nearly equal to an ideal black liquid. Furthermore, the black-liquid collector can be designed with either an absorbing back plate or a reflecting back plate. The collector performance is virtually the same for both configurations.

Virtually all of the carbon suspension fluids will act like the "Ideal Black" fluid assuming the concentration of blackening agent is adjusted so that 100 percent absorption occurs in the collector path length. The computer model will be valid for any black liquid having similar absorption parameters.

Single-Glazed Black Liquid Collector. Previous results considered the standard unglazed extruded panel of acrylic plastic (Acrylite[®]). The upper skin or sheet which is in direct contact with the black liquid would be made thicker than existing commercial panels. This generally would not be the most cost effective use of material. If a new die were to be made to extrude a new type panel, it would be best to make a three-layer skin (i.e., single glazed). The black liquid could occupy the lower chamber (channels) and the upper chamber would be sealed off to provide an insulated space. Such a panel would produce a double covering and is predicted to perform essentially like a conventional single-glazed collector.

Systems analysis of such a single-glazed acrylic panel have been performed for a "black" liquid flowing through the lower passage and a reflective, insulating backing. The overall performance was slightly better than a

TABLE 5-3. COLLECTOR PERFORMANCE
USING BLACK LIQUID SOLUTIONS,
100 PERCENT ABSORBING BACK PLATE

Liquid	Performance Parameter, $(\tau\alpha)^2/U_\ell$	Percent Performance Reduction
Ideal Black	.0676	--
5% Black Liquid*	.0668	1%
2.5% Black Liquid	.0654	3%
2.5% CuCl_2	.0615	9%

* 5% CuCl_2 + 1/4% Parker Ink (Black Liquid #2,
Table 5-1).

TABLE 5-4. COLLECTOR PERFORMANCE
USING BLACK LIQUID SOLUTIONS,
100 PERCENT REFLECTING BACK PLATE

Liquid	Performance Parameter $(\tau\alpha)^2/U_\ell$	Percent Performance Reduction
Ideal Black	.0676	--
5% Black Liquid*	.0665	1.5%
2.5% Black Liquid	.0645	4.0%
2.5% CuCl_2	.0536	20.0%

* 5% CuCl_2 + 1/4% Parker Ink (Black Liquid #2,
Table 5-1).

single-glazed collector such as the LennoxTM collector. However, in the analysis, the heat transfer through the ribs was neglected, and additional reflections due to the ribs were not included. Thus, the performance of the single-glazed panel will probably be no greater than, and perhaps slightly less than, a single-glazed Lennox collector. For the purposes of this analysis, these preliminary results have indicated that a single-glazed black liquid collector will have comparable performance to a conventional single-glazed collector.

The single-glazed panel would be a more cost-effective use of material than the previously analyzed panels, and could offer a significant improvement in performance. Furthermore, used in the black liquid mode, with a reflective backing material, this configuration offers a means of temperature control to protect the collector during stagnation. With the black liquid drained, the collector would reflect most of the incoming solar flux and remain cool.

For these reasons, the following systems analysis was conducted using the performance parameters of a single-glazed collector for the black liquid collector.

Heat Pump Model. The heat-pump model was developed by Kirshbaum and Veyo of Westinghouse for EPRI⁽⁵⁻¹³⁾. This model was chosen because it treats many heat-pump operating modes. For example, this heat-pump model allows for direct heating from the storage tank or solar collector by means of a liquid-to-liquid or air-to-liquid heat exchanger, and allows for heating directly from outside air. The model can be used to simulate pumping heat into storage and can treat the case where direct heating and heat-pump operation occur simultaneously.

The Westinghouse heat-pump model has also been integrated into the BCL/TRNSYS model. The heat pump characteristics used for the analysis were those of the advanced Brookhaven design (Figure 5-14). Although this heat pump is not presently commercially available, the DOE is sponsoring development of such a unit and it is considered within the state-of-the-art. Successful cost-effective solar assisted heat pump systems will require this type of heat pump coupled with a low cost collector such as the black liquid.

The characteristics of the Brookhaven heat pump, modified for a 2-1/2 ton unit, are shown in Figure 5.14. This heat pump provides the improved

HEAT PUMP PERFORMANCE CHARACTERISTICS
HEATING MODE
115° CONDENSER

FIGURE 5.14. CAPACITY AND COEFFICIENT OF PERFORMANCE OF IMPROVED BROOKHAVEN HEAT PUMP IN THE HEATING MODE (Source, Ref. 5.14)

performance at high evaporator temperatures which conventional heat pumps cannot provide. For comparison purposes, Figure 5-15 shows the Carnot Theoretical Curve compared to typical present heat pump heating coefficient of performance.

Systems Analysis Combinations. A systems analysis of several combinations of solar energy and heat pumps systems has been conducted to determine if the black liquid collector could be used effectively to supplement a liquid-to-air heat pump system. The black liquid collector must operate at temperatures below 80 C so as not to degrade the collector (plastic) material. In this temperature region and below the collector would be effective when used in combination with a heat pump which can still extract heat at evaporator temperatures below room temperature. The performance of four different cases have been examined.

1. *Air-to-Air Electric Heat Pump.* As a base case, the straight air-to-air electric heat pump has been evaluated. The performance of the combined systems must not only satisfy the load using less energy input, but must save enough energy to pay for the additional capital investment required to purchase the solar equipment.

2. *Direct Solar Heating with Parallel Air-to-Air Heat Pump Back-Up.* The simplest combined solar/heat pump system is the parallel system where the solar system supplies heat directly to the load, and a conventional air-to-air heat pump system is used as auxiliary backup when the solar system can supply no energy. The collector used in this analysis is a double glazed LennoxTM collector since this option generally will require a high efficiency collector.

3. *A Single Source Liquid-to-Air Heat Pump in Series with Solar Heated Storage Tank.* In this system the heat pump evaporator is heated by the liquid in the solar heated storage tank. The storage tank is replenished by solar energy when available. When the storage tanks gets close to freezing, electric resistance heating is used directly to heat the load. In this mode, the heat pump keeps the storage tank at a low temperature so that the solar collector always operates in its highest efficiency range. Thus, a low cost (e.g., black liquid) collector could be used effectively in this mode.

FIGURE 5.15 . CARNOT THEORETICAL vs PRESENT HEAT PUMP HEATING COEFFICIENT
OF PERFORMANCE (Source, Ref. 5.14)

4. *Dual Source Air-to-Air/Liquid-to-Air Heat Pump in Combination With a Solar Heated Storage Tank.* This case is the same as Case 3 with the addition of a dual source heat pump with the capability of operating with outside air when the storage tank is depleted. In Cases 3 and 4 the collector performance is that predicted for a single-glazed black-liquid collector.

Results from Systems Analysis. The results of the systems analysis are presented in Tables 5-5 and 5-6. Table 5-5 compares the performance of Cases 1, 2, and 3. Presented are the direct solar heating (Col. 1), the heating supplied by the heat pumps (Col. 2), and the auxiliary heating (Col. 3). Columns 4 and 5 are the yearly average solar collector efficiency and yearly average heat pump COP. The solar fraction (Col. 6) is the fraction of the load supplied by solar, including that which is processed by the heat pump. The final column is the total power required to satisfy the load for the year. This includes the auxiliary energy plus that required to operate the heat pump.

The total power required for the heating season with the improved heat pump (Case 1) is 12,400 kwh. The heating load is representative of a newly constructed home of approximately 170 M^2 floor area (1800 ft^2) located in Columbus, Ohio. The overall heat loss was estimated to be 1260 KJ/Hr/C (660 Btu/Hr/F).

The parallel solar/heat pump system (Case 2), with 56 m^2 (600 ft^2) of Lennox double glazed collector (LSC 18-1) and a 5.6 m^3 (200 ft^3) water storage volume, has a total power required of 7,600 kwh. This is a 40 percent reduction in total power required for the heat pump only case.

The series solar/heat pump (Case 3) shows a total power required of 12,200 kwh (3a) for a collector area and storage tank size the same as Case 2. The reason for this apparent poor performance can be determined by examining the other entries in the table.

The average collector efficiency and COP are significantly higher for Case 3 compared to Case 2, even though a single glazed collector was used in Case 3. Thus, the performance of the series solar/heat pump system is as expected. However, the auxiliary heating for Case 3 is many times greater than either Case 1 or 2 since the system operates in a heat-starved condition. Thus, the series system is penalized by the lack of heat in the storage tank,

TABLE 5-5. COMPARISON OF CASES 1, 2, 3

Configuration	Direct Solar 1000 KWH	Heat Pump 1000 KWH	Auxiliary Heating 1000 KWH	Solar Collector Efficiency	Heat Pump	Solar Fraction	Total Power Required 1000 KWH
Case 1 Brookhaven Heat Pump Only	0	28.5	3.0	0%	3.02	0	12.4
Case 2 Parallel System * Solar/Heat Pump Ac = 56 m ² Vs = 5.6 m ³	14.5	15.0	2.0	40.6%	2.73	.442	7.6
Case 3 Series System ** Solar/Heat Pump							
(a) Ac = 56 m ² Vs = 5.6 m ³	4.7	18.8	8.5	57.2%	5.10	.584	12.2
(b) Ac = 56 m ² Vs = 8.4 m ³	4.8	19.7	7.5	57.9	4.98	.602	11.5
(c) Ac = 56 m ² Vs = 11.2 m ³	4.7	20.4	6.8	58.4%	4.94	.616	11.0
(d) Ac = 84 m ² Vs = 16.9 m ³	6.8	22.0	3.1	49.1%	5.34	.729	7.2

* Requires double-glazed high-efficiency collectors. (Ac = collector area, Vs = storage volume)

** Black liquid collector.

TABLE 5-6. COMPARISON OF CASES 1, 2, 4

Configuration	Solar 1000 KWH	Pump 1000 KWH	Auxiliary Heating 1000 KWH	Solar Collector Efficiency	Heat Pump COP	Solar Fraction	Total Power Required 1000 KWH
Case 1 Brookhaven Heat Pump Only	0	28.5	3.0	0%	3.02	0	12.4
Case 2 Parallel System * Solar/Heat Pump Ac = 56 m ² Vs = 5.6 m ³	14.5	15.0	2.0	50.6%	2.73	.442	7.6
Case 4 Series System ** Solar/Heat Pump With Dual Source							
(a) Ac = 56 m ² Vc = 5.6 m ³	4.7	25.0	1.9	56.6%	4.19	.574	7.9
(b) Ac = 56 m ² Vc = 11.2 m ³	4.7	25.2	1.8	57.8%	4.28	.606	7.7
(c) Ac = 56 m ² Vc = 16.0 m ³	4.6	25.4	1.7	58.7%	4.39	.628	7.5
(d) Ac = 84 m ² Vc = 16.9 m ³	6.8	23.7	1.2	48.9%	4.98	.725	6.0

* Requires double-glazed high-efficiency collectors

** Black liquid collector

and must rely on electric resistance auxiliary a large part of the time. Enlarging the storage tank improves this situation; however, doubling the storage volume (3c) only reduces the auxiliary required to 6,800 kwh, an unacceptably high value.

In order to get the auxiliary energy required down to a reasonable level it is necessary to increase the collector area by 50 percent, and use a storage volume 3 times larger than the Case 2 storage volume (3d). This system is competitive on a performance basis with the Case 2 system. Although the Case 3 system is larger than the Case 2 system overall systems costs may be considerably less due to the potential low cost of the black liquid collector.

A more interesting result is presented in Table 5-6. The results of Case 1 and 2 are repeated here for easy reference. Looking at the Total Power Required, it is found that the series system with a dual source heat pump (4a) is competitive with the parallel system of the same size. The Case 4 system should be significantly less expensive than the Case 2 system. These results are shown graphically in Figure 5-16 and 5-17.

Although these results offer some encouragement, there are several variations of the series system which should be evaluated before a final system is selected. It is possible that the auxiliary heating could be reduced further and the average heat pump COP increased by utilizing outdoor air preheat whenever possible. In this mode the evaporator fluid would be preheated by outdoor air whenever the ambient temperature was greater than the evaporator temperature. The fluid would then be further heated by storage tank fluid to generate the performance needed.

One additional mode of operation which should be explored is the series solar/heat pump system used in a seasonal storage mode. In this mode, a very large storage tank is used to store heat from the summer season to the winter season. Much smaller collector areas are required but much larger storage tanks are needed. The addition of the heat pump would effectively increase the storage capacity by 30 to 40 percent by allowing the extraction of heat down to 1 or 2 C. In addition, a large buried storage tank may be able to utilize heat gain from the ground when tank temperatures are near freezing to supply additional energy to the heat pump.

Estimated System Costs. Table 5-7 gives estimated total system costs for the systems discussed in the previous sections. These are costs

FIGURE 5.16. COMPARISON OF PARALLEL SOLAR/HEAT PUMP SYSTEM WITH SERIES SOLAR/HEAT PUMP SYSTEM
(Columbus, Ohio, One Year)

FIGURE 5.17. COMPARISON OF PARALLEL SOLAR/HEAT PUMP SYSTEM WITH SERIES SOLAR/DUAL SOURCE HEAT PUMP (Columbus, Ohio, One Year)

based on current (1978) equipment adjusted to reflect the higher cost of the improved heat pump, controls, piping, etc. The black liquid collector was costed at \$4/sq ft ($\43 m^2) and the conventional double-glazed collector at \$17.50/sq ft ($\$188/\text{m}^2$).

These costs and the system performance data presented in Tables 5-5 and 5-6 indicate that the most cost-effective system will be the dual source improved heat pump coupled with the black liquid collector (Case 4a).

Detailed cost-payback analysis has not yet been performed since results are highly dependent on initial assumptions (interest rate, tax incentives, fuel cost, etc.).

TABLE 5-7. ESTIMATED SYSTEM COSTS

System	Total Cost
Heat Pump Only ⁽¹⁾	
Improved Air-to-Air, 2.5 Tons	\$ 2,200
Parallel ⁽²⁾ , Air-to-Air Heat Pump and 56 M ² Conventional Solar Collector	18,225
Series ⁽³⁾ , 84 M ² Black Liquid Collector and Water-to-Water Heat Pump	12,200
Series ⁽⁴⁾ , 56 M ² Black Liquid Collector and Dual Source Heat Pump	9,175

- (1) 2-1/2 ton heat pump cost estimate of \$1,750 plus \$450 installation.
- (2) Same heat pump cost, with 56 M² double-glazed conventional collector cost of \$10,500 plus \$3,600 installation, 5.5 M³ storage cost of \$725, and fixed solar system costs of \$1,200.
- (3) Same heat pump cost, with 84 M² black liquid collector cost of \$3,600 plus \$2,700 installation, 16.8 M³ storage cost of \$2,220 and fixed solar system costs of \$1,500.
- (4) Dual source heat pump cost of \$2,200 plus \$550 installation, with 56 M² black liquid collector cost of \$2,400 plus \$1,800 installation, 5.5 M³ storage cost of \$725, and fixed solar system costs of \$1,500.

5.2.4. Task 5. Construct Full-Size Collector and Test Loop

The overall objective of this task was to design and construct a full-size prototype black-liquid collector that could be evaluated outdoors in accordance with the ASHRAE Standard 93-77. Particular attention was given to selecting materials that would produce a durable and cost-effective design. In addition, the collector design parameters were chosen so that the computer model performance predictions could be verified with the measured experimental data.

Subtask 5.1. Preliminary Design. The preliminary design phase involved close liaison with the other previous tasks involving the selection of preferred black liquids and transparent cover materials, together with the results of the computer modeling study. Discussions were also held with personnel from Desert Sunshine Exposure Tests, Inc. (DSET)⁽⁵⁻¹⁵⁾ who conducted some of the outdoor performance tests.

Based on the results of the computer model, it was decided to build two full-size collectors so that different thicknesses of plastic covers could be evaluated. One collector was designed to use a presently available extruded acrylic glazing sheet which had a plastic cover thickness of 1.5 mm (0.059 inch). (A more complete description is given later.) The second collector was built to be "reversible", with one side using an acrylic sheet thickness of 6.35 mm (0.25 inch), and the other side with 12.7 mm (0.50 inch). Thus, by simply turning the second collector over, two different thicknesses of plastic covers could be evaluated.

Acrylic plastic was selected for these prototype collectors, rather than polycarbonate, due to its higher solar transmittance, better outdoor weatherability, and ease of fabrication. For example, reported transmittance values for standard sheets of acrylics and polycarbonates are 92 percent and 84 percent, respectively⁽⁵⁻¹⁶⁾. The one major limitation of acrylics, however, is that their recommended upper temperature limits under no-load service conditions are in the range of 79 to 110 C (175 to 230 F), depending on the molding grade⁽⁵⁻¹⁶⁾ (see Appendix B). The equivalent upper temperature limits for polycarbonates are in the range of 121 to 135 C (250 to 275 F)⁽⁵⁻¹⁶⁾ (see Appendix B). Nevertheless, since these collectors were being specifically designed to

operate at lower temperatures, as would occur with a series heat pump drawing heat out of the thermal storage reservoir, the lower temperature limits for acrylics were considered to be of secondary importance.

It was also determined that some of the preferred black-liquid mixtures would require an independent test loop in order to be compatible with the measuring equipment at DSET. Therefore, a complete liquid circulating loop was built which required a separate pump, heat exchanger valves, and tubing.

Subtask 5.2. Final Design. Figure 5-18 is an engineering drawing of the first prototype collector which was fabricated at BCL. The solar collector shown in Figure 5-18 utilized the extruded Acrylite^R SDPTM acrylic sheet available from CY/RO Industries⁽⁵⁻¹⁶⁾ and shown in cross-section on Figure 5-19. This is referred to in this report as an unglazed collector. The extruded aluminum glazing strips and gaskets shown in Figure 5-18 are also available from CY/RO.

Complete details of the CY/RO products are given in Appendix B. The use of these commercially available materials does not constitute endorsement for such a use as a black liquid collector, since the long-term liquid exposure effects are now known. However, a 6-months outdoor rooftop exposure test (May-October, 1978) of a CY/RO panel filled with many different liquids (including water and several black liquids) did not indicate any change in the physical properties of the acrylic sheet within this time period.

The headers were designed to circulate the black-liquid solution upward through the 72 smaller passages, while the two larger reinforced end channels were used only for hold-downs, as shown in Section A-A (Figure 5-18). The basic flow pattern, minifolds, and hole sizes (3/32") were designed to produce very uniform flow velocities in each of the channels, and field measurements have confirmed this. The insulation located behind the panel is covered with metal foil so that any sunlight passing through the black liquid will be reflected back for a second pass through the liquid. In addition when the collector is drained during nonuse, the foil will prevent the insulation and plastic collector from over-heating.

Thus, one can purchase an extruded panel cheaply, and for volume solar collector use the panel dimensions can be optimized. The ends of the panel are simply milled to a round shape to match the radius of the manifold tube which is pre-drilled to control flow and glued in place. The panel is

FIGURE 5-19. CROSS-SECTION OF ACRYLITE
SDP ACRYLIC SHEET

laid on standard foil-faced foam insulation and fastened in place with commercially available hardware. The two unused side channels provide edge insulation. No massive mounting container is needed so one has a lightweight, site-fabricated collector which is easily shipped as parts in bulk quantity.

Figure 5-20 shows the second solar collector which was fabricated at BCL, which is basically similar to the one in Figure 5-18 (but not a CY/RO panel), except that two different thicknesses of acrylic sheet were used for the top and bottom covers. The purpose of this arrangement was to allow testing with both a 6.35 mm (0.25 inch) and 12.7 mm (0.50 inch) plastic cover, simply by reversing the collector on its mounting board. This design is also an unglazed collector.

Subtask 5.3. Fabrication of Collectors. Figures 5-21 and 5-22 are photographs showing the first prototype collector, which corresponds to the drawing in Figure 5-18. In Figure 5-21, the collector is filled with the black liquid. In Figure 5-22, the close-up photograph shows the black liquid partially filling the passages, and also the inlet manifold, the aluminum mounting strip, and the aluminum foil covering the insulation. The appearance of the second collector was very similar to the first, except that only three ribs (or spacers) were used between the two cover sheets. The larger side channels did not have black liquid flowing in them and provide edge insulations.

The actual fabrication, or assembly, of the acrylic parts was accomplished quite simply using the recommended liquid solvent for acrylics, methylene chloride. After the parts were machined as shown in Figure 5-18 and 5-20, they were clamped or fitted together, and the solvent allowed to flow into the joints. Assembly was easy and no difficulties were encountered.

Following the assembly of each collector, they were leak-tested by pressurizing with air (to about 3 psig) and observing any loss of pressure. Both collectors were found to be leak-tight by this method.

The finished collector assemblies were mounted on plywood for rigid support during shipping and testing.

Subtask 5.4. Fabrication of Test Loop. A separate flow loop was required for the black liquid collectors during testing at DSET to isolate the black liquid from the precision measuring instruments.

FIGURE 5-20. ENGINEERING DRAWING OF ACRYLIC THICK SKIN EXPERIMENTAL BLACK LIQUID COLLECTOR

FIGURE 5-21. OVERALL VIEW OF DOUBLE SKINNED ACRYLIC COLLECTOR FILLED WITH BLACK LIQUID

FIGURE 5-22. CLOSE UP OF DOUBLE SKINNED ACRYLIC COLLECTOR PARTIALLY DRAINED

Figure 5-23 is a schematic of the black-liquid test loop. All plastic components were used, except for the heat exchanger which was copper. The 1/20 hp pump was magnetically driven, and the reservoir had a capacity of 13 gallons. About 10 gallons of black liquid were used in the loop. All of the tubing, reservoir, and heat exchanger were insulated during the actual tests.

With the arrangement shown, the flow rate of the black liquid through the test collector could be accurately adjusted and maintained during changing tilt angles of the collector, etc. The bypass valve was needed to allow the centrifugal pump to operate in its best performance range, and the reverse flow valve could be used to quickly pump down the collector. However, whenever the pump was shut off the collector automatically drained down since the return line was above the liquid level in the reservoir.

A coaxial water-cooled refrigerant-type heat exchanger (Packless Industries Model COBX-075-H) with 1.6 sq ft of surface area, was located near the outlet of the collector. The water flow lines were attached to the heat exchanger and test equipment used by DSET. Therefore, DSET test results could only measure the overall efficiency of the entire black liquid system, including the heat exchanger rather than the efficiency of the collectors themselves. However, calibrated thermocouples were placed at the collector inlet and outlet so that the collector efficiency itself could be calculated by Battelle. In addition to the two thermocouple temperature measurements, the flow rate of the black liquid was determined for each test interval by diverting the return flow from the collector into a measuring flask for a timed interval.

The same basic type of flow loop was used during the initial tests at Battelle. However, a transient heat up test method was used rather than the steady-state method used by DSET, so the heat exchanger circuit was not needed.

A third industrial laboratory used a system similar to DSET except measurements were made directly in the collector loop and a heat exchanger was used only for heat rejection. The flow rate was measured in the black liquid loop by weighing a standard volume sample in a measuring flask for a timed interval.

Subtask 5.5. Production Cost Estimate of Extruded Plastic Collector.

A production cost breakdown was developed for a plastic collector array that would be suitable for a black liquid solar system. The CY/RO Industries'

FIGURE 5-23. SCHEMATIC OF BLACK LIQUID COLLECTOR TEST LOOP

extruded unglazed Acrylite SDPTM acrylic sheet was used as the basic panel material. A cross section of this panel was shown previously in Figure 5-19. This is the same panel that was selected for Battelle's black liquid collector tests.

It was assumed that each collector module would be approximately 4 ft x 8 ft, and made in lots of 100 to 200 units. Also, a single-glazed (triple-layer) version was discussed with CY/RO engineers, which in effect gives a built-in cover sheet which is advantageous to minimizing heat losses from the front surface. The back of the panel was assumed to be insulated with a 25 mm (1.0 inch) layer of styrofoam.

The in-plant construction costs were estimated as follows:

	<u>Cost Per Sq Ft</u>
Single-glazed acrylic panel	\$2.25 - \$3.00
Tubing headers, top and bottom	0.15 - 0.20
Insulation, 1-inch styrofoam	0.20 - 0.25
Aluminum holdown frame	0.50 - 0.60
Labor, machining and assembly	<u>0.60 - 0.70</u>
Total	\$3.70 - \$4.75

The final selling price is estimated to be about 1.4 times this amount, or \$5.20 to \$6.60 per sq ft (or \$56 - \$71/m²). This is based on using multiplying factors of 1.2 on purchased parts and 2.5 on direct labor. In addition, these estimates have assumed rather limited volume production rates. Undoubtedly, costs for large-scale mass-produced quantities would be even lower, probably in the \$4 to \$5/ft² range or \$43 to \$54/m²).

5.2.5. Task 6. Collector Test Data Analysis

The objective of this task was to provide complete experimental performance data for the black liquid prototype solar collectors developed during the program. Two different designs were tested not only at Battelle, but at other independent testing laboratories.

Figures 5-24 and 5-25 show the results of the collector efficiency measurements which were obtained by the three separate laboratories. Laboratory 1 refers to Battelle's Columbus Laboratories, Laboratory 2 refers to a

FIGURE 5-24. MEASURED AND PREDICTED PERFORMANCE OF THE THIN-WALL EXTRUDED-ACRYLIC SOLAR COLLECTOR

FIGURE 5-25. MEASURED AND PREDICTED PERFORMANCE OF THE THICK-WALL ACRYLIC-SHEET SOLAR COLLECTOR

private company who also has been conducting research work on black liquid collectors and has been cooperating with Battelle on this program, and Laboratory 3 refers to DSET Laboratories, Inc. (formerly Desert Sunshine Exposure Tests, Inc.) located north of Phoenix, Arizona*. The predicted efficiency lines used in the computer modeling studies also are shown on the figures for comparison.

The following tabulation lists the straight line regression equations corresponding to Figures 5-24 and 5-25 for the various collectors tested.

<u>Collector</u>	<u>Efficiency Equation</u> ($\Delta T/I$, M^2C/watts)
Thin Wall Unglazed	
Lab 1 (BCL)	0.825 - 15.8 ($\Delta T/I$)
Lab 2	0.846 - 14.7 ($\Delta T/I$)
Lab 3 (DSET)	0.647 - 12.6 ($\Delta T/I$)
Predicted	0.761 - 16.1 ($\Delta T/I$)
Thick Wall Unglazed	
Lab 1 (BCL)	0.612 - 4.92 ($\Delta T/I$)
Lab 3 (DSET)	0.880 - 11.7 ($\Delta T/I$)
Predicted	0.750 - 8.52 ($\Delta T/I$)

In Figures 5-24 and 5-25 different black liquids were used by each of the three laboratories. These tests at Laboratory 1 (Battelle) used a special formulation which consisted of about 5.0 percent Copper Chloride and 0.25 percent Parker permanent black ink, by weight, as described elsewhere in this report. The black liquid used at Laboratory 2 (a private industrial company) was their own proprietary formulation based on a carbon suspension. The black liquid used for the testing at Laboratory 3 (DSET) was another proprietary liquid (also a carbon suspension) being developed by Loveland Industries⁽⁵⁻⁹⁾. Although the black liquid used during the initial testing at Battelle exhibited excellent spectral absorption characteristics both in the test cell and during outdoor tests, it was later observed that the Parker black ink gradually faded with outdoor exposure. Therefore, the Loveland liquid was tried during the efficiency measuring tests at DSET. However, that liquid mixture was not entirely satisfactory either, because of problems with

* A copy of the first DSET test report is included as Appendix C.

settling or particles which sometimes restricted the flow through the small orifices, and temperature stratification characteristics which caused the upper surface of the black liquid to become overheated. Although not much is public knowledge concerning the proprietary black liquid developed by Laboratory 2, some of these other problems seem to have been overcome.

In Figure 5-24, the primary reason for two of the curves being above the predicted line is that the wind speed during the outdoor tests was only about one-half of the 5 meter/second wind speed used in the modeling studies. The performance of the thin-wall unglazed solar collector is very sensitive to wind speed, since only a thin layer of clear plastic separates the black liquid from the ambient air. The main reason for the Laboratory 3 line falling below the predicted line was because of the flow distribution and temperature stratification problems discussed earlier.

The thin-wall unglazed collector was also tested with an extra plastic cover sheet installed. This combination was intended to simulate an extruded plastic collector having an additional cover with an air gap to minimize heat losses from the front surface of the collector. This arrangement was tested by Laboratory 2, and the regression efficiency line was the same as the predicted line on Figure 5-25. Although these results are comparable to the thick-wall unglazed collector shown in Figure 5-25, it is believed that even higher efficiencies (comparable to a conventional single-glazed collector) should be realizable at elevated temperatures with a more carefully designed and constructed cover sheet. Thus, a very thick wall and a single-glazed (triple-skin) configuration would be equivalent; however, the single-glazed construction mode would be more cost-effective. CY/RO⁽⁵⁻¹⁷⁾ has estimated that the cost of such a single glazed panel would be approximately 50 percent higher than the current double-skinned panel.

In Figure 5-25, the Laboratory 3 line is believed to be the most accurate of the two experimental lines. The reason for this is that the DSET tests were conducted under proper steady-state conditions, whereas the Battelle data were collected under transient operation with some of the useful heat being collected going to continually raise the temperature of the collector materials. This collector had a relatively large thermal mass, since it was built having two rather thick plastic sheets, one 6.3 mm (p.25 inch) thick and one 12.7 mm (0.50 inch) thick. This transient effect was judged to be quite minimal in the unglazed collector, as confirmed by the data.

Unfortunately, the data collected by DSET on the unglazed collector model were rather limited because cracks and leaks developed in the 6.3 mm (0.25 inch) cover plate. Only the data shown on Figure 5-25 were obtained before the tests had to be stopped. Therefore, no incident-angle-modifier or time-constant data were obtained for this collector, as are reported for the extruded thin-wall panel in Appendix C. However, the incident-angle-modifier values would most likely follow the traditional cosine pattern for single-glazed collectors. Also, the time constant would be rather large because of the total mass of the liquid and thick cover sheets. The reasons for cracks developing in the 6.3 mm (0.25 inch) cover sheet are believed to be caused by (1) the glued ribs coming loose from the cover sheet as internal pressure built up, and (2) stresses caused by having two different thicknesses of cover sheets. Repairs were made a couple of times in order to get the limited data shown.

During all the testing, the maximum collector outlet temperatures were limited to about 71 C (160 F). This was the recommended operating temperature limit given by the manufacturer for their extruded acrylic panels. However, during one of the final tests with the extra cover sheet over the thin-wall unglazed CY/RO collector, the temperature did rise to well over 82 C (180 F) and the collector developed quite a bit of distortion. Nevertheless, the collector was still operable, and no leaks developed. However, the heat losses from the back of the panel may have increased due to air leakage.

In summary, the extruded thin-walled unglazed acrylic panel appeared to be a very satisfactory, rugged, lightweight collector. With an extra cover sheet arrangement, its performance should equal that of single-glazed conventional collectors, while its cost should be relatively low, perhaps in the \$4 to \$5/ft² range.

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6.0 RELATIONSHIP OF BLACK LIQUID SOLAR COLLECTORS TO THE DOE NATIONAL PROGRAM PLAN

The Department of Energy (DOE) has prepared a National Program Plan for Research and Development in Solar Heating and Cooling^(6-1,2) which represents a thorough assessment of the status of solar heating and cooling technology and describes the Federal research and development program for solar heating and cooling, including those activities to be funded in whole or in part by the Federal Government.

The objectives of the DOE solar energy R&D program are to identify potentially cost-effective systems for building, agricultural, and industrial process heating and cooling applications, and to provide the emerging solar energy industry with the materials, components, information, and methodology needed for designing, producing, and installing these systems.

The black liquid collector is a low-temperature, low-cost, flat-plate liquid collector with several applications to the DOE program plan. Initially, the research program on black liquid collectors emphasized applications to the solar assisted heat pump system described as path H1 in the DOE National Program Plan (Figure 6.1). The research program was planned to consider SOLAR (Flat Plate) LIQUID HEATING COLLECTORS as an energy source for a HEAT PUMP to supply SPACE HEATING.

It has now been recognized that the black liquid collector has several other applications to the DOE National Program in addition to the heat pump application. Prime among these is the potential for direct heating of service hot water (Path W1, Figure 6.1). The black liquid collector is easily capable of supplying the temperatures necessary for domestic hot water service (120-160 F, 49-71C) for an appreciable fraction of the year. Another potential area is direct space heating (Path H4, Figure 6.1), although existing heat (hot water) distribution systems are presently not adequately designed to take advantage of this option. Larger pipes and forced air operating through heat exchangers would be necessary, since the temperatures generated by the black liquid system would not be adequate for conventional convection (fin and tube) heating systems. A floor hydronic distribution would be satisfactory for this system without modification.

The black liquid system in some design forms could also assist in space cooling (via the heat pump) by utilizing the collectors in the

FIGURE 6.1. RELATIONSHIP OF BLACK LIQUID SOLAR COLLECTORS TO THE DOE NATIONAL PROGRAM PLAN

summer as nocturnal radiators. The heat pump would be used to raise the storage tank temperature by day and the collectors would radiate to the open sky by night.

As outlined in this report, the performance of heat pump systems can be improved significantly by basic component changes such as the utilization of low-temperature, low-cost collectors coupled with new improved higher COP heat pumps. The black liquid system is one of the possible candidates for collectors suitable for use with a series heat pump system. The combination of the black liquid collector with the improved heat pump offers the potential of effective energy load management providing flexibility for utilities and a cost-effective system when compared to other system options such as the heat pump alone or the parallel solar/heat pump system.

Other applications of the black liquid system are possible such as in agricultural and industrial process heat (Path HL and Path WL - not shown in Figure 6.1), although these applications have not been extensively studied in this research project.

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7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

It has been found that the black liquid collector concept has the potential of significant cost savings when compared with a conventional single-glazed collector of comparable performance when operated in a lower temperature region compatible with service hot water, series heat pump systems and some applications of direct space heating.

Black liquid collectors when used in a series solar-assisted heat pump system will perform essentially the same as a conventional single-glazed collector. Current heat pumps, with their moderate seasonal COP's, do not use to best advantage the low-temperature source provided by the collector. The development of improved heat pumps is essential for the solar-assisted series heat pump heating option to be economically viable.

Black liquid collectors can be easily manufactured in an extruded form and are compatible with existing plastics technology. The performance properties can be modified by changing the extruded configuration and efficiency curves can be matched to given system requirements. Computer models used in the design process for specific operational characteristics provide satisfactory prediction of expected performance.

Of most significance is the potential low fabrication and installation cost of the black liquid collector when compared to conventional metallic plate absorber collectors.

At present, little is known about the long-term stability and performance of the black liquid collector, however; 15-20-year lifetimes are possible based on data for collector materials (plastics only) and should be expected. No data exist for plastics in contact with liquids for these time periods. Further work on aging, stress-cracking, ultraviolet exposure, and outdoor weathering in actual performing black liquid collectors is necessary for accurate lifetime predictions.

Specific conclusions obtained during this black liquid study are:

- Program objectives as proposed have been successfully demonstrated

- Black liquid collectors have the potential for very low cost production
- Further improvements are possible in both collector design and specific black liquids
- Computer modeling can accurately predict black liquid collector performance
- Black liquid collectors have application for service hot water heating, direct space heating, industrial water heating, and possibly some agricultural applications
- Black liquid collectors have the potential to assist in effective energy load management for utilities when coupled with the heat pump option
- Efficiencies of the black liquid collector are comparable to conventional single-glazed collectors in the lower temperature regions
- Black liquid collectors can be manufactured with performance parameters tailored to each prospective application
- All-plastic construction eliminates the corrosion problems associated with metallic collectors
- Black liquid collectors are much lighter and easier to install when compared with conventional collectors
- Black liquid collectors are suitable for mass production (extruded panel construction)
- Black liquid collectors can be distributed through standard building trade outlets and are suitable for "do-it-yourself" construction
- Problems of stagnation are eliminated since the collector does not collect appreciable heat when drained
- Panels can be easily repaired with simple patch kits
- Little is presently known about long-term stability of plastics in contact with black liquids and exposed to outdoor weather conditions

- Plastic black liquid collectors have definite upper temperature limits which must be observed
- The commercial quality black liquid has yet to be developed
- The development of an improved heat pump is necessary to fully utilize the black liquid collector/heat pump option
- A low cost collector is necessary for the series heat pump/solar system
- The series heat pump/solar system is a viable candidate in the DOE national program.

7.2 Recommendations

It is recommended that further effort in the commercial development of the black liquid collector be undertaken. The following specific areas are recommended for further research:

- Investigate both short and long-term effects of exposure of plastic materials to the solar environment
- Determine long-term effects on plastics from exposure to black liquids in operating systems
- Develop a commercial quality black liquid (low-cost, nonstaining, nontoxic, etc.)
- Determine optimum heat pump characteristics for the black liquid system
- Investigate further improvements in black liquid collectors via anti-reflection coatings, UV stabilizers, anti-moisture coatings, etc.
- Obtain long-term data on an operating black liquid system
- Study other potential areas for black liquid utilization within industry and agriculture

- Perform detailed cost and marketing analysis on black liquid collectors, collector/heat pump systems, and other possible configurations
- Analyze possibility of direct space heating with low-cost black liquid collectors/improved heat distribution systems
- Define mass production potential and feasibility
- Development of extruded triple-layer collector with built in cover sheet.

8.0 PUBLICATIONS/REPORTS

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TABLE A-1. COMMERCIALLY AVAILABLE BLACK WATER
SOLUBLE ORGANIC DYES

Commercial Name	Common Designation
Acid Black BX	Acid Black 1
Acid Black 10BN Conc.	Acid Black 1
Acid Black 10BR Conc. 126 percent	Acid Black 1
Alegarine Light Grey 2BLW	Acid Black 48
Aleazarol Black 3G	Mordant Black 16
Aleazarol Blue Black G	Mordant Black 38
Amacid Black 10 BR Conc.	Acid Black 1
Amaad Milling Black B	Acid Black 24
Amacid Negrosene J. Powder	Acid Black 2
Amafast Grey LVC	Direct Black 190
Amafast Grey RLN 200 percent	Direct Black 56
Amagene Black OB	Direct Black 80
Amagene Black VJ 150 percent	Direct Black 78
Amalan Black GBL	Acid Black 107
Amalan Grey B	Acid Black 58
Amalan Grey BRL	Acid Black 140
Amasol Black WA	Acid Black 52
Atalan Black BGL	Acid Black 107
Atlantichrome Black PV Conc.	Mordant Black 9
Atalntichrome Black T 100 percent	Mordant Black 11
Atlantic Resin Fast Grey 4GL 250 percent	Direct Black 62
Avilon Black B	Acid Black 63
Azoanthrene Jet Black K Ex Conc.	Direct Black 22
Belamine Prazo Black OB 150 percent	Direct Black 80
Belamine Fast Grey LWBG	Direct Black 71
Buffalo Black 8B	Acid Black 41
Buffalo Black SS	Acid Black 1
Buffalo Chrome Black F	Mordant Black 5
Caliochrome Black T Conc.	Mordant Black 11
Calcochrome Blue Black R	Mordant Black 17
Aolcoid Blue Black Ex Conc.	Acid Black 1
Calcocid Neutral Black 2B Conc.	Acid Black 26
Calcofast Black WA	Acid Black 52
Calcofast Grey	Acid Black 92
Calcofast Neutral Grey B	Acid Black 60
Calcomine Black EX	Direct Black 38
Calcomine Drazo Black VJ Conc.	Direct Black 78
Calcomine Fast Black F Conc.	Direct Black 9
Calco Nigrosine J. Crystals	Acid Black 2
Calcozine Black CBF	Basic Black
Calcozine Black MD	Basi
Capracyl Black BGL	Acid Black 107
Capracyl Gray GN	Acid Black 58
Carbide Fast Black G Ex	Direct Black 22

TABLE A-1. (CONTINUED)

Commercial Name	Common Designation
Chromacyl Black W	Acid Black 52
Chrome Black T 160 percent	Mordant Black 11
Chrome Fast Cyanine BNZ	Mordant Black 17
Chromogene Black T	Mordant Black 11
Chromolan Black WA	Acid Black 52
Cuprophenyl Black RL 200 percent	Direct Black 91
Cuprophenyl Grey GRL	Direct Black 94
Diamond Blue Black RBA	
High Cone	Mordant Black 17
Drazo Black OB Conc.	Direct Black 80
Drazene Black VJ Conc.	Direct Black 78
Drazophenyl Black AW Supra	Direct Black 80
Drazophenyl Black ZV Cone 150 percent	Direct Black 78
Duphenyl Black B Supra 200 percent	Direct Black 51
Duphenyl Black FG	Direct Black 22
Duphenyl Black G	Direct Black 19
Direct Agurine G	Direct Black 8
Direct Black CW	Direct Black 38
Direct Black RW 200 percent	Direct Black 4
Direct Fast Black FF 200 percent	Direct Black 9
Direct Fast Black L	Direct Black 51
Direct Fast Grey RLN	Direct Black 56
Dressing Black SS	Acid Black 29
Dupont Algarine Blue Black B	Mordant Black 13
Dupont Fiber Black VF	Direct Black 38
Dupont Neutral Gray L	Acid Black 48
Dupont Nigeria Black GX	Basic Black
Dupont Negrosine WSJ Crystals	Acid Black 2
Direct Fast Black FF 200 percent	Acid Black 24
Erie Black GX00	Direct Black 38
Erie Black KCA	Direct Black 19
Erie Black NCW Conc.	Direct Black 9
Erie Black RW Conc.	Direct Black 4
Erie Black RX00	Direct Black 38
Erie Fast Black G Conc.	Direct Black 22
Erie Chrome Black E	Mordant Black 26
Erie Chrome Black T Supra	Mordant Black 11
Erie Chrome Blue Black B	Mordant Black 3
Erie Chrome Blue Black R	Mordant Black 17
Erionyl Navy Blue B	Acid Black 26
Eriosin Black 2B	Acid Black 24
Eriosin Black 2BW	Acid Black 26A
Eriosin Blue Black 6B	Acid Black 26
Eriosin Blue Black B	Acid Black 1
Formanil Black G 200 percent	Direct Black 22
Intracid Black 2B Conc.	Acid Black 1
Intrakan Black BGL	Acid Black 107
Intralan Fast Black B	Acid Black 63
Intralan Grey BL	Acid Black 60

TABLE A-1. (CONTINUED)

Commercial Name	Common Designation
Irgalan Black GBL	Acid Black 131
Irgalan Black RBL	Acid Black 132
Irgalan Olive BGL	Acid Black 64
Lanamid Black GBL	Acid Black 107
Lanamid Gray GBL	Acid Black 58
Naphthylamine Black 10 BR Conc.	Acid Black 1
Neolan Black WA	Acid Black 52
Neolan Gray RC	Acid Black 127
Negrosine 12525 Conc. Crystals	Acid Black 2
Phenamine Black CL Conc.	Direct Black 38
Phenazo Black D	Direct Black 17
Phenazo Black OB	Direct Black 80
Phenazo Black V	Direct Black 78
Pontachrome Black PV	Mordant Black 9
Pontachrome Black TA	Mordant Black 11
Pontachrome Blue-Black F	Mordant Black 17
Pontacyl Black A	Acid Black
Pontacyl Blue-Black 5X	Acid Black 1
Pontacyl Fast Black BBD	Acid Black 24
Pontacyl Fast Black N2B	Acid Black 26A
Pontamine Black E double	Direct Black 38
Pontamine Black RRX	Direct Black 4
Pontamine Drazo Black OB	Direct Black 80
Pontamine Drazo Black ZVN	Direct Black 78
Pontamine Fast Black FF	Direct Black 9
Pontamine Fast Black L Cone	Direct Black 51
Pontamine Fast Black PGR	Direct Black 22
Seristan Black B	Direct Black 38
Solantine Black L Conc. 200 percent	Direct Black 51
Solantine Gray LVL	Direct Black 190
Solantine Gray RLN Conc. 200 percent	Direct Black 56
Solophenyl Gray 4GL	Direct Black 62
Solophenyl Grey RLN	Direct Black 56
Sulphone Cyanine Black BA	Acid Black 24
Superchrome Black TX Conc.	Mordant Black 11
Superchrome Black PV Conc.	Mordant Black 9
Superchrome Blue BC	Mordant Black 3
Superchrome Blue BEX Conc.	Mordant Black 17
Supralan Black 6GL	Acid Black 108
Supralan Black NB	Acid Black 107

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TABLE B-1. TYPICAL PROPERTIES OF ACRYLICS*

PHYSICAL PROPERTIES	Units	Value	Test Method
SPECIFIC GRAVITY		1.19	ASTM D-792-66
MECHANICAL			
Tensile strength	MPa (psi)	65 (9,500)	ASTM D-638-68
Tensile elongation	%	4	ASTM D-638-68
Modulus of elasticity	GPa (psi)	2.8 (400,000)	ASTM D-638-68
Compressive strength	MPa (psi)	124 (18,000)	ASTM D-695-69
Flexural strength	MPa (psi)	110 (16,000)	ASTM D-790-70
Shear strength	MPa (psi)	62 (9,000)	ASTM D-732-46
Impact strength:			
Notched Izod	J/m (ft-lb/in.)	21.4 (0.4)	ASTM D-256-70 FTMS 406 M1071
Charpy unnotched	J/m (ft-lb/in.)	374 (7)	ASTM D-256-70
Falling steel ball (2.27 kg (5 lb) ball falling distance to failure)	m (ft)	1.2 (4)	UL 972
Hardness:			
Rockwell	M-Scale	93	ASTM D-785-65
Barcol	Number	50	Standard spring instrument
Taber abrasion weight loss CS17 wheel, 1000 cycles, 1000 grams weight	mg	22.15	ASTM D-1044-73
OPTICAL			
Refractive index*		1.49	ASTM D-542-50
Reciprocal dispersive power	Abbe Refractometer No.	57.8	ASTM D-542-50
Light transmission	%	92.0	ASTM D-1003-61
Haze	%	1.0	ASTM D-1003-61
After accelerated aging:			FTMS 406 M3022
Light transmission	%	92.0	
Haze	%	1.0	
Spectral transmittance in UV range 290-330 nm	%	0	ASTM E-308-66
Yellowness index after 1 yr Florida exposure	%	+5	ASTM D-1925-70
Effect of accelerated aging, clear material:			ASTM E-42-65
Crazing		None	
Discoloration		None	
Warping		None	
THERMAL			
Heat distortion temperature 2 °C/m (3.6 °F/min.), 1.82 kPa (264 psi)	°C (°F)	97 (207)	ASTM D-648-56
Maximum recommended continuous service temperature	°C (°F)	82 (180)	
Thermal conductivity	W/mK (Btu-in./ft ² hr °F)	0.187 (1.3)	Cenco-Fitch
Specific heat at 25 °C (77 °F)	kJ/kg °K (Btu/lb °F)	1.46 (0.35)	ASTM C-351-61
Flammability (burning rate)	cm/m (in./min.)	2.54 (1.0)	ASTM D-635-68
Thermal stability		No blisters	Fed Spec L-P-391D
Coefficient of thermal expansion	μm/m °C (in./in./°F)	72 (4 x 10 ⁻⁵)	ASTM D-696-70

*See graph.

TABLE B-1. (Continued)

CHEMICAL RESISTANCE		TEST METHOD PER ASTM D-543-67	
Chemical after 7 days at 25 °C (77° F) immersion	% Weight Gain (≤ 1% is negligible)	Chemical after 7 days at 25 °C (77° F) immersion	% Weight Gain (≤ 1% is negligible)
5% acetic acid	Negligible	10% hydrochloric acid	Negligible
Acetone	Swells	3% hydrogen peroxide	Negligible
10% ammonium hydroxide	Negligible	99% isopropyl alcohol	Negligible
Carbon tetrachloride	Negligible	Lacquer thinner	Swells
10% citric acid	Negligible	99% methyl alcohol	15.3
Dibutyl sebacate	Negligible	10% nitric acid	Negligible
Distilled water	Negligible	Oleic acid	Negligible
85% ethyl acetate	Swells	5% phenol	Attacked
95% ethyl alcohol	1.4	10% sodium chloride	Negligible
Ethylene dichloride	Swells	10% sodium hydroxide	Negligible
Heptane (gasoline)	Negligible	30% sulfuric acid	Negligible
Hexane	Negligible	Toluene	Swells
MISCELLANEOUS			
Water absorption 24 hr at 23 °C (73° F)	%	0.24	ASTM D-570-63
Odor		None	
Taste		None	

Data given are average values and should not be used for specification purposes.

*Table adopted from material in Machine Design, March 16, 1978, pg 112 and Swedlow, Inc., Product Literature, Garden Grove, California.

Acrylic transmission and index of refraction variations with wavelength superposed on a solar spectrum background.

TABLE B-2. TYPICAL PROPERTIES OF POLYCARBONATES

ASTM Test	Property	General Purpose	High Flex Modulus	20% Glass Reinforced
<u>PHYSICAL</u>				
D792	Specific gravity	1.2	1.25	1.35
--	Specific volume (in. ³ /lb)	23	22.2	20.5
D570	Water absorption, 24 hr. 1/8 in. thick (%)	0.15	0.12	0.12
<u>MECHANICAL</u>				
D638	Tensile strength (psi)	9,000-10,500	8,000-9,600	16,000
D638	Elongation (%)	110-125	10-20	4-6
D638	Tensile modulus (10 ⁵ psi)	3.4	4.5	8.6
D785	Hardness, Rockwell M	62-70	85	91
D790	Flexural strength (psi)	11,000-15,000	15,000	19,000
D790	Flexural modulus (10 ⁵ psi)	3.0-3.4	5.0	8.0
D256	Impact strength, Izod (ft-lb/in. of notch)	12-16	4-6	2
D671	Fatigue endurance limit 10 ⁷ cycles (psi)	1,500	3,500	5,000
<u>THERMAL</u>				
C177	Thermal conductivity (Btu-in./hr-ft ² -°F)	1.35	1.41	1.47
D696	Coef of thermal expansion (10 ⁻⁵ in./in.-°C)	6.6-70	3.2	27
D648	Deflection temperature (°F) at 264 psi	270	288	295
	at 66 psi	280	295	300
	Continuous, no-load service temp (°F)	250	275	275
<u>ELECTRICAL</u>				
D149	Dielectric strength (V/mil) Short time, 1/8 in. thick	400	450	490
D150	Dielectric constant At 60 Hz	3.17	-	3.50-3.53
	At 10 ³ Hz	3.02	-	-
D150	Dissipation factor At 60 Hz	0.009	0.0008	0.0009
	At 10 ³ Hz	0.0021	-	0.009-0.0013

TABLE B-2. (CONTINUED)

ASTM Test		General Purpose	High Flex Modulus	20% Glass Reinforced
<u>OPTICAL</u>				
D542	Refractive Index	1,586	--	--
D1C03	Transmittance (%)	85-89	--	--
<u>FRICTIONAL</u>				
--	Coefficient of friction			
	Self	0.52	--	--
	Against steel	0.39	--	--

FIGURE B-1. ABSORPTION OF TYPICAL ACRYLIC PLASTIC

A Partnership of Cyanamid Plastics, Inc. and Rohacryl, Inc.

Acrylite®

ACRYLIC SHEET

Light Transmittance and Reflectance

Light and Radiation

In order to understand the light transmittance of clear and colored ACRYLITE®, as well as the relationship of special grades of ACRYLITE® to ultra-violet light, it is useful to review the nature of light and radiation.

Visible light is electro-magnetic radiation similar to X-rays, ultra-violet and infra-red light, or radio waves. Each type of radiation is identified by its range of wave lengths.

The visible light band of the spectrum is that range, between 400 and 700 millimicrons, which can be detected by the human eye. **This band of wave lengths is sensed as "light" because of the sensitivity of the human retina which acts as a detector for this band of radiation and not because of any inherent property of this type of radiation.**

On either side of the visible light band is a range of similar electromagnetic radiation which the eye cannot see.

ULTRA-VIOLET		VISIBLE					INFRA-RED	
	SUNBURN	VIOLET	BLUE	GREEN	YELLOW	ORANGE	RED	
PENETRATING HEAT RAYS							NON-PENETRATING HEAT RAYS	

We are primarily interested in the wave lengths from 200 to 2200 millimicrons as shown in Graph 1. This part of the spectrum can be divided into three components:

1. Ultra-violet band, from 200 to 400 millimicrons
2. The visible spectrum from 400 to 700 millimicrons
3. Infra-red band from 700 to 2200 millimicrons

Millimicrons are commonly used for measuring wavelength in the three bands listed above. Millimicrons can be converted into other units as follows:

1 Nanometer	= 1 Millimicron
10 Angstroms	= 1 Millimicron
1000 Millimicrons	= 1 Micron
1000 Microns	= 1 Millimeter

Graph 1 shows the relative distribution of solar energy within the range from 200 to 2200 millimicrons. The ultra-violet wave band, consisting of wave lengths from 200 to 400 millimicrons, accounts for about 3% of the transmitted solar energy; the visible wave band, from 400 to 700 millimicrons, accounts for approximately 45%; and the infra-red wave band, from 700 to 2200 millimicrons, accounts for about 52% of the total transmitted energy.

The intensity of radiation which actually penetrates the atmosphere and reaches the surface of the earth varies considerably, depending upon solar altitude and such factors as concentration of water vapor, CO₂, dust, and other contamination in the air.

X-ray Transmittance

X-rays and gamma rays are characterized by wave lengths shorter than those in the ultra-violet spectrum. They are not shown in Graph 1.

All types of clear ACRYLITE® transmit X-rays and gamma rays. The transmittance is inversely proportionate to the thickness of the sheet and is approximately 13.6 times greater than that of lead.

The transmittance characteristics are similar to those of human flesh; therefore, ACRYLITE® can be used as a support in medical as well as industrial X-ray applications. X-ray photographs of bone fractures can be made without removing ACRYLITE® splints.

Ultra-violet Radiation

Ultra-violet radiation, that band which lies between 200 and 400 millimicrons, is of interest to us because, although it amounts to only 3% of the total radiation that reaches the earth from the sun, **it is energetic enough to cause chemical reactions, weathering of polymers and fading of certain dyes.** As can be seen from the transmittance curves in Graph 2, ACRYLITE GP shows no transmittance below 345 millimicrons and ACRYLITE OP-2 shows no transmittance below 390 millimicrons. **Therefore, these two grades are considered ultra-violet absorbing.**

Erythema! ultra-violet radiation. The erythema! or "sunburn" band of the ultra-violet spectrum ranges from 280 to 320 millimicrons. This narrow band of radiation is responsible for sunburn. ACRYLITE GP as well as ACRYLITE OP-2 absorb erythema! radiation.

Germicidal ultra-violet radiation, having a wave length of approximately 260 millimicrons, is not present in sea level sunlight because it is absorbed in the upper atmosphere. However, it is emitted by germicidal lamps; ACRYLITE® parts should be shielded from their direct radiation which can cause degradation.

Visible Light

The visible light band ranges from 400 millimicrons, the wave length of dark violet, to 700 millimicrons which is the upper limit of red perception. Within this band the colors occur in the sequence seen in a rainbow, ranging from violet through blue, green, yellow, and orange to red. **Each wave length causes a particular sensation of color.** When light is emitted or reflected as a balanced blend of all wave lengths, the eye sees the light as white.

As can be seen from the curve showing the distribution of solar energy throughout the entire range from 200 to 2200 millimicrons, solar radiation happens to be most intense in the range from 400 to 700 millimicrons, where the human eye can sense radiation. (See Graph 1.)

However, the eye is not equally sensitive to the light emitted at all wave lengths. Graph 1 also shows a curve which illustrates that the human eye is most sensitive to light in the yellow and green parts of the spectrum.

Clear ACRYLITE® transmits visible light uniformly throughout the entire visible spectrum and therefore appears colorless. Transmission characteristics can be modified by dyes and pigments to create an infinite variety of colored sheets. Other materials can be added to scatter and absorb light; this will produce a range of diffusion for various densities of white and colored translucent sheets.

Clear ACRYLITE® is available in four grades: GP (General Purpose), MS-2 (Military Grade), OP-1, and OP-2.

General Purpose ACRYLITE® and MS-2 are classified as ultra-violet absorbing sheets according to the definition of the ASTM Standard D-702. The transmission characteristics are the same for both grades.

The transmission curves shown in Graph 2 are based on 1/8" thick sheets. In the range from 345 to 395 millimicrons the transmittance of ACRYLITE GP will be lower for thicker sheets. **Between 395 and 1000 millimicrons all thicknesses transmit 92% as shown.**

Outdoor exposure will change the transmittance characteristics very little. After several years of exposure, there may be a slight reduction of transmission below 400 millimicrons.

The special grades, OP-1 and OP-2, are modified by the elimination or addition of certain ingredients which will change the transmission characteristics at specific wave lengths. (See Graph 2.)

ACRYLITE® OP-1 (Ultra-violet transmitting) transmits radiation in the range from 250 to 370 millimicrons at percentages that vary from 0 to 92%. In this range GP ACRYLITE® absorbs almost all radiation. Beyond 390 millimicrons, the transmission characteristics of OP-1 are essentially the same as those of GP ACRYLITE®.

ACRYLITE® OP-2, the ultra-violet filtering grade, is used in museums to protect old documents and paintings from the harmful effects of ultra-violet rays.

Artificial Light

Ultra-violet, visible and infra-red light can be produced by artificial sources. Fluorescent lamps, mercury vapor lamps, germicidal lamps and welding arcs produce a significant amount of ultra-violet radiation in combination with visible light.

Artificial light sources produce radiation with characteristics that vary from source to source. In the case of the incandescent lamp, the light produced is the result of the radiation from the hot filament; the typical emission curve shows that the output increases from a low level at 400 millimicrons to a high level at 700 millimicrons, and then rises steeply into the infra-red range. **As a result, heat as well as light is emitted; also, colors appear warmer or redder than in daylight.**

In the case of fluorescent tubes, the light emitted can be controlled by the nature of the phosphor coating inside the tube. Fluorescent lamps are available in a number of different types; the manufacturers publish the spectrophotometric distribution curves of each type.

Infra-red Radiation

Infra-red radiation is the long wavelength radiation **beyond the sensitivity of the eye**, ranging from 700 to 1,000,000 millimicrons. The source

of this radiation may be the sun, infra-red heating elements, or any hot object. Each type of radiation is characterized by its specific range of wave lengths.

We are primarily interested in the near-infrared range from 700 to approx. 10,000 millimicrons.

Incandescent lamps and infra-red heat lamps emit radiation in both the visible and the infra-red spectra. A major portion of their energy, especially in the case of infra-red heat lamps, is radiated at wave lengths above 700 millimicrons. As the temperature of the source of energy decreases, radiation is emitted at longer wave-lengths.

It should also be noted that all solar radiation as well as artificially created radiant energy will be converted into heat, when absorbed by any material.

In the penetrating infra-red band, from 700 to 1400 millimicrons, clear 1/8" thick ACRYLITE® transmits approximately 90% of infra-red radiation (See Graph 3.) The rate of transmission decreases somewhat with increasing thickness. In the range from 1400 to 2200 millimicrons, ACRYLITE® transmits radiation at a gradually decreasing rate; 2200 millimicrons the transmission is almost zero.

GRAPH 3 TRANSMITTANCE CHARACTERISTICS OF CLEAR ACRYLITE

Light Transmittance of Clear ACRYLITE

The light transmittance depends on the reflectance at both surfaces and the absorption of light in the material. Because of the clarity of ACRYLITE, less than 0.5% of visible light is absorbed per inch of thickness.

Some light, however, is reflected at both polished surfaces. A beam of light striking a sheet of ACRYLITE perpendicular to the surface (at 0° angle of incidence) will lose approximately 4% at both surfaces due to reflection. Therefore, the overall light transmission will be approximately 92%.

If rays strike a sheet at angles of incidence greater than 30° from the vertical, the surface reflectance will be greater than 4%; therefore the light transmission will be smaller.

Consequently, when light falls on ACRYLITE from all angles, as from a sky of uniform brightness, the transmission factor will be approximately 85%.

GREENHOUSE GLAZING

The transmittance characteristics of clear ACRYLITE are equal or superior to those of ordinary window glass. Clear ACRYLITE can be used for glazing of greenhouses since plants will grow as well under ACRYLITE as they would under glass.

LIGHT PIPING

The very low light absorption of ACRYLITE is utilized in light piping applications, such as engraved signs, inspection lights, instrument dials, etc.

To prevent excessive light loss at curves, the radius of curvature should not be less than three times the thickness of the sheet.

It is important that the surfaces be highly polished and free from scratches to insure total internal reflection and to prevent scattering of the light.

The amount of light that will enter the sheet from the edge will depend on the thickness of the sheet and on the transparency of the edge.

Therefore, the edge through which the light enters should be highly polished. It is recommended that all other edges be polished also and painted white to assure maximum internal reflection.

Because the intensity of the transmitted light decreases with the square of the distance from the source, large sheets should be lighted either from two or all four edges.

Light Transmission of White Translucent ACRYLITE

White translucent ACRYLITE is available in a variety of densities to meet such requirements as light transmission, diffusion, lamp-hiding power and surface brightness.

The ability of a plastic sheet to diffuse light depends on the kind of colorant used in its formulation. For lighting applications, a formulation which offers maximum diffusion combined with high light transmission is most desirable.

The light transmission of each white ACRYLITE color will vary with the type and the concentration of the pigment used. **In addition, the light transmission of every white color will decrease with an increase in thickness.** This is due to the fact that the pigment concentration of the mix is not changed for different thicknesses. Although the pigment concentration remains constant, **the amount of pigment in the sheet will increase with the thickness;** a 1/4" thick sheet contains twice as much pigment as a 1/8" thick sheet and therefore transmits less light. (See Table A.)

Because both the light transmission and the light reflectance vary with the thickness, a 1/8" thick sample of any white color should never be used for selecting other thicknesses of the same color.

For accurate light transmission values refer to Table A shown below. Graph 4 on page 6 offers a visual presentation of the percentage figures shown in Table A.

TABLE A			
Light Transmission of White Translucent ACRYLITE®			
Color No.	Thickness		
	.125	.187	.250
051-6	67%	54%	44%
052-6	60	46	36
053-5	56	44	35
020-4	51	41	32
054-3	41	32	25
049-3	40	40	40
015-2	30	22	16
048-2	21	15	11

Above values are based on ASTM Test D-791-61T, using CIE Illuminant C

† The transmission of 049-3 is the same for all thicknesses.

Acrylite[®] SDP[™]

Acrylic Double Skinned Sheet

ACRYLITE SDP acrylic sheet is a double layer, light transmitting glazing material of outstanding heat insulation ability. It offers high stiffness, excellent resistance to impact stress, and exceptional weatherability. The product was designed for use in large area glazing, skylights, greenhouses, swimming pool enclosures and industrial applications.

TYPICAL PROPERTIES

Sheet thickness	0.630 in. ± 0.040 in. (16.0 mm ± 1.0 mm)				
Width of Sheet	47.250 in. ± 0.160 in. (1200 mm ± 4 mm)				
Lengths	8, 10, and 12 feet (2.4, 3.0, 3.6 m) other lengths available on request				
Skin thickness	approx.				0.060 in. (1.5 mm)
Rib thickness	approx.				0.040 in. (1.0 mm)
Distance between ribs	approx.				0.630 in. (16.0 mm)
Weight per unit area	approx.				1 lb./sq. ft. (48 N/m²)
Permissible purlin distances (with purlins perpendicular to the ribs)					
For area loads of:	10	20	40	60	lb./sq. ft.
Roof glazing	60	43	30	25	inches
Vertical glazing	85	60	43	35	inches
<div><div>(</div><div><div>479</div><div>958</div><div>1915</div><div>2873</div><div>Pa</div></div><div>)</div></div>					
Permissible area load, vertical glazing					
(for standard sheet widths, long sides secured)					
					14.0 lbs./sq. ft. (667.0 Pa)

TYPICAL PROPERTIES (CONTINUED)

Maximum bending moment relative to unit length					
Support perpendicular to ribs	290 ft. lbs./ft. (1300 Nm/m)				
Support parallel to ribs (supports spaced 45 in.)	120 ft. lbs./ft. (550 Nm/m)				
Permissible bending moment relative to unit length					
Support perpendicular to ribs-roof glazing	31 ft. lbs./ft. (140 Nm/m)				
vertical glazing	62 ft. lbs./ft. (280 Nm/m)				
Support parallel to ribs roof glazing	13 ft. lbs./ft. (60 Nm/m)				
vertical glazing	26 ft. lbs./ft. (120 Nm/m)				
Heat transfer coefficient ¹ (U) summer conditions					
					0.55 BTU/hr./sq. ft./°F. (3.2 W/m ² °C.)
winter conditions					
					0.58 BTU/hr./sq. ft./°F. (3.3 W/m ² °C.)
Coefficient of linear thermal expansion					
					4.0 x 10 ⁻⁵ /°F. (70 x 10 ⁻⁶ /°C.)
Maximum service temperature without load					
					160°F. (71°C.)
	Clear	White (#06531)	White (#06310)	Bronze (#43480)	Bronze (#93201)
Light Transmittance	83%	20%	70%	52%	24%
Solar Transmission	83%	19%	67%	57%	31%
Shading Coefficient	0.97	0.31	0.81	0.72	0.46
Average sound reduction					
					23 dB

¹ASHRAE

PHYSICAL APPEARANCE

ACRYLITE SDP is supplied as double skinned clear sheets. In addition to colorless and solar bronze, two translucent whites are available. Solid and translucent colors are available on special order. For shipment and storage, the interior channels of the sheet are kept clean by temporary seals.

ASSEMBLY

Special connecting and securing techniques are required for SDP sheet. Before placing an order, the particular project should be discussed with our technical service department. A detailed pamphlet on laying and fitting the sheet is available on request.

FIRE PRECAUTIONS

ACRYLITE SDP sheet is produced from an acrylic molding compound which is a combustible thermoplastic. Precautions used to protect wood and other combustibles from flames and high heat sources should also be observed with this material. Acrylic materials usually burn rapidly to completion if not extinguished. The products of combustion, if sufficient air is present, are carbon dioxide and water. However, in many fires sufficient air will not be available and toxic carbon monoxide will be formed, as it will from other common combustible materials. We urge good judgment in the use of this versatile material and recommend that building codes be followed carefully to assure it has been used properly. Access panels may be required for evacuation and venting of rooms glazed with SDP. SDP burns more rapidly than solid acrylic sheet. Noncombustible end caps must be used to prevent flame from contacting the open ends of SDP acrylic sheet.

CROSS-SECTION OF ACRYLITE SDP ACRYLIC SHEET

ACRYLITE SDP — more *News in Transparent Plastics.*

For more information on ACRYLITE SDP acrylic double skinned sheet contact your nearest CY/RO sales office or CY/RO Industries, Wayne, N.J. 07470, (201) 839-4800.

SALES OFFICES

ATLANTA, GEORGIA 30341
5180 Peachtree Industrial Blvd.
(404) 457-6322

CHICAGO, ILLINOIS 60666
P.O. Box 66189
(312) 296-4080

DALLAS, TEXAS 75247
7611 Carpenter Freeway
(214) 634-7560

LOS ANGELES, CALIFORNIA 90040
2300 South Eastern Avenue
(213) 724-9303

NEW YORK, NEW YORK 10020
630 Fifth Avenue
(212) 489-5513

IMPORTANT NOTICE

The information and statements herein are believed to be reliable but are not to be construed as a warranty or representation for which we assume legal responsibility. Users should undertake sufficient verification and testing to determine the suitability for their own particular purpose of any information or products referred to herein. **NO WARRANTY OF FITNESS FOR A PARTICULAR PURPOSE IS MADE.**

Nothing herein is to be taken as permission, inducement or recommendation to practice any patented invention without a license.

CY/RO INDUSTRIES, WAYNE, NEW JERSEY 07470 • A Partnership of Cyanamid Plastics, Inc. and Rohacryl, Inc.

Technical Data

SDP™ Polycarbonate Double Skinned Sheet

SDP polycarbonate sheet is a double layer, light transmitting glazing material of outstanding heat insulation ability. It offers high stiffness, extraordinary resistance to impact stress, and a high maximum service temperature. The product was designed for use in commercial, public and industrial buildings, gymnasiums and enclosed swimming pools.

TYPICAL PROPERTIES

Sheet thickness	0.630" $\pm$ 0.040" (16.0 mm $\pm$ 1.0 mm)			
Width of Sheet	47.250" $\pm$ 0.160" (1200 mm $\pm$ 4 mm)			
Lengths	8, 10, and 12 ft. longer lengths available on request			
Skin thickness	approx. 0.040" (1.0 mm)			
Rib thickness	approx. 0.035" (0.9 mm)			
Distance between ribs	approx. 0.630" (16.0 mm)			
Weight per unit area	approx. 0.92 lb./sq. ft.			
Permissible purlin distances (with purlins perpendicular to the ribs)				
For area loads of:	10	20	40	60 lb./sq. ft.
Roof glazing	54	36	24	18 inches
Vertical glazing	78	54	36	30 inches
Permissible area load, vertical glazing (for standard sheet widths, long sides secured)	6.8 lbs./sq. ft.			
Flexural stiffness relative to unit length				
Support				
perpendicular to ribs	260 ft. lb./ft.			
parallel to ribs (supports spaced 45")	160 ft. lb./ft.			

TYPICAL PROPERTIES (CONTINUED)

Permissible bending moment relative to unit length	
Support	
perpendicular to ribs	
roof glazing	19 ft. lb./ft.
vertical glazing	38 ft. lb./ft.
parallel to ribs (supports spaced 45")	
roof glazing	7 ft. lb./ft.
vertical glazing	14 ft. lb./ft.
Heat transfer coefficient ¹ (U)	
Summer conditions	0.55 BTU/hour/sq. ft./°F
Winter conditions	0.58 BTU/hour/sq. ft./°F
Coefficient of linear thermal expansion	$4.0 \times 10^{-5}/^{\circ}\text{F}$
Maximum service temperature without load	240°F (116°C)
Light transmittance (clear)	Approx. 73%
Average sound reduction	24 dB

¹ASHARE

PHYSICAL APPEARANCE

Polycarbonate SDP is supplied in clear sheets with smooth surfaces. Solid and translucent colors are available on special order. For shipment and storage, the interior channels of the sheet are kept clean by temporary seals.

ASSEMBLY

Special connecting and securing techniques are required for SDP sheet. Before placing an order, the particular project should be discussed with our technical service department. A detailed pamphlet on laying and fitting the sheet is available on request.

FIRE PRECAUTIONS

Polycarbonate SDP sheet is produced from a polycarbonate molding compound which is a combustible thermoplastic. Precautions used to protect wood and other combustibles from flames and high heat sources should also be observed with this material. Polycarbonate SDP sheet will burn when involved in fire but normally extinguishes itself when the flame or fire is removed. The products of combustion, if sufficient air is present, are carbon dioxide and water. However, in many fires sufficient air will not be available and toxic carbon monoxide will be formed, as it will from other common combustible materials. We urge good judgment in the use of this versatile material and recommend that building codes be followed carefully to assure it has been used properly. Access panels may be required for evacuation and venting of rooms glazed with SDP. SDP burns more rapidly than solid polycarbonate sheet. Noncombustible end caps must be used to prevent flame from contacting the open ends of SDP polycarbonate sheet.

For more information on SDP polycarbonate double skinned sheet contact CY/RO Industries,
Wayne, N.J. 07470, (201) 839-4800.

SDP—more News in Transparent Plastics.

CY/RO INDUSTRIES, WAYNE, NEW JERSEY 07470 • A Partnership of Cyanamid Plastics, Inc. and Rohacryl, Inc.

1. PRODUCT NAME

Insulating plastic glazing material

- Acrylite® SDP™ double skinned acrylic sheet
- Polycarbonate SDP™ double skinned sheet

2. MANUFACTURER

CY/RO INDUSTRIES
859 BERDAN AVENUE
WAYNE, NEW JERSEY 07470
PHONE: (201) 839-4800

3. PRODUCT DESCRIPTION

Basic Use: As primary glazing materials for curtainwalls, skylights, covered walkways, solariums, atriums and greenhouses. The panels provide good insulation and light transmission values in a load bearing material. Clear and transparent colors are available. Fabricates easily. Good weatherability. Joining systems are available.

Limitations: SDP panels are load-bearing, but non-structural. Optics are limited by the internal ribs which separate the external skins. Moisture accumulation may occur within the ribs, and a simple weep system should be employed.

Types:

Acrylite SDP Is an acrylic double skinned sheet, with smooth surfaces, and is available in clear, white and solar-bronze tints for standard glazing applications.

Polycarbonate SDP Is a polycarbonate double skinned sheet for applications where resistance to high impact or high service temperatures is needed. It is available with smooth surfaces in clear, white and solar-bronze tints.

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Standard Sizes:

	Acrylite SDP Sheet	Polycarbonate SDP Sheet
Thickness	0.630 in. $\pm$ 0.040 in. (16.0 mm $\pm$ 1.0 mm)	
Width	47.250 in. $\pm$ 0.160 in. (1200 mm $\pm$ 4 mm)	
Lengths	8 ft., 10 ft. and 12 ft. (2.4, 3.0, 3.6 m) (longer lengths are available)	
Skin Thickness	approx. 0.060 in. (1.50 mm)	approx. 0.040 in. (1.0 mm)
Rib Thickness	approx. 0.040 in. (1.0 mm)	approx. 0.035 in. (0.9 mm)

Composition & Materials:

Acrylite SDP sheet An extruded double skinned acrylic sheet in Clear, White or Solar-Bronze.

Polycarbonate SDP sheet An extruded double skinned polycarbonate sheet in Clear, White or Solar-Bronze.

4. TECHNICAL DATA

Permissible purlin distances (with purlins perpendicular to the ribs)

	Acrylite SDP Sheet				
For loads of:	10	20	40	60	lb./sq.ft. (Pa)
Roof Glazing	60 (1.50)	43 (1.10)	30 (0.80)	25 (0.60)	in. (m)
Vertical Glazing	85 (2.20)	60 (1.50)	43 (1.10)	35 (0.90)	in. (m)

	Polycarbonate SDP Sheet				
For loads of:	10	20	40	60	lb./sq.ft. (Pa)
Roof Glazing	72 (1.80)	51 (1.30)	36 (0.90)	29 (0.75)	in. (m)
Vertical Glazing	94 (2.40)	66 (1.70)	47 (1.20)	38 (1.00)	in. (m)

Permissible area load, vertical glazing (for standard sheet widths, long sides secured)

	Acrylite SDP Sheet	Polycarbonate SDP Sheet
	14.0 lbs./sq.ft. (667.0 Pa)	15.0 lbs./sq.ft. (690.0 Pa)

Permissible* bending moment relative to length—

Support perpendicular to ribs

Roof Glazing	31 ft.lb./ft. (140 Nm/m)	45 ft.lb./ft. (200 Nm/m)
Vertical Glazing	62 ft.lb./ft. (280 Nm/m)	76 ft.lb./ft. (340 Nm/m)

Support parallel to ribs (spaced at 45 in.)

Roof Glazing	13 ft.lb./ft. (60 Nm/m)	17 ft.lb./ft. (75 Nm/m)
Vertical Glazing	26 ft.lb./ft. (120 Nm/m)	28 ft.lb./ft. (125 Nm/m)

*Maximum bending moment for Acrylite SDP acrylic sheet is greater than figures shown.

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	Acrylite SDP Sheet	Polycarbonate SDP Sheet
Heat transfer coefficient ¹ (U) Summer Conditions	0.55 BTU/hour/sq.ft./°F. (3.2 W/m ² °C.)	
Winter Conditions	0.58 BTU/hour/sq.ft./°F. (3.3 W/m ² °C.)	
Coefficient of linear thermal expansion (in./in./°F.)	4.0 x 10 ⁻⁵ /°F. (65 x 10 ⁻⁷ /°C.)	
Maximum service temperature without load	160°F. (71°C.)	240°F. (116°C.)
Light transmittance (Approx.)		
Clear	83%	73%
White	20% (#06531)	9% (#99045)
White	70% (#06310)	—
Solar-Bronze	52% (#43480)	21% (#LS 13-170)
Solar-Bronze	24% (#93201)	—
Shading Coefficient		
Clear	0.97	0.88
White	0.31	0.25
White	0.81	—
Bronze	0.72	0.44
Bronze	0.46	—
Solar Transmission		
Clear	83%	74%
White	19%	14%
White	67%	—
Bronze	57%	29%
Bronze	31%	—
Average sound reduction	23 dB	24 dB
Flammability	Acrylite SDP and polycarbonate SDP sheets are combustible thermoplastics. Precautions used to protect wood and other combustibles should be observed. Access panels may be required for evacuation and venting of rooms glazed with these products. Further flammability data is available from a CY/RO representative.	

¹ASHRAE

5. INSTALLATION

Special connecting and securing techniques are required for Acrylite SDP and polycarbonate SDP sheets. Before placing an order, the particular project should be discussed with the CY/RO Technical Service Department. Examples of typical installation techniques are included in this SPEC-DATA Sheet. Detailed instructions for laying and fitting the sheet are available on request.

Building Codes: Acrylite SDP double skinned acrylic sheet and SDP double skinned polycarbonate sheet

were recently introduced by CY/RO Industries and are subject to the restrictions of local building codes. Since safety regulations vary in different localities, it is always advisable to check local building codes. Special applications for Acrylite SDP and polycarbonate SDP sheets that do not comply with a local building code can be evaluated by CY/RO Industries. If the application proves to be a proper and safe use of the materials, CY/RO will offer assistance in presenting data to help secure acceptance by local boards.

6. AVAILABILITY AND COST

Availability: Acrylite SDP and polycarbonate SDP double skinned sheets as well as PVC and Aluminum joining systems are marketed throughout the United States by CY/RO Industries. In Canada, contact Chemacryl Plastics Limited, Toronto.

Cost: Costs vary due to size and specific application requirements. Quotations for individual projects can be obtained from 9 sales offices throughout the United States and Canada.

7. GUARANTEE

Acrylite SDP double skinned acrylic sheet and SDP double skinned polycarbonate sheet are manufactured in accordance with the specifications set forth under "Technical Data". CY/RO Industries accepts no responsibility for defects or damage as a result of misuse, improper installation or other factors beyond its control.

8. MAINTENANCE

Acrylite SDP and polycarbonate SDP double skinned sheets are maintenance free, except for nominal washing, under normal use conditions. Clean with mild soap and water.

9. TECHNICAL SERVICE

Complete technical services are available through the manufacturer and trained personnel. Contact:

CY/RO INDUSTRIES
859 BERDAN AVENUE
WAYNE, NEW JERSEY 07470
(201) 839-4800
or a local CY/RO Sales Office.

10. FILING SYSTEMS

SPEC-DATA® II
Sweet's File
CY/RO Bltn's. MD 1, MD 2 and MD 3

DETAILS OF GLAZING SYSTEM FOR ACRYLITE® SDP AND POLYCARBONATE SDP DOUBLE SKINNED SHEET

VERTICAL GLAZING

SKYLIGHT GLAZING

SKYLIGHT GLAZING

ALTERNATE GLAZING METHODS

Wood

Steel / Aluminum

COMPOSITE BUILDING PANELS

7 p

CY/RO INDUSTRIES
August, 1977

CYRO
INDUSTRIES

CYRO Technical Data

Aluminum Glazing System for Continuous Glazing and Skylighting with Acrylite SDP™ Sheet

TECHNICAL DATA

GLAZING BAR	
Material	Aluminum
Weight: box-section element clamping bar	0.786 lb/ft 0.500 lb/ft
Alloy and temper	alloy 6063-T5
Tensile strength	22 000 psi
Both members joined together:	
Moment of inertia	$I_x = 0.24 \text{ in}^4$
Section modulus	$S_x = 0.384 \text{ in}^3$
e_{x1}	1.063"
e_{x2}	0.906"
Standard length	25'0", other lengths on request
Surface: mill finish, not anodized	
Seals	
Material	EPDM
Surface	siliconized
System	
max. glazing height	78" - 96"
Mullion spacing with full-width SDP sheets	48"

SUPPLY

Packed cartons of standard lengths with the required seals, connection angles and screws. Other lengths and accessories can be supplied by special agreement.

ASSEMBLY

The same box-section glazing bars are used for frames and mullions. They are butt-joined by means of a special connecting angle, which is shown in Fig. 2. For fixing the frame to the embrasure we recommend the use of Fischer plugs S 10 FH or the like. After attaching the exterior weather seal, Fig. 1, detail 'I', SDP sheet is inserted and secured with the clamping bar. Finally, the interior wedge-shaped seal, see Fig. 1, detail 'II', is pressed into its groove.

Fig. 2

Fig. 1

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CYRO Technical Data

PVC and Aluminum Glazing System Clamping and Glazing Bar for Acrylite SDP™ Sheet

TECHNICAL DATA

Glazing bar	
Material	Aluminum
Weight	0.496 lb. ft.
Alloy and temper	6063-T5
Tensile strength	22,000 psi
Surface: mill finish, not anodized	
Standard length	25'0", other lengths on request
System	
Mullion spacing with full-width SDP sheet	48"

SUPPLY

Supplied in standard lengths of clamping and glazing bars. Other lengths, and the connecting angles and screws, can be supplied by special agreement.

APPLICATION

The PVC and aluminum system can be used for greenhouse glazing and small area glazing (such as veranda roofs, sides and sun decks). It can be attached to most superstructures with connecting angles and fasteners.

The PVC and aluminum system can be used in conjunction with all aluminum systems as shown in Fig. 2. A connecting angle is fastened with stainless steel self-tapping screws. Any condensation which may form on the underside of SDP sheet is channelled to the exterior at the eave or sill.

Fig. 2

Fig. 1

CYRO

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APPENDIX C

DSET REPORT ON "SOLAR COLLECTOR PERFORMANCE TESTS"
FOR THE THIN-WALL EXTRUDED-ACRYLIC COLLECTOR

Report No. 7850809

DSET No. 19498S

SOLAR COLLECTOR PERFORMANCE TESTS

For:

Mr. D. K. Landstrom
Energy & Thermal Technology Section
BATTELLE COLUMBUS LABORATORIES
505 King Avenue
Columbus, Ohio 43201

From:

DSET Laboratories, Inc.
Box 1850 Black Canyon Stage
Phoenix, Arizona 85029

This report includes the statement on page 1.

By:

Approved by:

William J. Putman
Research Engineer

William T. Dokos
Manager, Solar Operations

September 19, 1978

R. Thomas Hamilton
Assistant Test Engineer

This test report contains only findings and results arrived at after employing the specific test procedures and standards listed. It does not constitute a recommendation for, or endorsement of, or certification of the product or material tested. Desert Sunshine Exposure Tests, Inc. makes no warranty, expressed or implied, except that the analysis has been made, and a report prepared, based upon the sample or samples furnished by the client. Any extrapolation of data from the sample or samples relating to the batch or lot from which it was obtained may not correlate and should be interpreted accordingly with extreme caution. We assume no responsibility for variations in quality, composition, appearance, performance, or other feature of similar subject matter produced by persons or under conditions over which we have no control.

BATTELLE COLUMBUS LABORATORIES

Introduction

This report presents the data and results of a thermal performance test conducted on a Battelle Columbus Laboratories solar collector system. The system consisted of and included:

- (1) Solar Collector #1, constructed from extruded, double-skinned, transparent acrylic sheet with 72 small vertical passages through which a "black fluid" was pumped. The "black fluid" performed the dual role of both absorber of incident solar radiation and of the heat-transfer medium.
- (2) A centrifugal all-plastic pump and motor with plastic diaphragm valves for flow.
- (3) A counterflow heat exchanger.

Measurements were actually made on the counterflow heat exchanger through which water from the DSET test facility was circulated in one direction while the "black fluid" from the Battelle system circulated in the other, rather than on the collector itself.

The test was performed consistent with the ASHRAE 93-77 thermal performance test procedure; however, it should be noted that due to the configuration of the collector system, the thermal performance results are indicative of the entire system and as such are not a direct measure of the collector's performance. Consequently, the results presented herein do not, by definition, reflect the thermal performance of the collector itself, but of the entire collecting device (collector, heat exchanger, pumps, etc.).

For the purposes of the this report, however, the data and results will be presented consistent with the ASHRAE 93-77 method of test. It should also be noted that due to the fluid and materials used in the collector, the client requested that the preconditioning not be performed. This, therefore, is a variance from ASHRAE 93-77.

Figure 1 Black Fluid Collector System

Description of Test Set-Up

The entire Battelle system was mounted on an Exactly Normal Incidence (ENI) solar tracking mount as shown schematically in Figure 1. Inlet and outlet temperatures for efficiency determinations were measured with platinum resistance thermometers at the heat exchanger on water circulated through the DSET test facility. Inlet and outlet temperatures (not used in the efficiency determinations) measured at the collector on the "black fluid" were determined with Type "T" thermocouples. Responsibility for constant flow of "black fluid" through the Battelle system was left to Battelle personnel. Flow measurements of "black fluid" were determined volumetrically by such personnel at a break in the "black fluid" loop between the heat exchanger and pump where the black fluid was allowed to flow into a reservoir before continuing through the loop (not shown in Figure 1).

Description of Test Method

The ASHRAE 93-77 thermal performance test procedures consist of four separate parts: (1) Preconditioning (omitted in this test), (2) Determination of the system's time constant, (3) Instantaneous efficiency performance tests, and (4) Determination of the incident angle modifier for the system.

Time Constant

The time constant is an indication of the transient response of the collector to a step change in insolation and is utilized to determine the proper data intervals for the instantaneous efficiency tests.

The test to determine the "Time Constant" is performed in accordance with ASHRAE 93-77 (Section 8.3.1, Method (1)). ASHRAE 93-77 defines the time constant as the time required for the outlet fluid temperature to attain 63.2 percent of its steady state value after the collector has been shaded with a cover to provide a step change in insolation.

Instantaneous Efficiency Test

The instantaneous efficiency tests are conducted to determine the efficiency of the system as a function of the incident solar radiation, ambient temperature, and heat exchanger inlet temperature.

ASHRAE 93-77 defines the solar collector efficiency as the amount of useful energy extracted from the collector divided by the amount of incident solar energy intercepted by the gross area of the collector.

At least sixteen (16) efficiency "data points" are obtained during the test in order that a governing "efficiency curve" can be generated.

All instantaneous efficiency testing is conducted in accordance with ASHRAE 93-77 and DSET Specification 75-SE2, appended herewith, utilizing a sun-tracking altazimuth mount which maintains the collector at normal incidence during the test periods, except in this case as previously stated measurements were made of the entire system.

Analysis of the efficiency data is performed by employing a 1st order least squares fit resulting in an efficiency equation given as a function of the inlet parameter, $(T_i - T_a / T_i)$.

Procedures and instrumentation employed for this test are described in DSET Specification 75-SE2 with the following exception: standard pressure gauges were used for pressure measurements. The pressure gauges used were not considered highly accurate; therefore, caution is advised in forming any conclusions based upon these measurements.

Incident Angle Modifier

In order to predict the system efficiency at incident angles other than zero, the incident angle modifier, K_{at} , is determined for the system. The incident angle modifier is a factor used to modify the performance curve (determined at normal incidence) to account for the changes in performance due to the sun's incident angle.

The test is conducted by adjusting the altazimuth mount such that incident angles of the collector are 30°, 45°, and 60°. Data are taken in each of the incident angle positions and the efficiency calculated (ASHRAE 93-77, Sec. 8.3.3, Method (1)). For an incident angle of 0°, data from the instantaneous efficiency test are used.

The data from the incident angle modifier test are analyzed to determine the equation that describes K_{at} as a function of $\frac{1}{\cos\theta} - 1$, where θ is the incident angle of the sun.

ASHRAE 93-77

Data and Results

Time Constant

The following data resulted in a time constant value of 13.1 minutes.

TIME CONSTANT

DATE: August 9, 1978

WIND: SW 600 fpm

<u>Solar Time</u>	<u>°F</u>		$\frac{T_o - T_i}{T_{o,int} - T_i}$
	<u>T_i</u>	<u>T_o</u>	
14:03:30	105.80	115.32	1.000
- - - - - Collector Covered - - - - -			
14:04:00	105.78	115.18	0.985
14:04:30	105.75	114.78	0.944
14:05:00	105.78	114.29	0.892
14:05:30	105.80	113.86	0.847
14:06:00	105.82	113.41	0.799
14:06:30	105.78	112.97	0.754
14:07:00	105.79	112.54	0.708
14:07:30	105.79	112.17	0.669
14:08:00	105.80	111.79	0.629
14:08:30	105.79	111.44	0.593
14:09:00	105.78	111.09	0.557
14:09:30	105.76	110.77	0.524
14:10:00	105.74	110.41	0.487
14:10:30	105.76	110.16	0.460
14:11:00	105.81	109.88	0.428
14:11:30	105.85	110.80	0.523
14:12:00	105.84	111.70	0.618
14:12:30	105.80	111.24	0.571
14:13:00	105.81	110.96	0.542
14:13:30	105.81	110.72	0.516
14:14:00	105.80	110.37	0.480
14:14:30	105.83	110.10	0.450
14:15:00	105.86	109.85	0.422
14:15:30	105.92	109.77	0.410
14:16:00	105.95	109.61	0.391
14:16:30	106.02	109.46	0.370
14:17:00	105.98	109.28	0.353
14:17:30	105.93	109.14	0.342

Instantaneous Efficiency Performance Test

The instantaneous efficiency test with the collector at normal incidence was conducted at a constant flow rate through the heat exchanger while the inlet temperature was varied for each set of efficiency points.

The data obtained and relevant calculated values are given in the attached tables. Following the tables is a graph of the instantaneous efficiency as a function of the inlet parameter, $(T_i - T_a / I_t)$.

Also included in the data section are inlet and outlet temperatures (Table 2) measured directly on the "black fluid" at the collector using Type "T" thermocouples. Time intervals were the same as the previous efficiency data.

Analysis of the efficiency data was performed employing a first order least squares fit which resulted in the following efficiency equation which is shown as the analysis curve on the graph.

$$\eta = 0.551 - 2.236 \left[\frac{T_i - T_a}{I_t} \right]$$

At an inlet parameter of zero the equation yields a value of 0.551 for the effective transmittance-absorptance product, $F_R \alpha_T$, where F_R is the heat removal factor.

Differentiation of the equation with respect to the inlet parameter results in the constant value of -2.236 for the overall heat losses, $F_R U_L$, from the collector.

Incident Angle Modifier

The incident angle modifier data are presented in the table following the instantaneous efficiency graph.

The incident angle efficiency data including normal incidence data obtained from the instantaneous efficiency test were extrapolated to a zero inlet parameter condition assuming the same slope as the normal incidence efficiency curve. These values and the corresponding values of $K_{\alpha T}$ are given below:

Incident Angle:	<u>0°</u>	<u>0°</u>	<u>30°</u>	<u>30°</u>	<u>45°</u>	<u>45°</u>	<u>60°</u>	<u>60°</u>
$K_{\alpha T} F_R \alpha_T$:	0.554	0.549	0.643	0.633	0.646	0.661	0.588	0.589
$K_{\alpha T}$:	1.010	1.000	1.171	1.153	1.177	1.204	1.071	1.073

The values of $K_{\alpha\tau}$ as a function of $\frac{1}{\cos\theta} - 1$ are shown in the graph following the table. As you will note, the data cannot be represented by the linear expression $K_{\alpha\tau} = 1 + b_0 (\frac{1}{\cos\theta} - 1)$, but ASHRAE 93-77 also allows mathematical correlation other than the previous equation and, in this case a more suitable equation is developed by a 2nd order least squares polynomial which follows:

$$K_{\alpha\tau} = 1.026 + 0.736 \left[\frac{1}{\cos\theta} - 1 \right] - 0.692 \left[\frac{1}{\cos\theta} - 1 \right]^2$$

Discussion of Results

Time Constant

In the calculation of the time constant for this collector, it should be noted that the ratio, $\frac{T_o - T_i}{T_{o,int} - T_i}$, increases from 14:11:30 to 14:12:00 and then decreases normally once again. This deviation could have been caused by variations in the flow rate of the "black liquid" through the collector. If the flow rate decreased during the time constant test, it could have increased the ΔT and thereby produce the observed increase in $\frac{T_o - T_i}{T_{o,int} - T_i}$.

Instantaneous Efficiency

A linear fit is used to describe the instantaneous efficiency data because the collector was operated at low temperatures ($T_{i,max} < 150^\circ\text{F}$) where the dominant heat loss factor is due to convection and, for the most part, convective losses are linear functions of the temperature differential between the absorber and ambient.

Collectors of this type, in which the heat transfer medium is in direct contact with the collector cover, generally exhibit a sensitivity to wind. This may have caused the deviations from the analysis line shown on the instantaneous efficiency graph.

A wide scatter of data points at the low inlet parameter was noted and carefully examined. It was found that all test variables under DSET control, i.e., insolation, mass flow, inlet temperature, etc., remained reasonably constant during data acquisition and stabilization portions of the test.

This then lends suspect to instabilities within the Battelle system as the culprit for the widespread data points. Wind variability is more likely*

Incident Angle Modifier

The incident angle modifier graph shows an increase in efficiency at off-angles up to 49° after which it decreases. A probable cause for this may be due to collector geometry in that at normal incidence any incoming solar radiation striking the collector ribs will see the aluminum foil backing and be reflected away from the collector. However, at off angles, the incoming radiation striking the top of the ribs no longer sees the reflective foil but sees

*Note added by BCL

the "black fluid" thereby increasing its optical efficiency. This effect, along with the standard cosine losses associated with a clear plastic cover, are thought to be responsible for the nature of the $K_{\alpha T}$ curve.

SOLAR COLLECTOR TEST

TABLE 1. INSTANTANEOUS EFFICIENCY

COMPANY: BATELLE SOLS LABS
 REFERENCE NO.: R2116
 DSET NO.: 19498S
 REPORT NO.: 7880809
 TEST DATE: 08/09/78
 INLET/OUTLET SEPARATION: 73.13 IN.

COLLECTOR MODEL NO.: 1
 COLLECTOR SERIAL NO.: BATELLE
 COVER TYPE: N/A
 APERTURE AREA: 22.85 SQ. FT.
 GROSS AREA: 24.50 SQ. FT.
 TRANSFER FLUID: WATER

TEST METHOD: DSET 75 - SE2.7 (ASHRAE 93 - 77)

EGR:BP TO:BG

SOLAR TIME	START	9:48	9:55	10:2	10:9	11:5	11:12
	END	9:55	10:2	10:9	10:16	11:12	11:19
LOCAL TIME	START	10:22	10:29	10:36	10:43	11:39	11:46
	END	10:29	10:36	10:43	10:50	11:46	11:53
MASS FLOW(LB/HR)		371.55	371.57	370.51	368.95	367.23	367.74
T IN (F)		144.95	144.59	144.51	144.55	131.92	131.83
INTEGRAL		16.91	16.87	16.86	16.86	15.39	15.38
T OUT (F)		150.13	149.67	149.02	149.33	138.38	138.27
INTEGRAL		17.52	17.46	17.39	17.42	16.14	16.13
T AMB (F)		97.06	95.37	96.11	96.21	97.44	97.32
INTEGRAL		11.32	11.13	11.21	11.22	11.37	11.35
CP BTU/LB/(F)		0.99990	0.99988	0.99985	0.99986	0.99917	0.99916
WIND DIRECTION		CALM	S	CALM	SE	S	S
WIND SPEED (FPM)		0	600	0	500	600	200
IT *		318.10	319.02	319.51	319.70	322.20	322.03
INTEGRAL		37.11	37.22	37.28	37.30	37.59	37.57
IDN *		275.54	277.41	278.30	278.50	281.67	281.54
INTEGRAL		32.15	32.36	32.47	32.49	32.86	32.85
% DIFFUSE		13.38	13.04	12.90	12.89	12.58	12.57
TILT ANGLE		34.23	32.91	31.62	30.34	21.62	20.80
AZIMUTH ANGLE		65.97	64.07	62.05	59.90	36.01	31.92
INCIDENCE ANGLE		0.	0.	0.	0.	0.	0.
IN/OUT HT. (IN)		41.1	39.7	38.3	36.9	26.9	26.0
P IN (PSI)		12.0	12.0	12.0	12.0	10.0	10.0
DELTA P ***		38.0	37.5	37.7	37.0	37.5	37.5
DELTA T		5.19	5.07	4.51	4.78	6.46	6.44
INTEGRAL		0.61	0.59	0.53	0.56	0.75	0.75
T FLUID AVG		147.54	147.13	146.76	146.94	135.15	135.05
TF - TA		50.48	51.76	50.65	50.73	37.71	37.73
TI - TA		47.88	49.22	48.39	48.34	34.49	34.51
(TF - TA)/IT **		0.159	0.162	0.159	0.159	0.117	0.117
(TI - TA)/IT **		0.151	0.154	0.151	0.151	0.107	0.107
EFFICIENCY, IT		0.247	0.241	0.213	0.225	0.300	0.300
HEAT GAIN *		78.67	76.95	68.18	71.93	96.73	96.64

SOLAR COLLECTOR TEST DATA

TABLE 1. INSTANTANEOUS EFFICIENCY

COMPANY: BATELLE COLS. LABS

REFERENCE NO.: R2116

DSET NO.: 194988

REPORT NO.: 7850809

TEST DATE: 08/09/78

INLET/OUTLET SEPARATION: 73.13 IN.

COLLECTOR MODEL NO.: 1

COLLECTOR SERIAL NO.: BATELLE

COVER TYPE: N/A

APERTURE AREA: 22.85 SQ. FT.

GROSS AREA: 24.50 SQ. FT.

TRANSFER FLUID: WATER

TEST METHOD: DSET 75 - SE2.7 (ASHRAE 93 - 77)

EGR: SP TO: BG

SOLAR TIME	START	11:19	11:26	11:26	11:33	11:40	11:47
	END	11:26	11:33	11:33	11:40	11:47	11:54
LOCAL TIME	START	11:53	12:00	14:00	14:07	14:14	14:21
	END	12:00	12:07	14:07	14:14	14:21	14:28
MASS FLOW (LB/HR)		365.74	365.15	381.11	375.04	376.16	375.08
T IN (F)		131.76	131.74	105.47	105.54	105.53	105.62
INTEGRAL		15.37	15.37	12.30	12.31	12.31	12.32
T OUT (F)		137.99	138.05	115.71	115.59	115.49	115.71
INTEGRAL		16.10	16.11	13.50	13.48	13.47	13.50
T AMB (F)		97.52	97.87	101.53	100.84	100.30	100.61
INTEGRAL		11.38	11.42	11.85	11.76	11.70	11.74
CP BTU/LB/(F)		0.99916	0.99916	0.99818	0.99818	0.99818	0.99818
WIND DIRECTION		S	S	SSW	SSW	S	S
WIND SPEED (FPM)		200	600	860	820	650	310
IT *		321.94	322.77	316.96	317.03	317.41	315.78
INTEGRAL		37.56	37.66	36.98	36.99	37.03	36.84
IDN *		282.11	283.23	273.33	272.61	273.26	271.67
INTEGRAL		32.91	33.04	31.89	31.80	31.88	31.69
% DIFFUSE		12.37	12.25	13.76	14.01	13.91	13.97
TILT ANGLE		20.08	19.46	27.05	28.23	29.45	30.71
AZIMUTH ANGLE		27.56	22.93	-53.29	-55.87	-58.28	-60.53
INCIDENCE ANGLE		0.	0.	0.	0.	0.	0.
IN/OUT HT. (IN)		25.1	24.4	33.3	34.6	36.0	37.3
P IN (PSI)		10.0	10.0	10.0	10.0	10.0	10.0
DELTA P ***		37.3	37.0	---	---	---	---
DELTA T		6.23	6.31	10.24	10.05	9.96	10.10
INTEGRAL		0.73	0.74	1.20	1.17	1.16	1.18
T FLUID AVG		134.87	134.89	110.59	110.56	110.51	110.67
TF - TA		37.35	37.02	9.06	9.73	10.21	10.05
TI - TA		34.23	33.87	3.94	4.70	5.23	5.00
(TF - TA)/IT **		0.116	0.115	0.029	0.031	0.032	0.032
(TI - TA)/IT **		0.106	0.105	0.012	0.015	0.016	0.016
EFFICIENCY, IT		0.289	0.291	0.502	0.484	0.481	0.489
HEAT GAIN *		92.95	93.99	159.05	153.53	152.59	154.29

SOLAR COLLECTOR TEST DATA

TABLE 1.

INSTANTANEOUS EFFICIENCY

COMPANY: BATTELLE COLB LABS
 REFERENCE NO.: R2116
 DSET NO.: 194988
 REPORT NO.: 7880809
 TEST DATE: 08/09/78
 INLET/OUTLET SEPARATION: 73.13 IN.

COLLECTOR MODEL NO.: I
 COLLECTOR SERIAL NO.: BATTELLE
 COVER TYPE: N/A
 APERTURE AREA: 22.85 SQ.FT.
 GROSS AREA: 24.50 SQ.FT.
 TRANSFER FLUID: WATER

TEST METHOD: DSET 75 - 922.7 (ASHRAE 93 - 77)

EGR:BP TO:BG

SOLAR TIME	START	14 57	15 4	15 11	15 18
	END	15 4	15 11	15 18	15 25
LOCAL TIME	START	15 31	15 38	15 45	15 52
	END	15 38	15 45	15 52	15 59
MASS FLOW(LB/HR)		376.79	375.56	375.60	376.11
T IN (F)		95.94	96.03	96.12	96.18
INTEGRAL		11.19	11.20	11.21	11.22
T OUT (F)		108.08	108.41	108.09	108.89
INTEGRAL		12.61	12.65	12.61	12.70
T AMB (F)		100.66	102.36	102.25	101.41
INTEGRAL		11.74	11.94	11.93	11.83
CP BTU/LB/(F)		0.99802	0.99802	0.99802	0.99802
WIND DIRECTION		S	S	SW	S
WIND SPEED (FPM)		650	500	700	350
IT *		307.28	304.50	301.59	299.15
INTEGRAL		35.85	35.53	35.19	34.90
IDN *		259.11	255.29	251.31	248.59
INTEGRAL		30.23	29.78	29.32	29.00
% DIFFUSE		15.68	16.16	16.67	16.90
TILT ANGLE		44.28	45.70	47.13	48.56
AZIMUTH ANGLE		-77.19	-78.47	-79.71	-80.91
INCIDENCE ANGLE		0.	0.	0.	0.
IN/OUT HT. (IN)		51.1	52.3	53.6	54.8
P IN (PSI)		08.0	08.0	08.0	08.0
DELTA P ***		---	---	---	---
DELTA T		12.14	12.38	11.97	12.71
INTEGRAL		1.42	1.44	1.40	1.48
T FLUID AVG		102.01	102.22	102.10	102.53
TF - TA		1.34	-0.14	-0.15	1.12
TI - TA		-4.73	-6.33	-6.13	-5.24
(TF - TA)/IT **		0.004	-0.000	-0.000	0.004
(TI - TA)/IT **		-0.015	-0.021	-0.020	-0.018
EFFICIENCY, IT		0.606	0.622	0.607	0.651
HEAT GAIN %		186.28	189.41	183.17	194.80

DESERT SUNSHINE EXPOSURE TESTS, INC.
BOX 185 - BLACK CANYON STAGE
PHOENIX, ARIZONA 85020

COMPANY: BATTELLE COLS. LABS
REFERENCE NO.: R2116
DSET NO.: 19498S
REPORT NO.: 78S0809
COVER: N/A
TRANSFER FLUID: WATER

MODEL NO.: I
SERIAL NO.: BATTELLE
AVG. MASS FLOW: 372.49 LB/HR
AVG. AMB. TEMP.: 99.05 DEG(F)
AVG. INSOLATION: 315.31 BTU/FT²/HR
GROSS AREA: 24.50 FT²

TEST METHOD: DSET 75-SE2.7 (ASHRAE 93-77)

Figure 1

* $(\text{DEG}(F))/\text{BTU}/\text{FT}^2/\text{HR}$

COLLECTOR TEST DATA

TABLE 2. INCIDENT ANGLE MODIFIER

COMPANY: BATTTELLE	COLLECTOR MODEL NO.: 1
REFERENCE NO.: R2116	COLLECTOR SERIAL NO.: BATTTELLE
DSET NO.: 194988	COVER TYPE: N/A
REPORT NO.: 7880810	APERTURE AREA: 22.85 SQ. FT
TEST DATE: 08/10/78	GROSS AREA: 24.50 SQ. FT
INLET/OUTLET SEPARATION: 73.13 IN.	TRANSFER FLUID: WATER

TEST METHOD		DSET 75 - SE2.7 (ASHRAE 93 - 77)		EGR-SP		JTO-TH	
SOLAR TIME	START	9:15	9:22	11:0	11:7	11:55	12:2
	END	9:22	9:29	11:7	11:14	12:2	12:9
LOCAL TIME	START	9:49	9:56	11:34	11:41	12:29	12:36
	END	9:56	10:3	11:41	11:48	12:36	12:43
MASS FLOW (LB/HR)		372.06	369.39	369.95	368.88	374.00	373.99
T IN (F)		95.74	95.77	96.49	96.59	97.04	97.04
INTEGRAL		11.17	11.17	11.26	11.27	11.32	11.32
T OUT (F)		101.87	102.01	106.57	106.83	108.97	108.81
INTEGRAL		11.88	11.90	12.43	12.46	12.71	12.69
T AMB (F)		96.63	95.38	99.17	99.28	101.53	101.84
INTEGRAL		11.27	11.13	11.57	11.58	11.85	11.88
CP BTU/LB/(F)		0.99797	0.99797	0.99801	0.99801	0.99803	0.99803
WIND DIRECTION		S	S	S	S	S	S
WIND SPEED (FPM)		200	400	225	600	600	52.5
IT *		157.95	159.35	235.27	233.10	282.43	283.03
INTEGRAL		18.43	18.59	27.45	27.19	32.95	33.02
IDN *		256.44	257.67	270.75	270.29	272.94	273.00
INTEGRAL		29.92	30.06	31.59	31.53	31.84	31.85
% DIFFUSE		----	----	----	----	----	----
TILT ANGLE		----	----	----	----	----	----
AZIMUTH ANGLE		----	----	----	----	----	----
INCIDENCE ANGLE		60.	60.	45.	45.	30.	30.
IN/OUT HT. (IN)		47.8	46.5	28.0	27.0	23.2	23.2
P IN (PSI)		14.0	14.0	12.0	12.0	12.0	12.0
DELTA P ***		41.7	41.4	41.5	41.5	---	---
DELTA T		6.13	6.24	10.09	10.25	11.93	11.77
INTEGRAL		0.71	0.73	1.18	1.20	1.39	1.37
T FLUID AVG		98.81	98.89	101.53	101.71	103.00	102.93
TF - TA		2.18	3.51	2.36	2.43	1.47	1.09
TI - TA		-0.88	0.40	-2.69	-2.69	-4.49	-4.79
(TF - TA)/IT **		0.014	0.022	0.010	0.010	0.005	0.004
(TI - TA)/IT **		-0.006	0.002	-0.011	-0.012	-0.016	-0.017
EFFICIENCY, IT		0.588	0.589	0.646	0.661	0.643	0.633
HEAT GAIN *		92.85	93.84	152.00	153.97	181.70	179.27

46 0700

1/2" X 1/2" TO 1/4" INCH 1/2" X 1/2" INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 2

SOLAR COLLECTOR TEST DATA

COMPANY BATELLE COLS LABS
 REFERENCE NO.: R2116
 DSET NO.: 194988
 REPORT NO.: 7880809
 TEST DATE: 08/09/78

TABLE 3. INSTANTANEOUS EFFICIENCY

COLLECTOR MODEL NO. 1
 COLLECTOR SERIAL NO. BATELLE
 COVER TYPE N/A
 APERTURE AREA 22.85 SQ. FT.
 GROSS AREA 24.50 SQ. FT.

SOLAR TIME	START	9:48	9:55	10:2	10:9	11:5	11:12
	END	9:55	10:2	10:9	10:16	11:12	11:19
LOCAL TIME	START	10:22	10:29	10:36	10:43	11:39	11:46
	END	10:29	10:36	10:43	10:50	11:46	11:53
T IN (F)		148.31	148.07	147.77	147.69	136.85	136.39
INTEGRAL		17.30	17.28	17.24	17.23	15.97	15.91
T OUT (F)		155.29	154.63	153.94	154.29	145.23	145.07
INTEGRAL		18.12	18.04	17.96	18.00	16.94	16.93
T AMB (F)		97.06	95.37	96.11	96.21	97.44	97.32
INTEGRAL		11.32	11.13	11.21	11.22	11.37	11.35
WIND DIRECTION	CALM	S	CALM	SE	S	S	
WIND SPEED (FPM)	0	600	0	500	600	200	
IT *	318.10	319.02	319.51	319.70	322.20	322.03	
INTEGRAL	37.11	37.22	37.28	37.30	37.59	37.57	
IDN *	275.54	277.41	278.30	278.50	281.67	281.54	
INTEGRAL	32.15	32.36	32.47	32.49	32.86	32.85	
% DIFFUSE	13.38	13.04	12.90	12.89	12.58	12.57	
TILT ANGLE	34.23	32.91	31.62	30.34	21.62	20.80	
AZIMUTH ANGLE	65.97	64.07	62.05	59.90	36.01	31.92	
INCIDENCE ANGLE	0.	0.	0.	0.	0.	0.	
DELTA T	6.97	6.56	6.16	6.60	8.38	8.68	
INTEGRAL	0.81	0.77	0.72	0.77	0.98	1.01	
T FLUID AVG	151.80	151.35	150.85	150.99	141.04	140.73	
TF - TA	54.74	55.98	54.74	54.79	43.60	43.41	
TI - TA	51.25	52.70	51.66	51.49	39.41	39.07	
(TF - TA)/IT **	0.172	0.175	0.171	0.171	0.135	0.135	
(TI - TA)/IT **	0.161	0.165	0.162	0.161	0.122	0.121	

SOLAR COLLECTOR TEST DATA

COMPANY: BATELLE COLS LABS
 REFERENCE NO: R2116
 DSET NO.: 19498S
 REPORT NO.: 78S0809
 TEST DATE: 08/09/78

TABLE 3. INSTANTANEOUS EFFICIENCY

COLLECTOR MODEL NO.: 1
 COLLECTOR SERIAL NO.: BATTELLE
 COVER TYPE: N/A
 APERTURE AREA: 22.85 SQ. FT.
 GROSS AREA: 24.50 SQ. FT.

SOLAR TIME	START	11:19	11:26	11:26	11:33	11:40	11:47
	END	11:26	11:33	11:33	11:40	11:47	11:54
LOCAL TIME	START	11:53	12:00	12:00	12:07	12:14	12:21
	END	12:00	12:07	12:07	12:14	12:21	12:28
T IN (F)		136.23	135.91	113.14	112.97	113.03	113.06
INTEGRAL		15.89	15.86	13.20	13.18	13.19	11.31
T OUT (F)		144.47	144.30	123.87	124.06	123.94	124.62
INTEGRAL		16.86	16.84	14.45	14.47	14.46	12.46
T AMB (F)		97.52	97.87	101.53	100.84	100.30	100.53
INTEGRAL		11.38	11.42	11.85	11.76	11.70	10.05
WIND DIRECTION		S	S	SSW	SSW	S	S
WIND SPEED (FPM)		200	600	860	820	650	310
IT *		321.94	322.77	316.96	317.03	317.41	315.78
INTEGRAL		37.56	37.66	36.98	36.99	37.03	36.84
IDN *		282.11	283.23	273.33	272.61	273.26	271.67
INTEGRAL		32.91	33.04	31.89	31.80	31.88	31.69
% DIFFUSE		12.37	12.25	13.76	14.01	13.91	13.97
TILT ANGLE		20.08	19.46	27.05	28.23	29.45	30.71
AZIMUTH ANGLE		27.56	22.93	-53.29	-55.87	-58.28	-60.53
INCIDENCE ANGLE		0.	0.	0.	0.	0.	0.
DELTA T		8.24	8.39	10.74	11.09	10.91	11.56
INTEGRAL		0.96	0.98	1.25	1.29	1.27	1.16
T FLUID AVG		140.35	140.10	118.50	118.52	118.48	118.84
TF - TA		42.83	42.23	16.98	17.68	18.18	18.30
TI - TA		38.71	38.04	11.61	12.14	12.73	12.53
(TF - TA)/IT **		0.133	0.131	0.054	0.056	0.057	0.058
(TI - TA)/IT **		0.120	0.118	0.037	0.038	0.040	0.040

SOLAR COLLECTOR TEST DATA

COMPANY: BATELLE COLS. LABS
 REFERENCE NO.: R2116
 DSET NO.: 19498S
 REPORT NO.: 78S0809
 TEST DATE: 08/09/78

TABLE 3. INSTANTANEOUS EFFICIENCY

COLLECTOR MODEL NO.: I
 COLLECTOR SERIAL NO.: BATTELLE
 COVER TYPE: N/A
 APERTURE AREA: 22.85 SQ. FT.
 GROSS AREA: 24.50 SQ. FT.

SOLAR TIME	START	14:57	15:04	15:11	15:18
END		15:04	15:11	15:18	15:25
LOCAL TIME	START	15:31	15:38	15:45	15:52
END		15:38	15:45	15:52	15:59

T IN (F)	106.00	105.92	106.21	106.29
INTEGRAL	12.37	12.36	12.39	12.40
T OUT (F)	119.01	120.42	119.23	120.43
INTEGRAL	13.89	14.05	13.91	14.05
T AMB (F)	100.66	102.36	102.25	101.41
INTEGRAL	11.74	11.94	11.93	11.83

WIND DIRECTION	S	S	SW	S
WIND SPEED (FPM)	650	500	700	350
IT *	307.28	304.50	301.59	299.15
INTEGRAL	35.85	35.53	35.19	34.90
IDN *	259.11	255.29	251.31	248.59
INTEGRAL	30.23	29.78	29.32	29.00
% DIFFUSE	15.68	16.16	16.67	16.90
TILT ANGLE	44.28	45.70	47.13	48.56
AZIMUTH ANGLE	-77.19	-78.47	-79.71	-80.91
INCIDENCE ANGLE	0.	0.	0.	0.

DELTA T	13.01	14.50	13.01	14.14
INTEGRAL	1.52	1.69	1.52	1.65
T FLUID AVG	112.51	113.17	112.72	113.36
TF - TA	11.84	10.81	10.47	11.95
TI - TA	5.34	3.56	3.96	4.88
(TF - TA)/IT **	0.039	0.035	0.035	0.040
(TI - TA)/IT **	0.017	0.012	0.013	0.016

BATTELLE COLUMBUS LABORATORIES

Introduction

This report presents the data and results of a thermal performance test conducted on a Battelle Columbus Laboratories solar collector system. The system consisted of and included:

- (1) Battelle Solar Collector #2, constructed from double-skinned, transparent acrylic sheet with four small vertical passages through which a "black fluid" was pumped. Again, as with Battelle solar collector #1 described in DSET Report No. 78S0809, the "black fluid" performed a dual role of both absorber of incident solar radiation and of the heat-transfer medium. The "black fluid" was the same as that used in the previous test except that it was diluted by approximately 50%.
- (2) A centrifugal all-plastic pump and motor with plastic diaphragm valves for flow.
- (3) A counterflow heat exchanger.

The test was performed in a manner consistent with the previous test as described in DSET Report No. 78S0809. However, near the end of the instantaneous efficiency portion of the test a leak occurred in the collector and testing was terminated. The preconditioning, time constant and incident angle modifier portions of the ASHRAE 93-77 testing procedure were not performed on the second Battelle system and only 12 instantaneous efficiency data points were determined.

As with Report No. 78S0809, the data and results of this test will be presented consistent with the ASHRAE 93-77 method of test but it should be noted that the results reflect the thermal performance of the entire system and not that of the collector itself.

Description of Test Set-Up

The entire Battelle system was mounted on an Exactly Normal Incidence (ENI) solar tracking mount as shown schematically in Figure 1. Inlet and outlet temperatures for efficiency determinations were measured with platinum resistance thermometers at the heat exchanger on water circulated through the DSET test facility. Inlet and outlet temperatures (not used in the efficiency determinations) measured at the collector on the "black fluid" were determined with Type "T" thermocouples. Responsibility for constant flow of "black fluid" through the Battelle system was left to Battelle personnel. Flow measurements of "black fluid" were determined volumetrically by such personnel at a break in the "black fluid" loop between the heat exchanger and pump where the black fluid was allowed to flow into a reservoir before continuing through the loop (not shown in Figure 1).

Description of Test Method

The ASHRAE 93-77 thermal performance test procedures consist of four separate parts: (1) Preconditioning (omitted per client's request), (2) Determination of the system's time constant (not performed due to leak in collector), (3) Instantaneous efficiency performance tests, and (4) Determination of the incident angle modifier (not performed due to leak in collector).

Instantaneous Efficiency Test

The instantaneous efficiency tests are conducted to determine the efficiency of the system as a function of the incident solar radiation, ambient temperature, and heat exchanger inlet temperature.

ASHRAE 93-77 defines the solar collector efficiency as the amount of useful energy extracted from the collector divided by the amount of incident solar energy intercepted by the gross area of the collector.

At least sixteen (16) efficiency "data points" are obtained during the test in order that a governing "efficiency curve" can be generated.

All instantaneous efficiency testing is conducted in accordance with ASHRAE 93-77 and DSET Specification 75-SE2, appended herewith, utilizing a sun-tracking altazimuth mount which maintains the collector at normal incidence during the test periods.

Data and Results

Instantaneous Efficiency Performance Test

The instantaneous efficiency test with the collector at normal incidence was conducted at a constant flow rate while the inlet temperature was varied for each set of efficiency points.

The data obtained and relevant calculated values are given in the attached tables. Following the tables is a graph of the instantaneous efficiency as a function of the inlet parameter, $(T_i - T_a / I_t)$.

Also included in the data section are inlet and outlet temperatures (Table 2) measured directly on the "black fluid" at the collector using Type "T" thermocouples. Time intervals were the same as the previous efficiency data.

Analysis of the efficiency data was performed employing a first order least squares fit which resulted in the following efficiency equation, which is shown as the analysis curve on the graph.

$$\eta = 0.702 - 2.099 \left[\frac{T_i - T_a}{I_t} \right]$$

At an inlet parameter of zero the equation yields a value of 0.702 for the effective transmittance-absorptance product, $F_R \alpha \tau$, where F_R is the heat removal factor.

Differentiation of the equation with respect to the inlet parameter resulted in the constant value of -2.099 for the overall heat losses, $F_R U_L$, from the collector.

Discussion of Results

A linear fit is used to describe the instantaneous efficiency data because the collector was operated at low temperatures ($T_{i,max} < 150^\circ\text{F}$) where the dominant heat loss factor is due to convection and, for the most part, convective losses are linear functions of the temperature differential between the absorber and ambient.

Collectors of this type, in which the heat transfer medium is in direct contact with the collector cover, generally exhibit a sensitivity to wind. This may have caused the deviations from the analysis line shown on the instantaneous efficiency graph.

Note that only three sets of data points were taken. While attempting to determine a point at an inlet temperature higher than the last set of data points obtained, the collector developed a leak. An effort was made to repair the collector by Battelle personnel with DSET assistance but the attempt was unsuccessful, possibly due to collector handling. No further data points were taken.

Consequently, due to the limited number of data points used to determine the efficiency curve, any extrapolation outside the region of the data points should be done with care since this may lead to erroneous conclusions.

DSET LABORATORIES, INC.
BOX 1950 - BLACK CANYON STAGE
PHOENIX, ARIZONA 85029

DSET SOFTWARE SYSTEM VERSION 06

COMPANY: BATTELLE COLS. LABS
REFERENCE NO.: R2116
DSET NO.: 19498S
REPORT NO.: 78S0831
COVER:
TRANSFER FLUID: WATER

MODEL NO.: 2
SERIAL NO.: 00000000
AVG. MASS FLOW: 213.00 LB/HR
AVG. AMB. TEMP.: 90.00 DEG(F)
AVG. INSOLATION: 818.00 BTU/FT2/HR
GROSS AREA: 26.00 FT2
TEST DATE(S): 08/31/78

TEST METHOD: DSET 75-SE2.7 (ASHRAE 93-77)

Figure 1

* DEG(F) / (BTU/FT2/HR)